

AN ANALYTICAL EVALUATION OF THE IMPACT OF IN-PLAN IRREGULARITY ON THE DYNAMIC CHARACTERISTICS AND LATERAL CAPACITY OF RC BUILDINGS

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Abstract In-plan irregularity can lead to severe damages of RC buildings as a result of additional stresses on the RC elements due to torsion effects. Considering the effect of the in-plan irregularities becomes a challenge for the seismic performance assessment. In this paper, 3D numerical models of four- and six-storey RC buildings with different levels of eccentricity were developed to estimate the behaviour of in-plan irregular RC buildings. Instead of changing the dimensions of the section of RC columns or using different structural configurations to impose eccentricity, the mass was lumped in a certain point which works as an artificial centre of mass (CM). Then, the artificial centre was controlled to produce several levels of irregularity. Nonlinear static pushover analysis was used to assess the performance of the considered building due to the lateral loading. The lateral capacity of the studied buildings were plotted, as such, it has been observed that the lateral capacity decreases with the increase of the eccentricity ratio due to the increase of the level of torsional stresses in those with higher eccentricity ratios. In addition, the eccentricity in the direction, which has a lower stiffness, is more effective on the building strength than the eccentricity in other direction.

Keywords: In-Plane Irregularity, Pushover Analysis, Capacity Curve.

INTRODUCTION

As it well known, RC buildings are considered one of the most commonly used buildings around the globe. Symmetric and regular buildings are easier to analysis and predict their performance, nevertheless, all existing buildings have an ingrained level of plane irregularity. This is due to the irregularity in design of architectural plans, poor distribution of structural elements over the building plan, or both. In-plan irregularity occurs as a result of the eccentricity between the centre of mass (CM) and centre of rigidity (CR) of the RC buildings. This irregularity has a significant negative impact on seismic performance [1, 2]. It has shown that, during earthquakes structures with irregularities in their plan/elevation are more vulnerable than their regular ones [2]. In-plan irregularities causes severe damages of RC buildings as a result of expected high torsional stresses on the RC elements. Consequently, these stresses cause early collapse of buildings and changes structure behaviour. Hence the failure behaviour of the structures varies compared to their regular counterparts. Based on this observation, real behaviour of these structures considering the irregularity and their capacity to resist the action of earthquake needs to be evaluated. Recently, many investigations were conducted to obtain more reliable seismic response of in-plan irregular buildings using nonlinear method [3-7]. So, this study aims to evaluation the effect of in-plan irregularity on the seismic performance of the RC buildings using nonlinear static procedures. To this end, 3D numerical models of four and six storeys RC buildings with different levels of eccentricity were developed using the open source software OPENSEES[8]. Those models were designed under gravity loads according to Egyptian

code [9] and their structural performance were evaluated using pushover analysis method. In this method, a distribution lateral load along the height of the structure is applied. In order to grasp the seismic behaviour of the buildings with different levels of irregularity in plane, the lateral loads are incrementally increased until either reaching the numerical instability or the failure of the structure[10]. The pushover analysis method was carried out for the considered study cases according to Egyptian code[9]. Several parameters were analysed in respect to the effect of in-plane irregularity namely eigenvalues (fundamental periods), maximum base shear and lateral displacement capacity.

STUDY CASES DESCRIPTION

A residential RC building was selected to evaluate the effect of the in-plan irregularity on the overall structural behaviour of the building. Figure 1 presents the architectural plan and structural system of the typical building floor. The height of the ground floor is 3.50 while all typical floors are 3.00 m. The area of considered building is 128.25 m² with dimensions 13.50 m and 9.5 m in x-direction and y-direction, respectively.

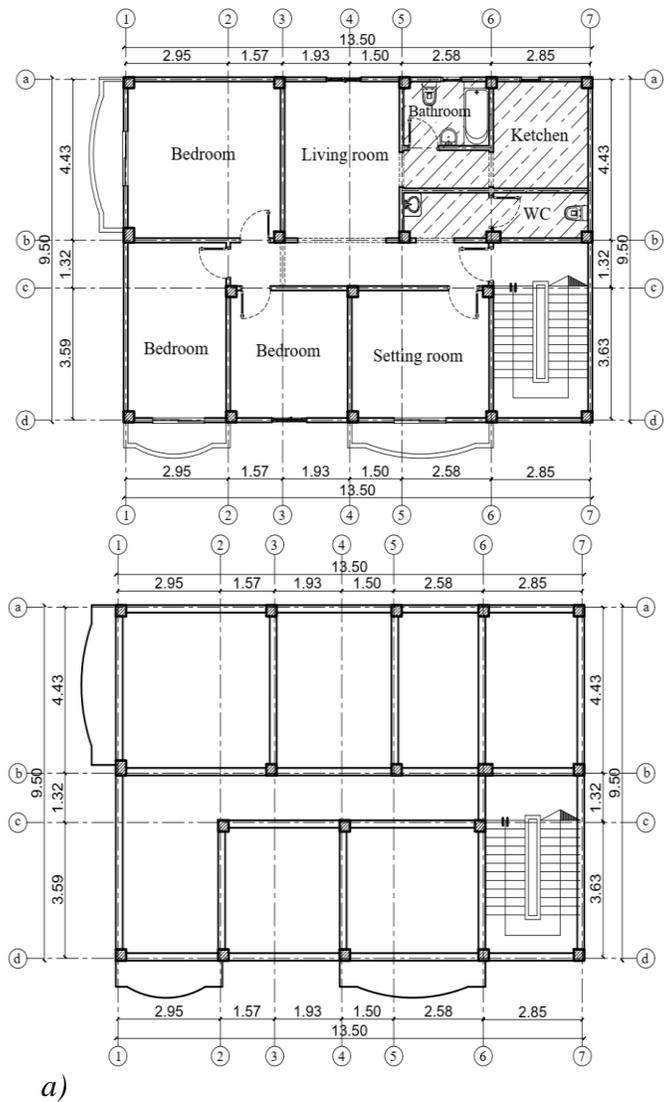
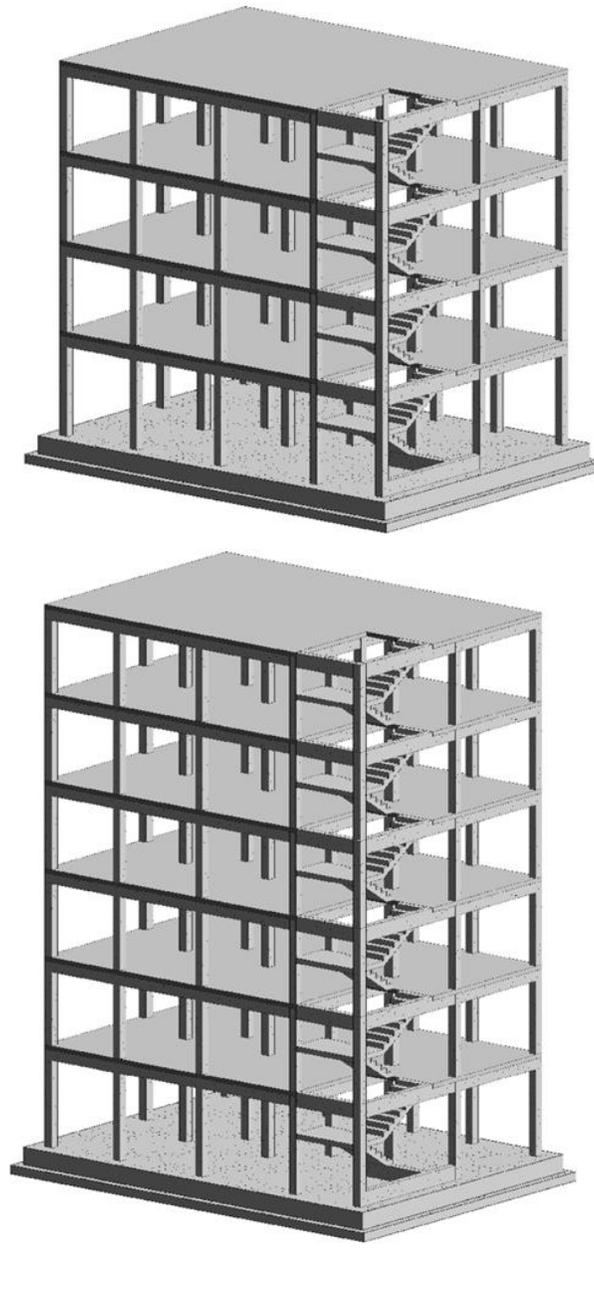


Figure 1. Typical plan view for the considered building: a) architectural plan b) structural system.

As shown in Figure 2, two numbers of the floor were considered RC buildings: four and six stories. To simulate the scenario of non-seismically designed structures, the two configurations were designed under gravity loads following the guidelines of the Egyptian code [9, 11]. The considered dead loads and live loads are listed in Table 1. In terms of RC materials, the characteristics compressive strength of concrete (f_{cu}) was 33.0 MPa, the yield stress of the steel (σ_y) was 500 MPa, and the steel elastic modulus (E) was 200 GPa. Figure 3 presents the resulting cross-section labels and allocates the centre of rigidity (CR) for four-story and six-story buildings, respectively. The columns and beams' cross-section details and dimensions were listed in Table 2 and Table 3, respectively. The thickness of all slabs was found to be 12 cm with #10@20 steel reinforcement.



a) *b)*
 Figure 2. A 3D view of the considered building: a) four stories b) six stories

Table 1. The considered weight and loads ECP-201

| Description | Units | Practice value |
|-------------------------|-------------------|----------------|
| Self-weight of concrete | KN/m ³ | 25.0 |
| Floor cover | KN/m ² | 1.50 |
| Masonry wall weight | KN/m ³ | 18.0 |
| Live load | KN/m ² | 2.0 – 3.0 |

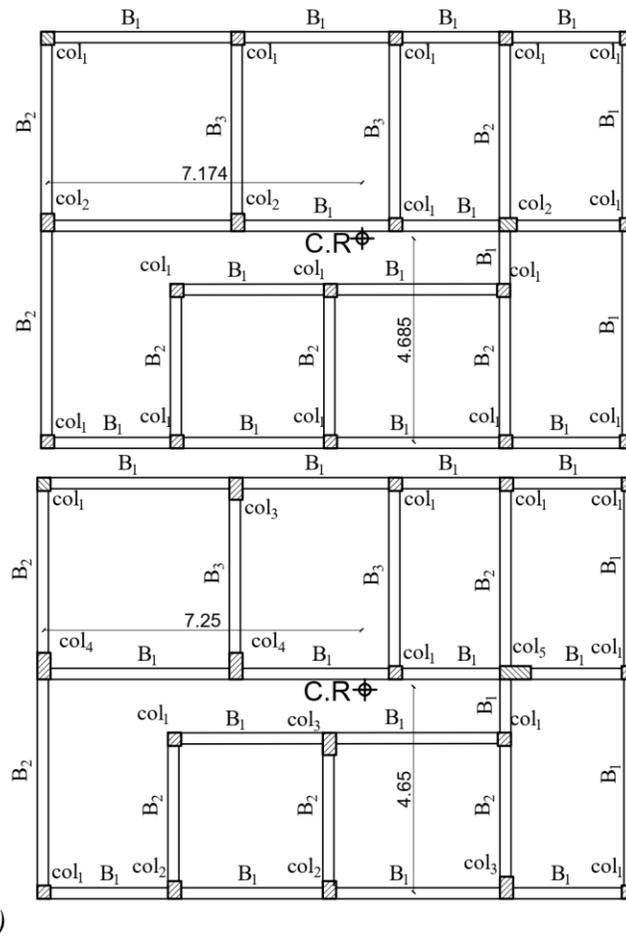


Figure 3. Cross-sections labels and CR location: a) four-story b) six-story

Table 2. The beams cross-sections details of four and six stories

| No of stories | Sample | Section (cm ²) | Reinforcement steel |
|---------------|------------------|----------------------------|---------------------|
| Four stories | Col ₁ | 30x30 | 8 Ø 12 |
| | Col ₂ | 30x40 | 10 Ø 12 |
| Six stories | Col ₁ | 30x30 | 8 Ø 12 |
| | Col ₂ | 30x40 | 10 Ø 12 |
| | Col ₃ | 30x50 | 12 Ø 12 |
| | Col ₄ | 30x60 | 14 Ø 12 |
| | Col ₅ | 30x70 | 16 Ø 12 |

Table 3. The cross-sections details of columns

| Sample | Section (cm ²) | Reinforcement steel | | | | | |
|-----------|-------------------------------|---------------------|--------|--------|--------|--------|--------|
| | | Start | | Middle | | End | |
| | | Upper | Lower | Upper | Lower | Upper | Lower |
| B1 | 25x50 | 5 Ø 12 | 2 Ø 12 | 3 Ø 12 | 4 Ø 12 | 5 Ø 12 | 2 Ø 12 |
| B2 | 25x50 | 5 Ø 12 | 3 Ø 12 | 3 Ø 12 | 5 Ø 12 | 5 Ø 12 | 3 Ø 12 |
| B3 | 25x50 | 2 Ø 12 | 4 Ø 12 | 3 Ø 12 | 6 Ø 12 | 2 Ø 12 | 4 Ø 12 |

FINITE ELEMENT MODEL DESCRIPTION

The open source software OpenSees [8] was used to perform the nonlinear pushover analysis for the considered numerical models. The buildings were presented as 3D centre line model with rigid diaphragms at slab level. In order to overcome the expected numerical instability, the RC frame elements (i.e. beams and columns) were considered and the floors presented by a rigid diaphragm. Also, other components of structure such as the infills panels were neglected. The RC frame elements were modelled using force-based elements known as a beam with hinges. The fibre-sections were considered not only at ends of the elements, but along the elements, to model the conceivable nonlinearity of the central part of the element. The plastic hinge length l_p was identified using the following equation proposed by Paulay and Priestley[12]:

$$l_p = 0.08l_e + 0.022d_b f_y \quad (1)$$

Where l_e is the length of the element, d_b is the diameter the steel reinforcement bars, f_y is the yield stress of the steel bars in mPa. As referred, the RC cross-sections were discretized using fibre model, in which concrete constitutive model, known as concrete04 in OpenSees, representing the uniaxial model proposed by Popovics [13] with degraded linear unloading/reloading stiffness and tensile strength with exponential decay was used to model the unconfined concrete. In order to count for the stirrups effect, the confined concrete was modelled using a confinement factor based on the expression proposed by Kent and Park[14]. Steel bars were modelled using the steel model termed as steel01 representing uniaxial bilinear material with kinematic hardening and optional isotropic hardening described by a non-linear evolution equation.

METHODOLOGY ANALYSIS

In order to study the influence of the in-plan irregularity on the global behaviour of the RC buildings, the distance between the centre of mass (CM) and the centre of rigidity (CR), hereinafter called as eccentricity value, needs to be controlled. Instead of changing the dimensions of the section of RC columns or using different structural configurations of the considered buildings which lead to losing the connection between the studied buildings, the imposed forces were applied at the centre of mass which is varied according to the target level of eccentricity. By implementing this approach, the study cases with different levels of irregularity in X-directing and Y-directing can be created. Finally, pushover analysis was applied whose details are described in detail as following. It is worth notice, to get a generalized relation between the eccentricity and maximum lateral strength, the level of eccentricity in this study reached 50% of building considered dimension which rarely happens in real buildings.

In context of defining the location of the centres of mass and rigidity, the following steps were applied

Step 1: After the building has been designed and the columns cross-sections have been identified, CR was calculated.

$$CR_x = \frac{\sum k_{xi} x_i}{\sum k_{xi}} \quad (2)$$

$$CR_y = \frac{\sum k_{yi} y_i}{\sum k_{yi}} \quad (3)$$

Where k_{xi} and k_{yi} are the lateral stiffness of the i -th lateral load-resisting element in the x and y directions; x_i and y_i are the locations of the i -th lateral load-resisting element in the x and y directions respectively. Equations 3, 4 are used to compute the individual stiffness for RC columns.

$$k_x = \frac{12EI_y}{h^3} \quad (4)$$

$$k_y = \frac{12EI_x}{h^3} \quad (5)$$

Where E is the elastic modulus of the lateral load-resisting element materials, I_x and I_y the moment of inertia of the lateral load-resisting element in x and y directions respectively, and h is the height of the lateral load-resisting element. The summation is taken over all lateral load resisting members.

Step 2: the lateral equivalent base shear were computed according to the Egyptian load code [9] as following;

$$F_b = S_d(T_1) \cdot \lambda w / g \quad (6)$$

Where $S_d(T_1)$ is the elastic response spectrum at fundamental natural period T_1 and 5% damping ratio (η), λ is the correction factor, W is the total weight of the building above the foundation level, and g is the gravity acceleration. The value of S_d is defined according to the spectrum acceleration type 1 assigned for Aswan territory with soil classification B. In regard to λ , it is defined according to the values provided in Egyptian code for the given building taxonomy.

The total based shear is distributed over the height of the building according the following expression;

$$F_i = \frac{Z_i W_i}{\sum_{j=1,n} Z_j W_j} \cdot F_b \quad (7)$$

Where F_i is the lateral load applied to the i -th story, Z_i , Z_j are the stories height above base level, W_i , W_j are the weight of the floors (dead load + 25% live load), F_b are the base shear force caused by earthquakes, n is the number of stories above the base level, and

Step 3: The lateral load along the height of the models was calculated using the formula specified in Egyptian Code. First pushover analysis for the case where CM and CR are identical (NO-ECC). The computed lateral loads were applied in Y-direction and concentrated in CM of every storey with value of F_i . The level of forces is monotonically increased until reaching the collapse point. Then a new CM is defined according to the new level of eccentricity in X-direction then the pushover is performed. Five different eccentricity levels were considered; (EX1, EX2, EX3, EX4, and EX5) which corresponding to 10%, 20%, 30%, 40%, and 50% of LX (dimension of building in X-direction), respectively. Figure 4 describes the adopted pushover procedures in X-direction. For completeness, the location of CM and the direction of lateral loads application were illustrated in Figure 4. For visual clarity of the next result figures, the following colour assignment has been used; the black for NO-ECC, blue for EX1, mauve for EX2, orange for EX3, yellow for EX4 and green for EX5.

Step 4: by repeating the previous step but in X-direction and changing the position of CM of in Y-direction as shown in Figure 5. In the case of the Y eccentricity; the following ID; EY1, EY2, EY3, EY4, and EY5 were assigned for 10%, 20%, 30%, 40%, and 50% of the dimension in the X-direction, respectively.

Step 5: Finally, the behaviour of irregular buildings in X-direction (EX1, EX2, EX3, EX4, and EX5) and Y-direction (EY1, EY2, EY3, EY4, and EY5) were compared to their regular counterparts. All previous steps have been repeated for six-storeys building.

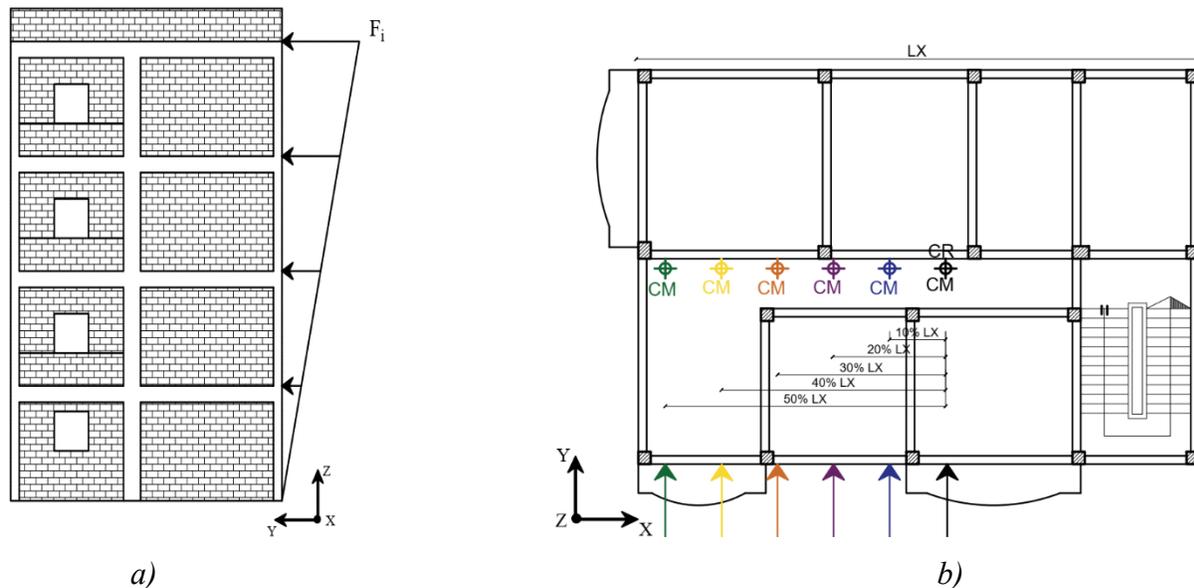


Figure 4. a) diagram of lateral load a distribution along the height of the building in Y-direction
b) location of the CM and the lateral load for NO-ECC, EX1, EX2, EX3, EX4, and EX5 cases

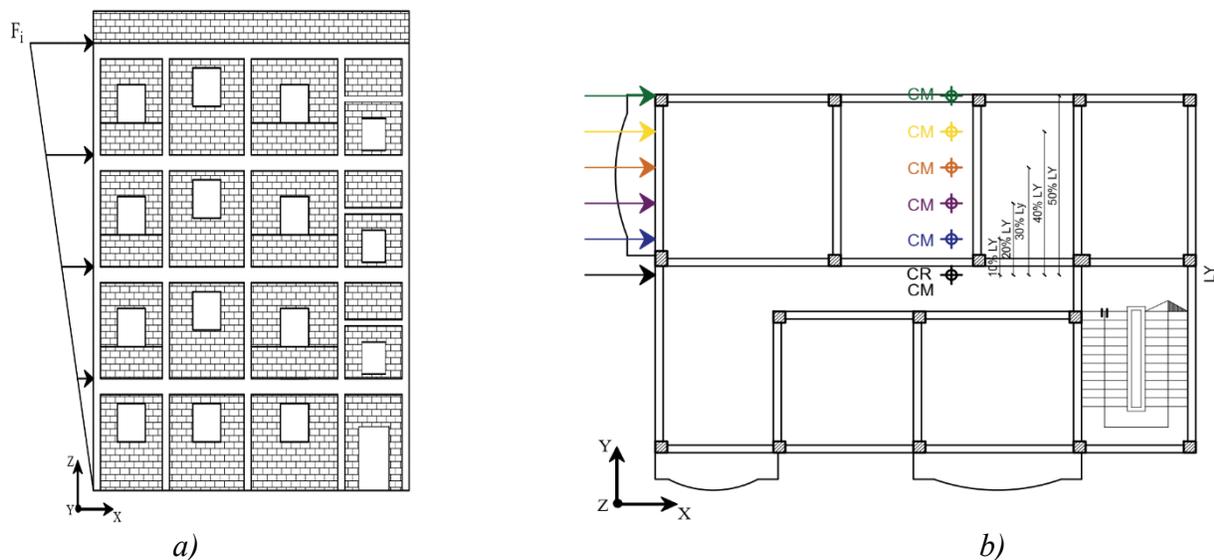


Figure 5. a) sketch of lateral load a distribution along the height of the building in X-direction
b) location of the CM and the lateral load for NO-ECC, EY1, EY2, EY3, EY4, and EY5 cases

RESULTS AND CONCLUSIONS

Dynamic Characteristics

Fundamental periods, which define how the structure will respond during the dynamic excitation, are one of the most important dynamic characterisation of RC buildings. However, the Egyptian code uses one empirical formula in order to define the fundamental first period of the RC building which given as following;

$$T_1 = c_t H^{3/4} \quad (8)$$

Where T_1 is the fundamental natural period, C_t is a factor that depends on structural system and construction material, and H is the height of the building.

To quantify the reliability of the previous expression for structures with in-plane irregularity, the eigenvalues analyses were performed for all considered models of the six storeys building (i.e. eleven models). The comparison between the obtained natural periods and those estimated using equation 8 is presented in the Figure 6. As can be seen, for all considered cases, the fundamental period increases with the increase of eccentricity ratio but with a higher rate in case of weaker direction. Also, the code provision equation always provides a conservative estimation of the fundamental period which leads to unreliable estimation for the base shear force according to equation 6.

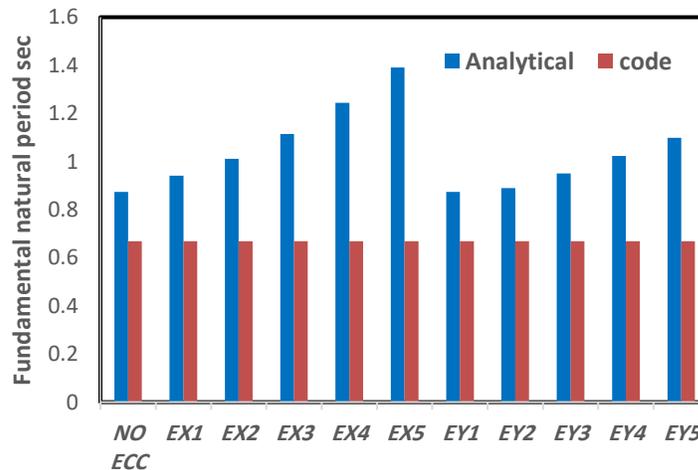


Figure 6. The fundamental natural period for six-story

Capacity Curves

In order to estimate the effect of the eccentricity on the global response of the considered buildings, the base shear was recorded along with the top displacements of the last floor. Counting for the effect of the twisting movement which makes external edges move higher than those at the middle, it is worth mentioning that, the displacements were plotted for those points which have the highest movement. Figure 7. a) and b) show the relation between base shear and the top displacement of the last floor for the four storeys building with two different imposed eccentricity directions in X and Y, respectively, along with the reference case (i.e. NO-ECC). As can be seen, the regular building (NO ECC) recorded the highest lateral strength which mainly due to the uniform distribution of loads over the RC element. In addition, the lateral strength decreases with the increase of the eccentricity ratio due to the increase of the level of torsional stresses in those with higher eccentricity ratios.

It can be concluded that buildings with higher ratios of eccentric are more prone to collapse than the previous one in the event of earthquakes.

Comparing both figure sides (i.e. a and b) in term of the peak lateral strength, it is clear that the rate of the decrease in the obtained maximum lateral strength in X-direction is higher than that in Y-direction, i.e. the corresponding reduction in maximum strength in case EX5 is higher than the reduction value in the corresponding eccentricity in Y (i.e. EY5). That implies that eccentricity has a higher impact in case of the lower stiffness direction. A Similar conclusion was found for the six-storey building as shown in Figure 8. a) and b) for X-direction and Y-direction respectively.

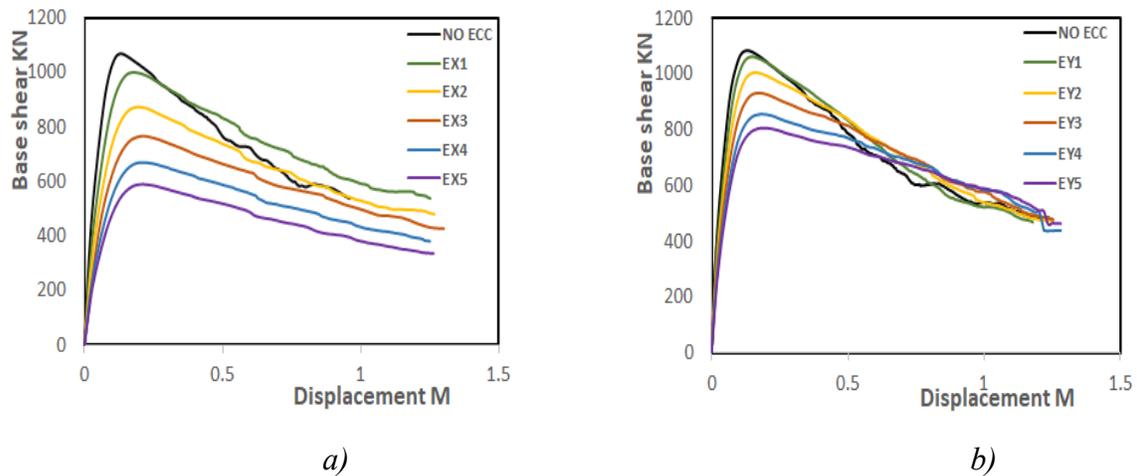


Figure 7. Capacity curve of the four-story buildings: a) X-direction b) Y-direction

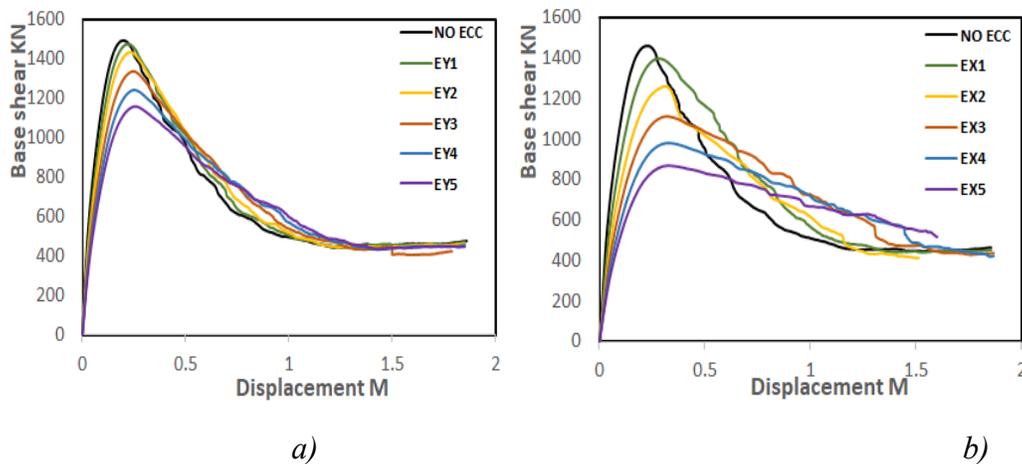


Figure 8. Capacity curve of the six-story buildings: a) X-direction b) Y-direction

The effect of the eccentricity on the building strength was illustrated in Figure 9. Where, EX 4S and EY 4S stand for the eccentricity in X-direction and Y-direction for four-story building respectively. While EX 6S and EY 6S stands for the eccentricity in X-direction and Y-direction for six-story building. As shown, increasing the eccentricity between CR and CM lead to decrease in the building strength. As aforementioned, the eccentricity in X-direction has higher impact on the building strength than the eccentricity in Y-direction for both four and six storeys building. That can be mainly due to the stiffness in Y-direction is higher than that in X-direction. Finally, the eccentricity in four-story building has a higher impact compared to six storeys buildings which can be interpreted by the increase of the lateral flexibility with increasing the of the height.

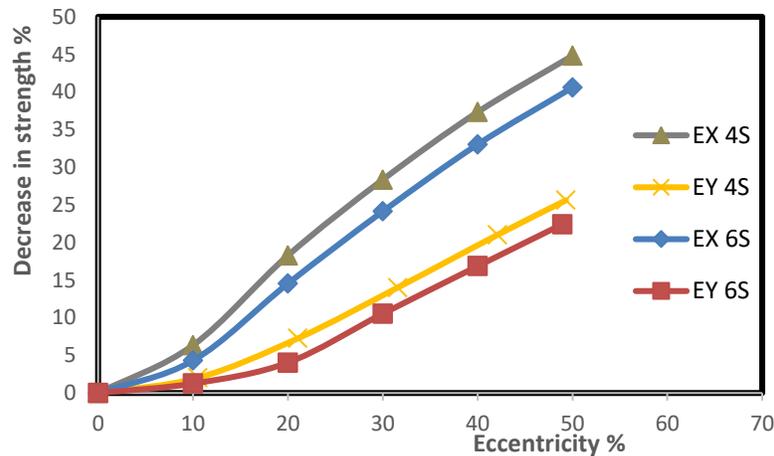


Figure 9. Effect of the eccentricity on the building strength

CONCLUSIONS

Several RC buildings with different irregularity in X-direction (EX1, EX2, EX3, EX4 and EX5) and Y-direction (EY1, EY2, EY3, EY4 and EY5) with four and six number of stories were analysed. In addition, their regular counterpart was analysed. Each building was analysed by using pushover analysis method. The distribution lateral load along the height of the structure is applied according to the Egyptian code. The behaviour of the irregular buildings was compared to the behaviour of regular counterparts through capacity curve. Fundamental natural period was calculated for all pervious buildings with different cases. These values were compared to their counterparts which obtained analytically.

The code provision equation always provides a conservative estimation of the fundamental period which leads to unreliable estimation for the base shear force.

Based on the capacity curve, the buildings with irregularities are most likely to suffer more damage during earthquakes than their regular counterparts. Increasing the distance between CR and CM will cause an increase in the additional stresses resulting from torsion moment, and consequently, will increase the probability of the collapse of a building when they are exposed to earthquakes. Increasing the eccentricity between CR and CM leads to a decrease in building strength. The eccentricity in the direction, which has a lower stiffness, is more effective on the building strength than the eccentricity in other direction. Finally, eccentricity negative impact on the lateral capacity of building increases with lower height buildings.

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