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

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This Thesis is Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Structural Engineering, Faculty of Graduate Studies, An-Najah National University, Nablus, Palestine.

2018

Dedication

To my father

To my mother

To my brothers

To my sister

To my precious ones

To all friends and colleagues

To my teachers

To everyone working in this field

To all of them

I literally dedicate this work

Acknowledgment

First of all, praise is to Allah for helping me in making this research possible.

Then, I would like to express great thanks and sincere gratitude to my supervisors

Dr. Abdul Razzaq A. Touqan

Dr. Mahmud M.S. Dwaikat

For their guidance, suggestions and assistance during the preparation of this thesis.

Special mention goes to my parents, brothers, sister, friends and colleagues.

الإقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل عنوان:

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

أقر بأن ما اشتملت عليه هذه الرسالة إنما هي نتاج جهدي الخاص، باستثناء ما تم الإشارة اليه حيثما ورد ، وأن هذه الرسالة ككل، أو أي جزء منها لم يقدم لنيل أي درجة أو لقب علمي أو بحثي لدى أي مؤسسة تعليمية أو بحثية أخرى.

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification

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Signature: **التوقيع :**

Date: **التاريخ :**

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List of Abbreviations

ACI	American Concrete Institute
ASCE / SEI	American Society of Civil Engineers- Structural Engineering Institute
ATC	Tentative Provision for the Development of Seismic Regulations for Buildings
C-D	Concrete Wall with Door Opening
C-W	Concrete Wall with Window Opening
EN	English version for Euro Code
F	moment of inertia ratio plus area ratio between walls to columns
H/B	Wall Aspect Ratio
KBC	Korean Building Code
NBCC	National Building Code of Canada
NEHRP	National Earthquake Hazards Reduction Program
R^2	Coefficient of Determination
RC	Reinforced Concrete
R_D	Displacement Ratio
R_O	Opening Ratio
R_S	Stiffness Ratio
R_T	Period Ratio
R_{TM}	Period Ratio Modal Analysis Value to Code Value
SEAOC	Structural Engineers Association of California
SW	Shear Wall
UBC	Uniform Building Code

List of Symbols

A:	Shear wall sectional area
A_B:	Building plan area
A_c:	Column area
A_e:	Horizontal cross sectional area of shear wall
A'_e:	Equivalent shear area
A_f:	Tributary floor plan area for wall in the direction of period calculation
A_i:	cross sectional area of shear wall in the direction of period calculation at level i of the floor
A_w:	wall area
B:	Plan dimension of the building in the direction of period calculation
β:	Ratio of long side to short side of building
b:	wall thickness
D_e:	Length of shear wall in the direction of period calculation
D_i:	Length of shear wall in the direction of period calculation
D_s:	Length of shear wall in the direction of period calculation
E_c:	Concrete modulus of elasticity
f_i:	Lateral Force at level i of the floor
G:	Shear modulus
g:	Gravity acceleration
H:	Height of the building
h_w:	Wall height
h:	height of the floor
I:	Moment of inertia
I_c:	Column moment of inertia
I_w:	Wall moment of inertia
j:	Polar moment of inertia of the plan
K:	Stiffness of the structure
L_w:	Wall length
M:	Mass of the structure
n:	Number of floors
P:	lateral load
ρ:	ratio of wall area to tributary floor area in the direction of period calculation
ρ_{as}:	Ratio of short side shear wall area to total floor area
ρ_{al}:	Ratio of long side shear wall area to total floor area
ρ_{min}:	Ratio of minimum shear wall area to total floor area
T:	Period of the structure

T_F:	Period due to flexural deformation
T_S:	Period due to shear deformation
t_w:	Wall thickness
W:	Unit floor weight
W_i:	Weight at level i of the floor
δi:	Elastic deflection due to lateral force at level i of the floor
υ:	Poisson’s ratio
Δ:	total Lateral deflection
Δ_f:	Lateral deflection due to flexure
Δ_s:	Lateral deflection due to shear

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Abstract

A common approach in resisting lateral forces is the use of reinforced concrete shear walls in low-rise and mid-rise 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 like doors and windows 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.

To generate data on the effect of openings on the fundamental period of shear walls, finite element analysis using SAP2000 structural analysis program is used as a main source in this study after verifying the results by comparing them to theoretical equations proposed by Hsiao in 2014 and hand calculations of period using Rayleigh's method.

Finite element analysis is made first by using linear elastic analysis at the wall level with different central window opening sizes, and for different wall heights. Then, multi-floor typical shear wall buildings with different central window opening sizes are studied for various numbers of floors and different stiffness ratios of walls to columns. The results are compared to ASCE7-16 code equations for estimating the fundamental period of shear wall structures.

After conducting this study, it is found that the openings in concrete shear walls have a major effect on the fundamental period and on the lateral stiffness of shear-walled structures. Central window opening ratio of 3% is the maximum ratio that can be neglected safely in a one floor building, and this ratio increases by increasing the number of floors. Door opening ratio of 65% converts the solid wall to behave as a frame. The effect of wall openings on the fundamental period of shear wall structures depends on the height of the building and on the deflection mode of the shear walls, where it is either shear or flexural deflection mode.

Finally, statistically regression is used to fit an equation for estimating the increase in the fundamental period of the shear – walled regular structures due to openings in the shear walls. Such an equation is quite useful in the conceptual design phase of buildings. The final results are discussed by conducting comparisons between finite element results and the fitted equation results.

1 Introduction

1.1 Scope

In general, buildings should have sufficient capacity to resist earthquake forces or any lateral loads. Different lateral resisting systems are used to increase the stiffness capacity; the most common lateral bracing system is the shear wall system.

In this chapter, shear wall system will be briefly introduced and the problem statement, research objectives, scope of this work, methodology, and thesis outline shall be discussed.

1.2 The shear wall systems

Reinforced concrete shear walls are the most frequently used form of lateral resisting structural elements. This construction may take many forms according to the location and function of the walls like core walls, coupled walls, and planar walls. Shear wall systems are the most appropriate systems in moderate sized buildings up to 20 floors, and in low-rise construction (Bungale). They are not preferred in the case of high-rise buildings, because of large use of materials in this system compared to other lateral bracing systems, like moment resisting frames. The shear wall systems are not preferred in the open spaced structures or glazed exterior walls due to architectural functions. 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 makes the buildings more rigid. Although the internal base shear force in this type of construction are generally more than that of other resisting systems, the capacity of the shear wall systems can accept this large forces induced by earthquakes.

As mentioned previously, 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.

1.3 Fundamental period

The structure oscillates back and forth due to free vibration when it is subjected to a horizontal displacement due to lateral load like earthquake. 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 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 used construction material, the lateral bracing system (reinforced concrete shear walls, reinforced concrete moment resisting frames, steel moment resisting frames, and dual 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 using the following equation:

$$\boldsymbol{T = 2\pi\sqrt{\frac{m}{k}}} \qquad 1.1$$

Where:

m: Mass of the structure.

k: Stiffness of the structure.

In theoretical models many methods were developed for calculating the fundamental period like Dunkerley's method (Bishop and Johnson), and the most famous of these methods is Rayleigh's method.

In Rayleigh's method the estimation of the natural period of the system is given by using lumped masses distribution model for quick estimation. This method depends on the conservation of energy principle assuming no damping, which states that the maximum kinetic energy must equal the maximum potential energy. The method is useful for multi-degrees of freedom system. Many codes use this method as a rational method and the time period is calculating using the following equation:

$$T = 2\pi\sqrt{\left(\sum_{i=1}^{n} w_i \delta_i^2\right) \div \left(g \sum_{i=1}^{n} f_i \delta_i\right)} \qquad 1.2$$

Where:

f_i: Lateral force at level i of the floor.

δ_i: Elastic deflection due to lateral force at level i of the floor.

g: Gravity acceleration.

w_i: Weight at level i of the floor.

1.4 Problem statement

Shear walls in buildings may have openings as doors or windows to achieve architectural functions. The openings cause a reduction in wall lateral stiffness, and this leads to a variation in overall fundamental period of the building. The designers generally ignore the effect of these openings in walls to simplify both modeling and analysis of the structures using finite element programs. Such choice of neglecting these openings may produce unreal results in seismic design of buildings. Moreover, when using the code formula in estimating the fundamental period of shear wall structures, ignoring the opening effect leads to unreal natural period which leads to non-representative design against seismic loads.

1.5 Research objectives

The general objectives in this study are the following:

- Investigation the effect of the openings sizes in shear walls on the fundamental periods of shear walls structures.

- Identifying the maximum ratios of openings in the wall to the size of the side wall that can be neglected in modeling the structures for the purpose of simplification.
- Recognizing the minimum opening ratio that converts the behavior of a solid wall to that of a frame, in order to help the designers to make their models as simple and safe as possible.
- Comparing the finite element results to the results of ASCE7-16 code formula adopted for approximating the fundamental period of shear wall structures.
- Deriving an equation for estimating the increase in the period of the shear-walled buildings due to openings in shear walls through statistical regression of the finite element results.

1.6 Assumptions

This thesis is restricted in assumptions to the following:

1. Material behaves linearly and yielding effect can be neglected.
2. P-delta effects will be neglected. These effects refer to the abrupt changes in ground shear, overturning moment, and the axial force distribution at the base of sufficiently structure or structural component when it is subjected to a critical lateral displacement due to lateral forces.
3. The thickness of the walls and slabs are calculated according to ACI318M-14 code and they found to be 20cm.
4. The slabs are assumed to be two-way flat plate slabs.

5. The columns are assumed squared in shape.
6. All members have concrete compressive strength of 24MPa.
7. The superimposed dead load is calculated and is found equals to $4kN/m^2$.
8. The openings are restricted to be squared central window openings.
9. The building is restricted to a regular squared shape in both plan and vertical directions. The regular case will be existed when the center of mass and the center of rigidity are on each other, or the distance between them is so small.
10. The fundamental period that will be considered is that taken from the first mode of the modal analysis.
11. The slabs and shear walls modeled as shell- thin elements.

1.7 Methodology

First, a literature review will be conducted so as to know the parameters which affect the fundamental period estimation in shear wall structures, and to understand analytical methods or experimental results that may be used to verify the finite element results. The commercial program SAP2000 based on using finite element method is then chosen to be the calculation tool, to find the results from different typical models that will be simulated in this thesis.

The simulation studies will be divided into two levels: The first level, called the “wall level”, is used to study the effect of concrete compressive strength, wall geometry, opening size on the stiffness and on the fundamental period of an individual wall, the second level, called the "building level", is used to study the effect of opening ratio, building height and stiffness ratio on period and stiffness of 3D buildings with regular distribution of planar shear walls.

The methodology that will be used to find the effect of openings on the fundamental period of the shear wall structures is to relate the modal period of both walls and buildings with openings to that without openings $\frac{T_{Modal\ analysis\ with\ openings}}{T_{Modal\ analysis\ without\ openings}}$, and when compared to the ASCE7-16 code formula in approximating the fundamental period of shear wall buildings the ratio will be used $\frac{T_{Modal\ analysis\ with\ openings}}{T_{code}}$.

The verification process has much importance when using finite element analysis program. This process will be carried out on both study levels. In the "wall level", the flexural and shear deflections of the studied wall will be calculated manually and compared to the program result. The deflection calculation will be carried out to both opening and solid walls. For solid wall, the acceptable difference between manual results and program deflection results is up to 5%, and for walls with openings, the acceptable difference between manual results and program deflection results is up to 25%. In the "building level" the period will be calculated manually using Rayleigh's method. The results shall be compared to program modal analysis, and the difference between manual and program results can be accepted up to 10%.

1.8 Thesis outline

This thesis is divided into five chapters. Chapter1 (Introduction) is an introduction to the research, problem statement, research objectives, scope of work, and methodology. Chapter 2 (Literature review) presents the results of the previous studies. Chapter 3 (Wall-level: modeling and results) discusses the modeling of individual concrete walls with different opening ratios. It also studies the effect of the wall aspect ratio and the wall concrete compressive strength on the lateral deflection of the wall, and to find the ratio where shear deformation can be neglected. The effect of opening ratio on the lateral deflection of the wall will also be presented. This chapter also discusses when a solid wall will behave as a frame by studying 5 models of different door openings sizes. Chapter 4 (Building-level: modeling and results) focuses on the ‘building level’ where two typical regular buildings with shear walls of variable opening ratios are studied, to see the effect of opening ratios and building height on the lateral displacement and fundamental period of these structures. The results of this study will be compared to ASCE7-16 code formula for estimating the period of such buildings. Moreover, this chapter will include sections for data fitting to find an equation for period ratio of the buildings which may have central window opening. Chapter 5 (Conclusions, Recommendations, and Future work) includes the conclusions, recommendations, and future research topics to extend the current work. The Appendices include the verification of finite element software results by using hand calculation methods for lateral deflection and fundamental period. These verifications are thus of prime importance to confirm that the software gives accurate results.

2 Literature review

2.1 General

This chapter gives brief information collected from many papers and studies, dealing with the behavior of reinforced concrete shear walls with and without openings. These studies will be divided into theoretical and experimental studies, and numerical studies. Moreover, this chapter discusses papers that made comparison between calculations of fundamental period for shear wall buildings and rational methods like Rayleigh method or dynamic modal analysis results. Most of these papers are related to experimental and analytical studies of the capacity of shear walls to resist dynamic loads.

2.2 Theoretical and experimental studies

In 1989 Sozen proposed a theoretical equation for estimating the fundamental period of shear wall structures without openings, where the flexural behavior of the walls dominates the lateral response and the lateral bracing system is the shear wall system. This equation was derived by simplifying an equivalent uniform cantilever beam model with fixed distance between floors and equal floors masses. The proposed Eq. 2.1:

$$\boldsymbol{T = 6.25\frac{h_w}{l_w} n\sqrt{\frac{wh_s}{gpE_c}}} \qquad 2.1$$

Where:

h_w: Total wall height.

l_w: Wall length.

n: Number of floors.

w: Unit floor weight.

h_s: Typical floor height.

g: Gravity acceleration.

E_c: Concrete modulus of elasticity.

p: 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).

In 1992, Wallace and Moehle carried out a research program on assessment of both base shear and fundamental period of shear walls. By using Sozen proposed equation (Eq. 2.1), the researchers checked the validity of this equation by comparing the calculated period of 10 bearing walls buildings (no columns and only shear walls) with number of floors in the range between 10 and 23 floors with measured period from small amplitude vibration earthquakes (Calcagni 1987, and Midorikawa 1990 earthquakes). The researchers drew the calculated period from Sozen equation versus recorded period during elastic motions of earthquakes as shown in Figure 2.1. This figure shows the accuracy of Sozen proposed equation (Eq. 2.1), where the values of the calculated tested buildings periods for both long and transverse direction of the buildings by Sozen equation and measured periods are around the 1:1 line, so they concluded that the measured and calculated periods agree reasonably well. Figure 2.2 shows the period calculated by Eq. 2.1 (Sozen equation) for 10 floors and 20 floors with different wall aspect ratios h_w/l_w equals to 3, 5, and 7 compared to the ratio of side wall area in one direction to total floor plan area, where h_w represents the height of the wall and l_w represents the length of the wall. From Figure 2.2 Wallace and Moehle noticed that if the ratio of side wall area in the direction of the calculation to the total floor plan area increased, then the period of the buildings decreased because the building will be more rigid.

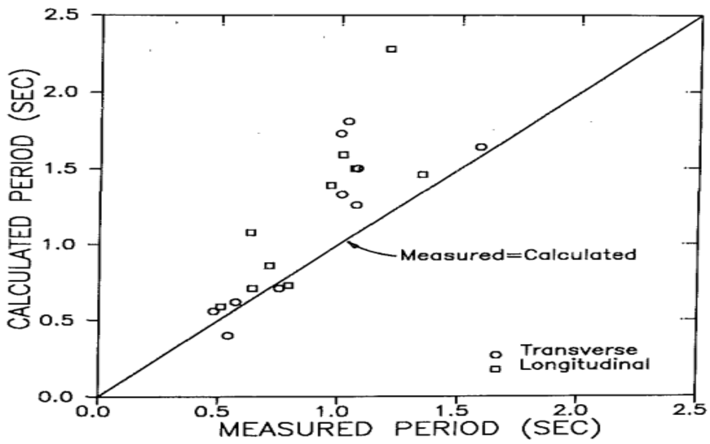

Figure 2.1: Comparison of computed and measured fundamental period in both building directions [Wallace and Moehle, 1992]

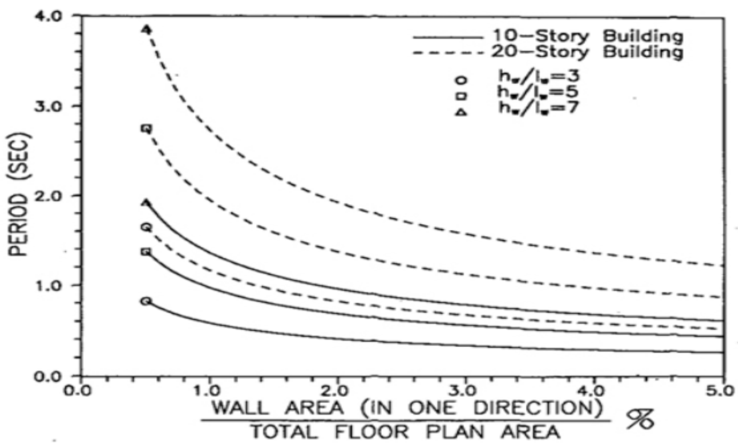

Figure 2.2: Calculated period versus relative wall area ratio [Wallace and Moehle, 1992]

In 1997, Goel and Chopra derived an equation for estimating the fundamental period of shear wall structures with no openings based on Dunkerley's method. The equation is developed based on the behavior of a cantilever beam with flexural and shear deformation as shown in equations from 2.2 to 2.4.

$$T = \sqrt{{T_F}^2 + {T_S}^2} \qquad 2.2$$

$$T_F = \frac{2\pi}{3.516}\sqrt{\frac{m}{EI}}H^2 \qquad 2.3$$

$$T_S = 4\sqrt{\frac{m}{kG}}\frac{1}{\sqrt{A}}H \qquad 2.4$$

Where,

T_F: Fundamental period due to pure flexural deformation

T_S: Fundamental period due to pure shear deformation

m: Mass per unit height

E: Concrete modulus of elasticity

I: Shear wall section moment of inertia

G: Shear modulus

k: Shape factor to account for non-uniform distribution of shear stresses (equals to $\frac{5}{6}$ for rectangular sections)

A: Shear wall section area

H: Height of the building

For the purpose of simplification, and after Goel and Chopra combined the previous equations, they concluded the following equations in a convenient form for buildings.

$$T = c' \frac{1}{\sqrt{A'_e}} H \qquad 2.5$$

$$c' = 40\sqrt{\frac{p}{k \cdot G}} \qquad 2.6$$

Where,

p : 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: Equivalent shear area expressed as a percentage of A_B.

$$A'_e = 100.\frac{A_e}{A_B} \qquad 2.7$$

$$A_e = \sum_{i=1}^{NW} \left(\frac{H}{H_i}\right)^2 \frac{A_i}{\left[1+0.83\frac{H_i}{D_i}\right]} \qquad 2.8$$

Where:

A_e: Equivalent shear area assuming that the stiffness properties of each wall are uniform over its height.

H_i , A_i, and D_i: 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 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, however they want to account for variation in properties 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. Also, they discovered that the empirical formulas in the US codes (UBC-97, SEAOC-96, NEHRP-94) (Eq. 2.9) for estimating the fundamental period of shear wall buildings were grossly inadequate as shown in Figure 2.3, where there are many measured periods under the code period formula values.

$$T_a = 0.02(H^{0.75}) \qquad 2.9$$

Where:

H : Height of the building in feet.

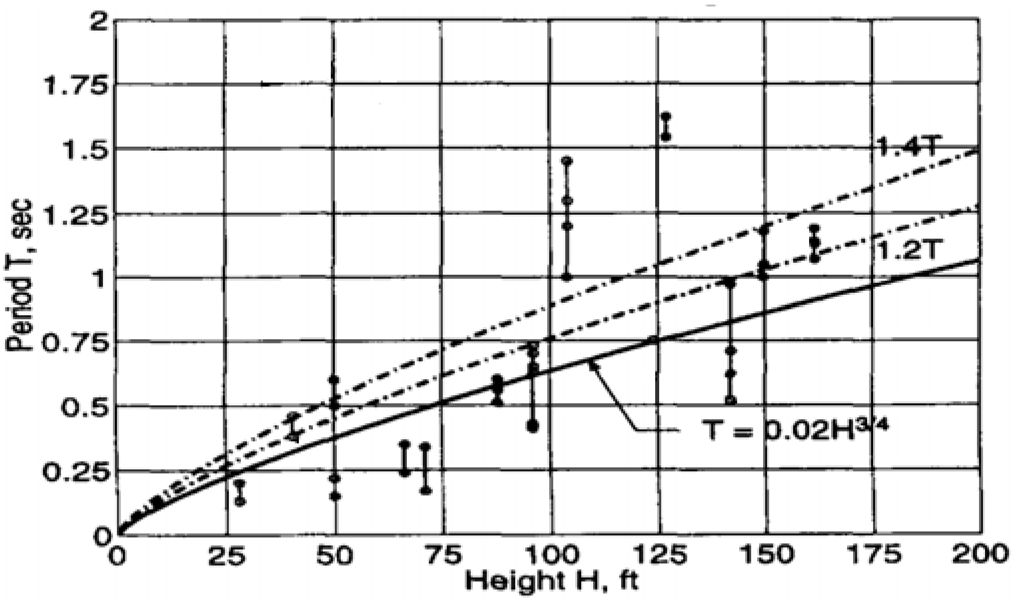

Figure 2.3: Comparison between period from UBC97 formula and the measured period at different heights of buildings [Goel and Chopra, 1997]

Goel and Chopra made a restriction on the period from rational analysis method like Rayleigh's method equals to 1.4 times the value from the empirical formulas like Eq. 2.9, and they clarified that the fundamental period obtained by empirical formulas should be smaller than true period obtained by modal analysis or rational analysis to obtain conservative estimation for base shear.

In 2000, Lee et al. carried out full scale measurement on the fundamental period of 50 reinforced concrete shear wall buildings with and without openings and with total height of buildings from 40m to 68m, and then compared these results with codes formula UBC-97 and SEAOC-96 alternative equation (Eq. 2.10), NBCC-1995 (Eq. 2.12), Korean Building Code (KBC-1988) (Eq. 2.13), and dynamic analysis.

$$T_{a-SEAOC96} = \frac{0.0743}{\sqrt{A_c}}\left(H^{0.75}\right) \tag{2.10}$$

$$A_c = \sum_{i=1}^{NW} A_e\left[0.2 + \left(\frac{D_e}{H}\right)^2\right];\ \frac{D_e}{H} \leq 0.9 \tag{2.11}$$

$$T_{a-NBCC} = 0.09\frac{H}{\sqrt{D_s}} \tag{2.12}$$

$$T_{a-KBC} = 0.09\frac{H}{\sqrt{B}} \tag{2.13}$$

Where:

H : Height of the building in meters.

A_c : Combined effective area of the shear walls in m^2.

A_e : Horizontal cross sectional area of shear wall in m^2.

D_e : Length in meter of shear wall in the direction parallel to the applied forces.

D_s : Length of wall in meters in the direction parallel to the applied forces.

B : Plan dimension of the building in the direction parallel to the applied forces without regard to shear wall dimensions.

The comparison showed a large gap between different codes formulas and the results obtained from experiments. The codes formulas generally give smaller values of the periods than the measured periods from earthquakes and dynamic analysis for many tested buildings.

Lee et al. concluded that none of the code formulas examined in their study are sufficient for estimating the fundamental period of buildings with RC shear walls dominated system. They proposed improved formula by regression analysis on the basis of the measured period data (Eq. 2.14).

$$T_R = \frac{0.4(H^{0.2})}{\sqrt{L_w} - 0.5} \qquad 2.14$$

Where:

H : Height of the building in meters.

L_w : Total wall length in meter aligned in the direction of calculation.

In 2010, Kwon and Kim took over 800 building fundamental periods from 67 earthquake events to evaluate the empirical formula in ASCE7-05 for concrete and steel moment resisting frames and for all other bracing systems. These buildings included steel, reinforced concrete moment resisting frames, and shear wall buildings with and without openings in shear walls. Kwon and Kim found high variation between period from the code empirical formula and the measured periods of low to medium rise buildings. The code formula (Eq. 2.15) for large numbers of reinforced concrete shear wall buildings overestimates the lower bound of the structural period which leads to un-conservative seismic design as shown in Figure 2.4, where the measured periods is under the lower bound. This conclusion is consistent with the research by Goel and Chopra 1997, where the large values of measured periods of reinforced concrete shear wall buildings were under $1.4T_a$ as shown in Figure 2.3.

Kwon and Kim recommended to use C_t=0.015 in the empirical formula (Eq. 2.15) instead of 0.02 in foot unit for empirical formula to estimate the fundamental period of all other bracing systems including the shear wall system.

$$T_{a-ASCE7-05} = 0.02(h^{0.75}) \quad 2.15$$

Where:

h : Height of the building in feet.

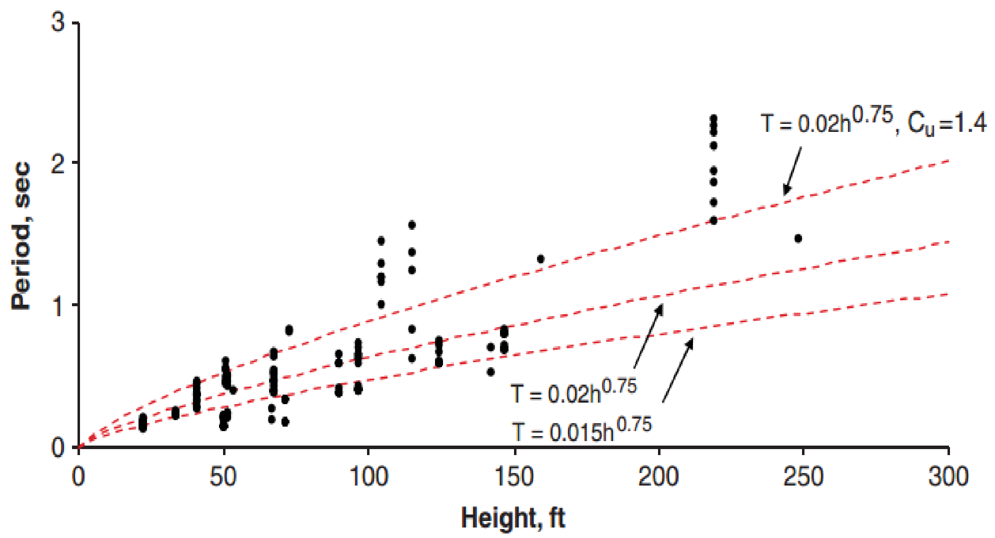

Figure 2.4: Comparison between periods calculated by ASCE7-05 equation versus buildings heights [Kwon and Kim, 2010]

In 2014, Farid Challah et al. derived a formula based on Dunkerley's method for determination of the fundamental period of shear wall buildings, where the lateral bracing system is the shear wall system. The equation (Eq. 2.16) considers only the flexural deformation for a cantilever beam model and ignores the shear deformation. It is also adopts the assumptions of uniform floors heights and uniform floors masses.

$$T_f = 1.8n(n+1)\sqrt{\frac{mh^3}{EI}} \qquad 2.16$$

Where:

n : Number of floors.

h : Height of the building.

m : Mass of typical floor.

E : Concrete modulus of elasticity.

I : Moment of inertia of bracing shear walls system.

In 2014, Hsiao proposed a new hand calculations method to estimate the rigidity and the lateral deflection of shear walls with openings with an acceptable difference between finite element method and his hand calculations method results.

The main difference between Hsiao method and Brandow et al. method is due to their assumption of the rotation of the top piers. Hsiao method allows the piers at the top to rotate, while Brandow et al. method assumes that the top piers are completely restrained from rotation.

Hsiao made the following assumptions while deriving his method: (1) The wall is in one floor only (2) A single opening or one layer of multiple openings with the same height elevation (3) The analysis is restricted to linear elastic (4) “The foundations are Rigid and no wall deflection due to foundation rotation”

The assessment of Hsiao method was made by applying it on three examples. Then, the results of Hsiao method were compared to Brandow et al. and finite element method. Hsiao concluded that his method is more accurate than Brandow method.

Hsiao method is divided into 9 steps, where the wall is subdivided into pieces and the equivalent frame method is used to find the deflection of each piece, and then the deflections are combined by a sort of superposition. The following is a summary of these steps:

- Step 1: Referring to Figure 2.5 the parameters are defined as follows:

  D_b: distance from the bottom of the wall to the bottom of the opening.

  D_t: distance from the top of the wall to the top of the opening.

  h_p: opening height.

  L_{p1} and L_{p2}: effective piers length.

  W_{p1} and W_{p2}: piers width.

  X_{b1} and X_{b2}: distance from the bottom of the effective piers length to the bottom of the opening.

  X_{t1} and X_{t2}: distance from the top of the effective piers length to the top of the opening.

  L_b: length of the beam in the equivalent frame.

  The parameters are calculated by using the following equations

$$X_{t1} = X_{t2} = 0.5\times W_{p1} \leq 0.5D_t \qquad 2.17$$

$$X_{b1} = X_{b2} = 0.5\times W_{p2} \leq 0.5D_b \qquad 2.18$$

$$L_{p1}=L_{p2}=h_p+X_{t1}+X_{b1} \quad 2.19$$

$$L_b=L_{wall}-0.5W_{p1}-0.5W_{p2} \quad 2.20$$

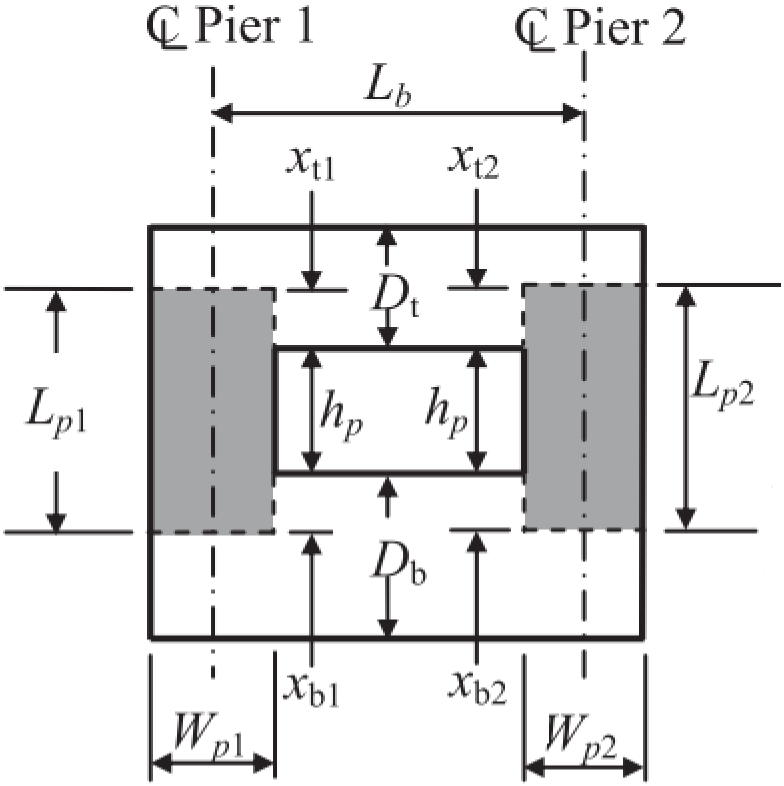

Figure 2.5: Parameters of Hsiao method for wall with opening [Hsiao, 2014]

- Step 2: Calculate moment of inertia for the piers and beam in the equivalent frame system. This frame is shown in Figure 2.6 which shows a schematic diagram for the equivalent frame:

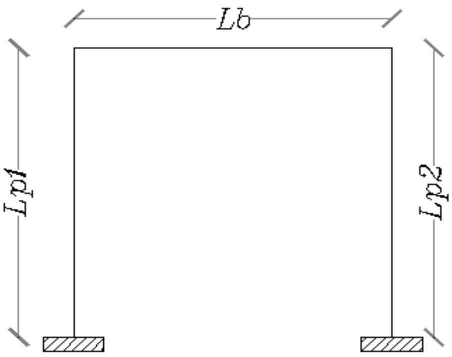

Figure 2.6: Equivalent frame dimension

- Step 3: Calculate flexural deflection in piers:

$$\Delta_{moment,pier1} = \left(\frac{{L_{p1}}^3}{4EI_{p1}}\right)\left(\frac{1}{3} + \left(\frac{1}{6K_1+1}\right)\right) \quad 2.21$$

$$K_1 = \left(\frac{EI_b}{I_b}\right)\left(\frac{L_{p1}}{EI_{p1}}\right) \quad 2.22$$

$$\Delta_{moment,pier2} = \left(\frac{{L_{p2}}^3}{4EI_{p2}}\right)\left(\frac{1}{3} + \left(\frac{1}{6K_2+1}\right)\right) \quad 2.23$$

$$K_2 = \left(\frac{EI_b}{I_b}\right)\left(\frac{L_{p2}}{EI_{p2}}\right) \quad 2.24$$

$$R_{pieri} = \frac{1}{\Delta_{moment,pieri}} \quad 2.25$$

- Step4: Calculate flexural deflection assuming total solid wall with no openings:

$$\Delta_{moment,solid\,wall} = \left(\frac{h^3}{3EI_{solid\,wall}}\right) \quad 2.26$$

- Step 5: Treating the strip which contains the opening as a solid strip by ignoring the opening and then calculate the flexural deflection of this strip at the top and at the bottom. The flexural deflection calculation at the bottom of the effective piers can be calculated by using Eq. 2.27 and the value of x_i in this case is the distance from the bottom supports of the wall to the bottom of the effective pier height, then calculate the flexural deflection at the top piers by using the same equation, but use x_i as the distance from the bottom supports of the wall to the top of the effective pier height. The value of h in both cases is the total wall height. Finally, calculate the flexural deflection of this solid strip by subtracting the results of this deflection.

$$\Delta_{moment,xi} = \left(\frac{{x_i}^2}{6EI}\right)(3h - x_i) \quad 2.27$$

- Step 6: Calculate the open strip flexural deflection by applying Eq. 2.28:

$$\Delta_{moment,open\ strip} = \frac{1}{R_{pier1} + R_{pier2}} \quad 2.28$$

- Step 7: Calculate the flexural deflection of the wall with opening by applying Eq. 2.29:

$$\Delta_{moment\ in\ the\ wall\ with\ opening} = \Delta_{moment,solid\ wall} - \Delta_{moment,solid\ strip} + \Delta_{moment,open\ strip} \quad 2.29$$

- Step 8: Calculate the total shear deflection in the wall by dividing the wall into three layers: layer from bottom of the wall to the bottom of the opening, layer of the open strip which contains the opening, and the top layer from the top of the opening to the top of the wall. Finally by using Eq. 2.30, sum the shear deflections from these three layers to get the total shear deflection:

$$\Delta shear_{x_1 \rightarrow x_2} = \frac{1.2 h_i}{A \cdot G} \quad 2.30$$

- Step 9: The total deflection in the wall with opening is obtained by applying Eq. 2.31:

$$\Delta_{total\ with\ opening} = \Delta_{shear\ \ with\ opening} + \Delta_{moment\ with\ opening} \quad 2.31$$

In 2015, Mohamed Abo Elsaad and Magdy Salama used recorded periods for shear wall buildings, which Goel and Chopra used in their paper published in 1997 to improve the formula for estimating the period of vibration of concrete shear wall buildings by regression analysis. They concluded that the coefficient C_t should be decreased from 0.02 to 0.014 when using the code equation (Eq. 2.15).

2.3 Numerical studies

In 2002, J'aidi studied the rigidity of concrete shear walls with and without openings. He carried out a numerical study using SAP90 to get the results after verifying it. J'aidi concluded that the rigidity of the solid concrete walls without openings is a function of the wall aspect ratio (height/length) being the most dominated factor, so the walls with the same aspect ratio, same material, and same thickness will have the same rigidity value.

J'aidi found numerically that the shear deformation can be neglected when the wall aspect ratio equals to 4. He suggested two patterns for both window and door openings as shown in Figure 2.7, Figure 2.8, Figure 2.9 and Figure 2.10, where the window opening patterns weren't at the center of a studied 3×4m wall. As a result of his study, the small window opening which captured about 2% of the wall area can be neglected, because this percentage of opening reduces the rigidity of the solid wall to about 90%, while 12% window opening area reduces the rigidity to about 50%.

177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192
161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176
145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160
129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144
113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128
97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Figure 2.7: Pattern A for window openings that are illustrated by the colored element in a 3x4m cantilever wall [J'aidi, 2002]

177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192
161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176
145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160
129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144
113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128
97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Figure 2.8: Pattern B for window openings that are illustrated by the colored element in a 3x4m cantilever wall [J'aidi, 2002]

177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192
161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176
145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160
129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144
113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128
97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Figure 2.9: Pattern A for door openings that are illustrated by the colored element in a 3x4m cantilever wall [J'aidi, 2002]

Figure 2.10: Pattern B for door openings that are illustrated by the colored element in a 3x4m cantilever wall [J'aidi, 2002]

In 2003, Balkaya and Kalkan compared the codes formula UBC-97 (Eq. 2.9), and Turkish seismic code-98 (Eq. 2.32) for estimating the fundamental period of reinforced concrete multi-story shear wall with no opening structures and they found that the equations yielded inaccurate results.

$$T_{a-Turkish} = 0.05(H^{0.75}) \qquad 2.32$$

Where:

H : Height of the building in meters.

They performed a numerical linear elastic modal analysis study using ETABS version 7.22 with 2D shell element on 80 different shear wall buildings in their local region by using tunnel form techniques with no beams or columns and only using cast in-place walls and slabs with almost the same thickness. In their study, they recommended to use the slab as it is without making any rigid or semi rigid diaphragm assumption in the models. The 80 different buildings were divided into two cases; squared ones with the building long side divided by the short side is less than 1.5, otherwise the buildings are considered as rectangular ones. The final fundamental period results are taken from the first mode of modal analysis. Their proposed equation (Eq. 2.33) has a set of factors which affect the period and all of these parameters have numerical coefficients found by non-linear regression. They concluded to use this formula (Eq.2.33) to improve the accuracy when calculate the fundamental period of such structures

$$T = Ch^{b1}\beta^{b2}{\rho_{as}}^{b3}{\rho_{al}}^{b4}{\rho_{min}}^{b5}j^{b6} \qquad 2.33$$

Where:

h : Total height of the building in meters.

β : Ratio of long side to short side dimension.

ρ_{as} : Ratio of short side shear wall area to total floor area.

ρ_{al} : Ratio of long side shear wall area to total floor area.

ρ_{min} : Ratio of minimum shear wall area to total floor area.

j : Polar moment of inertia of the plan $(I_{xx} + I_{yy})$.

The numerical coefficients values are as shown in Table 2.1.

Table 2.1: Numerical coefficients values for Equation 2.13[Balkaya and Kalkan, 2003]

Coefficients	Square plan	Rectangular plan
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

Bakaya and Kalkan conducted comparison between the results in codes empirical formulas (Eq. 2.9 and Eq. 2.32), dynamic analysis, and the proposed equation (Eq. 2.33) shown in Figure 2.11 and Figure 2.12 for rectangular plan case and squared plan case. Those figures show that Eq. 2.33 is accurate enough to be used in tunnel form shear wall construction techniques as Balkaya and Kalkan claimed.

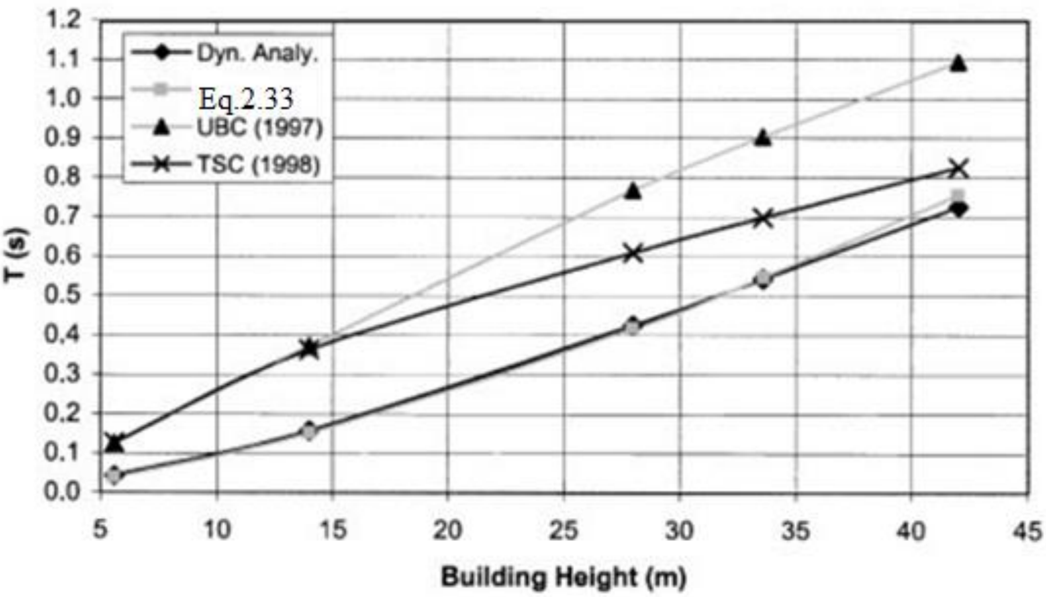

Figure 2.11: Comparison between periods calculated by proposed equation versus building height in rectangular case [Bakaya and Kalkan, 2003]

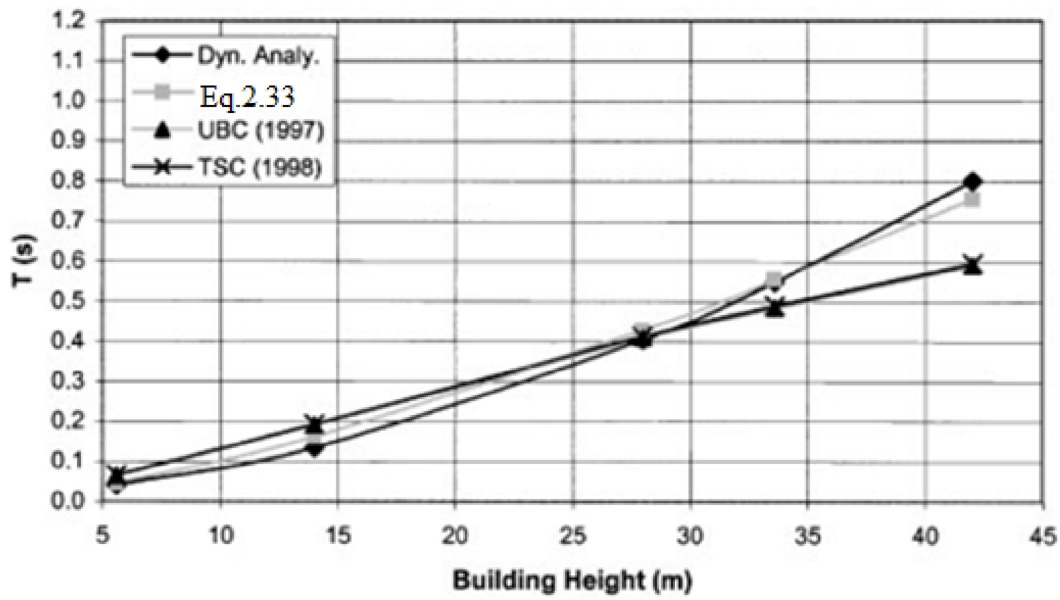

Figure 2.12: Comparison between periods calculated by proposed equation versus building height in squared case [Bakaya and Kalkan, 2003]

Balkaya and Kalkan didn't make any restriction when using their formula like restriction in the number of floors, restriction in the location and sizes of the openings. They also didn't consider the soil-structure interaction in their study.

In 2006, Neuenhofer evaluated the accuracy of a simplified hand method proposed by Brandow et al.1997 and Lindeburg at al. 2001 to calculate the lateral deflection of cantilever concrete shear walls with openings due to flexural and shear deformation as shown in Eq. 2.34 and Figure 2.13, where Neuenhofer claimed that this method is used in several design guidelines. Eq. 2.34 shows the final equation that can be used to find the total lateral deflection in a wall with opening due to flexure and shear deformation, while Figure 2.13 shows the methodology of applying Brandow et al. and Lindeburg at al. method.

$$\Delta_{wall\ with\ opening} = \Delta_{solid\ wall} - \Delta_{solid\ strip} + \Delta_{piers} \qquad 2.34$$

$$\Delta_{solid\ wall} = \frac{P}{Eb}\left(4\left(\frac{H}{L}\right)^3 + 2.88\frac{H}{L}\right) \qquad 2.35$$

$$\Delta_{solid\ strip} = \frac{P}{Eb}\left(\left(\frac{H}{L}\right)^3 + 2.88\frac{H}{L}\right) \qquad 2.36$$

$$\Delta_{piers} = \frac{P}{2Eb}\left(\left(\frac{H}{L}\right)^3 + 2.88\frac{H}{L}\right) \qquad 2.37$$

Where:

H : Wall height.

L : Wall length.

P : Lateral load.

E : Concrete modulus of elasticity.

b : Wall thickness.

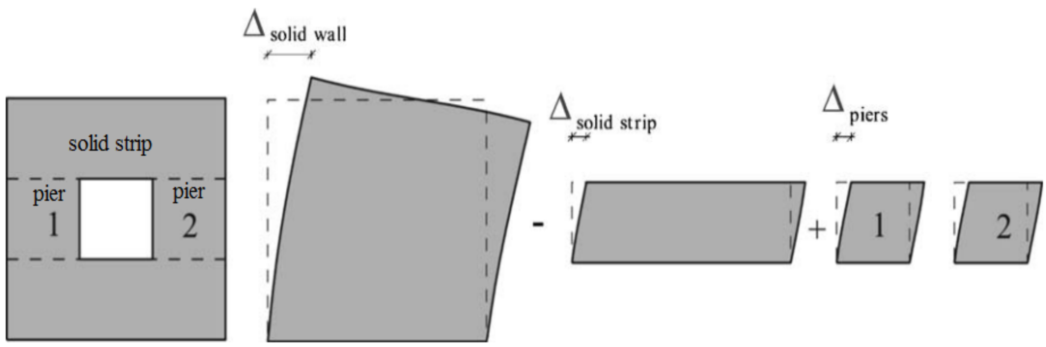

Figure 2.13: Hand method for finding displacement of shear wall with opening [Neuenhofer, 2006]

Neuenhofer compared this hand method in Eq. 2.34 and numerical finite element algorithm on MATLAB at two examples, one for window opening and another for door opening. Neuenhofer found that the lateral stiffness is strongly affected by the vertical location of the opening in the walls, and the hand calculation method doesn't consider this factor. Neuenhofer conducted two parametric studies to find the percentage of error between the hand method and numerical method one for window opening and another for door opening by fixing the wall geometry and change the vertical location of opening as shown in Figure 2.14, where “e” represents the vertical location of the opening. The final figures he concluded are shown as Figure 2.15 and Figure 2.16. Those figures show the location of opening versus both the ratio of wall stiffness and the percentage of error between simplified hand calculated compared to finite element methods for window and door openings in an individual cantilever wall.

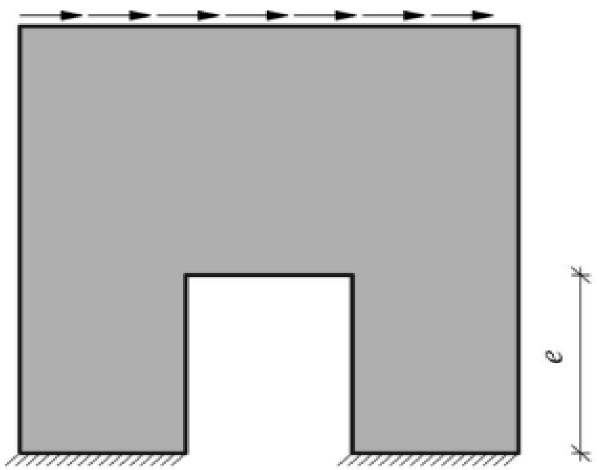

Figure 2.14: Cantilever shear wall with an opening of variable size [Neuenhofer, 2006]

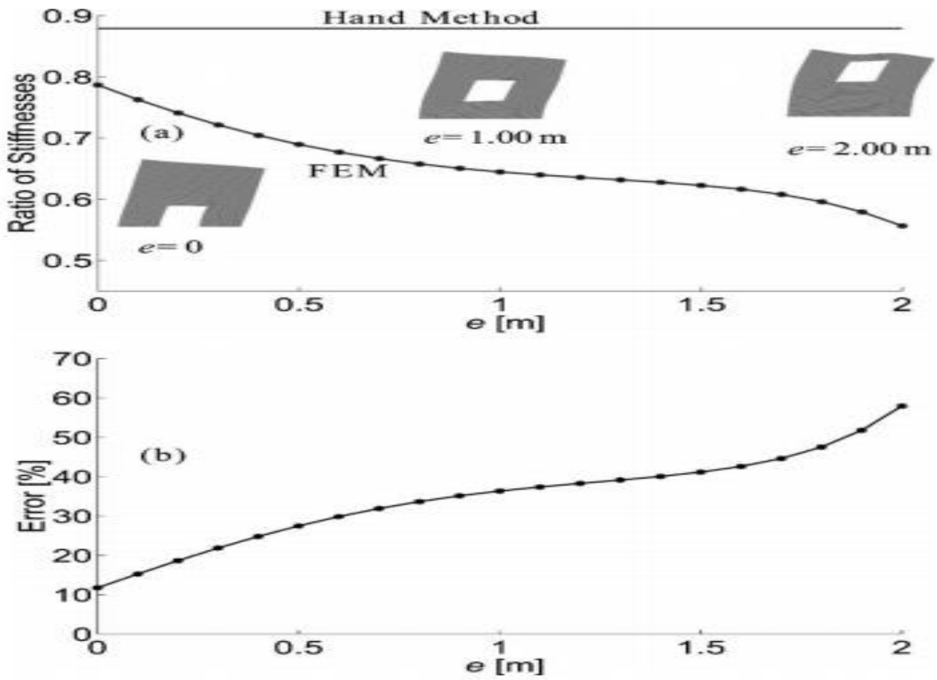

Figure 2.15: Window opening: (a) stiffness ratio relative to that of solid wall; (b) error of hand method compared to finite element [Neuenhofer, 2006]

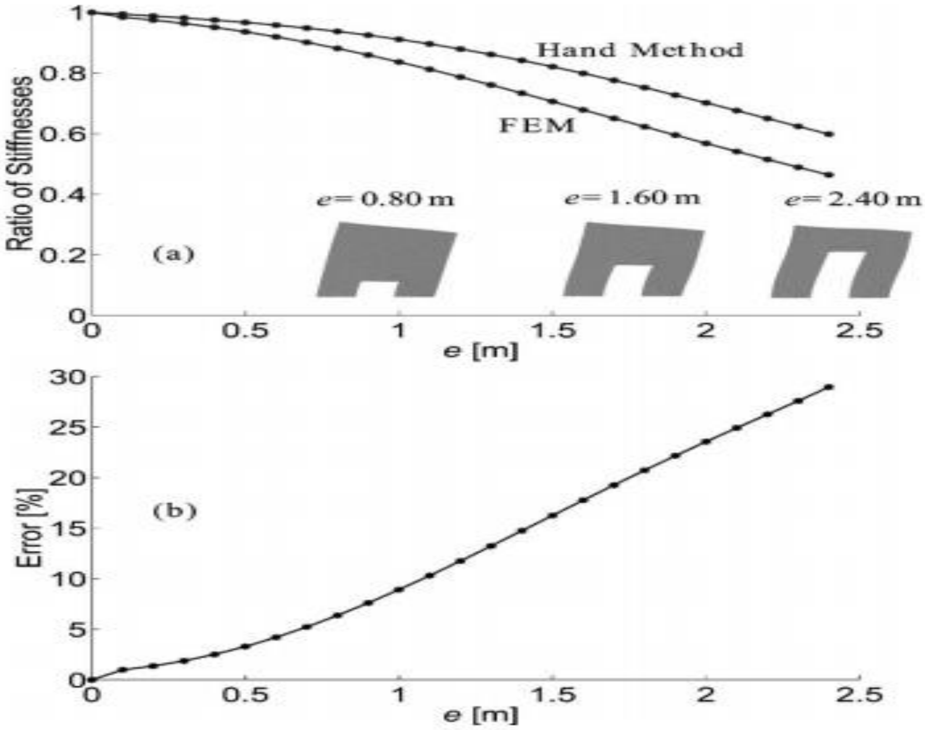

Figure 2.16: Door opening: (a) stiffness ratio relative to that of solid wall; (b) error of hand method compared to finite element [Neuenhofer, 2006]

From Figure 2.15 and Figure 2.16, the error between hand calculation method and finite element method increases when the vertical location of the opening increase and this error also increases when the opening ratio increaseGGGGG in meter.

The models were 3 buildings in their local region with different number of floors, different number of bays and with flat plate slabs and shear walls and no columns and beams. The concrete material used was C25/30. Slabs were assumed to be rigid diaphragms. The stiffness of members was taken as unchanged according to the recommendation of Euro code (EN1998-1) which states that the calculation of period can be performed with the assumption of un-cracked sections because modal analysis is always assumed linear, and can be based on the stiffness of unstressed structures.

Nyarko et al. concluded that the period obtained by modal analysis for their study was smaller than the value obtained by ATC3-06 and EC1998-1:2004. The difference in case of ATC3-06 ranges from 2.7% to 85% and the difference reached up to 80% for EC1998-1:2004. They recommended using the percentage of reinforced concrete walls and the number of bays as parameters in the code formula to make them more accurate.

In 2017, Aghayari et al. studied the behavior of coupled shear wall system because most structural design codes have no clear seismic design consideration for base shear and period for this system as Aghayari et al. claimed.

Aghayari et al. used finite element models built in ANSYS and divided into two categories. First category is the one-floor, two-floor, and three-floor

3D solid models with two-way slabs. The second category is one-floor individual wall with 5m length, 3.5m height, and 0.15m thickness with different central window opening ratios. As a result of their work, corrective coefficients were presented according to the numerical results.

They noticed that the empirical formulas in ASCE code for period estimation may not be reliable for real design yet in the case of coupled walls structures. They also noticed that the fundamental period is affected by the opening ratio and it is better to use some other structural parameters like relative wall area and opening ratio in the code equations for fundamental period calculations to be more accurate.

Based on this work, Aghayari et al. proposed a modification factor to consider the effect of opening ratio on the fundamental period of individual coupled wall as shown in Figure 2.17. Multiplication of this factor by the ASCE code empirical formula of period produces more accurate and reliable value.

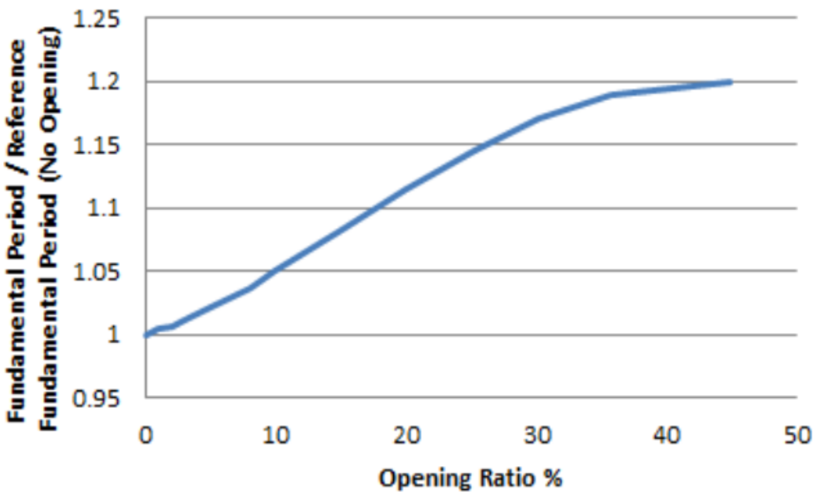

Figure 2.17: Period modification factor for coupled concrete shear wall structures [Aghayari et al., 2017]

2.4 Summary

Many studies were carried out on the behavior of shear wall systems as main bracing systems in the buildings, especially the fundamental period of shear wall structures. Most of these studies do 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 tried to improve the codes formulas for estimation of the fundamental period by using regression analysis to derive more conservative equations. Table 2.2 shows a summary of these improved equations that can be used for estimation of the fundamental period of concrete shear wall structures, while Table 2.3 shows a summary of the empirical formulas of fundamental period of concrete shear wall structures in many structural design codes. Details of these formulas were mentioned earlier in this chapter.

Table 2.2: Summary of improved equations for estimating the fundamental periods of concrete shear wall structures

The author/s	The improved equation	Consider openings	Assumptions
Sozen (1989)	$6.25\frac{h_w}{l_w}n\sqrt{\frac{wh_s}{gpE_c}}$	No	• The lateral deflection mode is dominant by flexure mode. • Same height and same mass of all floors.

Goel and Chopra(1997)	$c'\frac{1}{\sqrt{A'_e}}H$	No	• The lateral deflection mode is from both flexure and shear modes. • Same height and same mass of all floors.
Lee et al.(2000)	$\frac{0.4(H^{0.2})}{\sqrt{L_w} - 0.5}$	Yes	• No assumptions, because this formula is gutted from regression analysis of recorded periods due to elastic motions
Balkaya and Kalkan(2003)	$Ch^b \beta^{b2} {\rho_{as}}^{b3} {\rho_{al}}^{b4} {\rho_{min}}^{b5} j^{b6}$	No	• Linear elastic modal analysis • No assumption in diaphragm • The modeling is used 2D shell element.
Challah et al.(2014)	$1.8n(n+1)\sqrt{\frac{mh^3}{EI}}$	No	• The lateral deflection mode is dominant by flexure mode. • Same height and same mass of all floors.

Table 2.3: Summary of mentioned empirical equations in many codes for estimating the fundamental period of concrete shear wall structures

The code/s	The empirical equation	Consider openings
UBC97, SEAOC-96, NEHRP-94, and ASCE7-05	$0.02(H^{0.75})$	No
SEAOC-96 (alternative formula)	$\frac{0.0743}{\sqrt{A_c}}(H^{0.75})$	No
NBCC-1995	$0.09\frac{H}{\sqrt{D_s}}$	No
KBC-1988	$0.09\frac{H}{\sqrt{B}}$	No
Turkish code-1998	$0.05(H^{0.75})$	No
ATC3-06	$\frac{0.05H}{\sqrt{D}}$	No
EN1998-1	$\frac{0.075}{\sqrt{A_c}}H^{0.75}$	No

3 Wall-level: modeling and results

3.1 Level of modeling

The procedure of studying the effect of openings in shear walls in this thesis will be divided into two levels. In this chapter wall level study and the results shall be discussed for individual wall as a first level. The main purpose of this level is to identify the limits of central window opening and door opening to consider the opening effect on the behavior of the wall. The second level will be discussed in the next chapter.

Finite element simulation by SAP2000 shall be used in both levels. Linear elastic analysis will be conducted to each study case with suitable mesh size to get the lateral deflection. Moreover, modal analysis will be used to get the fundamental period of the simulation models.

3.2 Sensitivity study

Here, the effect of boundary conditions, mesh size, and the effect of concrete compressive strength (f'_c) on the wall lateral stiffness (K) will be studied. The aim of studying the boundary conditions is to know the suitable boundaries in modeling the wall. Although the mesh size effect needs to be studied, 0.3m squared mesh size shall be used at the start of this study, and this size will be approved later when the effect of mesh size is studied. The aim of studying the mesh size is to choose the largest suitable squared one which will be used in this thesis to guarantee that it will give accurate results. The effect of f'_c shall be studied to recognize if it has considerable effect or not.

3.2.1 Effect of boundary conditions

The effect of boundary conditions at the top of the wall between the shear wall and the slab shall be studied. This will be achieved by studying a simple 3D wall with slab model and an individual cantilever wall. The lateral deflection of a cantilever wall from SAP2000 will be compared to the same lateral deflection from a simple 3D wall with slab model without any rigid or semi rigid diaphragm assumption and using the same size of squared mesh of 0.3m for both models as a start. The 3D simple model and the cantilever wall model are shown in Figure 3.1.

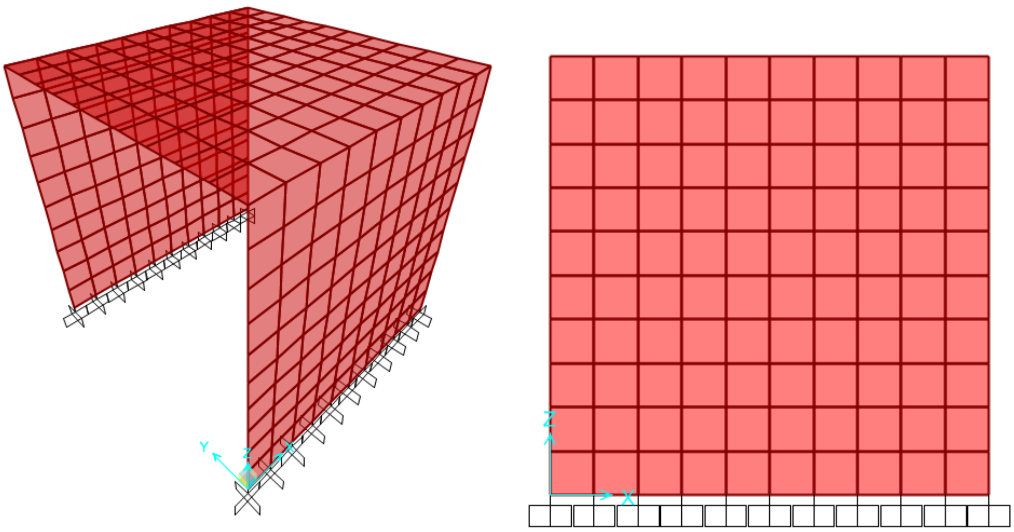

Figure 3.1: SAP2000 3×3×3m simple 3D model and the 3×3m cantilever 2D wall model

These models were made of concrete with modulus of elasticity (E) equals to 23000MPa, Poisson's ratio (υ) equals to 0.2, 3m squared walls and slab with the same thickness for each one and equals to 0.2m. The lateral load applied on the simple 3D model is 2000kN distributed on the 9m^2 slab area while 1000kN shear load is distributed on the top joints of the cantilever wall model.

The lateral deflection from the simple 3D model is found to be 1.454mm, and when a rigid diaphragm assumption is made, the lateral deflection found to be also 1.454mm, while 1.473mm is the lateral deflection from a cantilever wall model. This result confirms that modeling the wall as a cantilever wall is reasonably equivalent to the more realistic 3D model.

3.2.2 Effect of mesh size

A wall with 3m height, 3m width, and 0.2m thickness is made from concrete with E=23000MPa. A total lateral load of 1000kN is distributed at top nodes. Five models with mesh size in the range of 0.1m to 0.5m are analyzed using SAP2000. Figure 3.2 shows the planar cantilever wall and boundary conditions modeled with mesh size equals to 0.3m.

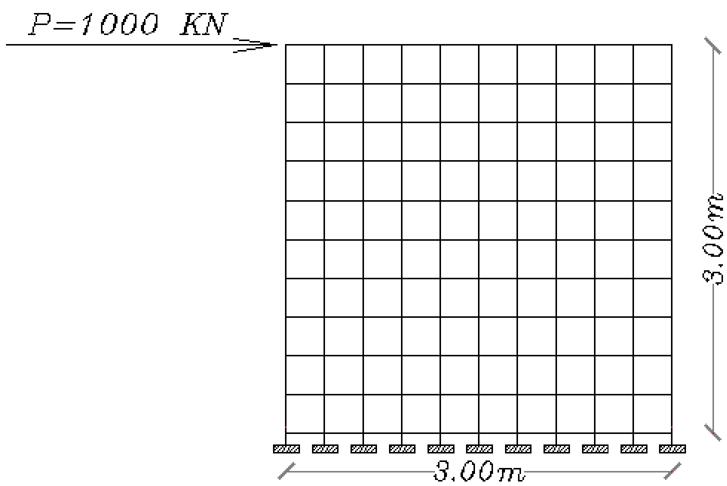

Figure 3.2: Planar 3×3m cantilever wall boundary conditions

Utilizing virtual work theorem, the deflection of the cantilever beam model at the top due to flexure and shear can be obtained as:

$$\Delta_{total} = \Delta_f + \Delta_s = \frac{PH^3}{3EI} + \frac{1.2PH}{GA} \qquad 3.1$$

Where:

Δ: total deflection, Δ_f: flexural deflection, Δ_s: shear deflection, P: load at the top, H: wall height, E: modulus of elasticity, I: moment of inertia, A:cross sectional area, G: shear modulus, v= Poisson's ratio.

$$G = \frac{E}{2(1+v)} \qquad 3.2$$

With v = 0.2, and $E = 23 \times 10^6$kN/m^2, the result will be

$G = \frac{23\times10^6}{2\times(1+0.2)}$ = 9.6$\times 10^6$kN/m^2.

$I = \frac{0.2\times3^3}{12}$ =0.45m^4.

$A = 0.2 \times 3$ = 0.6m^2.

Δ_{total}= 1.495mm.

Table 3.1 shows a comparison between the five models, where the difference between all models are less than 5%. This small difference can be neglected. Thus, when modeling the wall, a mesh size up to 0.5×0.5m can be used with acceptable accuracy in results. In this thesis a 0.3m squared mesh size will be used.

Table 3.1: Models displacement results for different mesh sizes from SAP2000

Model number	Square element size (m)	Load (KN)	Δ (mm)	Difference (%) $100\%.\frac{\Delta_{\text{manual}} - \Delta_{SAP}}{\Delta_{\text{manual}}}$
A	0.1×0.1	1000	1.480	1.00
B	0.2×0.2	1000	1.478	1.13
C	0.3×0.3	1000	1.473	1.47
D	0.4×0.4	1000	1.467	1.87
E	0.5×0.5	1000	1.456	2.60

3.2.3 Effect of concrete compressive strength

The effect of f'_c will be studied in the range of normal concrete strength. The normal concrete strength is between 20 and 40MPa. The relationship between modulus of elasticity and normal weight concrete compressive strength according to ACI318M-14 is given in this formula:

$$E = 4700\sqrt{f'c} \quad \text{(In MPa)} \qquad 3.3$$

Where:

f'_c = concrete compressive strength in MPa.

When simplifying Eq. 3.1, the lateral deflection in a cantilever concrete wall due to flexural and shear deformation will be (J'aidi, 2002)

$$\Delta_{total} = \left(\frac{P}{Et}\right)\left[4\left(\frac{H}{B}\right)^3 + 2.88\left(\frac{H}{B}\right)\right] \qquad 3.4$$

By substituting Eq. 3.3 into Eq. 3.4, the lateral cantilever normal concrete wall deflection will be:

$$\Delta_{total} = \left(\frac{P}{4700\sqrt{f'_c}t}\right)\left[4\left(\frac{H}{B}\right)^3 + 2.88\left(\frac{H}{B}\right)\right] \qquad 3.5$$

When the lower bound of f'_c was taken to be 20MPa, the Eq. 3.5 will be:

$$\Delta_{total} = \left(\frac{4.76\times10^{-5}P}{t}\right)\left[4\left(\frac{H}{B}\right)^3 + 2.88\left(\frac{H}{B}\right)\right] \qquad 3.6$$

When the upper bound of f'_c was taken and equals to 40MPa, the Eq. 3.5 shall be:

$$\Delta_{total} = \left(\frac{3.36\times10^{-5}P}{t}\right)\left[4\left(\frac{H}{B}\right)^3 + 2.88\left(\frac{H}{B}\right)\right] \qquad 3.7$$

For the same wall geometry, same lateral load, and when dividing Eq. 3.6 on Eq. 3.7 the effect of f'_c will be in the range of 1 to 1.42. Thus, decreasing the concrete compressive strength will increase the lateral deflection of a cantilever wall and this increase will be in the range of 1 to 1.42. Later and on all models, f'_c equals to 24MPa will be used because this concrete compressive strength value is the most common used in practice in Palestine.

As shown in Eq. 1.1 there is a relation between stiffness K and the fundamental period T. Eq. 3.3 shows that the value of f'_c shall be under the square root to find E which it will be used in finding the stiffness K, and this K will be also under the square root as shown in Eq. 1.1. Thus, the effect of f'_c on the fundamental period will be small.

3.3 Matrix of parameters

The parameters that will be studied are the following: wall height-to-length aspect ratio (H/B), opening area to the total wall side area (R_o), and opening type if window opening or door opening. These parameters are expected to have significant effect on the behavior of the wall.

3.3.1 Wall height-to-length aspect ratio (H/B)

As mentioned in section 3.2.3, Eq. 3.4 can be used to determine the deflection due to both shear and flexure deformation in a cantilever concrete wall assuming full sectional elastic behavior. The equation indicates that the lateral deflection is a function of the wall aspect ratio H/B. This means that the walls with the same aspect ratio, same material, same thickness, should have the same stiffness (J'aidi, 2002), but because of change in their masses it would give different results for natural period for walls of the same aspect ratio.

To find the ratio of the flexural deflection from the total cantilever wall deflection, divide the flexural deflection (from Eq. 3.1) by the total deflection (from Eq. 3.4). The contribution of flexural deformation is:

$$\frac{\Delta_f}{\Delta_{total}} = \frac{4\left(\frac{H}{B}\right)^2}{2.88+4\left(\frac{H}{B}\right)^2} \qquad 3.8$$

Using the same procedure, the contribution of the shear deformation is:

$$\frac{\Delta_s}{\Delta_{total}} = \frac{2.88}{2.88+4\left(\frac{H}{B}\right)^2} \qquad 3.9$$

From Eq. 3.8 and Eq. 3.9 the contribution of shear or flexural deformations to the total wall deformation is a function of wall aspect ratio. If the wall aspect ratio equals to 1, the contribution of flexural deformation will be 58% and the shear deformation contribution will be 42% from the total wall deflection, assuming elastic un-cracked section for the wall.

Figure 3.3 shows the relative contribution of shear and flexure deformation to total deformation drawn using Eq. 3.8 and Eq. 3.9 versus wall aspect ratio.

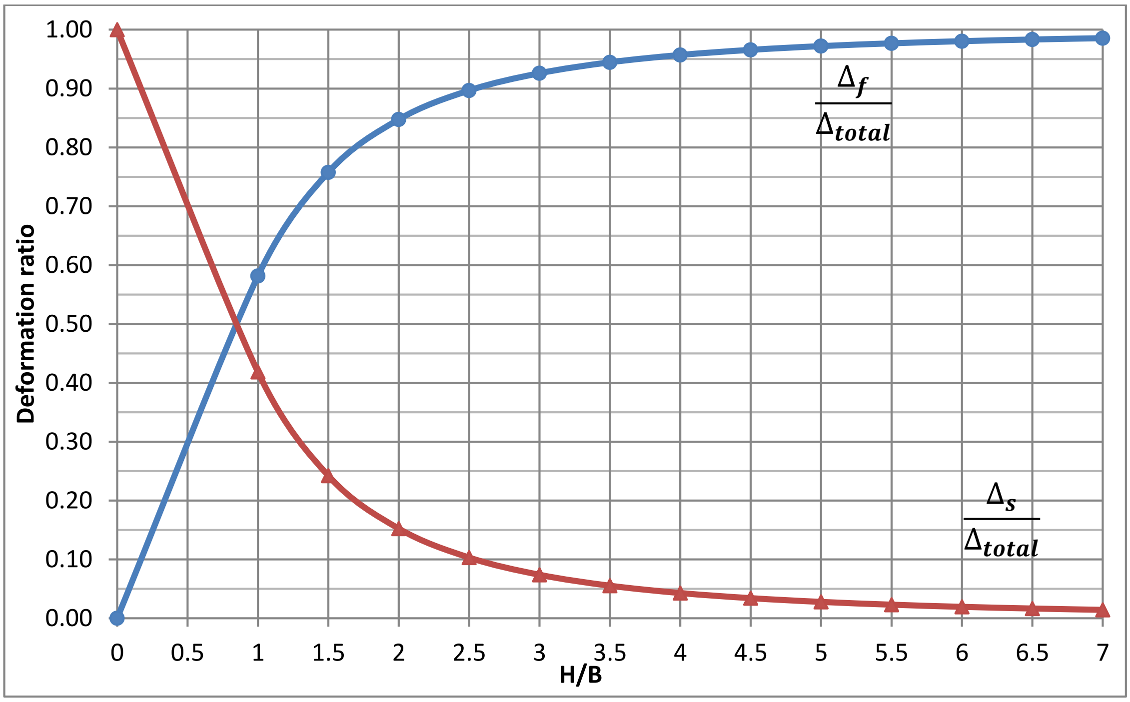

Figure 3.3: Relative contribution of shear and flexure deformation to total deformation for walls without openings.

To find out when shear deformation can be neglected, 5% difference due to shear deformation will be considered negligible, and when substituting this value in Eq. 3.9, the following result shall be gutted:

$$\frac{2.88}{2.88+4\left(\frac{H}{B}\right)^2} = 0.05 \rightarrow \frac{H}{B} = 3.7 \qquad 3.10$$

From Eq. 3.10, if the wall H/B ratio is less than 3.7, the shear deformation should be considered and be modeled using 2D area element or using Timoshenko beam element. Otherwise, the wall can be modeled as 1D Euler-Bernoulli beam element. The assumption of Euler-Bernoulli beam theorem is that any plane perpendicular to the neutral axis before bending will remain so after the beam is bent. While Timoshenko beam theorem accounts for the effect of transverse shear deformation and a rotation between the cross section and the bending line is allowed due to shear deformation. Therefore, the Euler-Bernoulli beam theorem underestimates the deflection because it models a stiffer beam. Because of that, beams with short length or expected to have large deflection have to be modeled with Timoshenko beam element.

3.3.2 Central window opening and opening ratio (R_o)

Wall openings in reality are either doors or windows. In this section, the effect of central window opening on the wall stiffness will be studied because these openings cause a variation in lateral stiffness that extends from that of a solid wall to that of a frame as shown in Figure 3.4.

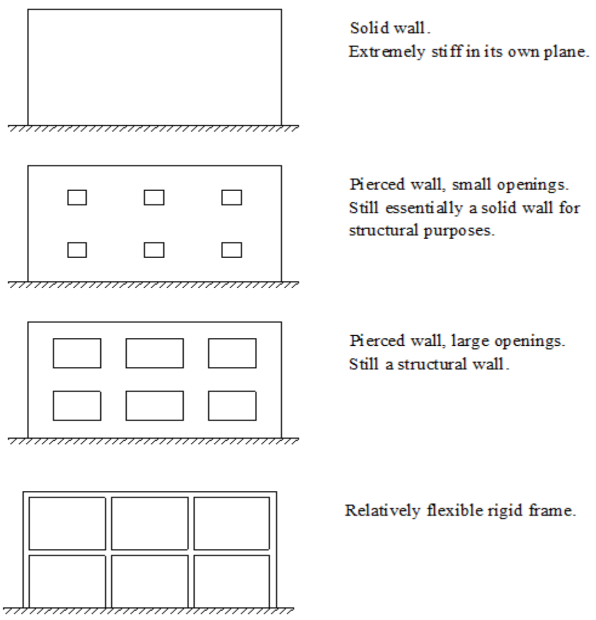

Figure 3.4: Transition in a monolithic planer construction, from a solid wall to a flexible, moment resisting frame [Ambrose, and Vergun, 1995]

It can be concluded that the fundamental period will be affected by the opening size due to the direct relationship between the fundamental period and the lateral stiffness of the structure. These openings affect the total stiffness of the structure and may reduce it which leads to an increase in the fundamental period. In the following study, the wall thickness, aspect ratio (H/B), and wall concrete material are assumed to be fixed and the wall opening ratio is the only parameter to be varied.

A 3×3m planer cantilever wall with f'_c equals to 24MPa, wall thickness equals to 0.2m, and top shear load equals to1000kN will be used to evaluate the effect of different central window and door openings in the next sections. Figure 3.5 shows model number C-W12 with dimensions as modeled in SAP2000. A deflection of each case is tabulated then the relationship between opening ratios in the wall and the corresponding change in stiffness are shown in graphs.

17 central squared window openings of varying sizes are suggested. In this section the largest ratio of central window opening in a wall whose effect on the lateral stiffness is small and can be neglected will be identified. The results of the lateral deflection (Δ), the lateral stiffness (K), and the stiffness ratio (R_S) are tabulated in Table 3.2. For the naming of the models, C refers to the concrete wall and W refers to window opening. The stiffness ratio (R_S) is defined as the ratio of the lateral stiffness of a wall with opening divided by the lateral stiffness of the same wall without openings. The opening ratio (R_O) represents the opening area in the wall divided by

the total wall side area. The verification of the lateral deflection results in Table 3.2 from SAP2000 is shown in Appendix A.

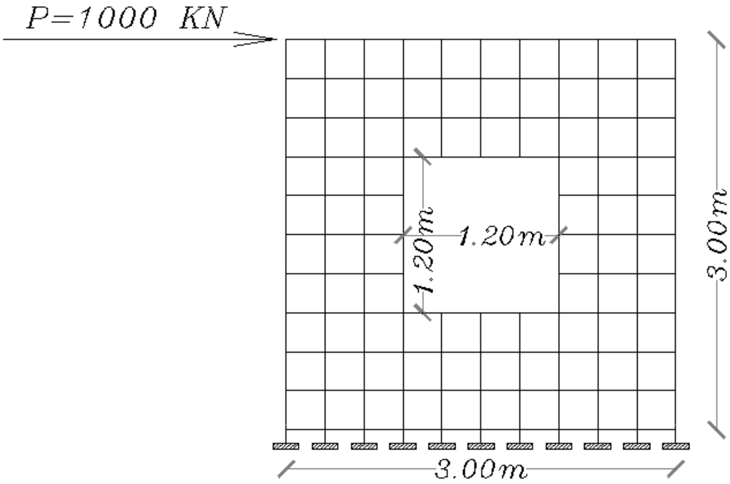

Figure 3.5: C-W12 3×3m cantilever wall model with central window opening

Table 3.2: results of window opening models with a 3×3m wall

Model number	Opening size (m)	Opening Ratio, R_O (%)	Δ (mm)	Stiffness K (10^4) (kN/m)	Stiffness Ratio, R_S (%)
C-W0	0.00	0.00	1.47	67.89	100
C-W3	0.3×0.3	1.00	1.52	65.79	96.90
C-W4	0.4×0.4	1.87	1.52	65.70	96.78
C-W5	0.5×0.5	2.78	1.55	64.52	95.03
C–W6	0.6×0.6	4.00	1.66	60.24	88.73
C-W7	0.7×0.7	5.44	1.76	56.81	83.69
C-W8	0.8×0.8	7.11	1.86	53.76	79.19
C-W9	0.9×0.9	9.00	2.00	50.00	73.65
C-W10	1 ×1	11.11	2.21	45.24	66.65
C-W11	1.1×1.1	13.44	2.54	39.37	57.99
C-W12	1.2×1.2	16.00	2.84	35.21	51.87
C-W13	1.3×1.3	18.78	3.28	30.49	44.91
C-W14	1.4×1.4	21.78	3.90	25.64	37.77
C-W15	1.5×1.5	25.00	4.66	21.45	31.61
C-W16	1.6×1.6	28.44	5.66	17.66	26.02
C-W17	1.7×1.7	32.11	7.16	13.96	20.57
C-W18	1.8×1.8	36.00	9.05	11.05	16.27

Discussion of results:

Figure 3.6 shows a comparison between the Hsiao analytical method and the finite element method for R_O ranging from 0 to 36, where the analytical results calculated in Appendix A are presented versus the SAP2000 results. From this figure, it can be noticed that the differences between the two methods are insignificant, where the slope equals to 1.0981 and the coefficient of determination (R^2) approximately equals 1. This is an indication that the SAP2000 results have acceptable degree of accuracy.

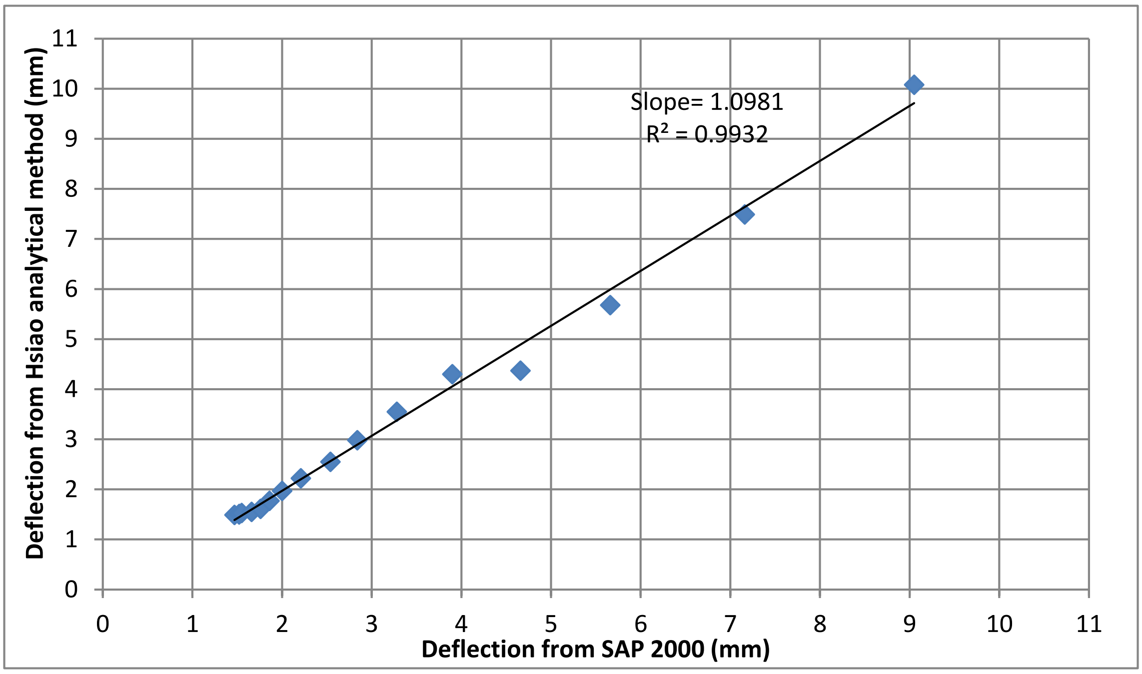

Figure 3.6: Lateral deflection values of the wall with central window opening from SAP2000 versus Hsiao method

Figure 3.7 shows the relationship between R_s and R_o as expected. Increasing the size of opening will decrease the stiffness of the wall. If 5% reduction in the wall lateral stiffness is considered negligible, then the opening area in the wall give such a reduction in stiffness equals 3% of the total wall side area. Thus, central window opening can be neglected in modeling the walls when its area ratio to total wall side area is up to 3%. In the common practice the 3% opening area appears in the bathroom window openings. Typical squared window opening of size 1.30×1.30m which is commonly used in practice reduces the stiffness of 3×3m solid wall to about 50%. The rapid drop in stiffness can be noticed when using large opening ratios. When the opening ratio is around 17% from the total wall area, the wall will lose 50% of it is stiffness.

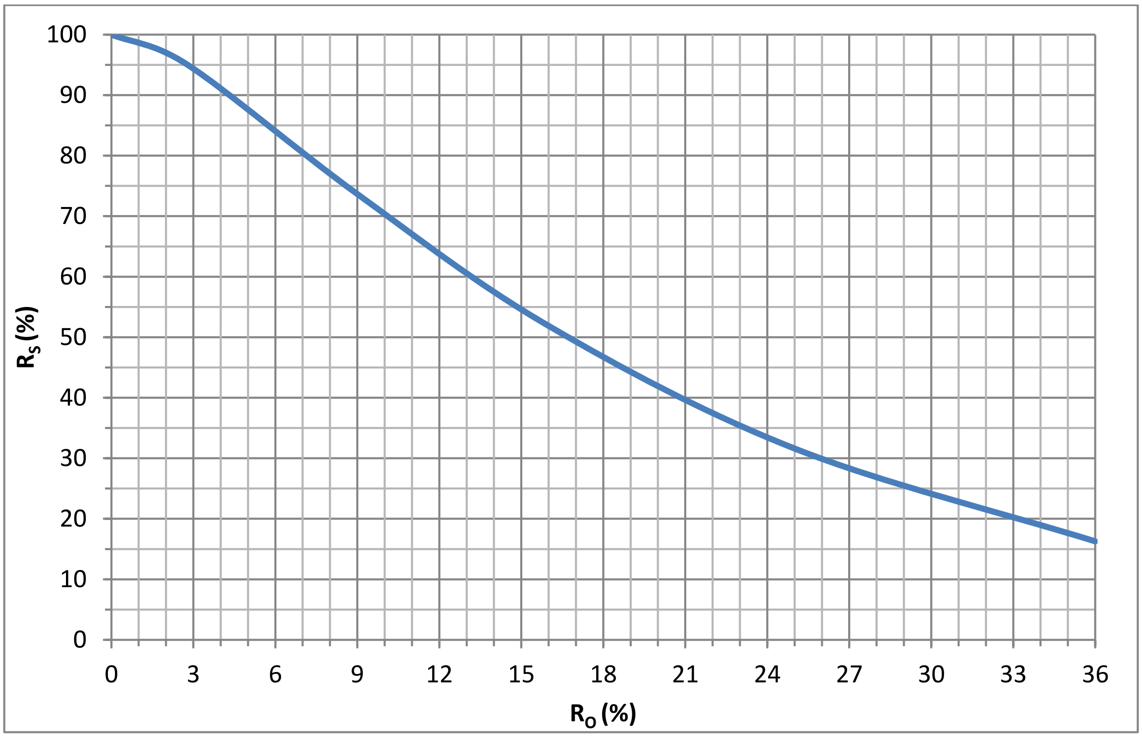

Figure 3.7: Squared windows opening ratio versus stiffness ratio of 3×3m wall

Effect of wall (H/B) ratio with central openings on the lateral displacement

35 cases for the same previous wall length, thickness and material are taken to study the effect of wall height and multiple openings on the top lateral displacement. 1000kN lateral load is applied on the top of the wall at each floor level where floor height is assumed to be 3m, and then the results of

top displacement (Δ), and displacement ratio (R_D) which is defined as the ratio of the lateral top displacement of a wall with opening divided by the lateral displacement of the same wall without openings are tabulated in Table 3.3. For the naming of the models, C-W refers to concrete wall and window opening respectively, then the first number and the second number refers to the opening ratio and (H/B) respectively. Figure 3.8 shows a schematic drawing for C-W12,2.

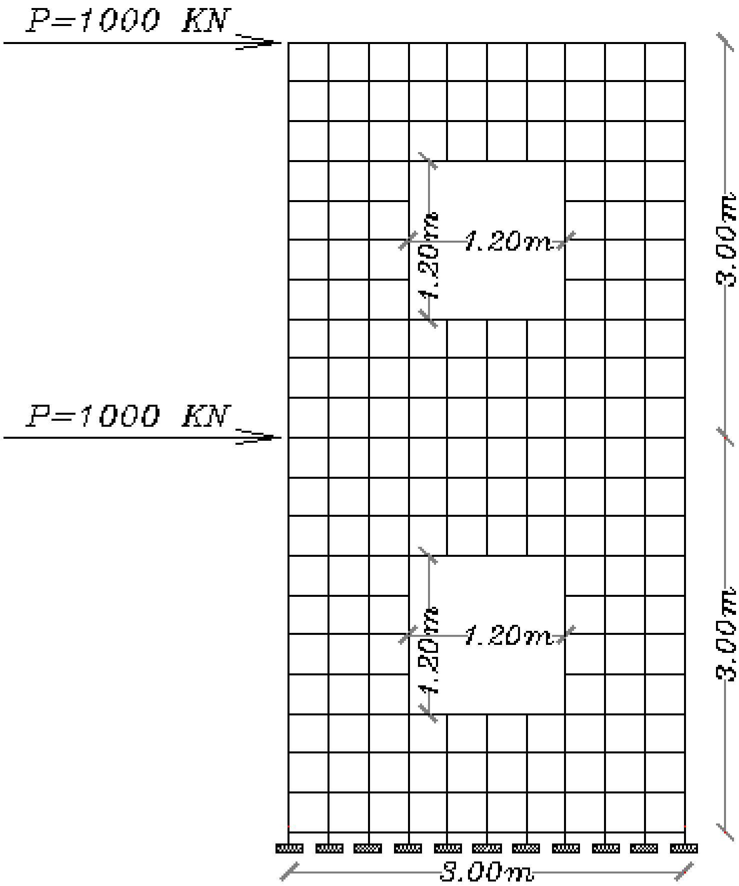

Figure 3.8: C-W12,2 model with boundary conditions and applied lateral loads

Table 3.3: lateral displacement results on different wall heights and central opening sizes

Model number	H/B (m)	Opening size (m)	Total opening ratio, R_O (%)	Top displacement ,Δ (mm)	Displacement Ratio, R_D
C-W0,2	2	0.00	0.00	10.92	1.00
C-W3,2	2	0.3×0.3	1	11.00	1.01
C-W6,2	2	0.6×0.6	4	11.52	1.05
C-W9,2	2	0.9×0.9	9	12.60	1.15
C-W12,2	2	1.2×1.2	16	15.30	1.40
C-W15,2	2	1.5×1.5	25	21.21	1.94
C-W18,2	2	1.8×1.8	36	35.15	3.22
C-W0,3	3	0.00	0.00	42.67	1.00
C-W3,3	3	0.3×0.3	1	42.78	1.00
C-W6,3	3	0.6×0.6	4	43.86	1.03
C-W9,3	3	0.9×0.9	9	46.21	1.08
C-W12,3	3	1.2×1.2	16	52.22	1.22
C-W15,3	3	1.5×1.5	25	65.94	1.55
C-W18,3	3	1.8×1.8	36	95.93	2.25
C-W0,6	6	0.00	0.00	531.00	1.00
C-W3,6	6	0.3×0.3	1	532.30	1.00
C-W6,6	6	0.6×0.6	4	536.95	1.01
C-W9,6	6	0.9×0.9	9	548.85	1.03
C-W12,6	6	1.2×1.2	16	581.63	1.10
C-W15,6	6	1.5×1.5	25	654.95	1.23
C-W18,6	6	1.8×1.8	36	809.32	1.52
C-W0,9	9	0.00	0.00	2487.50	1.00
C-W3,9	9	0.3×0.3	1	2488.11	1.00
C-W6,9	9	0.6×0.6	4	2501.2	1.01
C-W9,9	9	0.9×0.9	9	2539.54	1.02
C-W12,9	9	1.2×1.2	16	2650.85	1.07
C-W15,9	9	1.5×1.5	25	2901.55	1.17
C-W18,9	9	1.8×1.8	36	3399.91	1.37
C-W0,12	12	0.00	0.00	7562.73	1.00
C-W3,12	12	0.3×0.3	1	7562.87	1.00
C-W6,12	12	0.6×0.6	4	7593.03	1.00
C-W9,12	12	0.9×0.9	9	7690.39	1.02
C-W12,12	12	1.2×1.2	16	7982.19	1.06
C-W15,12	12	1.5×1.5	25	8640.97	1.14
C-W18,12	12	1.8×1.8	36	9908.36	1.321

Figure 3.9 shows the relationship between the displacement ratios versus opening ratios for different wall H/B ratio. From this figure, the increase in H/B shall reduce effect of openings. The reduction in R_D will be in a rapid form when the wall aspect ratio is small, where the effect of shear deformation contribution is significant compared with large aspect ratio.

The effect for the same R_O on the lateral displacement becomes smaller as the height of the building increases. This effect appears more clearly for low number of floors. The lateral deflection and the stiffness of the concrete shear wall with opening depend on the wall H/B ratio. If H/B increases, then the deflection mode becomes dominated by flexure. Thus, the area of the wall is not the dominant factor in the lateral deflection, but rather the moment of inertia. Reducing the central area of the wall by increasing the central R_O will reduce the wall moment of inertia by a small value, but it is reducing the shear area of the wall by large value. It can also be seen that 3% R_O still gives negligible reduction in the lateral stiffness of walls with different H/B ratios, where all values of R_D are less than 1.05 for H/B greater than 1.

To find out the maximum R_O that can be neglected, a threshold of 5% increase in R_D will be accepted as a negligible difference. From Figure 3.9 the value of R_O that can be neglected safely is 4.00%, 6.00%, 11.00%, 14.00% and 15.00% for H/B equals to 2, 3, 6, 9 and 12 respectively.

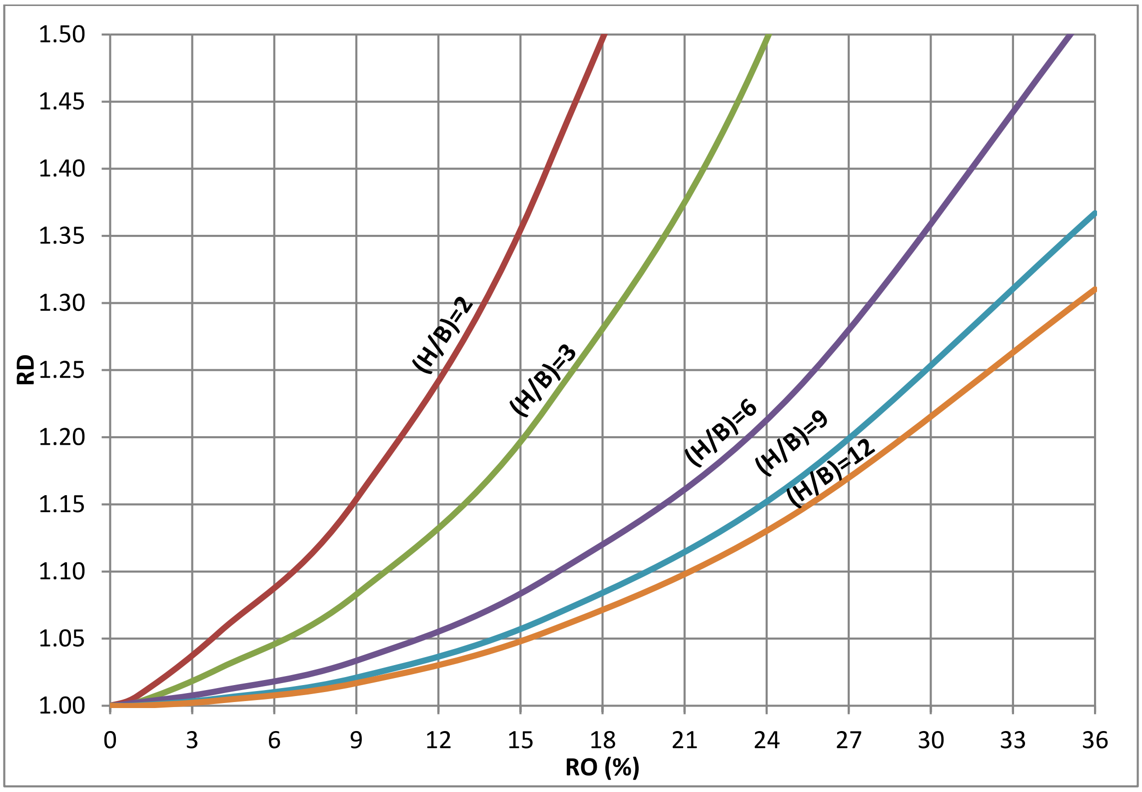

Figure 3.9: Displacement ratio R_D versus opening ratio R_O for different floor heights in shear wall with multiple openings

Moreover, if the engineer models the wall with opening as a solid wall for simplification issues, then the result of the lateral displacement must be modified by using lateral displacement modifiers. For the common central window opening of 1.30×1.30m, the top lateral displacement modifiers are 1.50, 1.30, 1.10, 1.09 and 1.07 for H/B equals to 2, 3, 6, 9 and 12 respectively. Multiplying these values with the top lateral displacement of concrete shear walls with no openings will give the top lateral displacement of the walls with central 1.3×1.30m window opening.

3.3.3 Door openings

In this section the effect of door opening in a wall on the lateral stiffness will be studied using 4 door openings of varying sizes that are suggested as shown in Figures 3.10 to 3.13. All of these figures show the wall model at the left and its equivalent frame model at the right with dimensions. These models will be named as C-D followed by the dimension of the opening, where C and D refer to concrete wall with door opening.

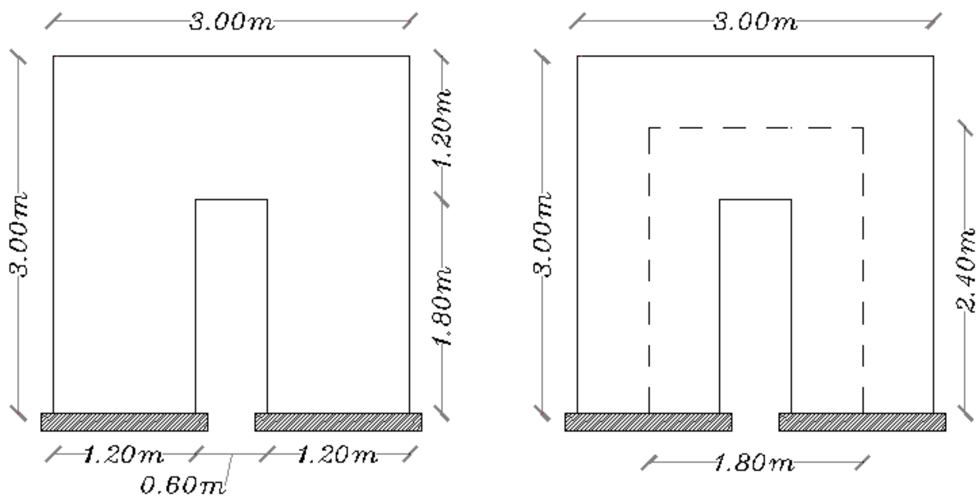

Figure 3.10: C-D6,18 solid wall and its equivalent frame model from left to right

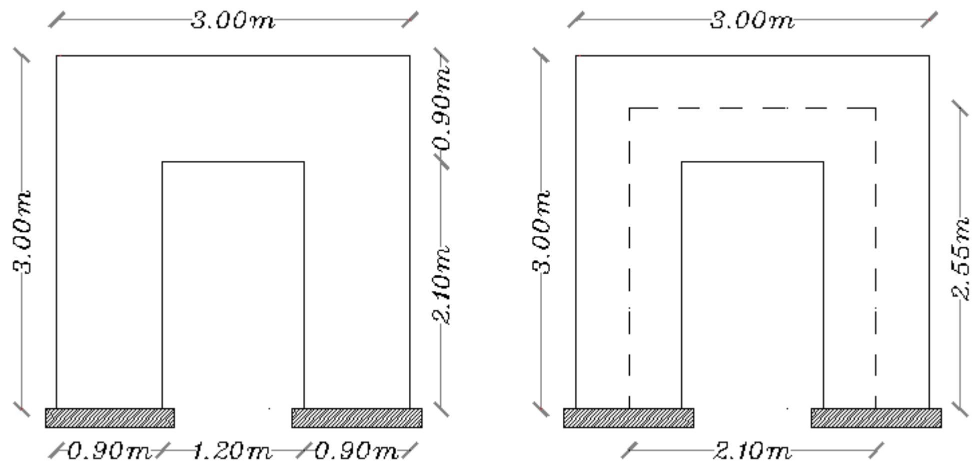

Figure 3.11: C-D12,21 solid wall and its equivalent frame model from left to right

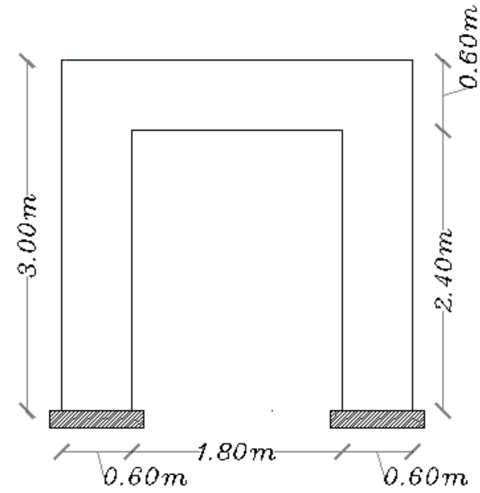

Figure 3.12: C-D18,24 solid wall and its equivalent frame model from left to right

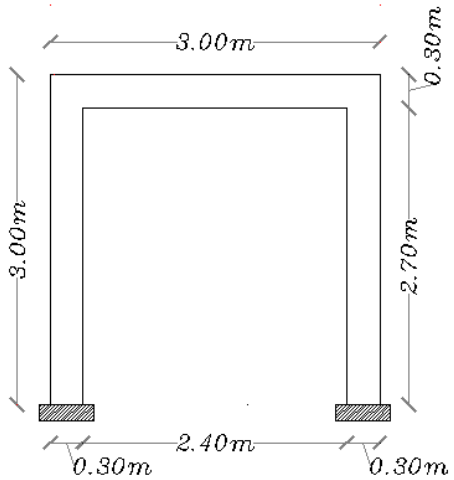

Figure 3.13: C-D24,27 solid wall and its equivalent frame model from left to right

The results of the total lateral deflection (Δ) from 2D wall, total deflection from 1D beam equivalent frame model, both flexural deflection (Δ_f) and shear deflection (Δ_s) from the equivalent frame model, the lateral stiffness (K), and the stiffness ratio (R_S) are tabulated in Table 3.4 and they are drawn in Figure 3.15.

The reason why both shear and flexural deflection are gutted from the equivalent frame model is because SAP2000 doesn't clarify the contribution of both shear and flexure deformation and gives only the total deflection of the 2D area element. The verification of the lateral deflection results in Table 3.4 from SAP2000 and other related calculations are shown in Appendix B.

Table 3.4: results of door opening models with a 3×3m wall from SAP2000

Model number	Opening size (m)	$\Delta_{2D\ area}$ Total (mm)	$\Delta_{1D\ beam}$ total (mm)	Δ_s (mm)	Δ_f (mm)	Stiffness K (10^4) (kN/m)	Stiffness Ratio, R_S (%)
C-D6,18	0.6×1.8	2.37	2.37	0.95	1.42	42.19	62.02
C-D12,21	1.2×2.1	4.75	4.94	1.24	3.70	21.05	30.95
C-D18,24	1.8×2.4	15.72	16.18	1.98	14.20	6.36	9.35
C-D24,27	2.4×2.7	135.02	136.30	4.13	132.17	0.74	1.09

Discussion of results:

Figure 3.14 shows a comparison between the lateral deflections from the Hsiao analytical method calculated in Appendix B and the finite element method results. From this figure, it can be seen that the differences between the two methods are insignificant, where the slope equals 1 and the coefficient of determination (R^2) equals 1 too. This is an indication that the finite element results have acceptable degree of accuracy.

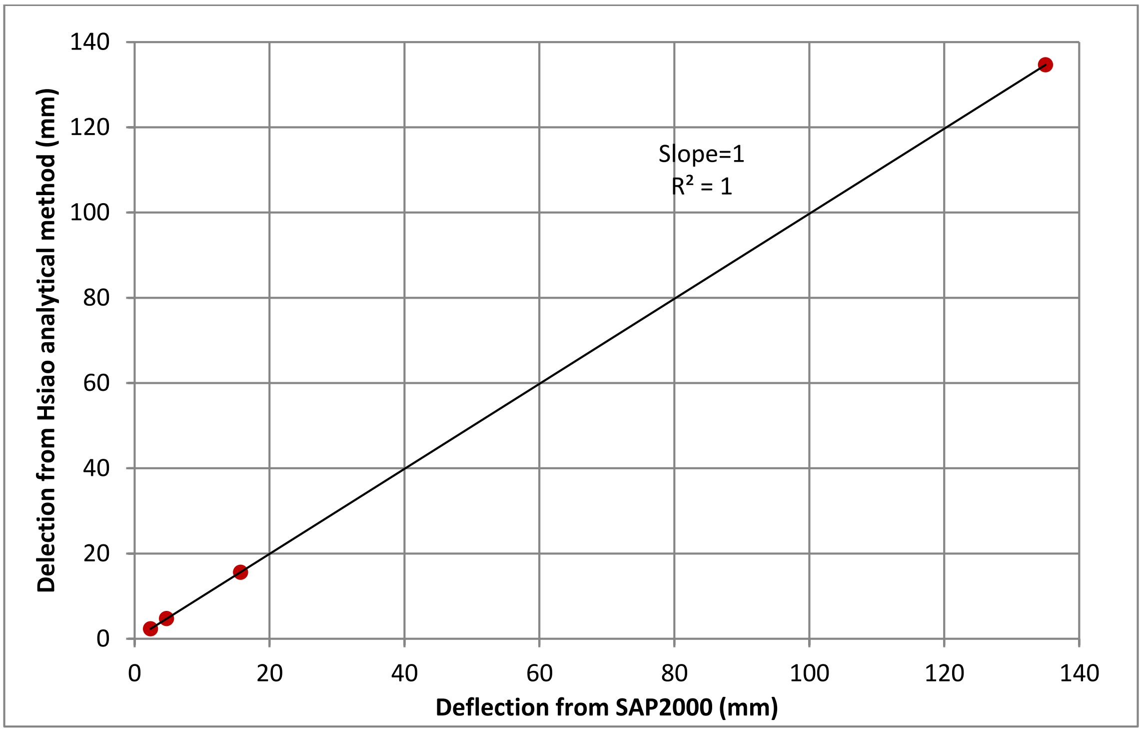

Figure 3.14: Lateral deflection values of the wall with door opening from SAP2000 versus Hsiao method

Figure 3.15 shows the relationship between R_s and R_o, where it has the same trend in the case of window opening. Increasing the size of opening will decrease the stiffness of the wall as expected and as shown previously. When the door opening ratio is 17% from the total wall area, the wall will lose almost 50% of its stiffness and this ratio is the same as in the case of window opening. The typical door opening of 1.00×2.00m which is commonly used in practice and represents 22.22% of R_O in a wall of 3.00×3.00m will result in a loss of the stiffness of this wall to about 60%.

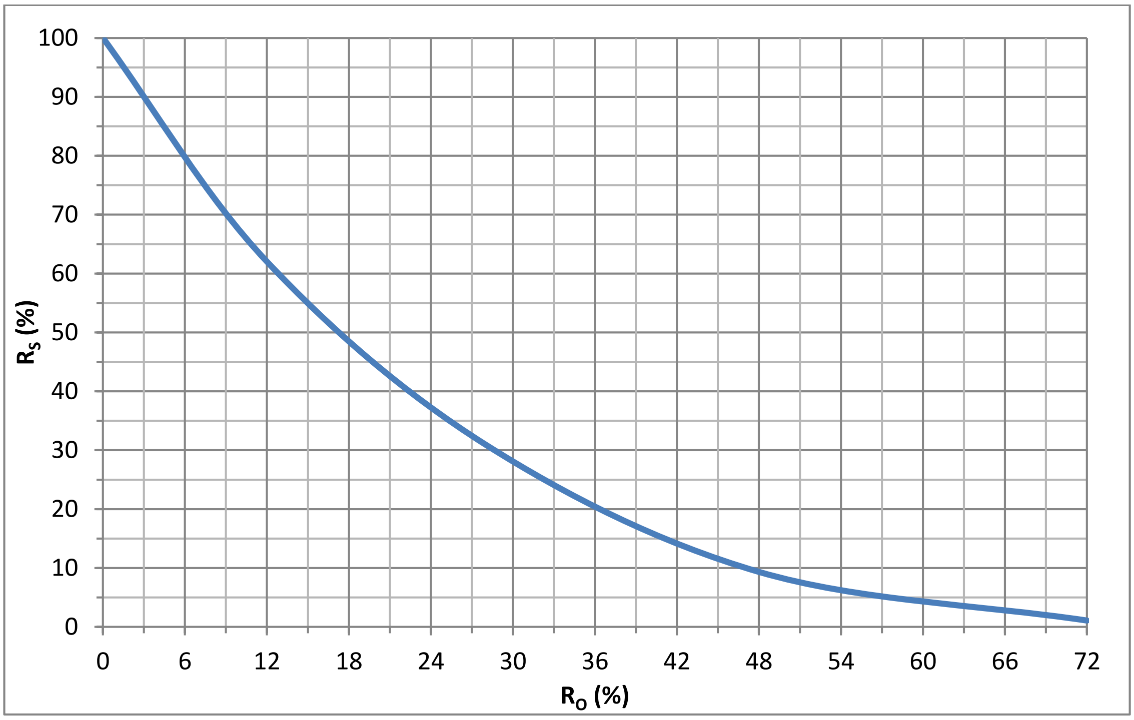

Figure 3.15: Door opening ratio versus stiffness ratio of 3×3m wall

Figure 3.16 shows the contributions of both shear and flexural deflections from the total deflection results drawn by using results listed in Table 3.4. Assuming a 5% of shear deformation contribution to be considered negligible, the minimum door opening ratio that converts the solid wall to a frame shall be equal to 65% from the total wall area, and from Figure 3.15 this ratio makes R_s of the wall equal to 2.90%.

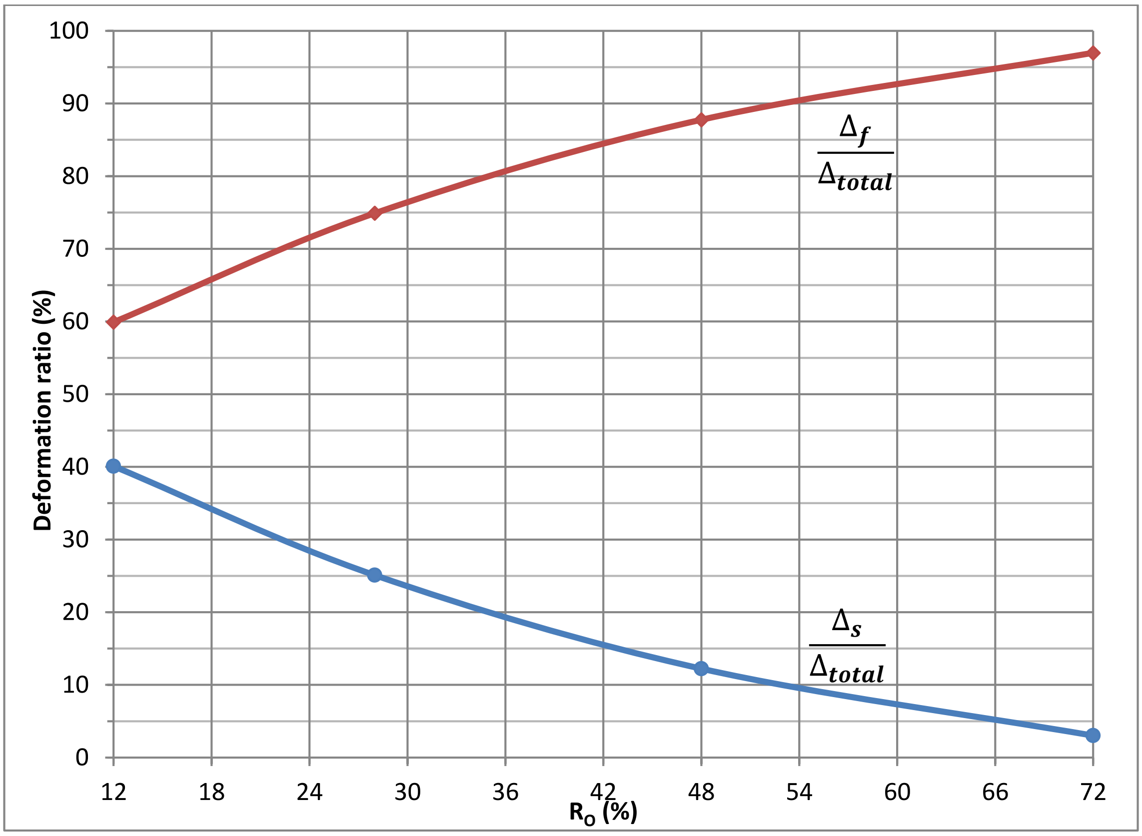

Figure 3.16: Relative contribution of shear and flexure deformation to total wall with door opening deformation in a 3×3m wall

3.4 Summary

In this chapter, the modeling and behavior of individual concrete shear walls are discussed, starting with the suitable boundaries and mesh size of the wall in modeling using SAP2000 and ending with the effect of door opening on the lateral stiffness of the wall. The boundaries of the wall are found to be a cantilever with fixed boundary conditions at bottom. The largest suitable mesh size can be 0.5m with acceptable accuracy in results. However, a more suitable size of mesh equals to 0.3m is used. The effect of concrete compressive strength on the lateral deflection of a cantilever wall without opening is also studied in the range of normal concrete strength.

The range of this effect on the lateral deflection of the wall is in the range of 1 to 1.42. A matrix of parameters that is expected to have an effect on the lateral stiffness of the wall is searched. This matrix includes a wall aspect ratio (H/B), opening type, and opening ratio R_O. The wall aspect ratio (H/B) is discussed in both cases of wall with and without opening, and it is found that the shear deformation contribution might be neglected when H/B is less than 3.7 when 5% difference due to shear deformation would be considered negligible.

The opening type is divided into window and door opening and both opening cases are studied. In the case of window opening, the effect of opening on the lateral deflection of the wall is discussed in both conditions: in central opening and in multiple central openings with different wall heights. It is found that the maximum window opening that could be neglected in modeling equals to 3% from the total wall area when 5% of the stiffness ratio R_S reduction is accepted. In multiple H/B ratios with central window opening, it is noticed that increasing the wall H/B will decrease the effect of openings in the lateral deflection and stiffness of the wall and this is because the deflection mode of the wall becomes dominated by flexure.

Finally, it is found that 65% of the door opening will convert a solid wall to a frame in its behavior when 5% difference due to shear deformation contribution may be considered negligible, and a typical door in a common practice with dimensions of 1.00×2.00m decreases a 3×3m solid wall stiffness by 60%.

4 Building-level: modeling and results

4.1 Introduction

In this chapter, the effect of the wall central window openings on the lateral stiffness and fundamental period of shear wall buildings will be studied. This study shall be conducted using two different regular floor layouts. These two cases represent two extremes with low to high ratio of shear walls. The goals of this chapter are to identify how the openings in the concrete shear walls affect the lateral stiffness and hence affect the fundamental period of those buildings. Also, to decide at which opening ratio the effect is significant for different floor numbers. Such information is vital for the simplification of the modeling of the building. Finally, to derive an equation that estimates the increasing in the fundamental period of the building due to central window openings.

4.2 Model description

In the following models the end conditions for both columns and shear walls shall be assumed to be fixed supports because the common practice in Palestine is to use footings with tie beams. Linear modal analysis will be used to get the fundamental period of these structures. The superimposed dead load is calculated in Appendix C and found to be equal to $4kN/m^2$. 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 4.1. In this table the dimensions calculated according to the ACI318-14 code are shown in Appendix D.

Table 4.1: The dimensions of structural members

Structural members type	Dimensions (cm)
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

Figure 4.1 shows the first building layout with dimensions between columns and shear walls with total floor plan area equals to 121m^2, while Figure 4.2 shows the second building layout with total floor plan area equals to 361m^2.

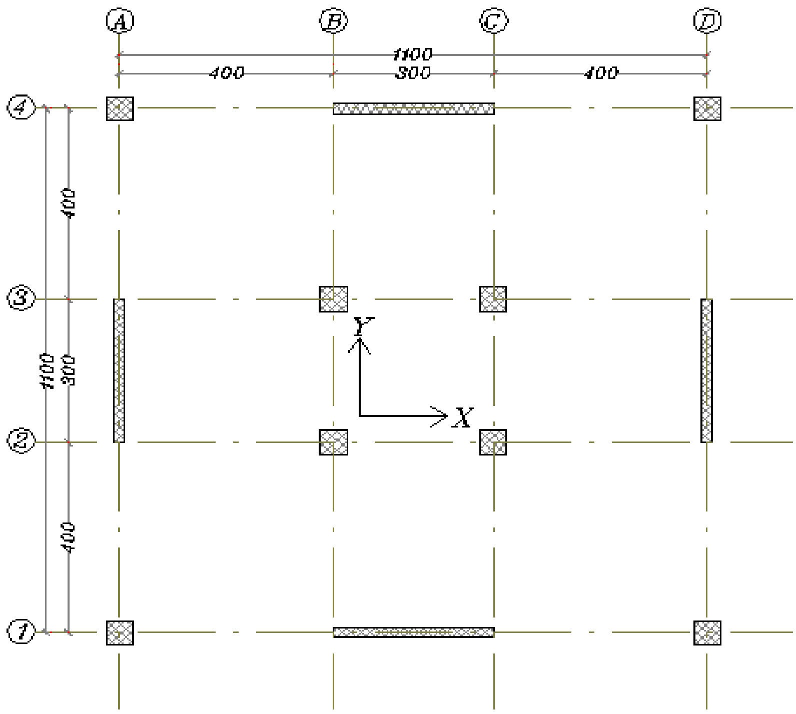

Figure 4.1: First building layout

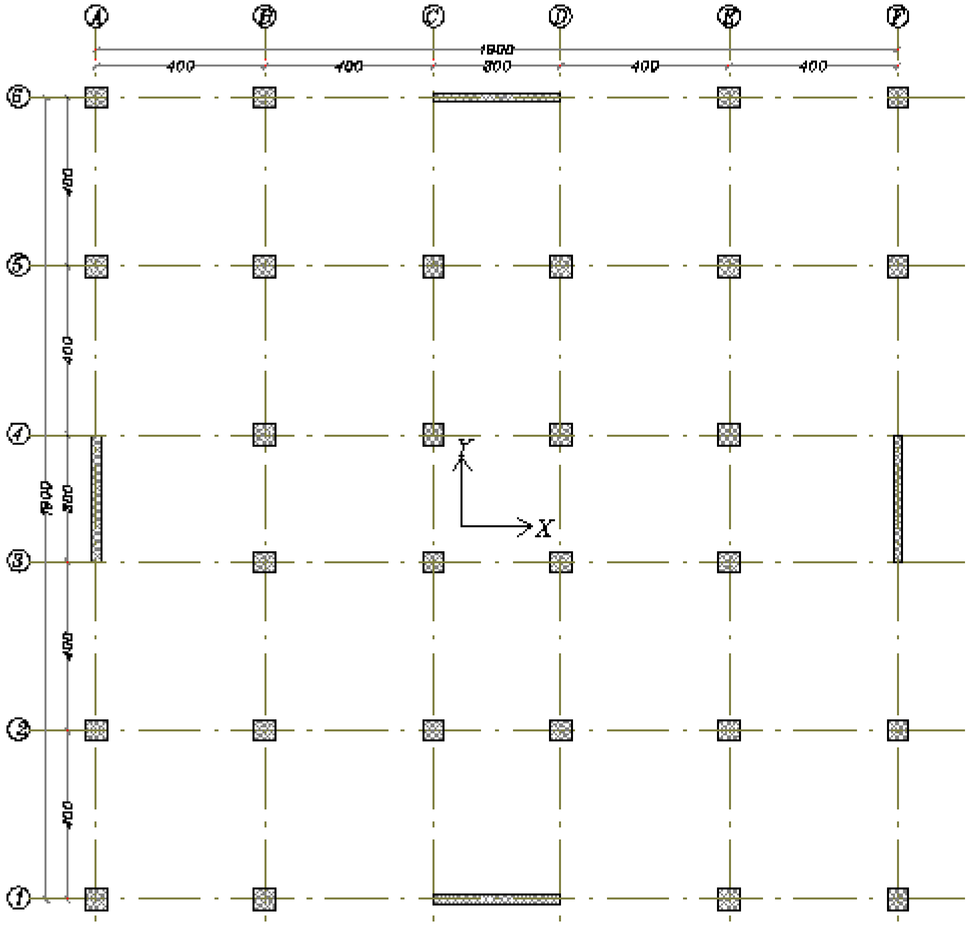

Figure 4.2: Second building layout

4.3 Matrix of parameters

In this level, 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), this F is calculated using Eq. 4.1. Note that the effect of wall H/B appears in 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 in wall H/B is from 6m to 36m as it is the most common buildings height in Palestine and B is fixed and equals to 3m. The range of F is from 6.000 to 0.005.

$$F = \frac{\sum I_w}{\left(\sum\frac{H}{B}\right)^3 \sum I_c} + \frac{\sum A_w}{\left(\sum\frac{H}{B}\right)\sum A_c} \qquad 4.1$$

Where,

I_w, I_c: Walls and columns moments of inertias respectively in the direction of calculation

A_w, A_c: Walls and columns areas respectively

H, B: Wall height and length respectively

The final matrix of parameters for the first building layout is shown in Table 4.2, while the same matrix for the second building layout is tabulated in Table 4.3. These matrices are 30 rows × 3 columns for each one, and it represents 30 models with different parameters. The model number in all matrices is named as: layout number- F, dimension of opening.

4% R_O represents 0.6×0.6m opening area, while 9% R_O represents 0.9×0.9m opening area. Also, 16% R_O represents 1.20×1.20m opening area, and 25% R_O represents 1.50×1.50m opening area. Finally, 36% R_O represents 1.80×1.80m opening area. And all of these opening areas are from the total wall area.

Table 4.2: Matrix of parameters for the first building layout

Model number	H/B	*F*	R_O (%)
1L-6.000,0	2	6.000	0
1L-6.000,6	2	6.000	4
1L-6.000,9	2	6.000	9
1L-6.000,12	2	6.000	16
1L-6.000,15	2	6.000	25
1L-6.000,18	2	6.000	36
1L-1.049,0	3	1.049	0
1L-1.049,6	3	1.049	4
1L-1.049,9	3	1.049	9
1L-1.049,12	3	1.049	16
1L-1.049,15	3	1.049	25
1L-1.049,18	3	1.049	36
1L-0.081,0	6	0.081	0
1L-0.081,6	6	0.081	4
1L-0.081,9	6	0.081	9
1L-0.081,12	6	0.081	16
1L-0.081,15	6	0.081	25
1L-0.081,18	6	0.081	36
1L-0.030,0	9	0.030	0
1L-0.030,6	9	0.030	4
1L-0.030,9	9	0.030	9
1L-0.030,12	9	0.030	16
1L-0.030,15	9	0.030	25
1L-0.030,18	9	0.030	36
1L-0.018,0	12	0.018	0
1L-0.018,6	12	0.018	4
1L-0.018,9	12	0.018	9
1L-0.018,12	12	0.018	16
1L-0.018,15	12	0.018	25
1L-0.018,18	12	0.018	36

Table 4.3: Matrix of parameters for the second building layout

Model number	H/B	*F*	R_O (%)
2L-1.714,0	2	1.714	0
2L-1.714,6	2	1.714	4
2L-1.714,9	2	1.714	9
2L-1.714,12	2	1.714	16
2L-1.714,15	2	1.714	25
2L-1.714,18	2	1.714	36
2L-0.300,0	3	0.300	0
2L-0.300,6	3	0.300	4
2L-0.300,9	3	0.300	9
2L-0.300,12	3	0.300	16
2L-0.300,15	3	0.300	25
2L-0.300,18	3	0.300	36
2L-0.023,0	6	0.023	0
2L-0.023,6	6	0.023	4
2L-0.023,9	6	0.023	9
2L-0.023,12	6	0.023	16
2L-0.023,15	6	0.023	25
2L-0.023,18	6	0.023	36
2L-0.009,0	9	0.009	0
2L-0.009,6	9	0.009	4
2L-0.009,9	9	0.009	9
2L-0.009,12	9	0.009	16
2L-0.009,15	9	0.009	25
2L-0.009,18	9	0.009	36
2L-0.005,0	12	0.005	0
2L-0.005,6	12	0.005	4
2L-0.005,9	12	0.005	9
2L-0.005,12	12	0.005	16
2L-0.005,15	12	0.005	25
2L-0.005,18	12	0.005	36

Note that the lateral displacement (Δ) will be calculated due to assumed 1kN/m^2 lateral uniform distributed 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.

The final results of the lateral displacement, lateral displacement ratio, period, and period ratio are tabulated in Table 4.4 for the first layout and in Table 4.5 for the second layout. The verification of the period results for Table 4.4 is shown in Appendix E, while the same verification for Table 4.5 is shown in Appendix F.

Table 4.4: Final results for the first building layout

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

Table 4.5: Final results for the second building layout

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

4.3.1 Results and discussion for both study cases

Figure 4.3 shows the relationship between the central window opening ratio versus the lateral displacement ratio, and Figure 4.4 shows the central window opening ratio versus period retio. 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 fundemental period of shear wall structures decreased. This is beacuse the shear wall undergoes a cantilever mode of deformation, where the effect of shear deformation are neglected by increasing the height of the building because of increasing the H/B of these walls.

From Figure 4.3, if a 5% is taken as a negligible variation in displacement ratio; the effect of opening ratio on the lateral displacement ratio can be neglected when the opening ratio is less than 4.00% of the total shear wall side area in building with height equals to 6m. This percentage increases to reach 8.00% for building height equals to 9m, 11.50% for building height equals to 18m, 15.00% for building height equals to 27m, and this percentage may increase to reach 16.50% for building height equals to 36m. Typical squared window opening of size 1.30×1.30m 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 6m, 9m, 18m, 27m, and 36m respectively.

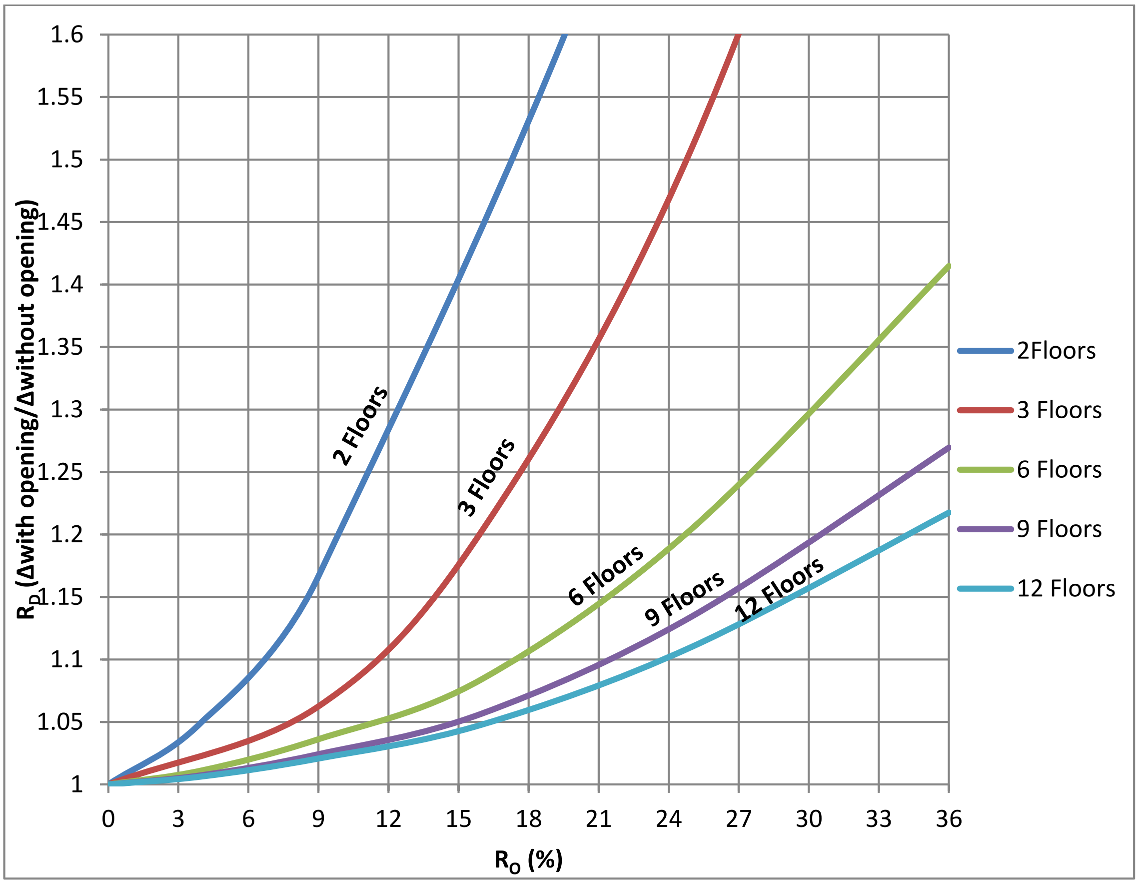

Figure 4.3: Opening ratio versus displacement ratio for different number of floors for the first building layout

Table 4.6 summarizes the maximum opening ratio and the corresponding height of the building obtained previously.

Table 4.6: The maximum R_O which cause negligible variation in R_D and the corresponding building height for the first building layout

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

The previous opening ratios of negligible variation can be found using period ratio curve from Figure 4.4; 6.50%, 10.00%, 18.00%, 22.00%, and

27.00% opening ratio can be neglected in modeling wall with buildings heights equal to 6m, 9m, 18m, 27m, and 36m respectively. Table 4.7 summarizes these maximum negligible opening ratio and the corresponding height of the building.

Table 4.7: The maximum RO which cause negligible variation in RT and the corresponding building height for the first building layout

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

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 displcement 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.

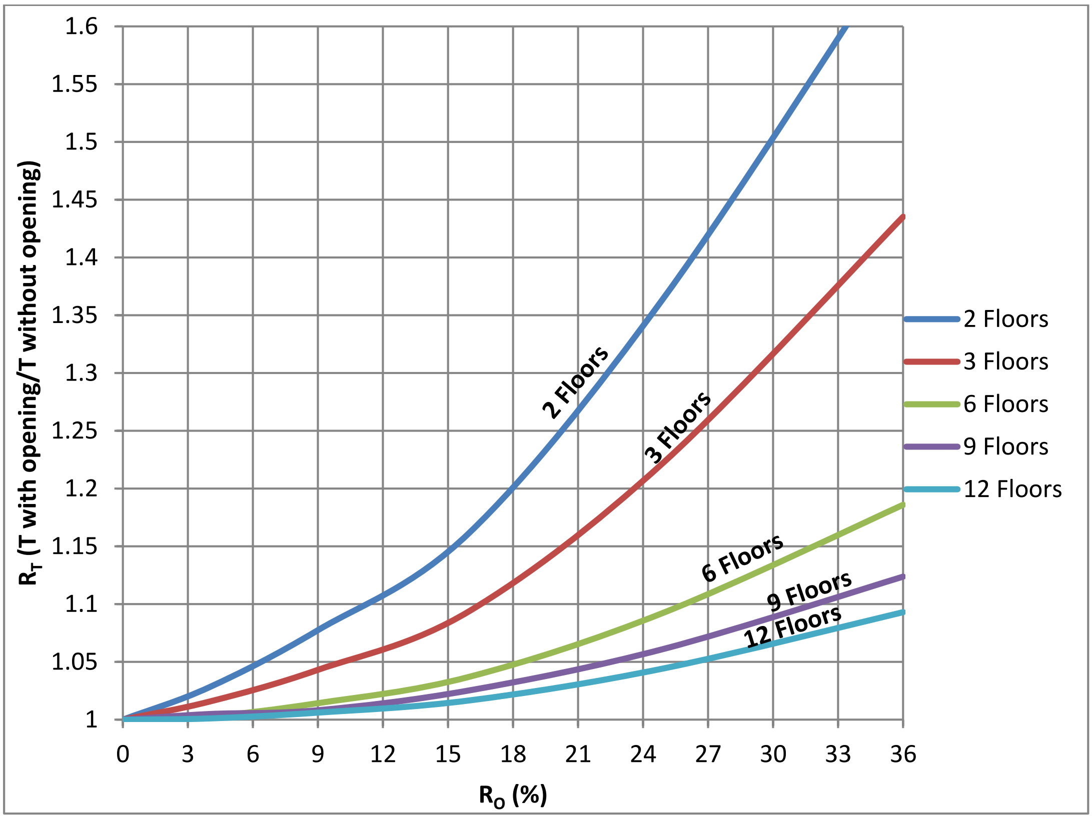

Figure 4.4: Opening ratio versus period ratio for different number of floors for the first building layout

Figure 4.5 shows the relationship between the central window opening ratio versus the lateral displacement ratio, and Figure 4.6 shows the central window opening ratio versus period retio, and these figures are for second building layout. From Figure 4.5, if a 5% is taken as a negligible variation in displacement ratio; the effect of opening ratio on the lateral displacement ratio can be neglected when the opening ratio is less than 4.00% of the total shear wall side area in building with height equals to 6m. This percentage increases to reach 9.00%, 13.00% , 18.00%, 22.00% for buildings heights equal to 9m, 18m, 27m, and 36m. For typical squared window opening of size 1.30×1.30m 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 6m, 9m, 18m, 27m, and 36m respectively.

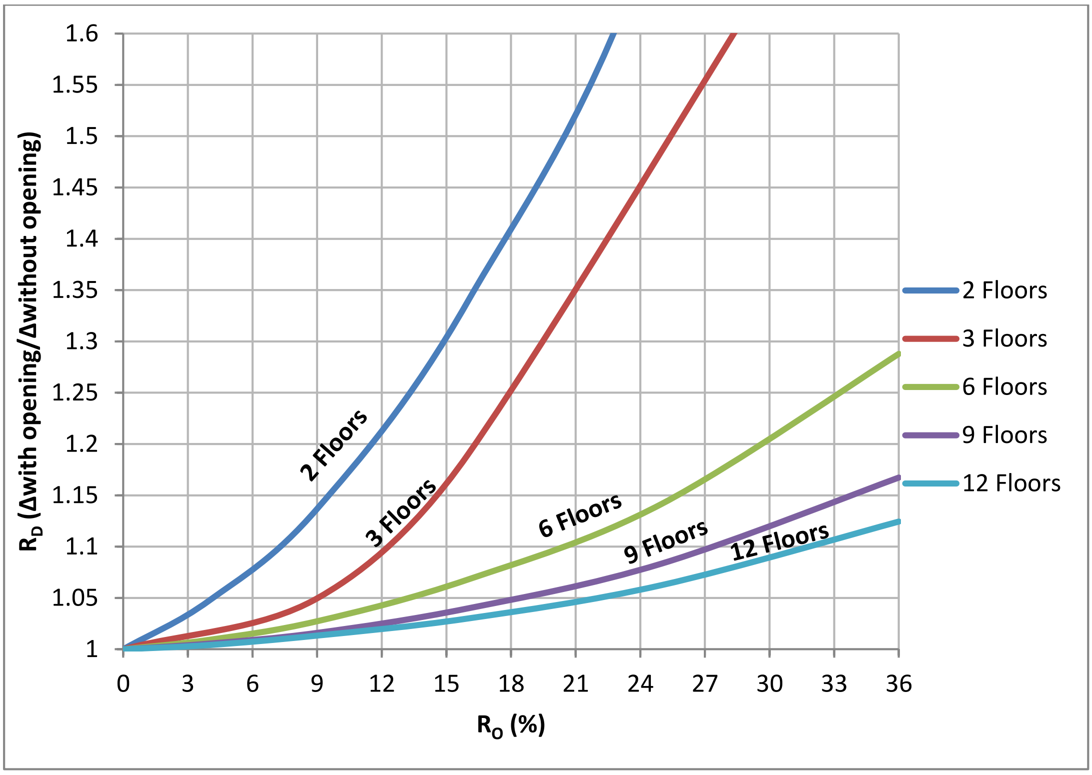

Figure 4.5: Opening ratio versus displacement ratio for different number of floors for the second building layout

Table 4.8 summarizes the maximum opening ratio and the corresponding height of the building obtained for second building layout.

Table 4.8: The maximum RO which cause negligible variation in RD and the corresponding building height for the second building layout

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

Figure 4.6 shows the relationship between opening ratio versus period ratio for the second building layout. The maximum R_O such it may be neglected safely without any effects on the period ratio will be 7.00%, 11.00%, 19.00%, 27.00%, and 32.00% for buildings heights 6m, 9m, 18m, 27m, and 36m respectively.

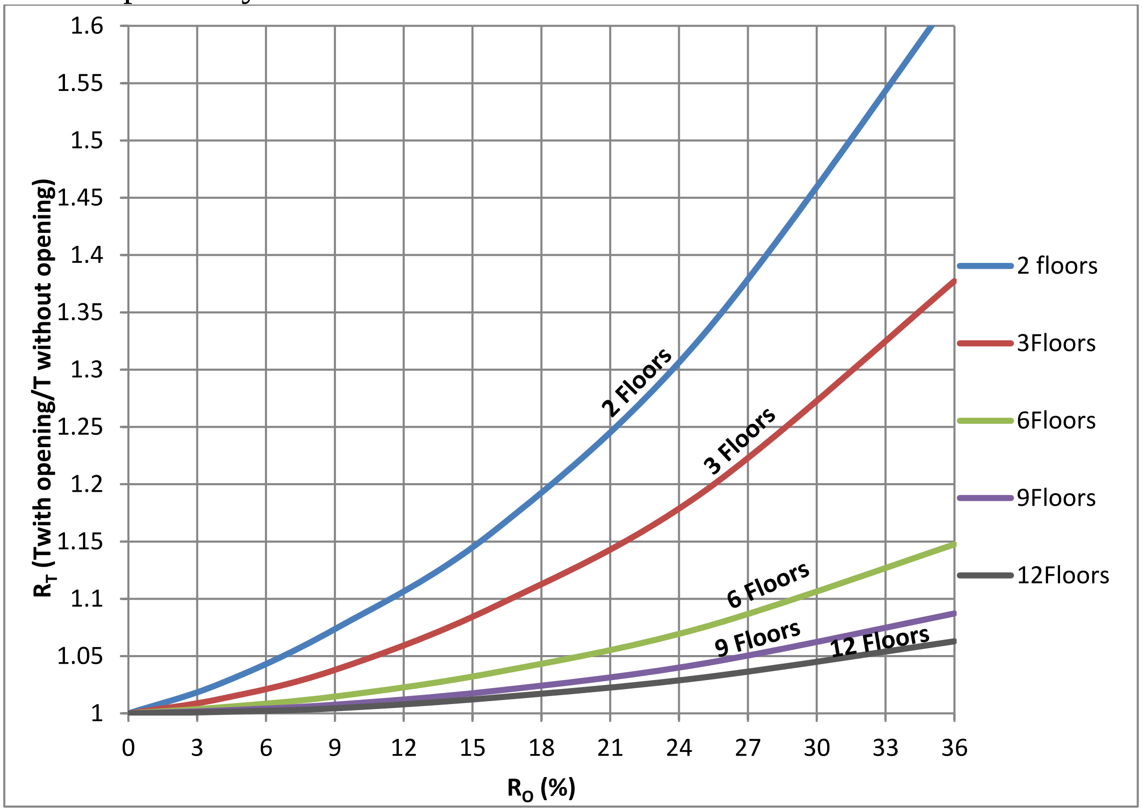

Figure 4.6: Opening ratio versus period ratio for different number of floors for the second building layout

Table 4.9 summarizes the maximum negligible opening ratio and the corresponding height of the building.

Table 4.9: The maximum RO which cause negligible variation in RT and the corresponding building height for the second building layout

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

4.3.2 Comparison to ASCE7-16 empirical code formulas

ASCE7-16 code has two equations that can be used to approximate the values of the fundemental period of shear wall structures. Eq. 4.2 is the general equation, and Eq. 4.3 is the more detailed equation.

$$T_{a-general} = C_t h^n \tag{4.2}$$

$$T_{a-detailed} = \frac{C_q}{\sqrt{C_w}} h^n \tag{4.3}$$

Where,

$C_t$and n: numerical values depending on the structural system, in shear wall system they are 0.0488 and 0.75 respectively.

h :the building height.

C_q: numerical value, it is equal 0.00058 in meter units.

$$C_w = \frac{100}{A_B} \sum_{i=1}^{x} \frac{A_i}{\left[1+0.83\left(\frac{h_n}{D_i}\right)^2\right]} \tag{4.4}$$

Where,

A_B: area of base of structure.

A_i :web area of shear wall i.

D_i: length of shear wall.

x: 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 dividid 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 spectrul response acceleration parameter at 1second, which is known as S_{D1}.

4.3.2.1 Comparison to ASCE7-16 general code formula

Figure 4.7 shows the relationship for the first building layout 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. If the building height is less than 9m, the modal analysis will give a period value less than the code equation for all opening ratios, but if the height equals to 18m and opening ratio equals to 17%, the code and modal analysis will give the same period value. Larger than this opening ratio, the modal analysis will give a period value larger than the code equation. Finally, the modal analysis shall give period values larger than the code value for buildings heights 27m and 36m. This result is very important because it is clarifying that the code value for estimating the fundamental period is not ok in 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 equation will be used, the design against earthquake load may be unreal in low-rise shear wall buildings.

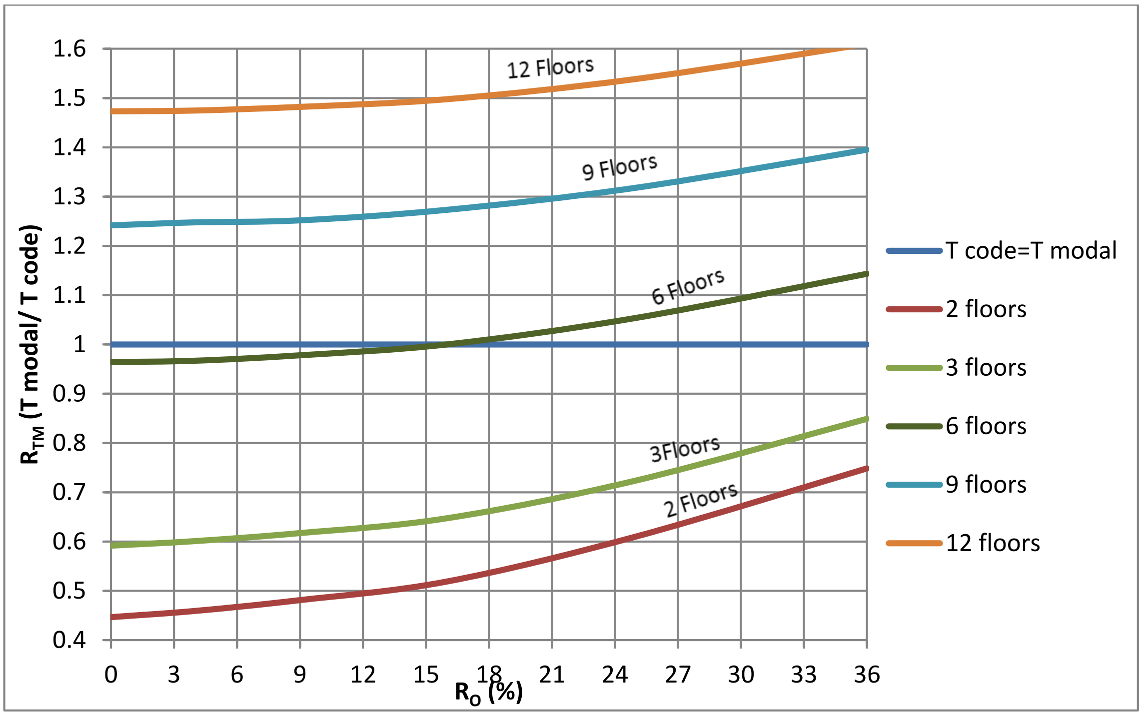

Figure 4.7: Opening ratio versus period ratio (T modal / T code) for different number of building heights for the first building layout using general code formula

Figure 4.8 shows opening ratios in walls versus the ratio between the periods from the modal analysis divided on the code value for the second building layout. If the opening ratio is less than or equals to 27%, the modal analysis will give a period value equals to or less than that obtained from the code equation for 2 floors and this opening ratio will decrease to reach 16% for 3 floors. For building heights equals to 18m or more, the modal analysis will always give a larger period value than code equation value.

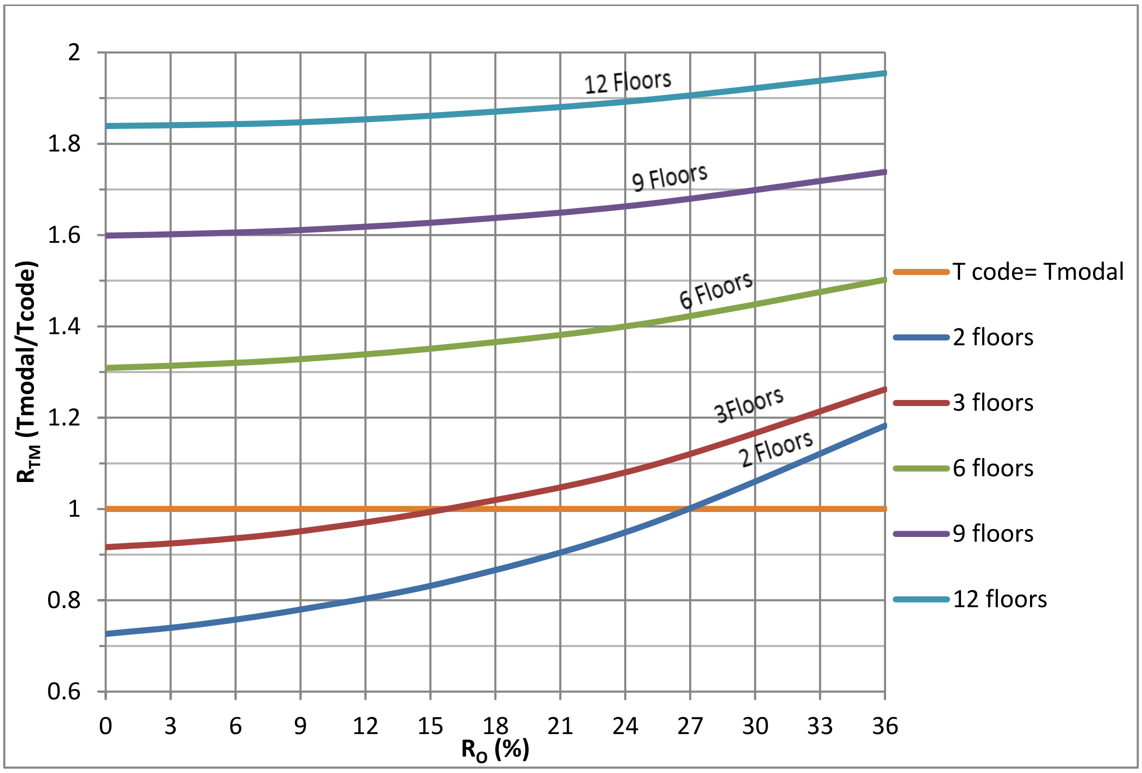

Figure 4.8: Opening ratio versus period ratio (T modal / T code) for different number of building height for the second building layout using general code formula

4.3.2.2 Comparison to ASCE7-16 more detailed code formula

When Eq. 4.3 will be used to approximate the fundamental period, it gives 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.

Figure 4.9 shows the results for the first building layout, while Figure 4.10 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 Eq. 4.3 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 code Eq. 4.3 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.

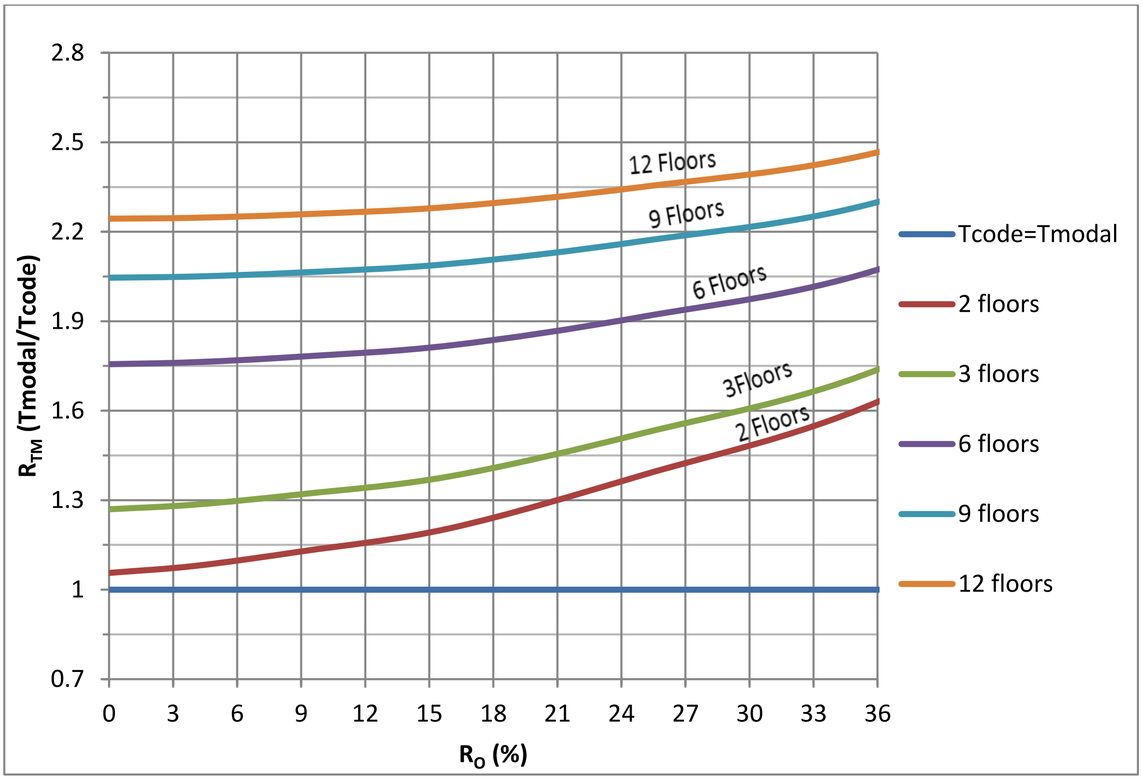

Figure 4.9: Opening ratio versus period ratio (T modal / T code) for different number of building height for the first building layout using detailed code formula

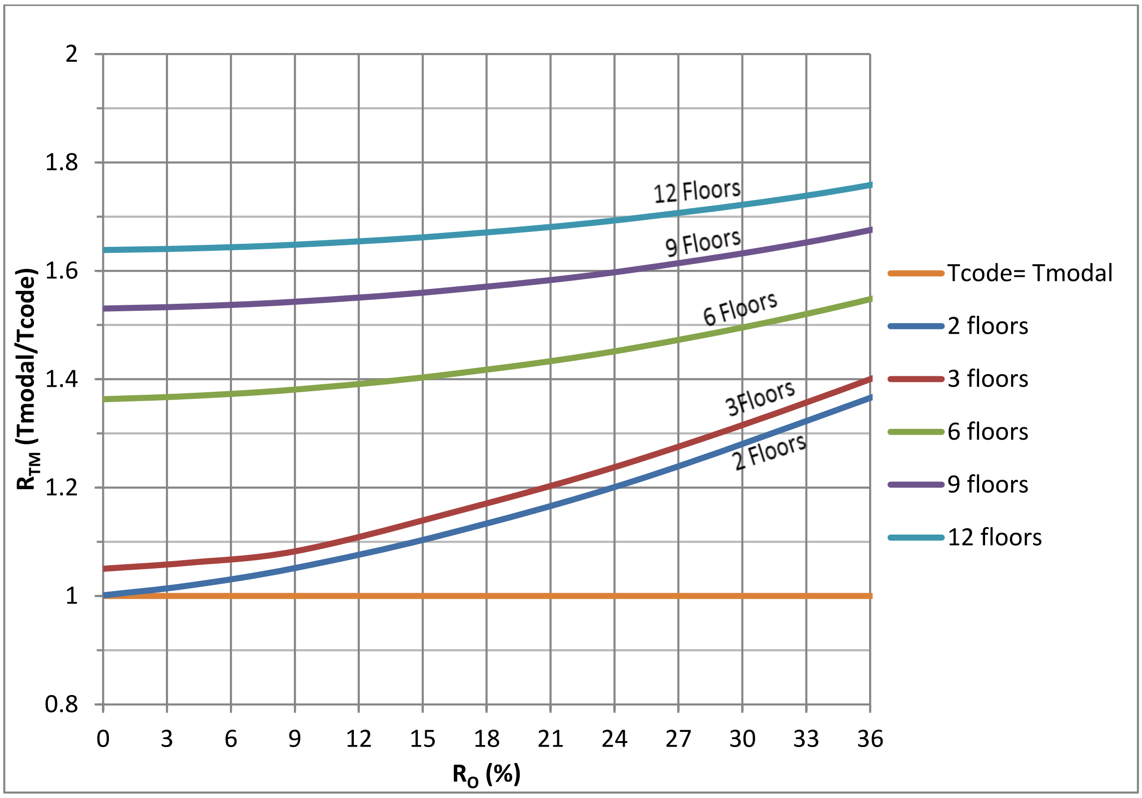

Figure 4.10: Opening ratio versus period ratio (T modal / T code) for different number of building height for the second building layout using detailed code formula

4.4 Data fitting

After conducting the previous simulations for both extreme cases and confirming that the obtained results match the common sense, it is desired to have an equation for period ratio that can be used to predict the increase in the fundamental period of shear wall regular buildings due to openings in walls for similar conditions. MATLAB software is used to develop such equation. The procedure of the fitting is as follows: First, the results from the parametric study in the building model were used to fit the equation by minimizing the norm of error between equation and data points. 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 4.3 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).

4.4.1 Period ratio equation for shear wall buildings with openings in walls

From figures 4.4 and 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 shape of the developed Eq. 4.5 will be a linear function of R_O. The final equation is:

$$1.00 \leq R_T = m_1 R_O + m_2 \leq 1.60 \qquad 4.5$$

Where,

R_T: 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

R_O: 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 the following equations:

$$m_1 = 0.0123\, F^{0.3631} \qquad 4.6$$

$$m_2 = 0.9533\, F^{-0.008} \qquad 4.7$$

Where,

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

Eq. 4.5 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.

Figure 4.11 shows the comparison between the finite element results and Eq. 4.5 results for the data used in derive the equation. It is noticed that the differences between the SAP2000 results and the proposed Eq. 4.5 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.

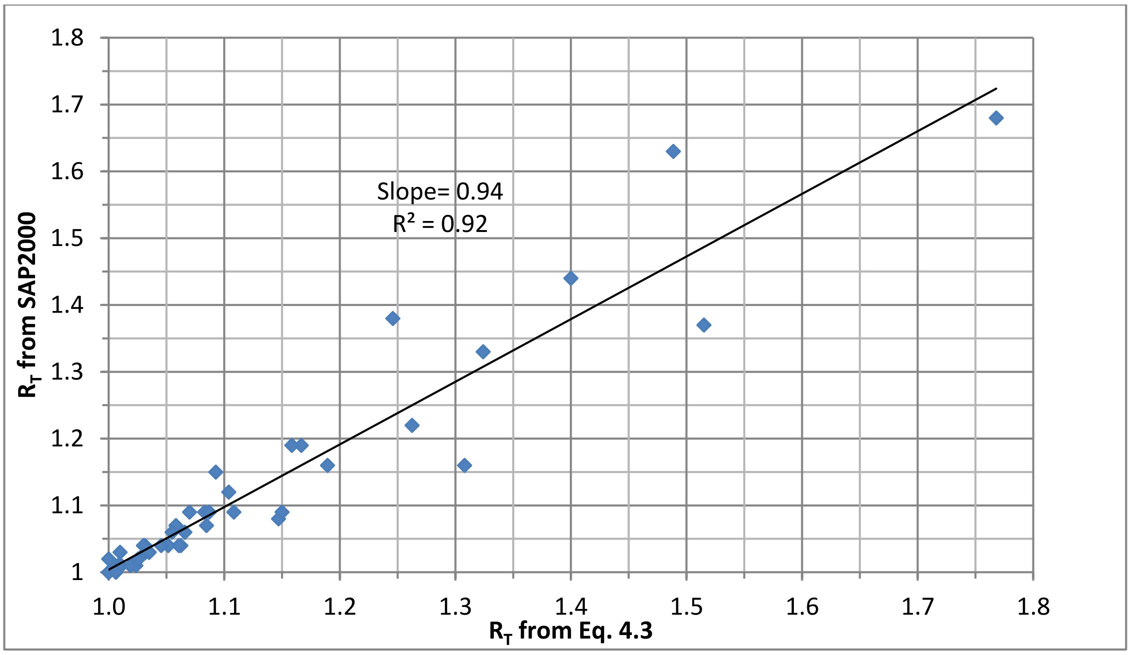

Figure 4.11: Comparison between period ratio (R_T) from both SAP2000 and Eq. 4.3 for data used in derived equation

For further verification and to check the validity of the Eq. 4.5, independent data points from different cases were generated by using SAP2000. Table 4.10 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 4.10: Matrix of parameters for the independent models

Model number	F
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 4.11 shows the comparison between the finite element results and Eq. 4.5 results for the independent data used in verified equation. The maximum relative error noticed equals to 9.80% which it is accepted.

Table 4.11: Comparison of results between SAP2000 and the developed equation for independent models

Model number	R_T from SAP	R_T from Eq. 4.5	Relative error = $100\%.\dfrac{R_{T\,SAP} - R_{T\,Equation}}{R_{T\,SAP}}$
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

4.5 Summary

In this chapter the effect of shear wall central window openings on the modal period is studied for typical regular 3D building layouts. The parameters that are expected to have significant effect on the lateral displacement and on the fundamental period of the buildings include the opening ratio (R_O), and the total moment of inertia between walls and columns plus the total shear area between walls and columns (F).

As a result, it is noticed that increasing the height of the building will decrease the effect of openings on the lateral deflection calculations and on the fundamental period of the building calculations, and this is because shear deformation contribution will be reduced by increasing the wall aspect ratio H/B, and when H/B increases the deflection mode becomes flexure. Thus, the area of the wall is not the dominant factor in the lateral deflection calculations when increasing H/B and the most dominant factor is the moment of inertia of the wall.

An equation to estimate the period ratio is developed by using the results from the parametric study on the two typical regular layouts, and then the validity of this equation is checked on a set of eight independent models. The accuracy of this equation is accepted with a maximum error of 12.75%.

ASCE7-16 code equations for estimating the fundamental period of shear wall buildings are discussed for both building layouts. It has been concluded that the general equation will give period results larger than the values from linear modal analysis in low-rise buildings and this may lead to unreal design against earthquake load, while the detailed equation will give period results lesser than the values from linear modal analysis . It is better to take the opening ratio into account and this equation provides more realistic results compared to the code equation.

5 Conclusions, Recommendations, and Future work

5.1 Overview

In this study, the effect of openings on the fundamental period and lateral deflection of shear wall structures were studied. The modeling prosess was devided into two levels. First level, to study the effect of openings on the individual wall. Second level, to study the effect of these openings on 3D typical regular buildings. An equation to predict the increase in the period was also proposed. In the following sections, the main findings and results of the study will be summarized.

5.2 Research findings

Based on this thesis results, 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 wall aspect ratio (H/B) has a major effect on the modeling of the shear walls. If this ratio is less than or equal to 3.7, then the wall shall be modeled using 2D area element or using Timoshenko beam element. Otherwise, the wall can be modeled as 1D Euler-Bernoulli beam element.

3- The effect of concrete compressive strength on the lateral deflection in a cantilever reinforced concrete shear wall is in the range of 1 to 1.42. If using the lower bound of moderate reinforced concrete which is equal to 20MPa, then the lateral deflection is equal to 1.42 times the deflection from the upper bound of moderate reinforced concrete, where it is equal to 40MPa in a cantilever shear wall.

4- For central window wall opening in one floor only, it is safe to neglect it in modeling the wall when the opening ratio is up to 3% from the wall side area, while if the opening ratio reaches 17%, then the wall stiffness is reduced to a half.

5- 65% opening ratio will convert the solid wall to behave as a frame in the case of door openings.

6- The effect of wall openings on the fundamental period of shear wall structures depend on the height of the building in 3D building level, 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.

7- The opening ratio which can be neglected in the modeling phase is in the range from 4.00% in 6m building height to 16.50% in 36m building height, and these ratios are from the first building layout and for second building layout they will be 4.00% and 22.00% respectively.

8- 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.

5.3 Proposed equation

Based on statistical regression and fitting of results for both 3D regular building layouts, the following equation can be used to approximate the period ratio which represents the increasing in the value of the fundamental period due to opening in the concrete shear walls. This equation is:

$$1.00 \leq R_T = m_1 R_O + m_2 \leq 1.60 \qquad 5.1$$

Where,

R_T: 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

R_O: 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 the following equations:

$$m_1 = 0.0123\, F^{0.3631} \qquad 5.2$$

$$m_2 = 0.9533\, F^{-0.008} \qquad 5.3$$

Where,

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

Eq. 5.1 can be used as a 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.

It shall be noted that the previously mentioned equation has limitations that must be considered when used. This equation is valid under the following limitations:

1- This equation can be used for regular shear wall buildings only similar to layout 1 or 2 with no vertical and horizontal irregularities. The regular case will be existed when the center of mass and the center of rigidity are on each other, or the distance between them is so small.
2- It is used in the case of central window openings only.
3- The range of (F) varies from 6.000 to 0.005.
4- The range of opening ratio (R_O) is from 0% to 36%. This range covers the windows openings sizes in the common practice.
5- The height of the building (H) is between 6.00m to 36.00m and this range covers the common practice used in Palestine.

5.4 Future work

The following are suggested researches to be continued:

- Studying the effect of openings on the fundamental period in shear wall buildings by using nonlinear dynamic analysis to make comprehensive comments.

- Studying the effect of diaphragm rigidity on the lateral deflection and the fundamental period in shear wall buildings.
- Studying the effect of opening in other different patterns of distribution in a wall as multi window openings, multi-door openings, and the case of a wall containing door and window openings at the same time.
- Studying the effect of openings on the fundamental period of shear wall structures in other different wall distribution cases in 3D building level.
- Studying the effect of openings in different wall boundary conditions in the wall level model.
- Propose an equation for period ratio of the shear wall building for the case of door opening.
- Studying the effect of mass and stiffness variation between floors in shear wall buildings with openings in walls on the fundamental period.

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Appendices

Appendix A: Verification of lateral deflection for central window opening

In this section, the lateral deflection for the individual wall with central window opening and the relative error between SAP2000 and Hsiao manual method will be calculated and tabulated in Table A.1.

Table A.1: Verification of the lateral deflection and the percentage of error of a 3×3m wall with window opening

Model number	Opening size (m)	Opening Ratio (%)	$\Delta_{SAP2000}$ (mm)	$\Delta_{Hsiao\ method}$ (mm)	Error (%)
C-W0	0.00	0.00	1.47	1.49	1.36
C-W3	0.3×0.3	1.00	1.52	1.50	1.31
C-W4	0.4×0.4	1.78	1.52	1.51	0.66
C-W5	0.5×0.5	2.78	1.55	1.53	1.29
C–W6	0.6×0.6	4.00	1.66	1.55	6.60
C-W7	0.7×0.7	5.44	1.76	1.61	8.52
C-W8	0.8×0.8	7.11	1.86	1.77	4.83
C-W9	0.9×0.9	9.00	2.00	1.97	1.50
C-W10	1.0 ×1.0	11.11	2.21	2.22	0.45
C-W11	1.1×1.1	13.44	2.54	2.55	0.39
C-W12	1.2×1.2	16.00	2.84	2.99	5.28
C-W13	1.3×1.3	18.78	3.28	3.55	8.23
C-W14	1.4×1.4	21.78	3.90	4.30	10.25
C-W15	1.5×1.5	25.00	4.66	4.37	6.22
C-W16	1.6×1.6	28.44	5.66	5.68	0.35
C-W17	1.7×1.7	32.11	7.16	7.49	4.60
C-W18	1.8×1.8	36.00	9.05	10.08	11.38

Model C-W12 is taken as a sample calculation to apply the Hsiao method which it is clarified in chapter 2 step by step. Figure A.1 shows the dimensions in mm of C-W12 model.

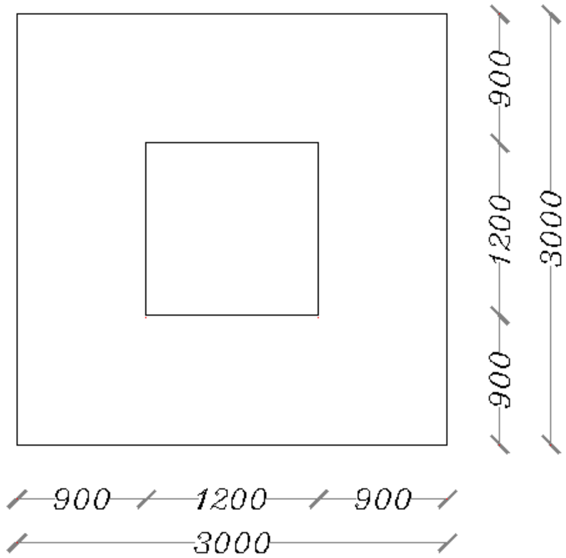

Figure A.1: Model C-W12 with dimensions

- Step1: Referring to Figure 2.15 and Figure A.1 the parameters of this example are:

  W_{p2}=W_{p2} = 900 mm, and 0.5D_t =0.5D_b = 450mm, so

  X_{t1} =X_{t2}=X_{b1} =X_{b2} = 450mm.

  L_{p1}=L_{p1} $= h_p$+X_{t1}+X_{p1}=1200+450+450 = 2100mm.

- Step2: The equivalent frame system that will be used as shown in Figure 2.16 is:

  L_b=3000-900=2100mm

  $I_b= \frac{200\times900^3}{12}$ =1.215×10^{10} mm^4

  I_{p1}=I_{p2} $= \frac{200\times900^3}{12}$ =1.215×10^{10} mm^4

- Step3: Calculate the flexural deflection in piers.

  K_1 =K_2=1

$\Delta_{moment,pier1}$=$\Delta_{moment,pier2}$=3.95×10^{-6} mm/N.

The flexural rigidity for pier 1=R $_{pier1}$= $\frac{1}{\Delta_{moment,pier1}}$ =253469 N/mm

The flexural rigidity for pier 2 =R $_{pier2}$= $\frac{1}{\Delta_{moment,pier2}}$ =253469 N/mm

- Step4: Calculate the flexural deflection assuming total solid wall with no opening

  $I_{solid\ wall}$= $\frac{200\times3000^3}{12}$ = 4.5×10^{11} mm^4.

  $\Delta_{moment,solid\ wall}$ = 8.7×10^{-7} mm/N.

- Step5: Substituting in Eq.2.32 for both layers as described previously.

  X_1=h-0.5D_t=3000-450=2550mm.

  X_2=D_{b1}-X_{b1}=900-450=450mm.

  $\Delta_{moment,2550}$= 6.75×10^{-7} mm/N.

  $\Delta_{moment,450}$= 2.79×10^{-8} mm/N.

  $\Delta_{moment,solid\ strip}$= 6.75×10^{-7} - 2.79×10^{-8}=6.48×10^{-7}mm/N.

- Step6: Calculate the open strip flexural deflection.

  $\Delta_{moment,open\ strip}$= 1.97×10^{-6}mm/N.

- Step7: Calculate the flexural deflection of the wall with opening

  $\Delta_{moment\ in\ the\ wall\ with\ opening}$ =2.19×10^{-6}mm/N.

- Step8: Calculate the total shear deflection in the wall for three layers as described in chapter 2.

  It is the sum of the shear deflection of the following three layers by using the following equation:

  1) The layer from the bottom of the wall to the bottom of the opening.

In our case $\Delta shear_{0\rightarrow900}=\frac{1.2\times900}{200\times3000\times9583.333}$ = 1.88×10^{-7}mm/N.

2) The layer from the bottom of the opening to the top of the opening

In our case $\Delta shear_{900\rightarrow2100} = \frac{1.2\times1200}{200\times(900+900)\times9583.333}$

= 4.17×10^{-7}mm/N.

3) The layer from the top of the opening to the top of the wall.

In our case $\Delta shear_{2100\rightarrow3000}=\frac{1.2\times900}{200\times3000\times9583.333}$

= 1.88×10^{-7}mm/N.

$\Delta_{shear\ in\ the\ wall\ with\ opening}$ = 1.88×10^{-7}+4.17×10^{-7}+1.88×10^{-7}

$\Delta_{shear\ in\ the\ wall\ with\ opening}$ = 7.93 ×10^{-7}mm/N.

- Step9: calculate the total wall deflection with opening

  $\Delta_{total\ with\ opening}$ =7.93 ×10^{-7}+2.19×10^{-6} =2.99×10^{-6} mm/N.

When 1000kN lateral load is applied as in our case then the total deflection in this wall with opening is $\Delta_{total\ with\ opening}$=2.99 mm.

$$\%\ of\ Error = 100\% \times \left|\frac{\Delta_{SAP2000}-\Delta_{Hsiao\ method}}{\Delta_{SAP2000}}\right| = 5.28\% < 25\% \rightarrow \text{OK}$$

Appendix B: Verification of lateral deflection for door opening

In the following section, the lateral deflection for the individual wall with door opening and the relative error between SAP2000 and Hsiao manual method will be calculated and tabulated in Table B.1.

Table B.1: Verification of the lateral deflection and the percentage of error of a 3×3m wall of door opening

Model number	Opening size (m)	$\Delta_{SAP, 2D\ area}$ Total (mm)	$\Delta_{Hsiao\ method}$ Total (mm)	Error (%)
C-D6,18	0.6×1.8	2.37	2.12	10.54
C-D12,21	1.2×2.1	4.75	4.53	4.63
C-D18,24	1.8×2.4	15.72	15.35	2.35
C-D24,27	2.4×2.7	135.02	134.43	0.43

Model C-D18,24 is taken as a sample calculation to apply the Hsiao method. Figure B.1 shows the dimensions in m of C-D18,24 model.

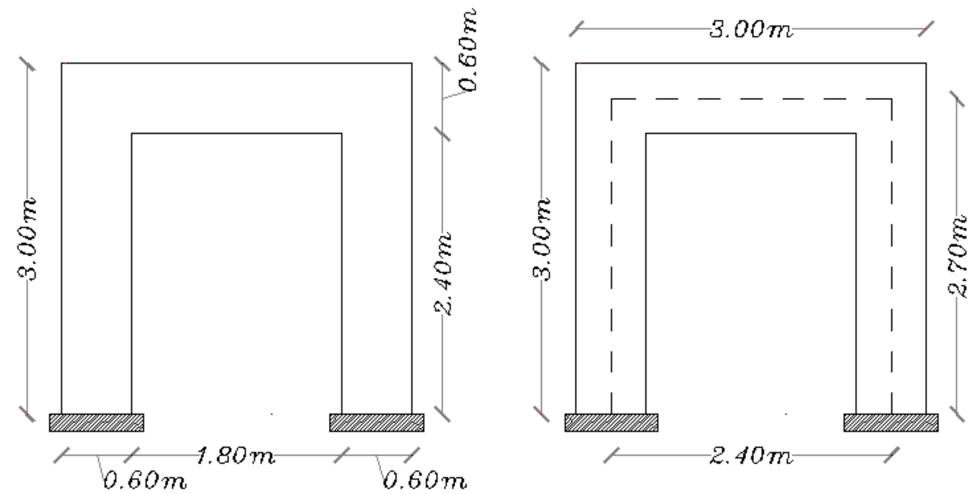

Figure B.1: C-D18,24 solid wall and its equivalent frame model from left to right

- Step1: Referring to Figure 2.15 and Figure B.2 the parameters of this example are:

W_{p2}=W_{p2} = 600 mm

X_{t1} =X_{t2}=300mm.

L_{p1}=L_{p1} $= h_p$+X_{t1}=2400+300= 2700mm.

- Step2: The equivalent frame system that will be used as shown in Figure 2.16 where:

L_b=3000-600=2400mm

I_b= $\frac{200\times600^3}{12}$ =3.6×10^9 mm^4

I_{p1}=I_{p2} $= \frac{200\times600^3}{12}$ =3.6×10^9 mm^4

- Step3: Calculate flexural deflection in piers.

K_1 =K_2=1.125

$\Delta_{moment,pier1}$=$\Delta_{moment,pier2}$=2.74×10^{-5} mm/N.

The flexural rigidity for pier 1=R $_{pier1}$= $\frac{1}{\Delta_{moment,pier1}}$

= 36392.64 N/mm

The flexural rigidity for pier 2 =R $_{pier2}$= $\frac{1}{\Delta_{moment,pier2}}$

= 36392.64 N/mm

- Step4: Calculate flexural deflection assuming total solid wall

$I_{solid\ wall}$= $\frac{200\times3000^3}{12}$ = 4.5×10^{11} mm^4.

$\Delta_{moment,solid\ wall}$ = 8.7×10^{-7} mm/N.

- Step5: Substituting in Eq.2.32 for both layers as described previously.

X_1=h-0.5D_t=3000-300=2700mm.

X_2=D_{b1}-X_{b1}=0.00mm.

$\Delta_{moment,2550}$= 7.40×10^{-7} mm/N.

$\Delta_{moment,solid\ strip}$= 7.40×10^{-7} mm/N.

- Step6: Calculate the open strip flexural deflection.

  $\Delta_{moment,open\ strip}$= 1.38×10^{-5}mm/N.

- Step7: Calculate the flexural deflection of the wall with opening

  $\Delta_{moment\ in\ the\ wall\ with\ opening}$ =1.39×10^{-5}mm/N.

- Step8: calculate the total shear deflection in the wall for three layers as described previously.

  It is the sum of the shear deflection of the following two layers by using the following equation:

  1) The layer from the bottom of the opening to the top of the opening

  In our case $\Delta shear_{0\rightarrow2400}= \frac{1.2\times2400}{200\times(600+600)\times9583.333}$ = 1.25×10^{-6}mm/N.

  2) The layer from the top of the opening to the top of the wall.

  In our case $\Delta shear_{2400\rightarrow3000}=\frac{1.2\times600}{200\times3000\times9583.333}$ = 2.29×10^{-7}mm/N.

  $\Delta_{shear\ in\ the\ wall\ with\ opening}$ =1.25×10^{-6}+2.29×10^{-7}=1.48×10^{-6}mm/N.

- Step9: calculate the total wall deflection with opening

  $\Delta_{total\ with\ opening}$ =1.39×10^{-5}+1.48 ×10^{-6}=1.535×10^{-5} mm/N.

When 1000kN lateral load is applied as in our case then the total deflection in this wall with opening is $\Delta_{total\ with\ opening}$=15.35 mm.

$$\%\ of\ Error = 100\% \times \left|\frac{\Delta_{SAP2000}-\Delta_{Hsiao\ method}}{\Delta_{SAP2000}}\right| = 2.35\% < 25\% \rightarrow \text{OK}$$

Appendix C: Calculation of the superimposed dead load

Table C.1 shows the common densities of the construction materials according to the Jordanian code for loads and forces.

Table C.1: Densities of the common used construction materials in Palestine

Material type	Density (kN/m^3)
Fill materials (fine aggregate)	18
Mortars	22
Plastering	22
Reinforced concrete	25
Tiles	24

The common thicknesses of the slab covered materials are the following:

- ✓ 3cm tile thickness.
- ✓ 2cm mortar thickness.
- ✓ 10cm fills under the tiles.
- ✓ 1.5cm plastering thickness.

$0.5 kN/m^2$ is used for internal partitions, and the total superimposed dead load (SID) will be as the following:

$$SID = 0.03 \times 24 + 0.02 \times 22 + 0.1 \times 18 + 0.015 \times 22 + 0.5$$

$$\therefore SID = 3.79 kN/m^2 \rightarrow use\ 4 kN/m^2$$

Appendix D: Checks for sizes of structural members

D1-check for two way flat plate slab thickness

according to Table 8.3.1.1 in ACI 318M-14, the minimum thickness for the two way flat plate slabs for Fy=420MPa, no drop pannels, and no edge beams is equal to $\frac{l_n}{30}$ for exterior panels and $\frac{l_n}{33}$ for interior panels and this thickness shall be increased by 10%.

The most critical case in all layouts is equal to 4.00m for exterior panels.

$$h_{min} = 1.1 \times \frac{l_n}{30} = 1.1 \times \frac{4}{30} = 0.147m$$

$\therefore$ *the provided* $0.2m$ *slab thickness is ok*

D2-check for shear wall thickness

according to Table 11.3.1.1 in ACI 318M-14, the minimum thickness of the wall equals to the maximum of (100mm, $\frac{1}{25}$ unsupported floor height).

$$h_{wall\ min} = \max(0.10, \frac{3}{25}) = 0.12m$$

$\therefore$ *the provided* $0.2m$ *wall thickness is ok*

D3-check for columns cross-sections

For the first layout Table D.1 shows the ultimate self-weight of structural elements included within the tributary area for 1 floor, and Table D.2 shows the ultimate weight of distributed load over the tributary area for 1 floor, and Table D.3 shows the final results for the needed and the provided columns cross sections .

Table D.1: Ultimate self-weight of structural elements included within the tributary area for the first layout

Type of element	Load factor	γ_c (kN/m^3)	Dimension (m) Length	Width	Depth	Factored weight (kN)
Slab	1.2	25	3.50	3.50	0.20	73.50
Column	1.2	25	3.00	0.60	0.60	32.40
					$\sum$	105.90

Table D.2 : Ultimate weight of distributed load over tributary area for the first layout

Load pattern	Load factor	Distributed load (kN/m^2)	Tributaru area (m) Length	Width	Factored weight (kN)
SID	1.2	4	3.50	3.50	58.80
LL	1.6	2	3.50	3.50	39.20
				$\sum$	98.00

So, for one floor the total ultimate load = 105.90+98.00 = 203.90kN

Table D.3: The final results for the needed and the provided columns cross sections for the first layout

Number of floors	Total ultimate load (kN)	Squared column needed (cm)	Provided column (cm)	Safe or note
2	407.80	21×21	25×25	Safe
3	611.70	25×25	30×30	Safe
6	1223.40	35×35	45×45	Safe
9	1835.10	43×43	55×55	Safe
12	2446.80	50×50	60×60	Safe

For the second layout Table D.4 shows the ultimate self-weight of structural elements included within the tributary area for 1 floor, and Table D.5 shows the ultimate weight of distributed load over the tributary area for 1 floor, and Table D.6 shows the final results for the needed and the provided columns cross sections .

Table D.4: Ultimate self-weight of structural elements included within the tributary area for the second layout

Type of element	Load factor	γ_c (kN/m^3)	Dimension (m) Length	Width	Depth	Factored weight (kN)
Slab	1.2	25	4.00	4.00	0.20	96.00
Column	1.2	25	3.00	0.6	0.6	32.40
					∑	128.40

Table D.5: Ultimate weight of distributed load over tributary area for the second layout

Load pattern	Load factor	Distributed load (kN/m^2)	Tributaru area (m) Length	Width	Factored weight (kN)
SID	1.2	4	4	4	76.80
LL	1.6	2	4	4	51.20
				∑	128.00

So, for one floor the total ultimate load = 128.40+128.00 = 256.40kN

Table D.6: The final results for the needed and the provided columns cross sections for the second layout

Number of floors	Total ultimate load (kN)	Squared column needed (cm)	Provided column (cm)	Safe or not
2	512.80	23×23	25×25	Safe
3	769.20	28×28	30×30	Safe
6	1538.40	40×40	45×45	Safe
9	2307.6	49×49	55×55	Safe
12	3076.80	56×56	60×60	Safe

Appendix E: Verification of the fundamental period for first layout

To verify the results of periods, Rayleigh's method (Eq.1.3) is used for sample calculation in the first layout and applied on the model number 1L-0.081,6. To apply this method the weight at each level of the floor is found to be the dead load from slab own weight plus two halves of weights for columns and shear walls above and below the intended level plus the superimposed dead load at each slab level.

The lateral force is assumed to be 5kN/m^2. Elastic deflection for each floor is found from SAP2000 and used in Rayleigh's formula as shown in Table E.1.

The calculation of the total single floor dead load as shown in the following:

Slab own weight for single floor = $11 \times 11 \times 0.2 \times 25 = 605\text{kN}$

Columns own weight in single floor = $8 \times 0.45 \times 0.45 \times 3 \times 25 = 121.5\text{kN}$

Shear walls with opening own weight in a single floor = $4 \times (3 \times 3 - 0.6 \times 0.6) \times 0.2 \times 25 = 172.8\text{kN}$

Superimposed dead load in single floor=$11 \times 11 \times 4 = 484\text{kN}$

Table E.1: Verification of the fundamental period of model 1L-18,54,6

Level	w_i (kN)	f_i (kN/m^2)	Floor Area (m^2)	f_i (kN)	δ_i (m)	$w_i\delta_i^2$ (kN.m^2)	$f_i\delta_i$ (kN.m)
6	1236.15	5	121	605	0.0768	7.291	46.464
5	1383.30	5	121	605	0.0625	5.403	37.813
4	1383.30	5	121	605	0.0472	3.082	28.556
3	1383.30	5	121	605	0.0318	1.399	19.239
2	1383.30	5	121	605	0.0173	0.414	10.467
1	1383.30	5	121	605	0.0056	0.043	3.388
					$\sum$	17.632	145.927

T_1 using Rayleigh's method equals to 0.700 second, while T_1 from SAP equals to 0.701 second. Thus the difference between Rayleigh's method and modal analysis equal to 0.14% less than 10% which is accepted.

Appendix F: Verification of the fundamental period for second layout

To verify the results of periods, Rayleigh's method (Eq.1.3) is used for sample calculation in the first layout and applied on the model number 2L-0.023,6. To apply this method the weight at each level of the floor is found to be the dead load from slab own weight plus two halves of weights for columns and shear walls above and below the intended level plus the superimposed dead load at each slab level.

The lateral force is assumed to be 5kN/m^2. Elastic deflection for each floor is found from SAP2000 and used in Rayleigh's formula as shown in Table F.1.

The calculation of the total single floor dead load as shown in the following:

Slab own weight for single floor = $19 \times 19 \times 0.2 \times 25 = 1805\text{kN}$

Columns own weight in single floor= $28 \times 0.45 \times 0.45 \times 3 \times 25 = 425.25\text{kN}$

Shear walls own weight in single floor=$4 \times (3 \times 3 - 0.6 \times 0.6) \times 0.2 \times 25 = 172.8\text{kN}$

Superimposed dead load in single floor=$19 \times 19 \times 4 = 1444\text{kN}$

Table F.1: Verification of the fundamental period of model 2L-18,15,6

Level	w_i (kN)	f_i (kN/m^2)	Floor Area (m^2)	f_i (kN)	δ_i (m)	$w_i\delta_i^2$ (kN.m^2)	$f_i\delta_i$ (kN.m)
6	3548.03	5	361	1805	0.1478	77.506	266.779
5	3847.05	5	361	1805	0.1235	58.676	222.918
4	3847.05	5	361	1805	0.0960	35.454	173.280
3	3847.05	5	361	1805	0.0665	17.013	120.033
2	3847.05	5	361	1805	0.0373	5.352	67.327
1	3847.05	5	361	1805	0.0125	0.601	22.563
					$\sum$	194.602	872.900

T_1 using Rayleigh's method = 0.946 second, while T_1 from SAP equals to 0.954 second. Thus the difference between Rayleigh's method and modal analysis equal to 0.84% less than 10% which is accepted.

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قدمت هذه الأطروحة استكمالا لمتطلبات الحصول على درجة الماجستير في هندسة الإنشاءات بكلية الدراسات العليا في جامعة النجاح الوطنية، نابلس – فلسطين.

2018

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الملخص

إن استخدام جدران القص الخرسانية المسلحة هو أمر دارج في تشييد المباني المنخفضة ومتوسطة الإرتفاع لمقاومة الأحمال الجانبية. تمثل هذه الجدران العناصر الرئيسية لمقاومة هذه الأحمال بسبب قوتها وصلابتها العالية, وقد تحتوي هذه الجدران على فتحات مثل الأبوب والنوافذ بسبب المتطلبات الوظيفية الأمر الذي يمكن أن يؤدي الى تأثير كبير على الصلابة الجانبية لهذه الجدران. لذلك فمن الأهمية بمكان تقييم أثر الفتحات على الأداء الديناميكي لجدران القص.

تم توليد بيانات ونتائج لأثر وجود الفتحات في جدارن القص على الزمن الرئيسي للمنشات ذات جدران القص بإستخدام برنامج التحليل الهيكلي المعتمد على العناصر المحدودة (SAP2000), وذلك بعد التحقق من نتائج الإزاحة الجانبية للجدار المحتوي على فتحات باستخدام طريقة الحل اليدوي والتي إقترحها هاسياو في العام 2014 والتحقق من نتائج الزمن الرئيسي للنماذج باستخدام طريقة ريلوف.

التحليل بطريقة العناصر المحدودة للنماذج تم أولا باستخدام التحليل الخطي المرن على مستوى الجدار وذلك باستخدام أبعاد مختلفة للفتحات المركزية في الجدار ولارتفاعات مختلفة للمبنى. وبعد ذلك, تمت دراسة مبنيين نموذجيين بارتفاعات مختلفة وبفتحات نوافذ مركزية مختلفة الأبعاد في الجدران ونسب صلابة مختلفة بين الأعمدة والجدران. وتمت مقارنة النتائج مع المعادلات التقريبية المقترحة لحساب الزمن الرئيسي للمنشات ذات جدران القص في كود الأحمال والقوى الصادر عن الجمعية الأمريكية للمهندسين المدنيين (ASCE/SEI 7-16) .

وقد خلصت الدراسة إلى أن الفتحات في جدران القص الخرسانية لها أثر كبير على الزمن الرئيسي والصلابة الجانبية للمنشات ذات جدران القص. وتم التوصل إلى أن 3% هي أكبر نسبة للفتحات في الجدار والتي يمكن إهمالها بشكل امن في مرحلة النمذجة لحالة فتحة نافذة في طابق واحد وستزيد هذه النسبة بزيادة عدد الطوابق, وإن 65% هي نسبة الفتحة التي ستؤدي الى تحويل الجدار المصمت ليعمل كإطار. وقد تبين أن أثر الفتحات في جدارن القص يعتمد على إرتفاع المبنى وعلى شكل التشوه في الجدار بحيث يكون إما تشوه قص او تشوه إنحناء.

وأخيرا, تم تطوير معادلة لحساب الزيادة في الزمن الرئيسي للمباني المنتظمة ذات جدران القص باستعمال التحليل الإحصائي للنتائج, ومن ثم تم التحقق من صحتها بإجراء مقارنة بين نتائج طريقة العناصر المحدودة والنتائج التي تم التوصل إليها من خلال المعادلة.