Seismic Performance of Staircases in the 3D Analysis of RC Building

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Abstract

Stairs play an important role as an escape way and are considered a source of safety in the building during an earthquake. Neglecting the stairs in the 3D analysis model is the main cause of the stairs' failure during the earthquake. Although the previous researchers had focused on the behavior of stairs when changing single variables such as height, location, and layout under seismic loads, no detailed investigation that gathers these variables together was considered. This research studies the effects of changing the number of storeys for a building subjected to an earthquake when considering and neglecting stairs in the 3D analysis with and without shear walls. The effect of the volume and location of the shear wall has been considered through conducting computational analysis using ETABS software to help the structural engineer choose the proper system of stairs and shear walls. Neglecting the staircase in the 3D analysis affects the structure's performance, which leads to ignoring many stresses transferred to the stairs, causing several damages to the stairs during an earthquake. For the existing building without a shear wall, considering the staircases in the analysis improves the performance of the structure under seismic loads.

Keywords: Stairs; Stiffness; Displacement; Over-strength Factor; Fundamental Period of Vibration; Non-linear Static Analysis.

1. Introduction

Stairs are important elements of a structure that are required to be operable for escaping during an earthquake and post-earthquake events such as reconstruction to ensure occupant evacuation and safety [1, 2]. The interaction between the structure and stairs during an earthquake causes damage due to inadequate design, which neglected the unequal distribution of lateral load, stiffness, and torsion in the staircase [3-5]. The connections between the structure and the stairs are subjected to high stress, and the capacity to maintain the connectivity is important to strengthen the seismic performance and to endure the functionality of the stairs [6]. The use of rigid connections attracts high stress, which leads to a high potential for connection failure [6]. Changren et al. [7] studied three different connection methods. Maxwell mechanical model was combined with a viscoelastic damping bearing to produce an optimized damping bearing to be used in staircase modeling [7]. By using the damping bearing, the unequal distribution of stiffness, ductility, and seismic performance were improved, and the floor shear force was reduced due to its energy dissipating characteristic [7]. Bilal et al. [8] investigated the behavior and effect of the existence of stairs, concluding that the time

period was significantly reduced if considering stairs in the analysis. Also, the drift was reduced due to the bracing effect. A horizontal bracing effect is developed by the existence of a staircase, leading to a decrease in the vibration period and inter-storey displacement [9].

The more bracing effect, the more changes in the distribution of straining actions [9]. The straining actions and the layer displacement angles are decreased gradually with the increase of the structure height [9-11]. On the other hand, the existence of a staircase can produce high torsional eccentricities and attract large seismic loads, leading to the failure of supporting elements such as columns and landing beams [12]. The vibration periods and straining actions were affected by the location of stairs [9]. According to Bilal et al. [8], the most effective location of a staircase is in the middle bay of the building rather than the end bay due to the lower attraction of shear force in the middle bay case.

The existence of a shear wall leads to a significant increase in the peak lateral shear force and reduces the forces and moments in the frame members due to the attraction of these straining actions by shear walls and their behaving as stiff members [13]. On the other hand, the asymmetry of the shear wall leads to irregularity in the structure plan, producing torsional moments during earthquakes [14-16]. Another approach was studied by Cong et al. [17] for supporting the staircase by using a reinforced concrete frame with a separate slab adjacent to the frame columns that carry the floors around the staircase. This case led to avoiding the shear failure in the building columns around the staircase and achieving a higher lateral stiffness by 53.46% than the ordinary frame model [17]. The current study investigates the effect of the changing number of storeys on a building subjected to an earthquake when considering and neglecting stairs in the 3D analysis with and without shear wall. Also, the effect of the volume and location of the shear wall can be determined through conducting computational analysis using ETABS software.

2. Modeling and Analysis

2.1. Geometric and Material Definition

The main study parameters are the height of the building, the existence and location of stairs and shear walls, whether inside or outside the building, and the volume of the shear wall. In each studied case, the relationship between displacement of the building and shear force was recorded. Also, each model studied different building heights of 5, 8, 11, 15, 20, and 25 storeys (Six cases).

The height of each floor is 3 m, and the span between columns is 5 m in *x* and *y* directions. For the material definition of slabs, the grade of concrete was 40 N/mm² and included 25 kN/m³ for weight per unit volume, 28E06 kN/m² for modulus of elasticity, 0.2 for Poisson ratio, 9.900E-06 for coefficient of thermal expansion, 32000 kN/m² for specified concrete compressive strength, and 460000 kN/m² for bending and shear yield stress of steel. For the material definition of columns and shear walls, the grade of concrete was 60 N/mm² with the same properties as grade 40 N/mm² except for the modulus of elasticity of 32E06 kN/m² and the specified concrete compressive strength of 48000 kN/m². The utilized columns were 250×800 mm in cross section with cracked section design modifiers of 0.01, 0.7, and 0.7 for torsional constant, moment of inertia about the x-axis, and y-axis, respectively. The concrete cover for the columns was 25 mm thick and reinforced with 16 bars of 20 mm in diameter. For shear walls, the width was 250 mm and the modifiers were adjusted to be 0.7 for all bending modifiers. For the post-tension slabs, the thickness was 220 mm as shell type with no modifiers. Table 1 presents the models used in this study with the inclusion of stairs and shear walls and their locations.

Table 1. The parameters in each model

Model	Case of Model	Stairs		Shear wall	
		Existence	Location in the building	Existence	Location in the building
B1	Case 1	N.A	Inside	N.A	--
B2	Case 2	Included	Inside	N.A	--
B3	Case 3	N.A	Inside	Included Around stair void	Inside
B4	Case 4	Included	Inside	Included Around stairs void	Inside
B5	Case 5	Included	Inside	Included Around stairwell	Inside
B6	Case 6	N.A	Inside	Included Around stairwell	Inside
B7	Case 2	Included	Outside	N.A	--
B8	Case 3	N.A	Outside	Included Around stairs void	Outside
B9	Case 4	Included	Outside	Included Around stairs void	Outside
B10	Case 1	N.A	Outside	N.A	--

N.A refer to not included in the model

Six cases of modeling the building concerning the existence and location of stairs and shear walls are being investigated. Case 1 neglects stairs in the analysis. Case 2 is taking stairs into consideration in the analysis. Case 3 includes the shear wall and neglecting the stairs. Case 4 includes the shear wall and stairs in the analysis. Case 5 includes the shear wall inside the stairs and neglects the stairs in the analysis. Case 6 includes the shear wall inside the stairs and neglects the stairs in the analysis. Models from B1 to B6 study the stairs and shear wall inside the building, while models from B7 to B10 study the case of an outside location. Figure 1 presents the applied flow chart in this research. Figure 2 shows the dimensions of the studied stairs. Figure 3 demonstrates the layout and location of stairs and shear walls in each model. Figure 4 shows the main reinforcement of the studied stairs according to the Egyptian code for design and construction of reinforced concrete structures [18].

Data Collection through Literature

Identifying the Studying Parameters

Choosing the Building plan and geometry of stairs and shear wall

Seismic Analysis using ETABS Software

Data Analysis

Results, Discussion, and Conclusions
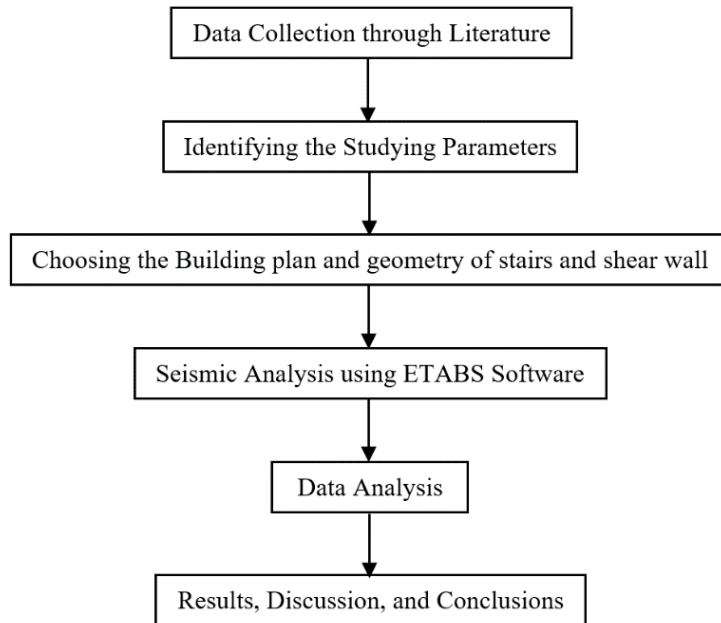
Figure 1. Flow Chart of the Modeling

Figure 2. Geometric of stairs

Model (1) with no stairs inside the building

Model (2) including the stairs only inside the building

Model (3) including the shear wall only inside the building

Model (4) including stairs and shear wall inside the building

Model (5) including stairs and shear wall around stairwell

Model (6) including the shear wall only around stairwell

Model (7) including the stairs only outside the building

Model (8) including the shear wall only outside the building

Model (3) including stairs and shear wall outside the building

Model (10) with no stairs outside the building

Figure 3. Models Configuration

Figure 4. Main Reinforcement of stairs

2.2. Load Definition

Dead load and imposed load were calculated according to Egyptian code for loads [19]. The foundation support was assigned to be fixed. For static seismic load, the type of case load in x direction (QX) is auto lateral load UBC97 with quake self-weight of zero, time period (Ct) is 0.2, over strength factor (R) is 5.5, zone factor is 0.15, and importance factor is 1. For dynamic seismic load, UBC97 spectrum was added with 0.18, and 0.25 as values of seismic coefficient parameters Ca and Cv, respectively, the scale factor is 9.81, R is 5.5, eccentricity ratio is 0.05, U1 for X- direction is
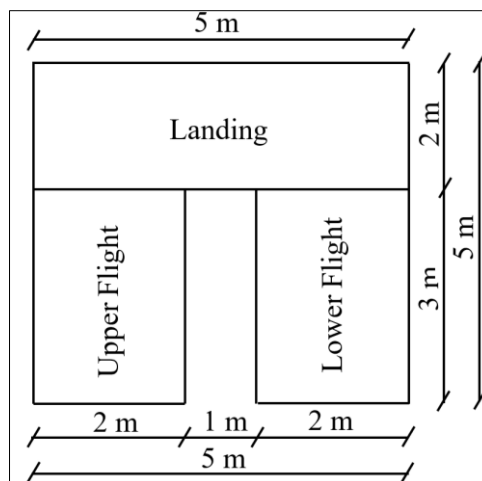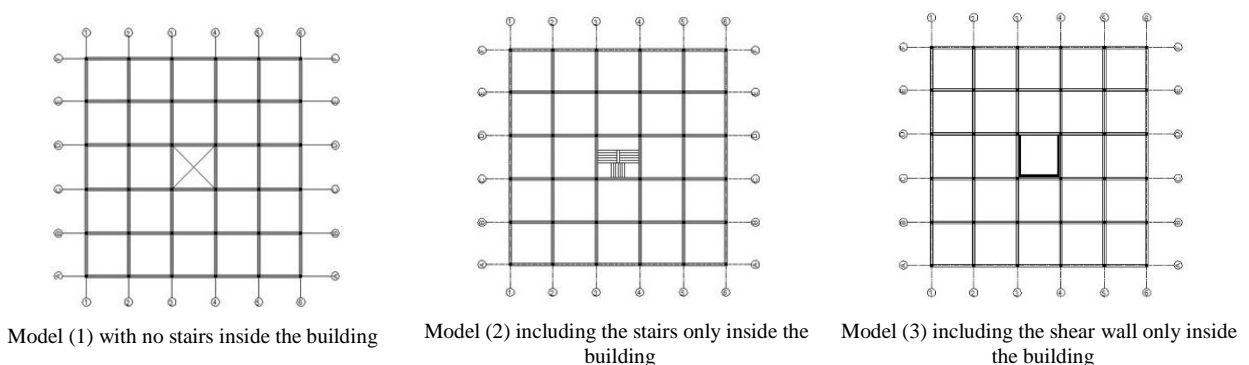
1.7818 scale factor, and U2 for Y- direction is 1.7818 scale factor. For wind load, the type of case load in x direction (WX) is auto lateral load BS6399-95. For the wind exposure parameters, wind direction angle is 90 degree, front coefficient is 0.8, rear coefficient is 0.3, effect speed is 30 m/sec, size effect factor is 1, and dynamic augment factor is 0.25. The relationship between displacement and shear force for various number of storeys for x and y direction are shown in Figures 5 and 6, respectively.
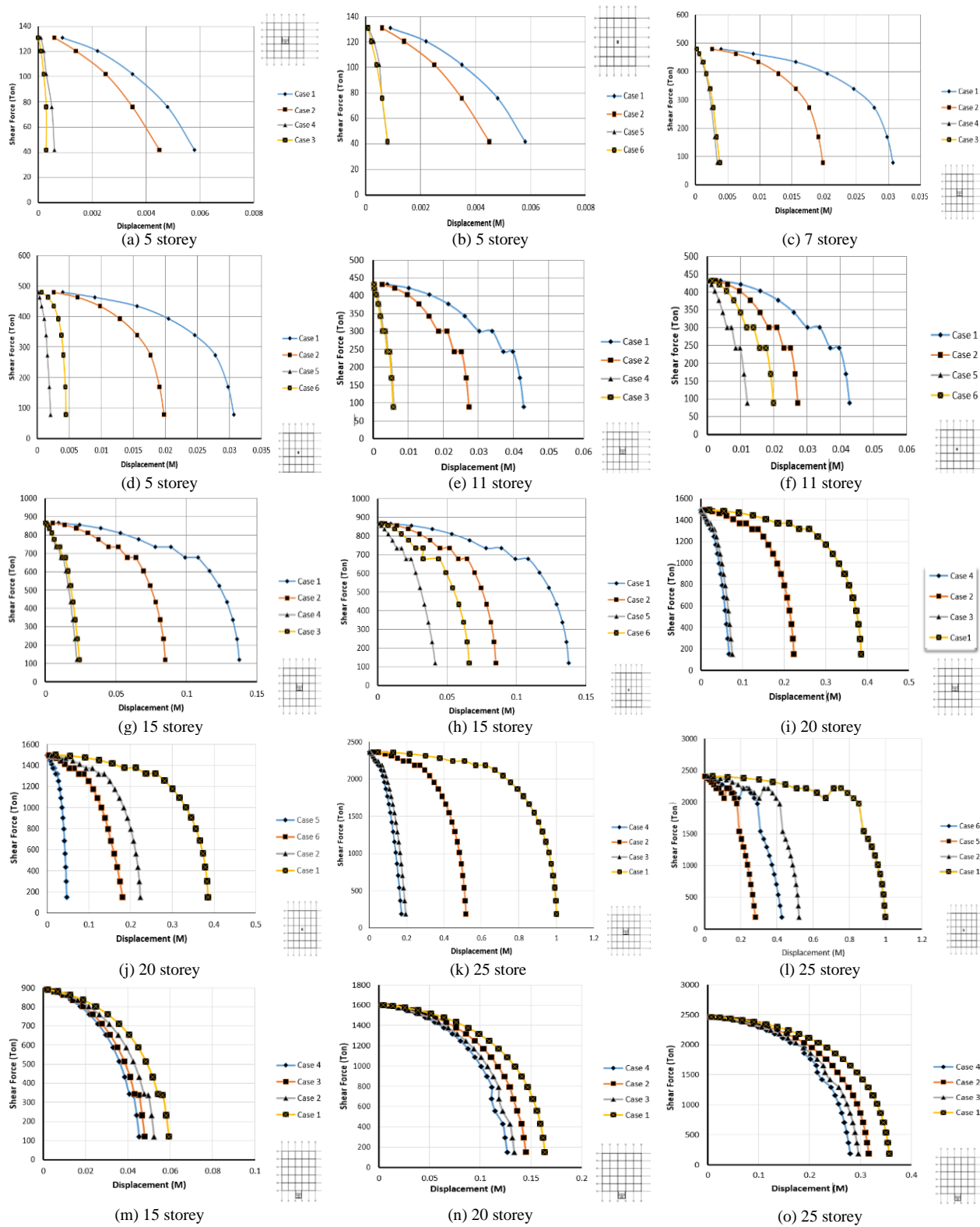

Figure 5. Shear force – displacement relation in x-direction a, c, e, g, i, k, m, n, and o figures for shear wall located around stairs b, d, f, h, j, k, and l Figures for shear wall located inside stairs

(a) 5 storey   (b) 5 storey   (c) 7 storey

(d) 7 storey   (e) 11 storey   (f) 11 storey
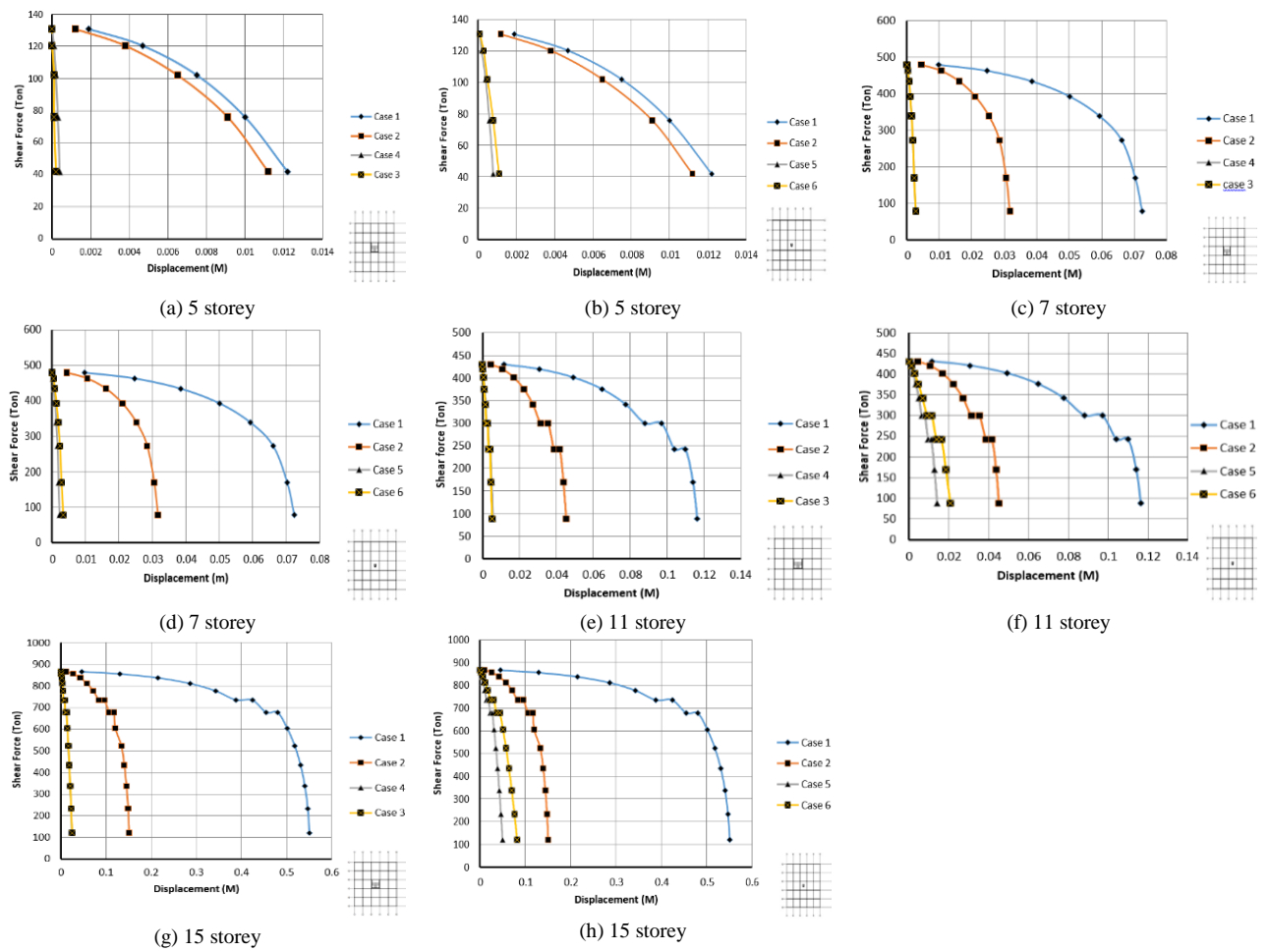
(g) 15 storey   (h) 15 storey

Figure 6. Shear force – displacement relation in y-direction a, c, e, and g figures for shear wall located around stairs b, d, f, and h figures for shear wall located inside stairs

3. Result and Analysis

3.1. Displacement When Changing the Location of Stairs

The staircase behavior was studied considering the important role that they play as structural seismic connections in the response and the behavior in space structures. As shown in Table 2, the case of stairs located inside the building had a better displacement reduction than the case of outside location. The staircase located inside the building was supporting the high rise building with magnitude about 50% when earthquakes happened and decreased the damage and displacement.

Table 2. Displacements range when changing the location of stairs

Location of stairs	15 storey	20 storey	25 storey
Inside	Less than 0.05	Less than 0.1	Equal 0.2
Outside	Equal 0.05	more than 0.1	more than 0.2

3.2. Time Period When Changing the Location of Stairs

It was observed that placing a staircase outside the building reduces the time period of the structure. The range of time period of the first mode of high rise building under seismic loads increased with the increase of the damage level due to the reduction of stiffness. The time period increased with the increase of storeys number and depending on the shape of the building. Table 3 shows the time periods of the different cases of models with 15, 20, and 25 storeys.

Table 3. Time periods of buildings with different number of storeys

Case of Model	Location of Stairs	15 storey	20 storey	25 storey
Case 1	Inside	15 sec	7.5 sec	Building not safe
	Outside	11 sec	Building not safe	10 sec
Case 2	Inside	7 sec	11 sec	17 sec
	Outside	Building not safe	Building not safe	Building not safe
Case 3	Inside	15 sec	7.5 sec	Building not safe
	Outside	11 sec	Building not safe	10 sec
Case 4	Inside	5 sec	7 sec	10 sec
	Outside	7 sec	6 sec	8 sec

It was observed that in case of neglecting the stairs in the analysis (case 1), the time period was reduced for outside staircase void and the building become unsafe for 20, and 25 storey building in the cases of outside, and inside staircases, respectively. The minimum time period was observed in 15 storey building in case of stairs inclusion inside the building with shear wall around it with value of 5 sec. The maximum time period was recorded in 25 storey building in case of including the stairs only in the analysis inside the building. Tables from 4 to 6 demonstrate the displacements for the different cases of models with shear wall located around and inside the stairs.

Table 4. Displacements in case of stairs is inside building with shear wall inside stairs

Storeys number	Case1	Case2	Case3	Case4
5 storey	0.006	0.005	0.0001	0.0001
8 storey	0.033	0.02	0.005	0.005
11 storey	0.06	0.028	0.005	0.005
15 storey	0.13	0.08	0.025	0.02
20 storey	0.4	0.22	0.09	0.06
25 storey	1	0.5	0.2	0.19

Table 5. Displacements in case of stairs is outside with shear wall around the stairs

Storey number	Case1	Case2	Case3	Case4
15 storey	0.08	0.05	0.04	0.03
20 storey	0.17	0.15	0.13	0.125
25 storey	0.38	0.32	0.3	0.28

Table 6. Displacements in case of stairs is outside with shear wall inside the stairs

Storey number	Case1	Case2	Case5	Case6
5 storey	0.006	0.005	0.0001	0.0001
8 storey	0.05	0.03	0.007	0.009
11 storey	0.12	0.05	0.01	0.02
15 storey	0.15	0.09	0.04	0.05
20 storey	0.4	0.24	0.08	0.19
25 storey	1	0.5	0.25	0.4

The displacement decreased for models with shear wall around stairs and outside the building in cases of modeling 1 and 2. The effect of shear wall location inside or outside the stairs was recorded. Models with shear wall inside the stairs exhibit more displacement than models with shear wall around the stairs. From comparing between the models with stairs inside and outside building, the models with stairs inside building have better performance than models with stairs outside building when the earthquake occurs.

The behavior of models with shear wall inside stairs and inside building was similar to models with shear wall outside stairs and outside building. The highest displacement was recorded in models which neglected stairs in the analysis (case 1). By considering the stairs in the analysis (case 2), the displacement and stiffness of the building was improved. Tables from 7 to 9 show the time period when change the location of stairs with respect to the building and stairs.

Table 7. Time period in case of stairs is outside with shear wall around the stairs

Storey number	Case1	Case2	Case3	Case4
15 storey	7.50 sec	xxx	6.00 sec	5.50 sec
20 storey	11.00 sec	xxx	8.00 sec	7.00 sec
25 storey	10.00 sec	xxx	9.00 sec	7.50 sec

**Table 8. Time period in case of stairs is inside with shear wall around the stairs**

Storey number	Case1	Case2	Case3	Case4
5 storey	3.00 sec	2.50 sec	1.25 sec	1.25 sec
8 storey	5.00 sec	3.00 sec	2.00 sec	2.00 sec
11 storey	8.00 sec	4.70 sec	3.00 sec	3.50 sec
15 storey	14.00 sec	6.50 sec	4.00 sec	4.50 sec
20 storey	xxx	10.00 sec	8.00 sec	7.00 sec
25 storey	xxx	15.20 sec	13.00 sec	10.00 sec

**Table 9. Time period in case of stairs is inside with shear wall inside the stairs**

| Storey number	Case1	Case2	Case5	Case6
5 storey	3.00 sec	2.75 sec	1.75 sec	2.00 sec
8 storey	5.00 sec	3.20 sec	3.00 sec	3.00 sec
11 storey	8.00 sec	5.00 sec	4.00 sec	4.50 sec
15 storey	14.50 sec	7.00 sec	6.00 sec	6.50 sec
20 storey	xxx	11.00 sec	9.00 sec	10.00 sec
25 storey	xxx	17.00 sec	14.00 sec	15.00 sec

3.3. The Effect of Changing Building Height on the Time Period

In Figure 7, modeling (A) refers to the staircase inside the building with a shear wall around it, modeling (B) refers to the staircase inside the building with a shear wall inside the stairs, modeling (C) refers to the stairs outside the building with a shear wall around the stairs, and modeling (D) refers to the outside staircase with a shear wall inside the stairs. From Figure 7-a, it was observed that the highest time period was recorded for a 15-storey building, with a value of 4.83 times that of a 5-storey building. This observation indicates that the structure system should be replaced with another suitable system. From Figure 7-b, considering stairs in the analysis improved the behavior through all modeled storeys due to the produced bracing effect, which increased the global stiffness of the building. Also, the effect of increasing the area of shear wall was observed and implied in the decrease of time period when using shear wall around the stairs void. From Figure 7-c, including shear wall in the analysis improved the overall behavior when neglecting stairs in the model, leading to endure the increase of storeys number achieving time period of 13 sec in case of a 25-storey building, which is less than the case of neglecting stairs and shear wall by 13.3 %. From Figure 7, locating the stairs outside the building with a shear wall around them increased the time period due to the distance between the center of mass and the center of rigidity, producing torsional moments and decreasing the effects of bracing and stiffness for the stairs and shear wall, respectively. So, the most proper location of stairs was in the middle of the building, with a shear wall around the stairs, which presents a good agreement with previous researchers as Bilal et al. [8].

(a) The case of neglecting stairs and shear wall in analysis

(b) The case of considering only stairs in analysis
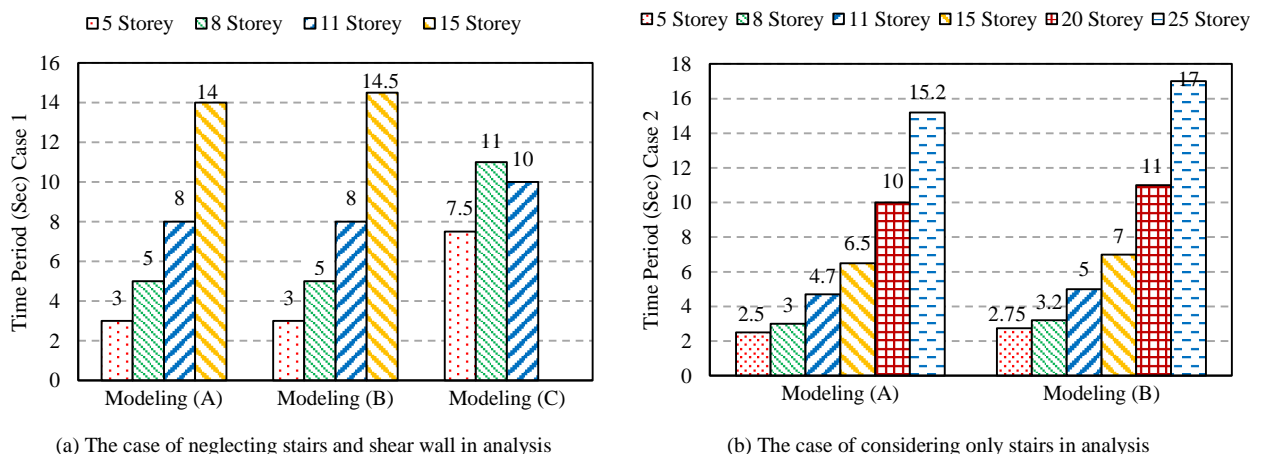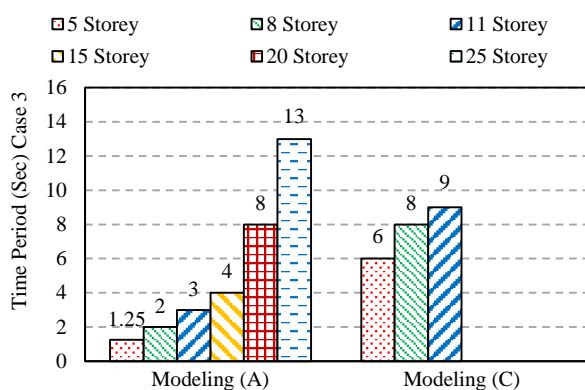
(c) The case of including shear wall and neglecting stairs in analysis
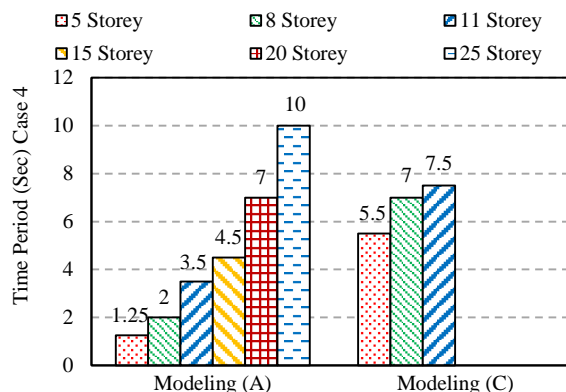
(d) The case of including shear wall and stairs in the analysis

Figure 7. The effect of changing building height on the time period

4. Conclusions

One of the main reasons for the failure of stairs is that the designer neglected the stairs in the 3D analysis of the building during the earthquake. Some cases studied the position of stairs in the building, and others studied the combination of stairs and shear wall. The results and evaluations of this study are summarized as follows:

- Considering the staircase in the analysis for the existing building, which does not have any shear walls, improves the performance of the structure during the earthquake. By neglecting stairs in the analysis, the highest displacement and the longest time period were recorded;

- Considering stairs in the analysis improved the behavior through all modeled storeys due to the produced bracing effect, which increased the global stiffness of the building. The building became unsafe for a 20-storey building with outside stairs and a 25-storey building with inside stairs;

- Including shear wall in the analysis improved the overall behavior when neglecting the stairs in the model, leading to endure the increase of storeys number achieving time period of 13 seconds in the case of a 25-storey building, which is less than the case of neglecting stairs and shear wall by 13.3%;

- The effect of increasing the area of shear wall was observed and implied in the decrease of time period when using shear wall around the stairs void. Models with a shear wall inside the stairs exhibit more displacement than models with a shear wall around the stairs;

- The minimum time period was observed for the inside staircase with a shear wall around it, with a value of 1.25 sec, and the maximum time period was in a 25-storey building when including the stairs only in the analysis inside the building;

- The displacement was increased in the case of stairs outside the building, with a shear wall around the stairs. Therefore, the most proper location for stairs is in the middle of the building, with a shear wall around them.

5. Declarations

5.1. Author Contributions

Conceptualization, O.H.A., and A.A.S.; methodology, O.H.A., and A.A.S.; software, O.H.A., and A.A.S.; formal analysis, O.H.A., and A.A.S.; writing—original draft preparation, O.H.A., A.R.H., and A.A.S.; writing—review and editing, O.H.A., A.R.H., and A.A.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] International Code Council (ICC). (2013). 2012-2014 Code Development Cycle, New Jersey, USA. Available online: https://cdn-web.iccsafe.org/wp-content/uploads/01-Prelims.pdf (accessed on January 2022).

[2] FEMA-E74. (2021). Reducing the risks of non-structural earthquake damage – a practical guide. Federal Emergency Management Agency. Washington, D.C. USA. Available online: https://bit.ly/34xZJzM (accessed on December 2021).

[3] Kam, W. Y., Pampanin, S., & Elwood, K. (2011). Seismic performance of reinforced concrete buildings in the 22 February Christchurch (Lyttelton) earthquake. Bulletin of the New Zealand Society for Earthquake Engineering, 44(4), 239–278. doi:10.5459/bnzsee.44.4.239-278.

[4] Bull, D. (2011). Stairs and access ramps between floors in multi-storey buildings. A report on the Canterbury earthquakes Royal Commission. Holmes Consulting Group, Christchurch, Wellington, New Zealand.

[5] Li, B., & Mosalam, K. M. (2013). Seismic Performance of Reinforced-Concrete Stairways during the 2008 Wenchuan Earthquake. Journal of Performance of Constructed Facilities, 27(6), 721–730. doi:10.1061/(asce)cf.1943-5509.0000382.

[6] Wang, X., & Hutchinson, T. C. (2018). Computational assessment of the seismic behavior of steel stairs. Engineering Structures, 166, 376–386. doi:10.1016/j.engstruct.2018.03.074.

[7] Changren, K., & Hanqin, W. (2020). Study on seismic performance of frame structure with viscous damping staircase. Journal of Physics: Conference Series, 1676(1). doi:10.1088/1742-6596/1676/1/012069.

[8] Bilal, A., Mohammad, Z., & Baqi, A. (2022). Effect of Dog-Legged Staircase on the Seismic Response of Hill Buildings. Lecture Notes in Civil Engineering, 175, 175–183. doi:10.1007/978-981-16-4617-1_14.

[9] Sun, H., Zhang, A., & Cao, J. (2013). Earthquake response analysis for stairs about frame structure. Engineering Failure Analysis, 33, 490–496. doi:10.1016/j.engfailanal.2013.06.023.

[10] Mir, F. U. H., & Rai, D. C. (2020). Experimental and parametric investigation of effects of built-in staircases on the dynamics of RC buildings. Earthquake Engineering and Structural Dynamics, 49(6), 527–542. doi:10.1002/eqe.3251.

[11] Saeidi Rashk Olia, A., Oliaei, M., & Heidarzadeh, H. (2021). Performance of Ground Anchored Walls Subjected to Dynamic and Pseudo-Static Loading. Civil Engineering Journal, 7(6), 974–987. doi:10.28991/cej-2021-03091703.

[12] Wang, X., Astroza, R., Hutchinson, T. C., Conte, J. P., & Restrepo, J. I. (2015). Dynamic characteristics and seismic behavior of prefabricated steel stairs in a full-scale five-story building shake table test program. Earthquake Engineering and Structural Dynamics, 44(14), 2507–2527. doi:10.1002/eqe.2595.

[13] Rao Botsa, S., & Dasgupta, K. (2017). Influence of Staircase and Elevator Core Location on the Seismic Capacity of an RC Frame Building. Journal of Architectural Engineering, 23(4), 05017007. doi:10.1061/(asce)ae.1943-5568.0000274.

[14] Belletti, B., Martinelli, E., Michelini, E., Tavano, M., & Vecchi, F. (2022). Seismic Risk Assessment of Existing RC Frame-Buildings with Shear Walls. In Seismic Behaviour and Design of Irregular and Complex Civil Structures IV, Vol. 50, 273–285. doi:10.1007/978-3-030-83221-6_23.

[15] Badla, O., Bouzid, T., & Vazquez, P. M. (2021). Inelastic Analysis of Mdof Systems Damaged by Earthquakes, Posteriorly Subjected to Wind Load. Civil Engineering Journal, 7(3), 575–593. doi:10.28991/cej-2021-03091675.

[16] Gokdemir, H., Ozbasaran, H., Dogan, M., Unluoglu, E., & Albayrak, U. (2013). Effects of torsional irregularity to structures during earthquakes. Engineering Failure Analysis, 35, 713–717. doi:10.1016/j.engfailanal.2013.06.028.

[17] Cong, S., Zhang, Z., Zheng, Q., & Xu, Z. (2021). Seismic behavior of reinforced concrete frame staircase with separated slab stairs. Structures, 34, 4284–4296. doi:10.1016/j.istruc.2021.10.026.

[18] Housing and Building Research Center, (ECP203-2018). (2018). Egyptian Code for Design and Construction of Reinforced Concrete Structures. Ministry of Development, New Communities, Cairo, Egypt.

[19] Housing and Building Research Center. (2012). Egyptian Code for Loads. Ministry of Development, New Communities, Cairo, Egypt.