

Comparative Study of The Effects of Wind and Earthquake Loads on High-rise Buildings

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Abstract

It is very essential to consider the effects of lateral loads induced from wind and earthquakes in the design of reinforced concrete structures, especially for high-rise buildings. The Egyptian Code of Practice for Calculating Loads and Forces in Structural and Building Works, 1993 and 2003 gives simplified methods for calculating such loads. In some cases effects of earthquakes are found to be dominant and more critical than wind effects. This depends on some factors defined by codes. In this research the both effects will be studied and compared according to the Egyptian Code 1993 and 2003. The codes are reviewed for wind and earthquake analysis and discussed to show all factors affecting the design. A computer program is developed to analyze the structural buildings behavior under wind pressure defined as well as equivalent static loads for earthquakes considering all factors in the codes. Application examples for buildings with different heights, floor weights and boundary conditions for both winds and earthquakes such as the intensity of the wind pressure, the seismic zone coefficient, the importance factor, structural system factor and the soil coefficient are analyzed and discussed for the purpose of comparison. Some recommendations are suggested to improve the resistance of the structural and environmental systems of the buildings with respect to lateral loads. Finally Egyptian seismic map, tables of different shape effect and structural systems are provided to help structural designers and researches during design process.

Keywords: High-rise buildings, Egyptian Code, Wind pressure, Equivalent static loads, Zone factor, Structural factor, Soil factor, Importance factor.

1. Introduction

In order to design a structure to resist wind and earthquake loads, the forces on the structure must be specified. The exact forces that will occur during the life of the structure cannot be anticipated. Most National Building Codes identify some factors according to the boundary conditions of each building considered in the analysis to provide for life safety. A realistic estimate for these factors is important; however the cost of construction and therefore the economic viability of the project is essential [1]. Owing to lack of earthquake and wind forecasting centers the Egyptian Codes 1993 [2] and 2003 [3] give more concentration on calculating these lateral loads and the corresponding additional stresses to be taken into account in the design of the structures.

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The codes introduces simplified methods for the design which depend on different factors for wind and earthquake that govern the design and influence the results. Michael and Majid [4] and Taranath [5] stated the design basic concepts, gravity systems, lateral loads and dynamic loads affecting the structural behavior of the high rise buildings. Mousaad et al [6] represented a practical procedure for the response predication and reduction in high rise buildings under wind loads. The methodology proposed for the estimation of the response of high-rise buildings under wind loads has the advantages of combining lateral along-wind, lateral cross-wind, and torsional responses altogether. The proposed methodology permits the response of tall buildings to be assessed and controlled in the preliminary design stages, this can help decision makers involved in the design process, to choose among innovative design solution like structural control, considering several damping techniques, modifying geometry, or even changing materials [6]. Azab [7] discussed the structural sustainability techniques for RC high-rise buildings. For structural sustainability at the early scheme of the design stage, and due to a lot of unconventional form of towers and tallest waves over the world, an initial assessment of the structure will be necessary to achieve the required architectural concepts in the shortest time as possible [7]. An experimental study of a high-rise building model in tornado-like-winds was discussed by Yang [8]. The wind loads (both force and moments) acting on the test model induced by tornado-like wind were found to vary significantly with the position of the test model relative to the center of the tornado-like vortex. Shear strength analysis and predication of reinforced concrete transfer beams in high-rise buildings were studied, where significant increase in the shear capacity was observed by providing orthogonal web reinforcement and a designed node for ductile failure can be achieved through orthogonal web reinforcement [9]. Based on the study of different design codes of deep beams, the suitability of the proposed empirical expressions was studied according to UK's guide –2– construction industry research and information association “supplementary rules” design model (CIRIA), Guide-2, British standards (BS) code and Indian code of practice for plain and reinforced concrete 2000 (IS) code and there were good agreements among the other design methods. [9]. Griffis reviewed some building codes to clarify the serviceability limit states of the tall buildings under wind load, it was concluded that the current practice of using 50-year or 100-years mean recurrence internal wind loads to evaluate building drift with currently accepted drift and acceleration were based on a mean recurrence internal of 10 years [10]. A single degree of freedom oscillators model was used to study the nature of wind loads and dynamic response by Boggs and Dragovich [11]. Shunsuker [12] reviewed the development of seismic design requirements and the construction of high-rise reinforced concrete buildings in Japan. Shunsuke stated that structural members should not be damaged under permanent gravity loading, deformation and vibration of floor slabs and girders should be examined for serviceability [12]. Wood and Whittaker [13] outlined the aspects of seismic design incorporated in a high storey building designed and constructed in Dubai. For medium to tall buildings, where considerable frame action was implied, the detailing of element and zones might be more critical but could still potentially follow the simplified design methods outlined by U.S. Uniform design building code (UBC) for structures [13]. Mendis et al [14] used simple quasi-static treatment of wind loading, which was universally applied to design of typical low to medium-rise structures for the design of tall buildings, where dynamic response levels play an important role in the detailed wind design of facade systems [14]. Merrick and Bitsuamlak [15] studied the shape effects on the wind-induced response of high-rise buildings. They concluded that certain shapes that are prone to wind phenomena, such as vertex-shedding, which can generate high dynamic loads, govern the design of the tall buildings and the general wind loadings patterns are very useful in the buildings design circles [15]. Mir and Moon [16] mentioned the structural development in tall buildings making sorting of tall buildings according to structural systems, interior structures, exterior structures method of design and finally design code. Mir and Moon concluded that with the development of increasingly tall buildings light members, serviceability issues like lateral away, floor vibration, and

occupant comfort need to be given more attention by the researchers and the structural designers [16]. Comparative study on structural systems for tall buildings was conducted by El Leithy et al. The volume of concrete increases almost linearly with the height of the structure with respect to gravity loads. While, for resisting wind loads the volume of concrete increases at a drastically accelerating rate. The key idea in limiting the wind drift in tall buildings was by changing the structural form of the building into something more rigid and stable to confine the deformation and increase stability [17].

1.1 Research significance

In this paper a computer program has been developed to analyze the reinforced concrete tall buildings under wind and earthquake loads taking into account the new changes in the Egyptian design building Codes [2 and 3]. This paper explain briefly also the effect of wind or earthquake loads on reinforced concrete tall buildings, where five different parameters for the comparative study between wind and earthquake effects are considered according to Egyptian design building codes 1995 and 2003. Wind pressure, zone factor according to Egyptian design building code [1], structural system factor, importance factor and finally soil factor were talking into considerations and there effects on the performance of tall buildings were discussed.

2. Revision of Egyptian Code [2]

2.1. Wind Analysis

The code identifies the pressure or the suction induced by the wind using the following equation and Fig. 1 and 2:

$$P_e = c_e k q \quad (1)$$

where:

P_e : external design wind pressure affecting statically on the unit area of the external surfaces of the building.

q : wind pressure depends on the geographic site, Table (7-1) of the code [2].

k : factor of exposure defines the distribution of the wind according to the height of the building from the ground surface, Table (7-2) of the code [2].

c_e : pressure or suction distribution factor on the external surface of the building.

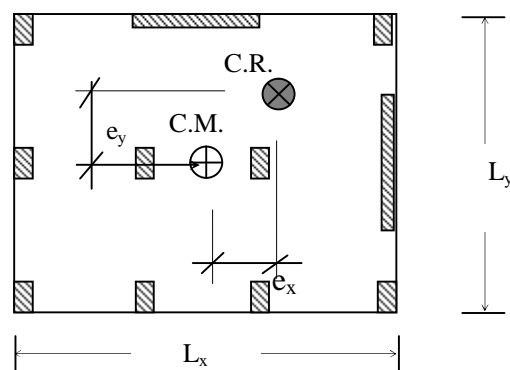


Fig. 2. Center of mass and center of rigidity.

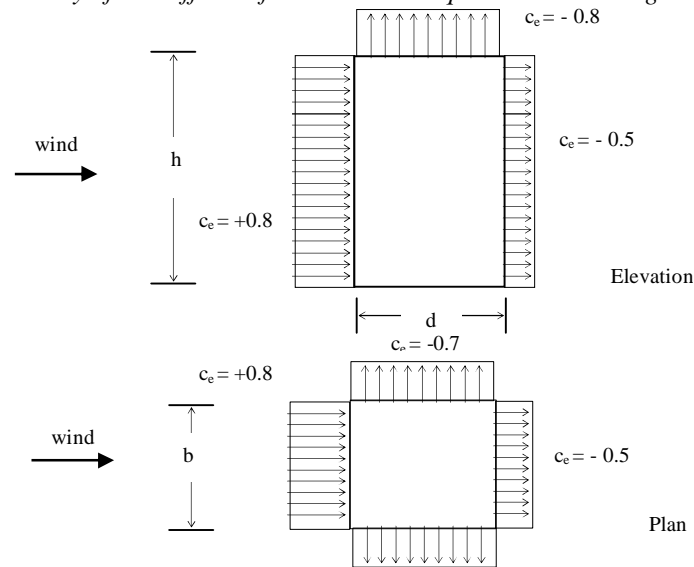


Fig. 1. Factor of pressure distribution on the external surface of the building.

where:

C.R. : Center of rigidity.

C.M. : Center of mass.

2.2. Seismic Analysis

The Egyptian design building code of practice for calculating loads and forces in the structural and building works [2], explains a simple method which specify the equivalent static loads for the seismic effect. The application of this method of design is restricted by the following conditions:

- 1- The height of the building ≤ 100 m.
- 2- The ratio of the height to the breadth in direction of applied seismic force should not exceed 5.0. i.e.:

$$r = \frac{H}{B} \leq 5.0 \quad (2)$$

- 3- The structural system is uniform along the height of the building.

The total seismic shear force on the base of the structure is calculated at each direction by the formula and Fig. 3:

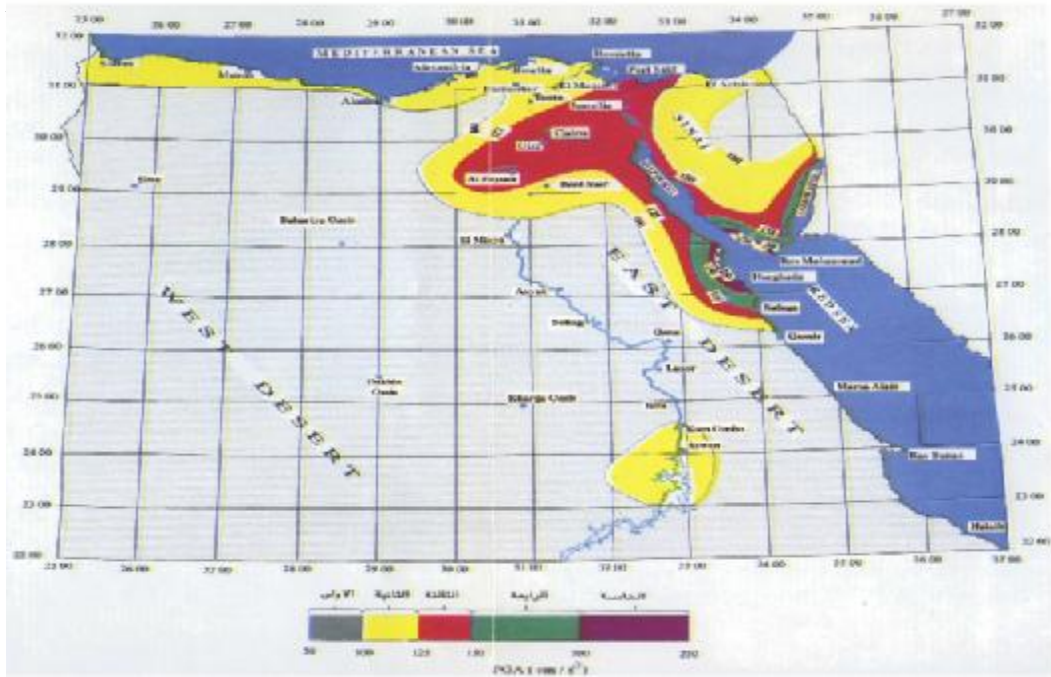


Fig. 3. Five seismic design zones According to ECCP 2003 [3]

$$V = (Z I K C S) W \quad (3)$$

where Z = Seismic zone coefficient,

$Z = 0.1$ for first zone,

$Z = 0.2$ for second zone, and

$Z = 0.3$ for third zone.

I = Importance factor,

$I = 1.25$ (buildings for emergency purposes), and

$I = 1.0$ (for other buildings).

K = Structural system factor,

$K = 1.33$ (box system or shear walls),

$K = 0.67$ (ductile frames),

$K = 0.8$ (non-ductile frames), and

$K = 1.0$ (combined system of shear walls and frames).

C = Period coefficient,

$$C = \frac{1}{15\sqrt{T}} \leq 0.12 \quad (4)$$

T = fundamental natural period,

(a) for ductile moment resisting frames: $T = 0.1 N$

where N = total No. of floors.

(b) for other systems:

$$T = \frac{0.09 H}{\sqrt{B}} \quad (5)$$

B = the dimension of the building, in m, in the direction of the applied earthquake force.

H = height of the building

S = Soil coefficient,

S = 1.0 (Rock or dense soil),

S = 1.15 (medium dense soil), and

S = 1.3 (loose soil).

W = Design weight of the structure,

W = Dead load (Live load ≤ 5 KN/m²)

W = Dead load + 0.5 Live load (Live load > 5 KN/m²)

The total seismic shear force V is divided to static forces F_j acting at the level of each floor at the center of mass by the following equation:

$$F_j = (V - F_t) \frac{W_j H_j}{\sum_{i=1}^n W_i H_i} \quad (6)$$

where W_j = design weight of the floor j :

H_j = height of the floor j from the base.

F_t = horizontal force at the top surface of the building.

If $T \leq 0.7$ sec. then $F_t = 0.0$,

If $T > 0.7$ sec. then $F_t = 0.07 T.V \leq 0.25 V$

The story shear force at any floor (j) is the sum of the lateral forces at and above this level.

$$V_j = F_t + \sum_{i=j}^n F_i \quad (7)$$

The overturning moment at a particular floor (j)

$$M_j = F_t (H_n - H_j) + \sum_{i=j}^n F_i (H_i - H_j) \quad (8)$$

In-plane forces on each column or wall due to direct shear are computed from:

$$F_{vx} = V_x \frac{K_x}{\sum K_x}, \quad F_{vy} = V_y \frac{K_y}{\sum K_y} \quad (9)$$

where K_x, K_y = stiffness of each vertical member resisting lateral load in X and Y directions.

A torsion moment M_t results from the eccentricity between the center of mass (C.M.) and the center of rigidity (C.R.) :

where C.M. = the center of mass at (x_m, y_m) :

$$x_m = \frac{\dot{a} P_x}{\dot{a} P}, \quad y_m = \frac{\dot{a} P_y}{\dot{a} P} \quad (10)$$

P = the reaction of each column or wall, and

C.R. = the center of rigidity (x_r, y_r) :

$$x_r = \frac{\sum K_x \cdot x}{\sum K_x}, \quad y_r = \frac{\sum K_y \cdot y}{\sum K_y} \quad (11)$$

K_x, K_y = represents the stiffness of each column or wall about x, and y axes respectively.

The torsion eccentricity:

$$e_x = x_r - x_m, \quad e_y = y_r - y_m \quad (12)$$

The Egyptian Codes [2 and 3] specifies the design eccentricity (e_{xd}, e_{yd}) where:

$$\begin{aligned} e_{xd} \text{ the max of } e_x = x_r - x_m \pm 0.05 L_x \quad \text{and} \quad e_x = 1.5 (x_r - x_m) \\ e_{yd} \text{ the max of } e_y = y_r - y_m \pm 0.05 L_y \quad \text{and} \quad e_y = 1.5 (y_r - y_m) \end{aligned} \quad (13)$$

The torsion moment is calculated from the following formula:

$$M_{tx} = V_x e_{xd}, \quad M_{ty} = V_y e_{yd} \quad (14)$$

The in-plane force on each column or wall due to torsion results from the eccentricity between the center of mass (C.M.) and the center of rigidity (C.R.) at any level are computed from:

$$F_{tx} = M_{tx} \frac{K_x d_x}{J_r}, \quad F_{ty} = M_{ty} \frac{K_y d_y}{J_r} \quad (15)$$

where d_x, d_y = are the distances of each column or wall from the center of rigidity .

$$J_r = \text{Torsion stiffness} = \sum (K_x d_x^2 + K_y d_y^2) \quad (16)$$

The Egyptian code [2 and 3] specifies also the max. lateral displacements between any two successive floors by $0.005 H_i$, where H_i is the difference between the two floor levels.

3. Computer Program

In this paper a computer program has been developed to analyze the reinforced concrete buildings under wind and earthquake loads taking into account the new changes in the Egyptian Codes [2 and 3]. The program calculates the stiffness of vertical members that resist the lateral loads. It calculates also the center of mass and the center of rigidity of the building. Moments, lateral shear forces and the additional shear forces due to torsion on each vertical element resisting lateral load at the each

floor are also calculated. All the results are illustrated graphically by the program to clearly showing the results.

3.1. Design Example

This example studies the effect of the wind and earthquake using the Egyptian Code-93 on a twelve-story office building 18x30 m shown in Fig. 4. The story height is 3m. The structural system resisting lateral forces consists of columns and shear walls as shown in the Fig. 4. Interior columns are 0.7x0.7 m, exterior columns are 0.5x0.5m in X and Y directions shear walls are 0.25x6.0m. The building is located in seismic zone 3 as shown in Fig. 3 and Table 1 on medium soil. The wind pressure is 0.9 KN/m². The live load is 3 KN/m², and the average dead load of each floor is 7000 KN and for the roof floor equal to 4000 KN.

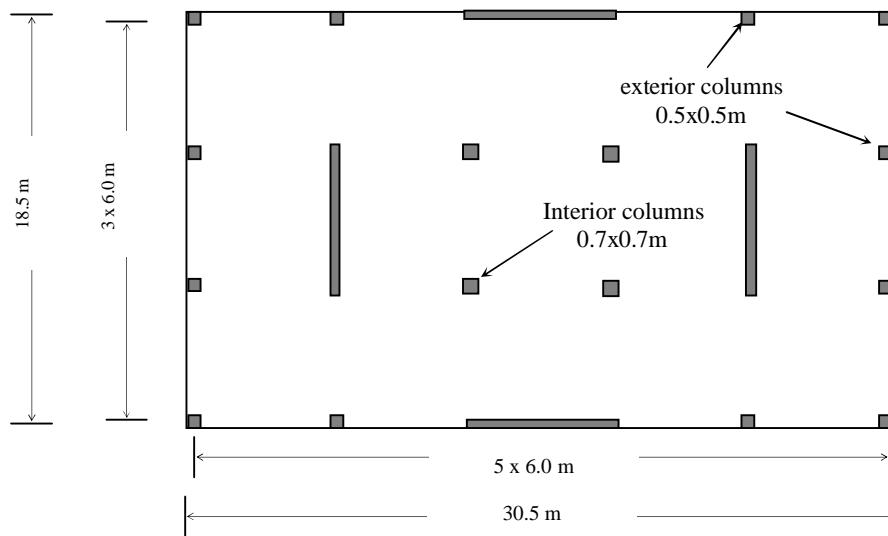


Fig. 4. Plan of the 12 story building.

Table 1: Comparison between effect of wind and earthquake for different buildings on different factors

Factor	Case 1: Minimum effect	Case 2: Maximum effect
Intensity of wind pressure	0.50 kN/m ²	0.90 kN/m ²
Zone factor = (Zone N)	0.1= (Zone 1)	0.3= (Zone 3)
Structural system factor	0.67	1.33
Importance factor I	1.0	1.25
Soil factor	1.0	1.30

3.1.1. Given data and results:

(L) Length of the building = 30.00 m

(B) Width of the building = 18.00 m

No. of floors (N) = 12 floor

Height of the building = 36 m

3.1.2. Wind Data:Intensity of wind pressure = 0.9 KN/m²

Factor of pressure (action) = 0.8

Factor of (suction) = 0.5

3.1.3. Earthquake Data:

Zone factor Z = 0.3

Importance factor I = 1.0

Structural system factor K = 1.33

Soil factor S = 1.15

3.1.4. Properties of Columns and walls:

Sec. No.	Lx	Ly	Area	Ix	Iy
1 Column	0.50	0.50	0.25	0.005	0.005
2 Column	0.70	0.70	0.49	0.020	0.020
3 Wall.	0.25	6.0	1.50	4.500	0.008
4 Wall	6.00	0.25	1.50	0.008	4.500

3.1.5. Center of Mass = Center of Rigidity: $\bar{X} = 15.0$ m $\bar{Y} = 9.0$ m e_{xd} by the code = 1.525 m e_{yd} by the code = 0.925 mJr= Torsion stiffness = $\sum K_x d_x^2 + K_y d_y^2 = 1474.066$ m⁶**3.1.6. Wind Forces in X-Direction and in Y-direction (KN/m²):**

Height Level	Action q	Suction q	Total q
(30.0 - 36.0)	10.80	0.670	1.755
(20.0 - 30.0)	0.936	0.585	1.521
(10.0 - 20.0)	0.792	0.495	1.287
(0.0 - 10.0)	0.720	0.450	1.170
Torsion moment M_{tx}			= 860.93 m.KN

Figure 1 shows the distribution of wind forces in KN/m^2 in both directions according to the Egyptian Code [2].

3.1.7. Max. forces at the base due to wind in Y-direction:

$$\begin{aligned} \text{Max. wind force at the base } V_y &= 1534.45 \text{ KN} \\ \text{Max. wind moment at the base } M_y &= 29868.34 \text{ m.KN} \\ \text{Torsion moment } M_{ty} &= 2340.04 \text{ m. KN} \end{aligned}$$

3.1.8. Max. forces at the base due to wind in X-direction:

$$\begin{aligned} \text{Max. wind force at the base } V_x &= 930.73 \text{ KN} \\ \text{Max. wind moment at the base } M_x &= 18116.86 \text{ m.KN} \end{aligned}$$

3.1.9. Earthquakes in X-Direction or in Y-direction:

$$\begin{aligned} \text{Period (T) (Y-dir.)} &= 0.7533 \text{ sec.} \\ \text{Period factor (C) (Y-dir.)} &= 0.0768 \\ \text{Max. base shear force (V}_y\text{) = Z.I.K.C.S.W} &= 2960.60 \text{ KN} \\ T_y > 0.7 \text{ sec} \quad \text{then force at the top } F_t &= 0.07 T_y.V_y = 15.611 \text{ KN} < 0.25 V_y \\ \text{Period (T) (X-dir.)} &= 0.5867 \text{ sec.} \\ \text{Period factor (C) (X-dir.)} &= 0.0870 \\ \text{Max. base shear force (V}_x\text{) = Z.I.K.C.S.W} &= 3354.76 \text{ KN} \\ T_x < 0.7 \text{ sec} \quad F_t &= 0.000 \text{ KN} \end{aligned}$$

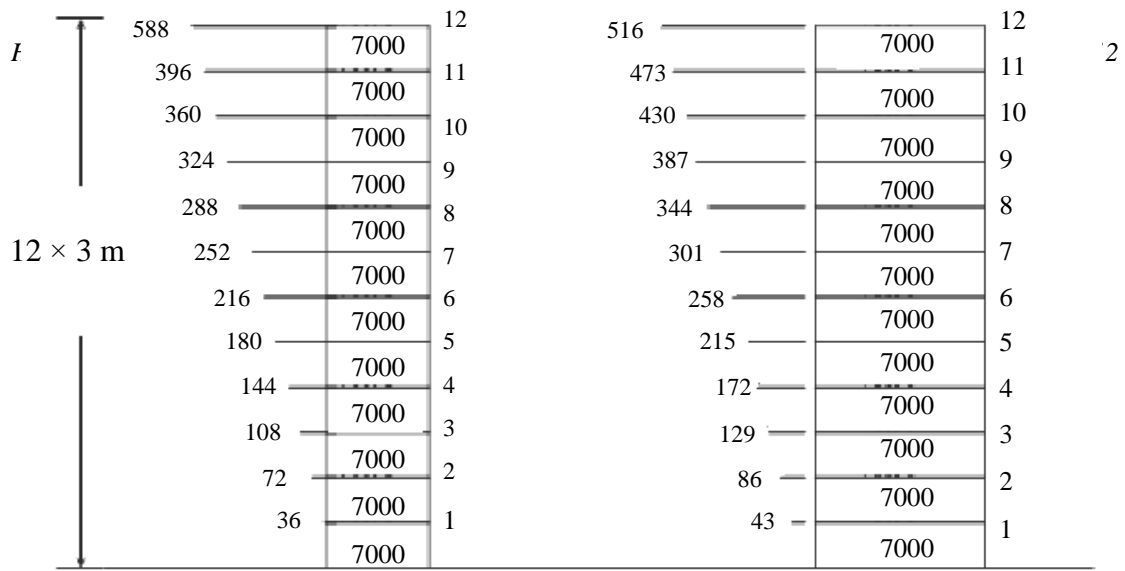
Fig.5 shows the distribution of earthquake forces in KN/m^2 in both directions according to the Egyptian Code [2] by the equivalent static load method

3.1.10. Max. forces at the base due to earthquake in Y-direction:

$$\begin{aligned} \text{Max. base shear force (V}_y\text{)} &= 2960.60 \text{ KN} \\ \text{Max. wind moment at the base } M_y &= 75732.14 \text{ m.KN} \\ \text{Torsion moment } M_{ty} &= 4514.91 \text{ m.KN} \end{aligned}$$

3.1.11. Max. forces at the base due to earthquake in X-direction

$$\begin{aligned} \text{Max. base shear force (V}_x\text{)} &= 3354.76 \text{ KN} \\ \text{Max. wind moment at the base } M_x &= 83868.95 \text{ m.KN} \\ \text{Torsion moment } M_{ty} &= 3103.15 \text{ m.KN} \end{aligned}$$



(a) Seismic loads in Y- direction

(b) Seismic loads in X- direction

Fig. 5. Seismic design lateral forces in KN.

Figs. 6 and 7 give the shear forces at the base of the buildings in ton due to wind in direction Y and X respectively and Figs. 8 and 9 give the moments at the base of the buildings in ton due to wind in direction Y and X respectively

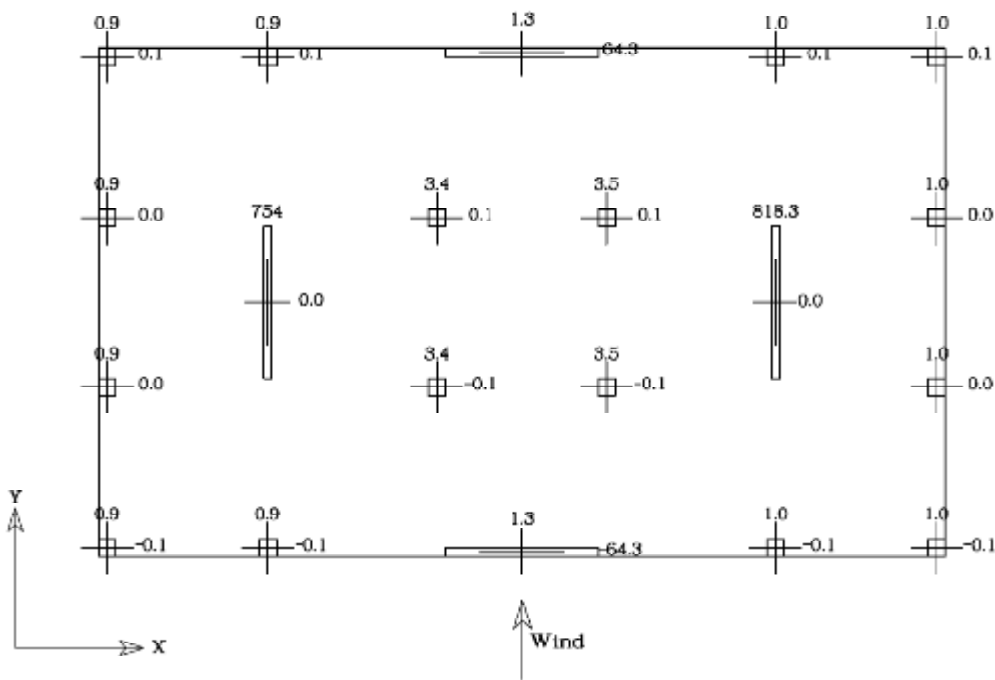


Fig. 6. Shear base forces due to wind in Y- directions (in KN)

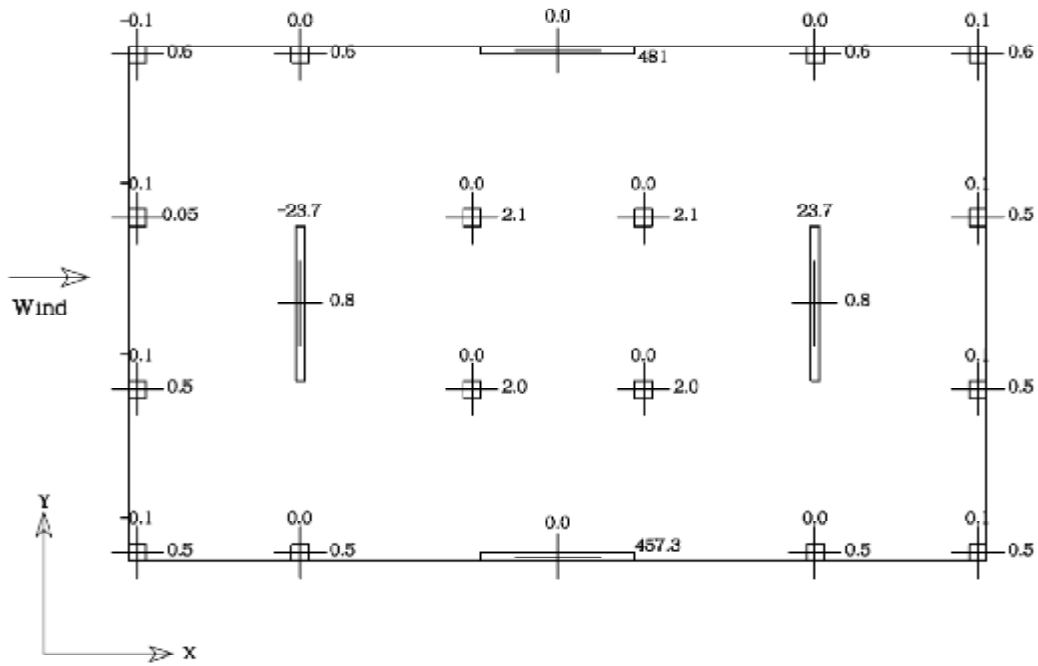


Fig. 7. Shear base forces due to wind in X- directions (in KN)

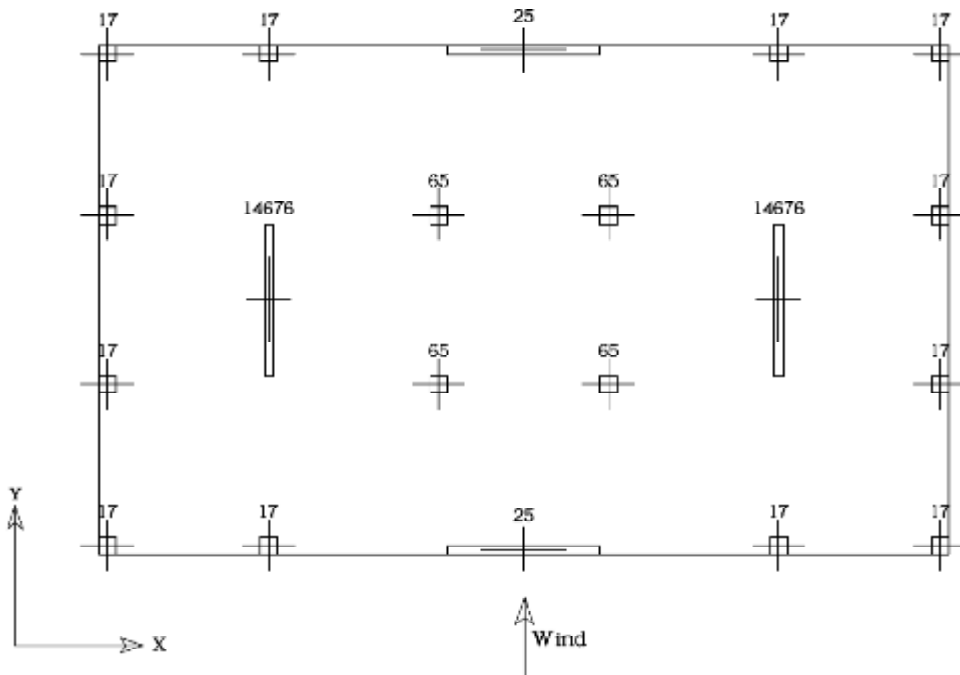


Fig. 8. Moments at the base due to wind in Y- directions (in KN. m)

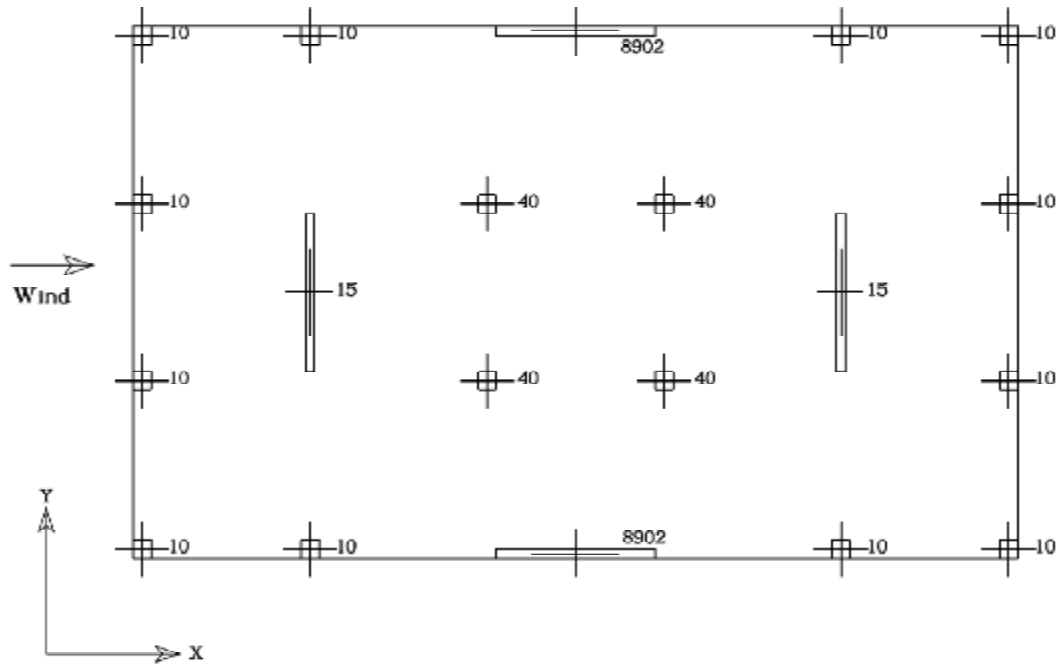


Fig. 9. Moment at the base due to wind in X- directions (in KN. m)

Figs. 10 and 11 give the shear forces at the base of the buildings in KN due to earthquake in direction Y and X respectively and Figs. 12 and 13 give the moments at the base of the buildings in KN. m due to earthquake in direction Y and X respectively

According to the code provision, the required sections of columns should be designed to resist the max. stresses of the wind pressure or seismic earthquake in each direction separately [2].

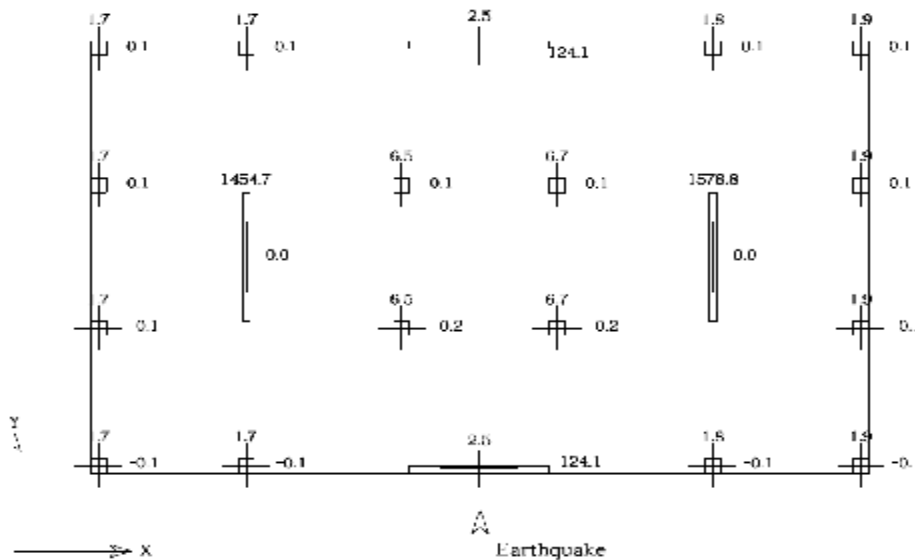


Fig. 10. Shear base forces due to earthquake in Y- direction (in KN)

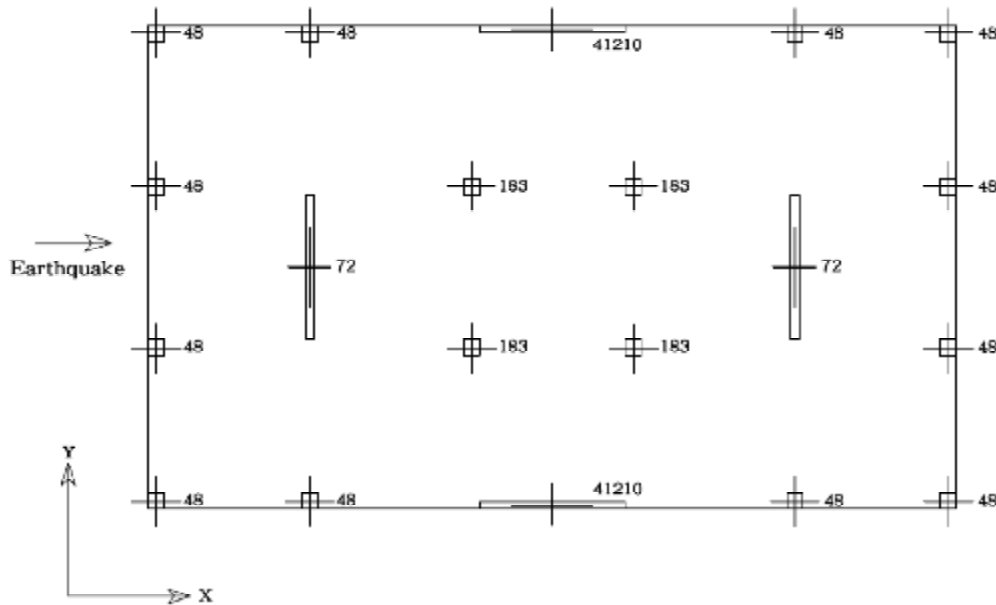


Fig. 13. Moment at the base due to earthquake in X- direction (in KN. m)

4. Comparison Between The Effect of wind and Earthquake According to The Egyptian Code-93 [2]

The previous example shown in Fig. 4. is solved 60 times to represent the following cases:

- 1- Thirty buildings with different number of floors (number of floors =1 to 30 floor) are analyzed to compare the effect of building height on the analysis of both wind and earthquake. The height of the buildings ranged from 3.0m to 90.0 m to cover short and tall buildings.
- 2- To show the minimum and the maximum effect of the wind and earthquake, the thirty buildings are analyzed for two cases:

Figure 15 compares the shear forces at the base of the thirty buildings in KN for both wind and earthquake along Y- direction which is normal to the long direction of the building, while Fig. 16 compares the shear forces at the base of the thirty buildings in KN for both wind and earthquake along X-direction.

Fig. 17 compares the moments at the base of the thirty buildings in ton for both wind and earthquake along Y- direction which is normal to the long direction of the building, while Fig. 18 compares the moments at the base of the thirty buildings in ton for both wind and earthquake along X- direction which is normal to the short direction of the building.

It is shown that wind is more effective than earthquake for tall buildings when minimum design factors are considered in the analysis (case 1), while earthquake is found to be more effective for short buildings Table 1. The wind effect increases rapidly when the height of the building increases. The shear forces and the moments at the base resulted from wind when the load is applied normal to the long direction, i.e. Y- direction, are more than that resulted when applied on the short direction, while for earthquake the forces at the base are less than the other direction.

For case 2, the effect of earthquake is very large because it depends on many design factors which lead to uneconomic solution. The difference between wind and earthquake base shear and moment decreases when the height of the building increases as shown in Table 1.

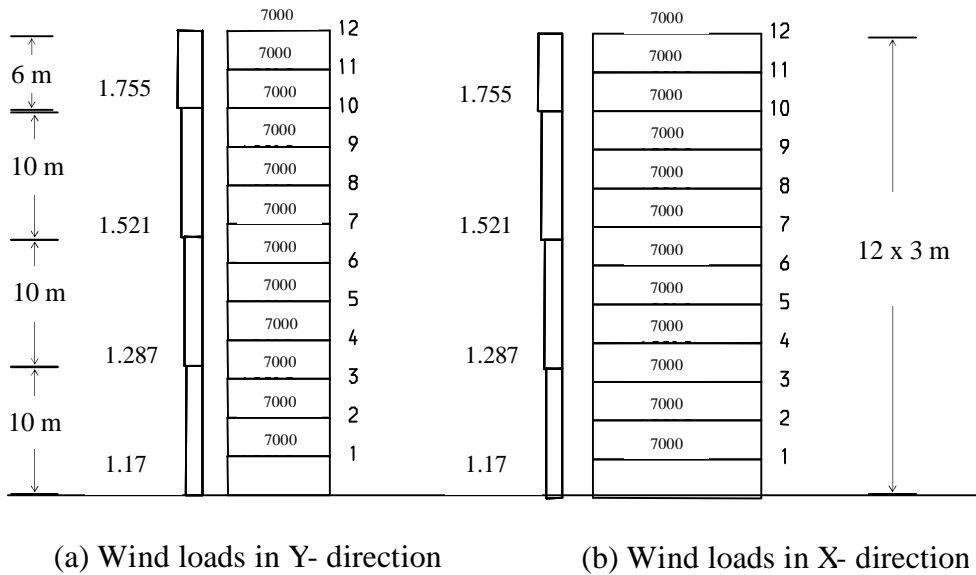


Fig. 14. Wind design lateral forces in KN/m^2

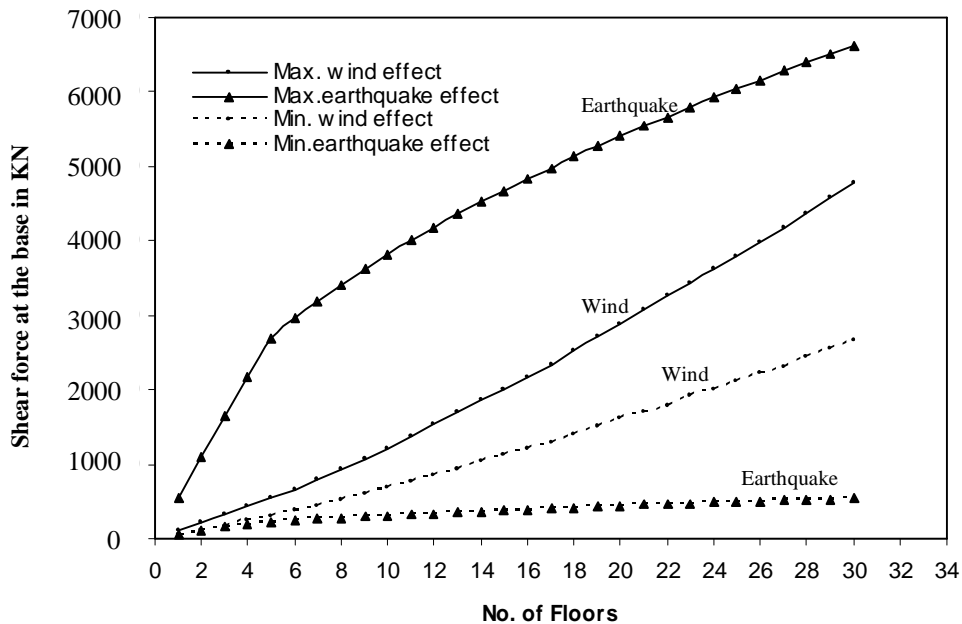


Fig. 15. Shear forces at the base in KN for buildings in Y- direction with different numbers of floors

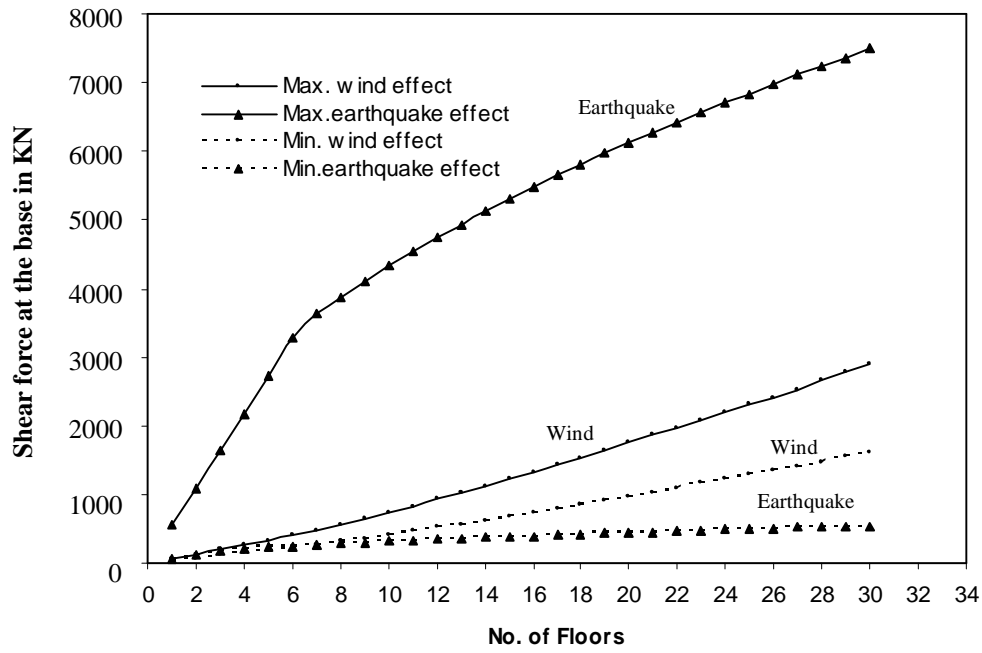


Fig. 16 Shear forces at the base in KN for buildings in X- direction with different numbers of floors

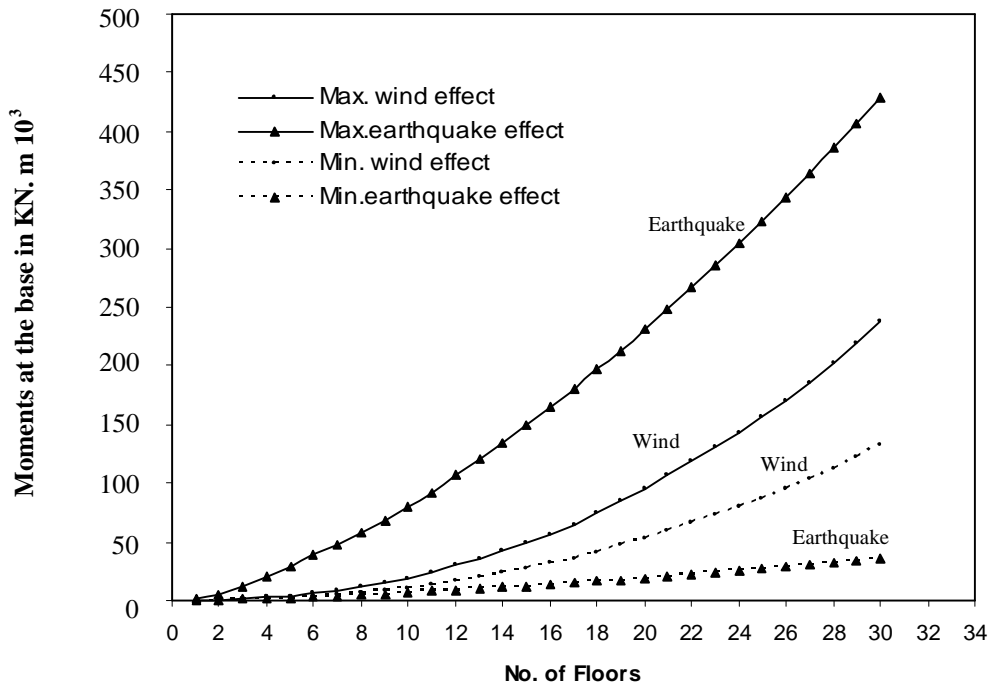


Fig. 17. Moments at the base in KN. m for buildings in Y- direction with different numbers of floors

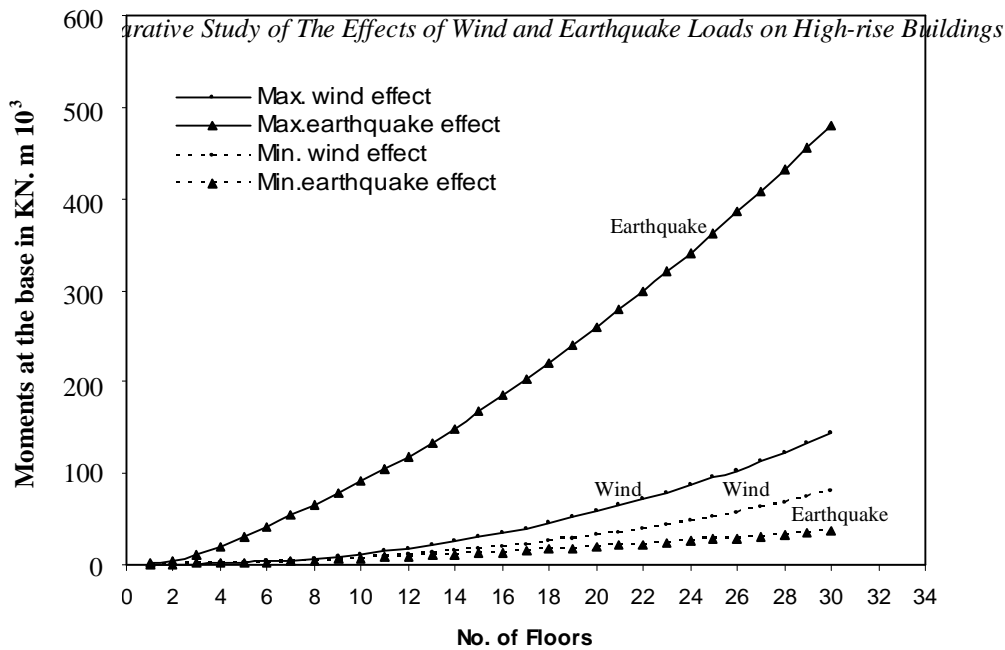


Fig. 18 Moments at the base in KN. m for buildings in X- direction with different numbers of floors

5. Conclusions

It is concluded from this study that:

- 1- The effective parameters for wind forces affecting any building are the area subjected to wind as well as the intensity of wind defined by the code according to its the location.
- 2- The effective parameters for earthquake forces for any building defined by the code are the zone factor according to its location, the importance of the building, the kind of structural system, the period coefficient which depends on the dimensions of the building, the soil coefficient and the weight of the building.
- 3- The variation of the results by seismic analysis is more than that of the wind analysis because of depending on many design factors. One of the most important factors is the weight of the building as well as the kind of the structural system the. Ductile frames are recommended for tall building or when earthquake govern the design.
- 4- For building systems consists of shear walls and frames, the presence of shear walls dominate the calculation of lateral forces especially when the lengths of shear walls in the influence direction of lateral loads are suitable. The relative areas of concrete for the interior, exterior and shear walls in the design example was about 1 : 2 : 7.8 respectively while lateral forces distributed by about 1 : 3.5 : 830. It can be considered that the shear walls almost resist all lateral loads and column resistance can be neglected in this case.
- 5- Wind is more effective than earthquake for tall buildings with shear walls when minimum design factors are considered, while earthquake was found to be more effective than wind when maximum design factors are considered.
- 6- Earthquake is found to be more effective for short buildings. The wind and earthquake effects increase rapidly when the height of the building increases.
- 7- Buildings should be designed in both directions independently for the critical forces of wind or earthquake separately. The total shear force and the moment at the base result from seismic analysis when loads acting normal to the short side may be greater than the other direction.

List of symbols

P_e	: Wind pressure affecting statically on the unit area of the external surfaces of the building
Q	: Wind pressure depends on the geographic site
k	: Factor of exposure defines the distribution of the wind according to the height of the building from the ground surface
c_e	: Pressure or suction distribution factor on the external surface of the building
V	: Total seismic shear force on the base of the structure
Z	: Seismic zone coefficient
I	: Importance factor
K	: Structural system factor
C	: Period coefficient
T	: Fundamental natural period
N	: No. of floors
B	: Width of the building
H	: Height of the building
S	: Soil coefficient
W	: Design weight of the structure
F_j	: Static forces
W_j	: Design weight of the floor
H_j	: Height of the floor
F_t	: Horizontal force at the top surface of the building
K_x, K_y	: Stiffness of each vertical member resisting lateral load in X and Y directions.
M_t	: Torsional moment
$C.M.$: Center of mass
P	: Reaction of each column or wall
$C.R.$: Center of rigidity
dx, dy	: Distances of each column or wall from the center of rigidity
J_r	: Torsion stiffness
H_i	: Difference between the two floor levels

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