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The Effect of Shear Wall Positions on the Seismic Response of Frame-Wall Structures

Anas M. Fares

Abstract**—**The configuration of shear walls in plan of building will affect the seismic design of structure. The position of these walls will change the stiffness of each floor in the structure, the diaphragm center of mass displacement, and the drift of floor. Structural engineers preferred to distribute the walls in buildings to make the center of mass almost close enough to the center of rigidity, but to make this condition satisfied, they have many choices: construct the walls on the perimeter, or use intermediate walls, or use walls as core. In this paper and by using ETABS, each case is studied and compared to other cases according to three parameters: lateral stiffness, diaphragm displacement, and drift. It is found that the core walls are the best choice for the position of the walls in the buildings to resist earthquake loads.

Keywords**—**Lateral loads, lateral displacement, reinforced concrete, shear wall, seismic, ASCE7-16 code, ACI code, stiffness, drift.

I. INTRODUCTION

THERE is no doubt that shear walls are the common vertical diaphragms that are used to resist the lateral loads such as the seismic load. These members take many forms according to their distribution in the buildings or to their functions like the core, the coupled, and the planar walls [1]. These vertical diaphragms are more suitable to use in low-rise constructions up to 20 floors [2]. Moreover, they are not the choice in the open spaced buildings or in the external glazed walls because of architectural functions [3]. The walls' members offer good stability for buildings because of small drift between floors and this will lead to both small natural frequency and small natural period of these buildings. The shear walls may be constructed together with frames to form shear wall-frame interaction system, and this system is one of the most popular systems in the world in resisting seismic loads in medium-to-high rise buildings [4]. This system has a preferred range to application from 10 floors to 50 floors or even taller buildings [5]. The interaction between the moment resisting frame and the shear wall is shown in Fig. 1 [6]; the frame basically deflects in a shear mode while the shear wall responds by bending as a cantilever.

Compatibility of horizontal deflection introduces interaction between the two systems which tends to impose a reverse curvature in the deflection pattern of the system. It is not always easy to differentiate between the two modes of deformation. For example, under lateral load a frame consisting of closely spaced columns and drop and deep beams will response as shear walls in a bending mode. Similarly, a shear wall weakened by a row of openings may tend to act as a frame by deflecting in a shear mode. Therefore, the combined action depends on the relative rigidities of the elements used in this system [5].

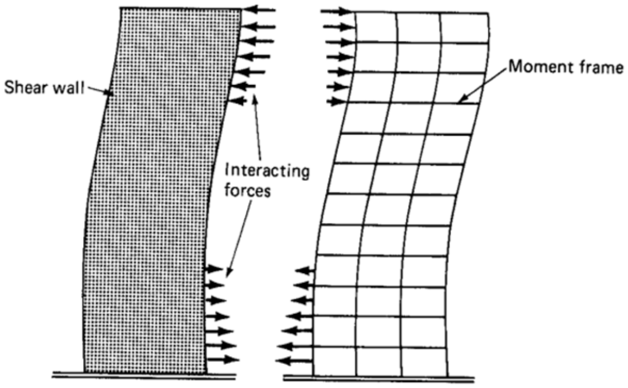

Fig. 1 Shear Wall-Frame interaction [6]

Since many walls contain openings, there is a variation in relative stiffness that extends from that of a solid wall to that of a flexible frame.

Patterns of windows or door openings in the walls will be required due to architectural functions. If this happens, walls are coupled to each other by beams to refer as coupled shear walls as shown in Fig. 2, the overturning moment is resisting totally at the base by flexural stresses in the wall without any openings. Otherwise the resisting of overturning moment occurs by axial force and moment at the base of the coupled shear walls that have large opening.

In the case of coupled shear walls, the resisting moment at the base of structure, M, is shown in (1):

$$M = M_1 + M_2 + Td \qquad (1)$$

where M_1, and M_2 are the base moments at each coupled wall $T$and d are the axial load and distance between the coupled walls respectively.

II. PROBLEM STATEMENT

Shear walls in buildings are distributed in many locations such as in the perimeter, internal, or in the center of the building. The position of these walls will affect the lateral displacement of the diaphragms, and the fundamental period of the whole of the structure, and these two factors are playing major role in the seismic design of these structures. This paper discusses the suitable position of walls in building that may

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Open Science Index, Civil and Environmental Engineering Vol:13, No:3, 2019 waset.org/Publication/10010185

reduce the lateral drift occurred by earthquake.

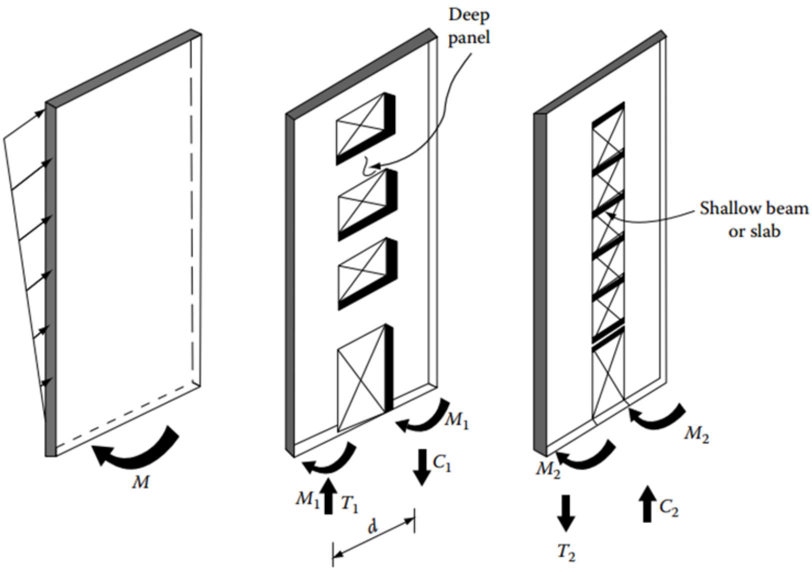

Fig. 2 Shear wall-Frame interaction [2]

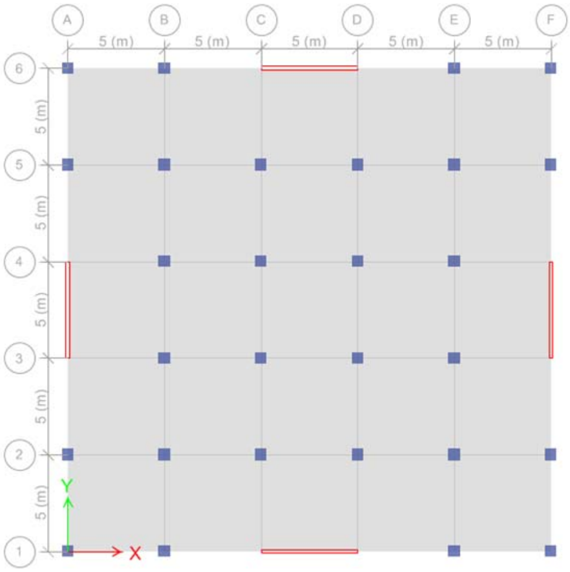

Fig. 3 Layout of the perimeter walls (PW) model

III. Finite Element Model Description

In the studies, ETABS [7] is used to simulate the models, the supports of both columns and shear walls are assumed to be fixed supports because the common practice in Palestine is to use footings with tie beams. 12 floors with floor height equal to 3 m are used in all models because these numbers are common in Palestine especially in the residential buildings. Concrete with compressive strength 24 MPa is used in all models. Linear elastic analysis is also used with modal analysis to get the stiffness of each floor, lateral displacement of each floor, and the fundamental period of these structures. The superimposed dead load is assumed to be equal to 4 kN/m^2 as this value is typical according to the type of the finishing materials in Palestine. The mass source in calculation of modal analysis is from dead load plus superimposed dead load only. The characteristics of all structural members that will be used are shown in Table I. The final dimensions of structural members are calculated according to ACI318-14 code [8]. The live load is assumed to be equal to 2 kN/m^2 as this value is suitable for the residential buildings according to the ASCE7-16 code [9].

TABLE I
Dimensions of Structural Members

Structural members type	Dimensions
Flat plate slabs thickness	20
Shear walls thickness	20
Columns dimension	60×60

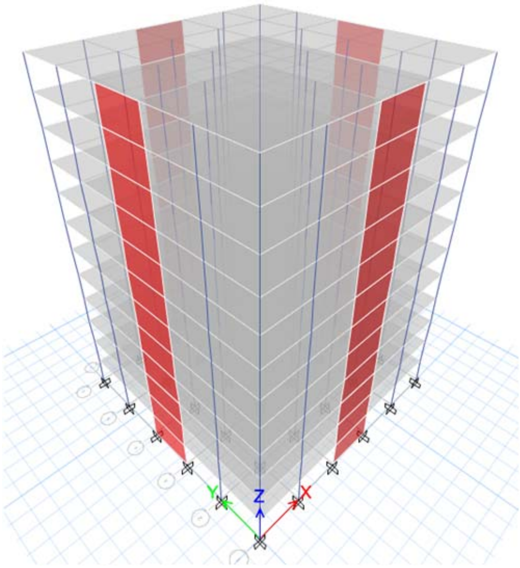

Fig. 4 3D simulation of the perimeter walls (PW) model

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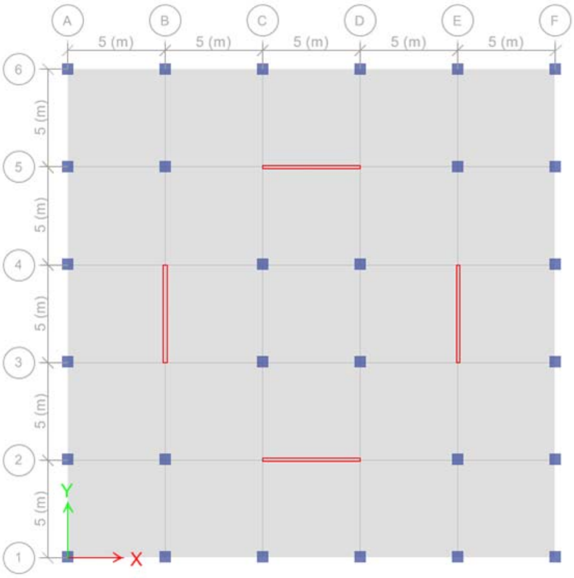

Fig. 5 Layout of the intermediate walls (IW) model

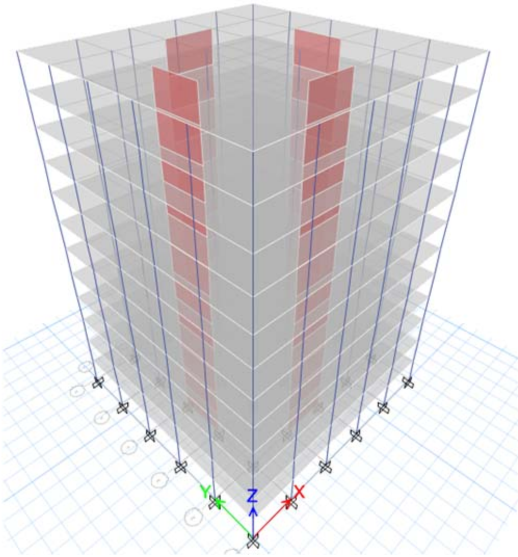

Fig. 6 3D simulation of the intermediate walls (IW) model

The position of shear walls is distributed into 3 cases: perimeter walls (PW), intermediate walls (IW), and central core walls (CW) as shown in Figs. 3-8. The slabs are assumed to act as semi-rigid diaphragms as in the reality; the walls and slabs are defined as shell thin areas in ETABS, and all structural members are assumed to be no cracking.

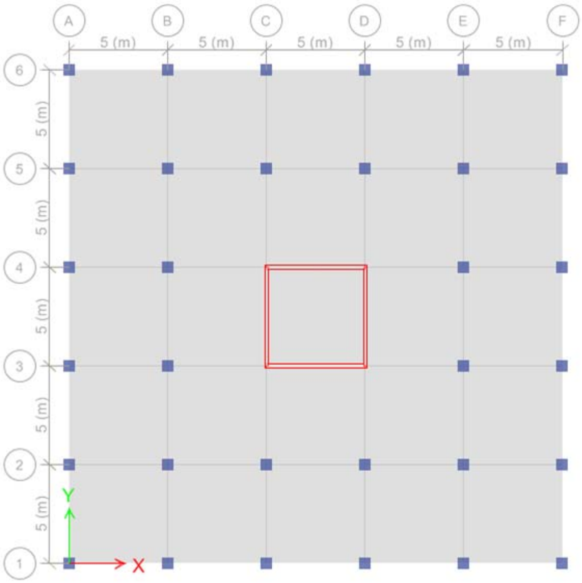

Fig. 7 Layout of the central core (CW) model

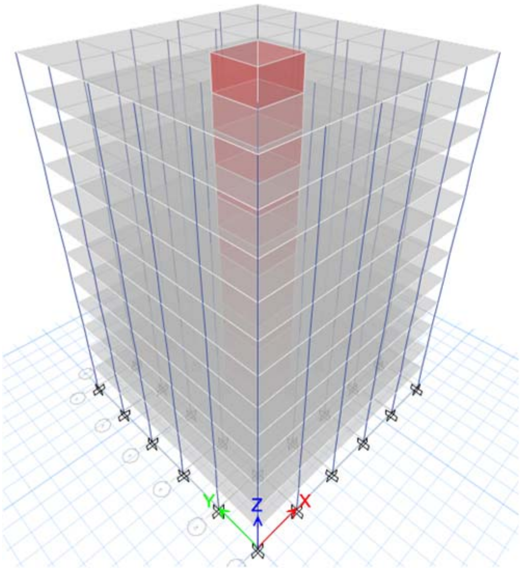

Fig. 8 3D simulation of the central core (CW) model

IV. SEISMIC FORCE CALCULATION

In this study the ASCE7-16 code is used to find the factors to calculate the seismic force. Table II summarizes these factors. The basic seismic force resisting system is the dual system with ordinary shear walls. Response spectrum analysis method is used in this study and the acceleration function diagram of the studied cases is shown in Fig. 9. In Palestine, the basic ground motion parameters corresponding to 475 years of earthquake retain period is closer to reality than 2500 years of earthquake retain period. Thus, the equations considering 10% probability occurs of being exceeded in 50 years are shown in (2) and (3) [10]:

$$S_{DS} = S_{MS} \tag{2}$$

$$S_{D1} = S_{M1} \tag{3}$$

TABLE II
ASCE7-16 SEISMIC LOAD FACTORS

Item	Value
Soil type	B
Importance factor	1.00
Z	0.20
S_s	0.50
S_1	0.25
F_a	1.00
F_v	1.00
S_{MS}	0.50
S_{M1}	0.25
S_{DS}	0.50
S_{D1}	0.25
R	5.50
C_d	4.50
Ω_0	2.50

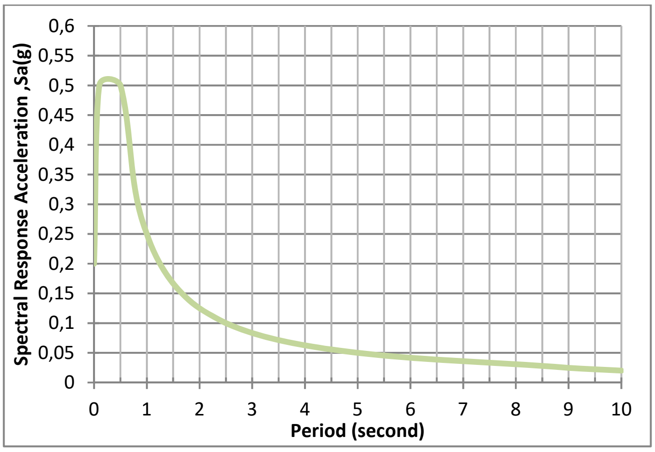

Fig. 9 The acceleration response spectrum

V. FLOORS' LATERAL STIFFNESS RESULTS

The position of shear wall has a great impact on the lateral stiffness of the floor during the earthquake. The goal of this section is to compare the stiffness results of different shear wall configurations and analyzing the data. Table III shows the final results of the three study cases where seismic force in the X direction is used.

TABLE III
STIFFNESS VALUES (KN/M) FOR THREE STUDY CASES

Floor number	PW $(\times 10^3)$	IW $(\times 10^3)$	CW $(\times 10^3)$
12	67.901	84.626	115.516
11	125.749	156.099	219.567
10	172.206	210.559	309.430
9	208.893	251.539	388.033
8	239.607	284.498	460.233
7	268.405	314.522	532.355
6	299.594	346.629	612.139
5	339.009	387.181	711.178
4	397.015	446.958	850.769
3	498.070	551.801	1078.214
2	723.759	795.274	1534.131
1	1766.735	1578.899	3386.765

From Fig. 10, it can be noticed that the core walls model gives the largest values of floors stiffnesses. It is almost double the stiffness of the perimeter walls and intermediate walls. Also, the perimeter walls and intermediate walls are moving very close to each other, but intermediate walls tend to show slightly higher stiffness values at all floors. Central core, however, is showing much more stiffness compared to other two models and the line representing its stiffness is placed well above the other two. Note that the stiffness of central core and other two models are much higher at lower levels, but gradually decrease in top floors. This is due to the influence of height on stiffness of shear walls and frames at different levels.

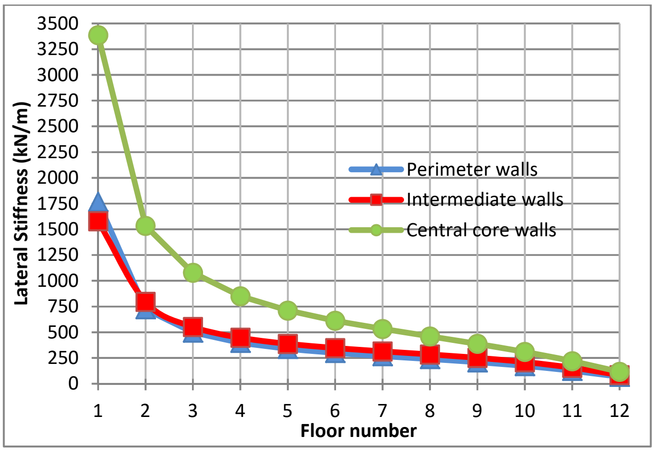

Fig. 10 Floor numbers versus stiffness values for all models

VI. DIAPHRAGM CENTER OF MASS DISPLACEMENT RESULTS

The diaphragms will move laterally due to the earthquake force. This lateral displacement can be presented as diaphragm center of mass displacement. In Table IV the value of this displacement and the corresponding floor number is tabulated where seismic force in the X direction is used.

TABLE IV
DIAPHRAGM CENTER OF MASS DISPLACEMENT FOR THREE STUDY CASES

Floor number	PW (mm)	IW (mm)	CW (mm)
12	96.75	82.84	50.69
11	88.61	76.24	45.76
10	79.78	69.14	40.65
9	70.53	61.58	35.44
8	60.89	53.57	30.18
7	50.96	45.21	24.94
6	40.95	36.67	19.82
5	31.14	28.19	14.96
4	21.88	20.08	10.48
3	13.60	12.72	6.56
2	6.78	6.56	3.38
1	2.27	2.23	1.12

As we can see from Fig. 11, the core walls model gives the smallest floors displacement and this is because this model gives the highest values of the lateral stiffness for each floor. The perimeter walls model gives the highest diaphragm lateral displacement for all floors and these values are closed enough to the values for intermediate shear walls model.

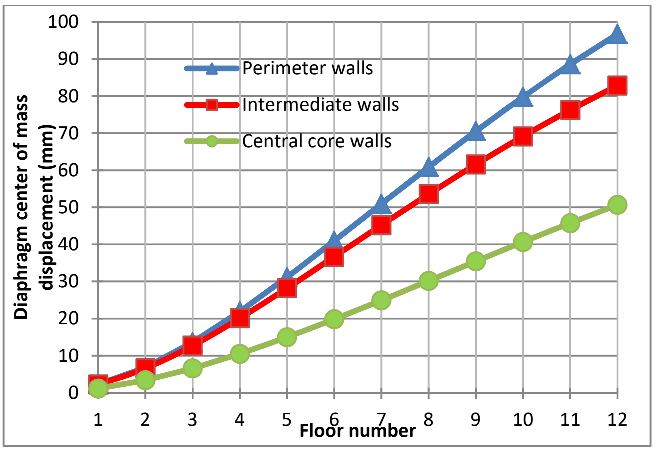

Fig. 11 Floor numbers versus diaphragm center of mass displacement values for all models

VII. FLOORS DRIFT AND COMPARISON TO THE ASCE7-16 LIMITATION

Story drift is essential in the design of the building to resist the earthquake force. The ASCE7-16 gives limitation that the drift of any designed building must not exceed the code limitation. According to table 12.12.1 in the code [8] the maximum allowance drift for risk category I and II and for all other structures the maximum drift is equal to 0.020 multiplied by the floor height and in this study the floor height is equal to 3.00 m thus the maximum story drift is equal to 60 mm. Table V shows the results of drift corresponding to each floor number for all cases where seismic force in the X direction is used.

TABLE V
STORY DRIFT FOR EACH FLOOR

Floor number	PW (mm)	IW (mm)	CW (mm)
12	8.27	6.64	4.91
11	8.81	7.09	5.11
10	9.24	7.56	5.22
9	9.64	8.01	5.27
8	9.93	8.36	5.25
7	10.01	8.54	5.12
6	9.81	8.48	4.88
5	9.26	8.11	4.48
4	8.29	7.36	3.93
3	6.82	6.15	3.20
2	4.78	4.35	2.29
1	2.27	2.21	1.05

From Fig. 11, it can be noticed that all the drift values from models are less than the allowance from the ASCE code. However, the core walls model gives smaller drift than the intermediate walls and the perimeter walls models. This conclusion confirms that the core walls model is the best choice in the distribution of walls in the earthquake design. This small drift will make the building rigid enough and more stable.

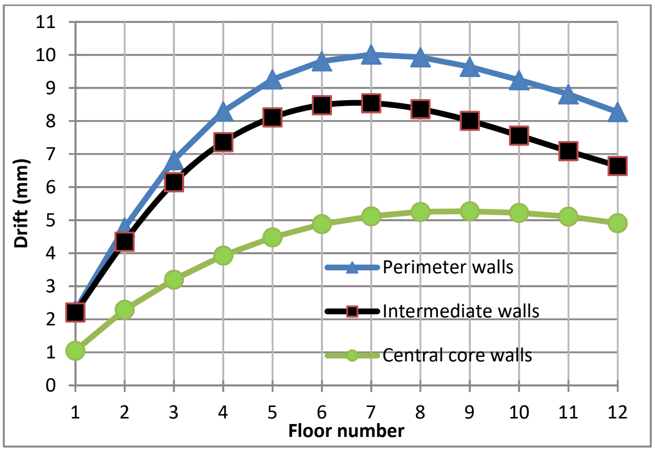

Fig. 12 Floor numbers versus drift values for all models

VIII. CONCLUSIONS

Based on this study, the following conclusions are drawn:

1. The position and distribution of shear walls in building will affect the design of this building to resist earthquake.
2. The core walls are the best choice rather than the perimeter intermediate walls due to large floor stiffness of each floor in building.
3. The core walls model produces the lowest drift values for each floor and smallest diaphragms center of mass displacement compared to another models and this conclusion emphasizes that the core wall is the best choice.

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