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STIFFNESS EFFECTS OF STRUCTURAL ELEMENTS ON THE SEISMIC RESPONSE OF RC HIGH-RISE BUILDINGS

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The stiffness of structural elements (columns, beams, and slabs) significantly contributes to the overall stiffness of reinforced concrete (RC) high-rise buildings (H.R.B.s) subjected to earthquake. In order to investigate what percentage each type of element contributes to the overall performance of an H.R.B. under seismic load, the stiffness of each type of element is reduced by 10% to 90%. A time history analysis by SAP2000 was performed on thirteen 3D models of 12-story RC buildings in order to illustrate the contribution of column stiffness and column cross sections (rectangular or square), building floor plans (square or rectangular), beam stiffness and slab stiffness, on building resistance to an earthquake. The stiffness of the columns contributed more than the beams and slabs to the earthquake resistance of H.R.B.s. Rectangular cross-section columns must be properly oriented in order for H.R.B.s and slender buildings to attain the maximum resistance against earthquakes.

Keywords: Structural elements, reinforced concrete (RC), stiffness, seismic response, high-rise buildings.

1. INTRODUCTION

Reinforced concrete presents a special challenge of capturing the most suitable cross-section properties, especially when undergoing extensive cracking during earthquake loading. The choice between gross and cracked cross-sectional properties is associated with axial, flexural, shear, and torsional actions [1]. Reductions in cross-sectional properties are on the alarmingly unsafe side, in terms of seismic performance. Also, the seismic capacities of concrete tend to degrade with age.

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The effects of stiffness reduction on the seismic capacity of buildings have been studied by various researchers (e.g., Ahmed *et al.* [2], Čaušević *et al.* [3], Subramanian and Velayutham [4], Micelli *et al.* [5], etc.).

From a structural engineer's point of view, a tall building or a multi-story building is one that, by virtue of its height, is strongly affected by lateral forces which play an important role in its structural design. The maximum slenderness ratio (H/B) achieved in different well-designed buildings worldwide is generally around 10, and that of a maximum floor plan aspect ratio (L/B) is around 4.

The difference in the ratios of contribution of the stiffness of the beams, columns, and slabs in the overall stiffness of the structure will lead to changes in the behavior of the structure as a whole as it pertains to resistance to seismic loads. For this factor to be studied herein, the stiffness of each type of element has been reduced separately, while the values of stiffness of the remaining elements are kept constant at a certain value. The study in this paper also found that the axial load ratio significantly affects the stiffness ratio of vertical structural elements.

Cracks in structural elements (columns, beams, and slabs) will lead to a reduction in the stiffness of these elements. The present research has been carried out to study the quantitative effect of cracking and deflection amplification on the response of RC buildings and buildings with different aspect ratios.

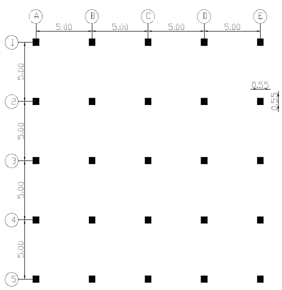
The stiffness of structural elements (columns, beams, and slabs) significantly contributes to the overall stiffness of reinforced concrete (RC) high-rise buildings (H.R.B.) subjected to earthquakes. In order to investigate what percentage influence each type of element contributes to the overall performance of an H.R.B. under seismic load, the stiffness of each type of element was reduced by 10% to 90%.

A time history analysis by SAP2000 V.17 [6] was performed on thirteen 3D models of 12-story RC buildings in order to illustrate the contribution of several factors, such as column stiffness and column cross sections (rectangular or square), building floor plan (square or rectangular), beam stiffness, and slab stiffness on building resistance to an earthquake. Top displacements, top accelerations, base shear forces, base bending moments, and base normal forces were investigated to judge the stiffness contribution of each type of element to the overall stiffness.

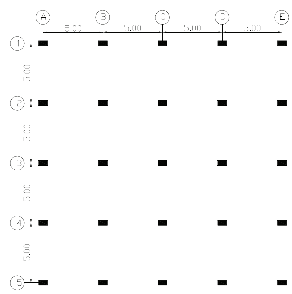
2. Models Description

The stiffness of columns, beams, and slabs plays a significant role in the overall stiffness of the H.R.B., and for this reason thirteen 3D 12-story building models, each 3m in height (36m total height) with a fixed base were tested to show the contributions to the resistance of an H.R.B. subjected to earthquake.

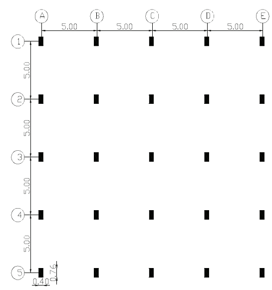
Figure 1 shows a square floor plan with different RC column configurations models. Figure 1(a) represents a square floor plan model with square cross-section RC columns as a control case (control case for the square floor plan model), with 5m spacing between columns. Figures 1(b) and 1(c) illustrate a square floor plan building with rectangular cross-section RC columns in the X and Y direction orientation, respectively. Figures 1(d) and 1(e) show reciprocal and special arrangements of rectangular cross-section RC columns in square floor plan models.



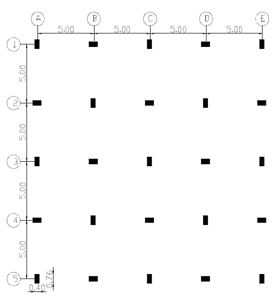
a) Square columns



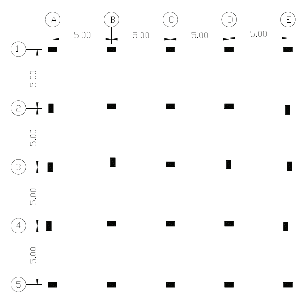
b) X-orientation rectangular columns (---)



c) Y-orientation rectangular columns (|||)



d) Reciprocal arrangement X and Y orientation rectangular columns (|-|)

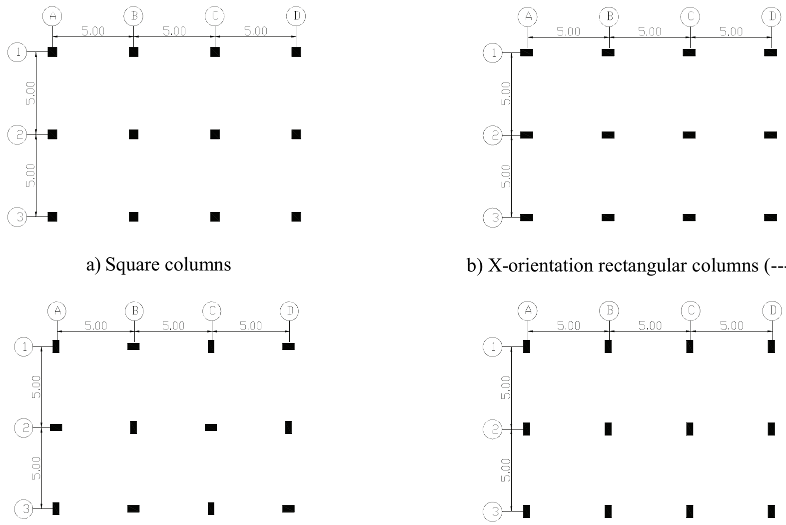


e) Special arrangement rectangular columns (col(1))

Fig. 1. Square floor plan models with different column orientations and arrangements

Figure 2 shows a rectangular floor plan model of 12 floors with a rectangular ratio of 1.5 and spacing of 5m. Figure 2(a) represents a rectangular floor plan model with square RC columns (control case for the rectangular floor plan model) with 5m spacing, 12 floors, each 3m in height. Figure 2(b) shows a rectangular floor plan model with rectangular RC columns in the X-direction orientation. Figures

2(c) and 2(d) illustrate a rectangular floor plan model with rectangular RC columns with reciprocal arrangement and Y-direction orientation, respectively.



a) Square columns

b) X-orientation rectangular columns (---)

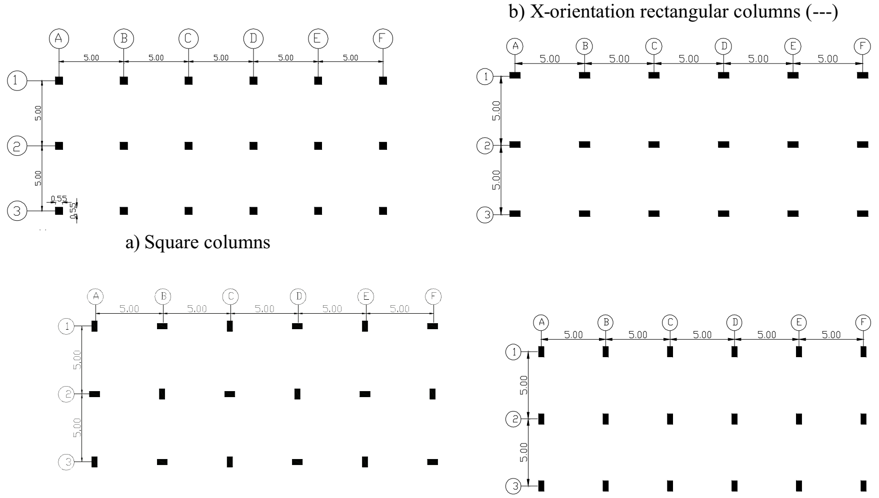
c) Reciprocal arrangement X and Y orientation rectangular columns (| - |)

d) Y-orientation rectangular columns (| | |)

Fig. 2. Rectangular floor plan (ratio 1.5) models with different column arrangements and orientations

Figure 3 shows a rectangular floor plan with a rectangular ratio of 2.5 and 12 floors, each 3m in height. Figure 3(a) represents a rectangular floor plan model with square cross-section RC columns of 5m spacing (control case for the floor plan of the rectangular model with a ratio of 2.5). Figures 3(b), (c), and (d) show rectangular floor plan models with rectangular cross-section RC columns with an X-direction orientation, reciprocal arrangement, and Y-direction orientation, respectively.

All models were subjected to 200 kg/m^2 as a live load (in the level of slabs of each floor), and to a cover of 150 kg/m^2, and also the self-weight of the elements as a dead load. Each element has been designed according to the Egyptian Code of Practice [7], [8]. Concrete compressive strength after 28 days equals 350 kg/cm^2 and the allowable stress equals 100kg/cm^2, while the used reinforcement allowable stress equals 2000kg/cm^2.



b) X-orientation rectangular columns (---)

a) Square columns

c) Reciprocal arrangement X and Y orientation rectangular columns (| - |)

d) Y-orientation rectangular columns (| | |)

Fig. 3. Rectangular floor plan (ratio 2.5) models with different column arrangements and orientations

Table 1. Dimensions and reinforcements of structural elements (Column, Beam, and Slab)

Element	Reinforcement				Dimensions (mm)
	Top (mm)	Bottom		Stirrups /m’	
		straight	bent		
Column	16ϕ18			6ϕ8	550x550
Beam	3ϕ12	4ϕ16	2ϕ16	6ϕ8	250x600
Slab	6ϕ10/m’ in both directions			----	Thickness 120

Square and rectangular columns, beams, and slabs were designed according to the Egyptian code of reinforced concrete [7] and Table 1 shows the dimensions and reinforcements of each designed type of element.

The recorded accelerogram of the El Centro (1940) earthquake, which lasted 40 sec and achieved a peak ground acceleration (PGA) of 0.50g, was selected for the time history analysis of each model in order to study the effect of an earthquake on different building model cases. The buildings were modeled in 3D in the commercial structural analysis and design software SAP2000 V.17 [6].

The dynamic response of a building is affected not only by its stiffness, but also by mass distribution and damping [9-12]. Herein, damping was taken into account in all the numerical analyses, and the assumption of constant damping (5% for all modes) for each numerical model was incorporated in

SAP2000 V.17 [6]. The P-Delta effect was taken into account in all the numerical analyses by SAP2000 V.17 [6].

The objective of this study is to find the effect of stiffness of the different structural elements (column, beam, and slab) in high-rise buildings on their seismic capacity, and also to find the effect of stiffness of rectangular columns when changing their orientation and the rectangularity ratios of the models.

To calculate an approximate value for the first mode time period (fundamental vibration period), the equation : $T = C_t. H^{0.75}$ can be used, where T is the time period of the 1st mode in seconds, H is the building height from foundation level in meters, and C_t is a factor which depends on the structural system (0.085 for steel frames, 0.075 for concrete frames, and 0.05 for other systems), so a rough estimate of the first mode time period of the 12-floor building is: $T = 0.075*(36)^{0.75} = 1.102$ sec.

In this paper, the value of the first mode time period T for each 3-D 12-floor building model was obtained from the SAP2000 V.17 software [6] by performing modal analysis.

3. Results and Discussion

Figure 4 shows the percentage ratios between the different values of stiffness reduction in beams, columns, and slabs, with respect to the control case (full stiffness of all structural members). Reduction of column stiffness by 20% (i.e., 80% column stiffness: C0.8), decreased maximum deformation in the X and Y directions by nearly 5% and acceleration in the X and Y directions by 15%, and the first mode time period increased by 5%. The effect of reducing beam stiffness by 60% (i.e., 40% beam stiffness: b0.4), decreased the displacements in the X and Y directions by 40%. Reducing slab stiffness by 90% (i.e., 10% slab stiffness: S0.1) gave the same effect as reducing columns stiffness by 60%. Reducing the stiffness of columns by 60%, beams by 60%, and slabs by 90% increased displacements in the X and Y directions by 62%.

Figure 5 illustrates the percentage ratios between the control case and the decreasing stiffness of the structural elements in the square floor plan model with square columns. The total base normal force in the columns was almost not affected by reducing the stiffness of different RC structural elements. Reducing column stiffness by 20% reduced the total shear force capacity of the model by 10% in both directions, while reduced the moments by 15%. Reducing column stiffness by 40% reduced the shear capacity of the building by 25% and moment capacity by 33%, but by reducing columns stiffness by 60% the shear and bending capacities decreased 40% and 50%, respectively. Reducing beam stiffness by 60% reduced the shear and bending capacities by 30% and 20%, respectively. Reduction of slab stiffness by 90% reduced the shear and bending capacities by 30% and 20%, respectively. The combination of stiffness reduction between columns and beams (20% columns + 60% beams, 40%

columns + 60% beams, 20% columns + 60% columns + 90% slabs) reduced the shear and bending capacities of the model by 30% and 20%, respectively, but a 60% stiffness reduction in both columns and beams (60% columns + 60% beams) reduced the shear and bending capacities by 42% and 46%, respectively. Base normal force model capacity was almost not affected by the variation of stiffness in the different RC elements.

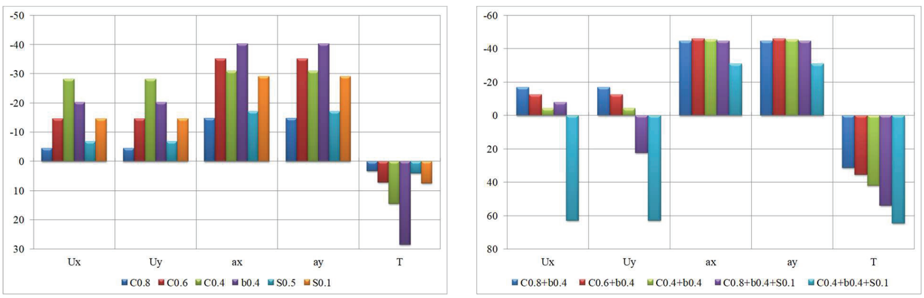


Fig. 4. Percentage ratios of displacement, acceleration, and first mode time period for the square building with square column cross sections

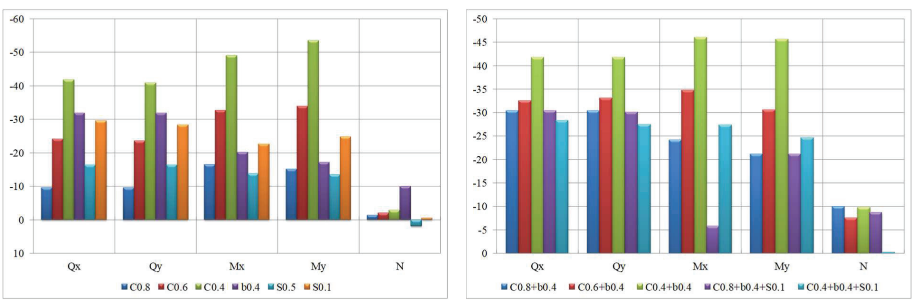
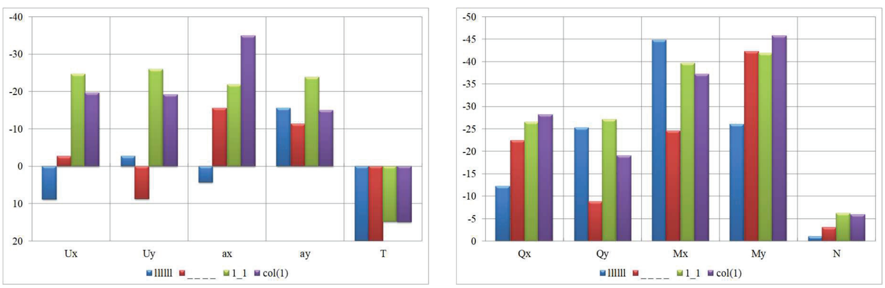


Fig. 5. Percentage ratios of base shear force, base bending moment, and base normal force for the square building with square column cross sections

Figure 6 represents the percentage ratios of top displacement, top acceleration, and time period of the first mode, base shear, base moment, and base normal force of the square building with rectangular columns, with 60% stiffness reduction and with different orientations of rectangular columns. Figure 6(a) illustrates the top displacement and top acceleration, which were reduced by more than 20% with respect to the control case (square model with square cross-section RC columns) for a reciprocal arrangement (1-1) (one column horizontal behind a vertical column orientation of rectangular columns) and the special arrangement of columns (col(1)), but for the Y-direction orientation of columns the displacement and acceleration increased by nearly more than 5% with respect to the control case. Figure 6(b) illustrates the base shear force, base bending moment, and base normal force percentage ratio capacities of the square floor plan model with rectangular columns with different orientations. Base shear capacity decreased by more than 25% for the reciprocal arrangement and by 40% for bending capacity, and normal force was slightly affected by the variation of the orientation of the columns.

Figure 7 shows the percentage ratios between the control and variant cases of column, beam, and slab stiffness for the rectangular floor plan model with square cross-section RC columns. Displacements were reduced by nearly 15% for a 20% column stiffness reduction, while for the combination of column, beam, and slab stiffness reduction by 60%, 60%, and 90%, respectively, the displacement increased by 80%. The time period of the first mode increased by nearly 50% more than that of the control case, for a combination reduction (20% columns + 60% beams + 90% slabs) of stiffness.



a) Percentage ratios of displacement, acceleration and first mode time period

b) Percentage ratios of base shear force, base bending moment and base normal force

Fig. 6. Square building with rectangular column cross sections with a column stiffness reduction of 60%

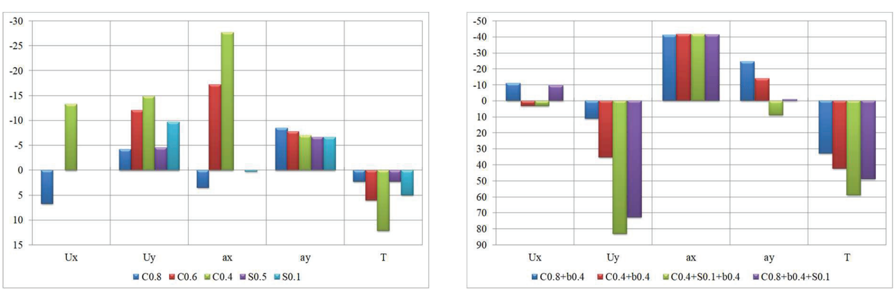
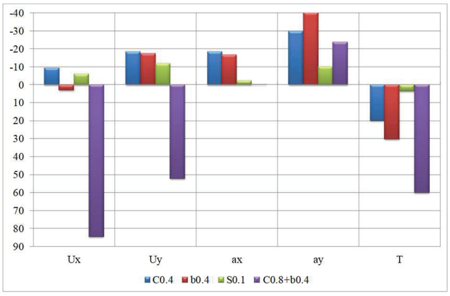
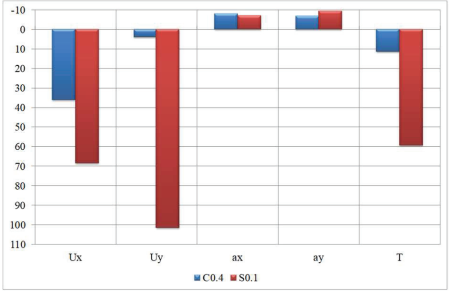


Fig. 7. Percentage ratios of displacement, acceleration, and first mode time period for the rectangular (ratio 2.5) building with square column cross sections

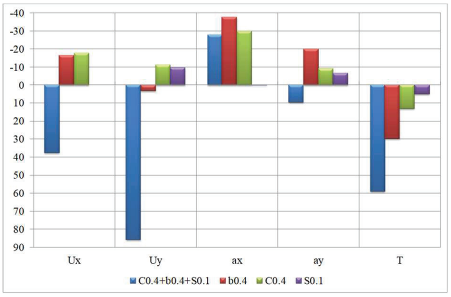
Figure 8(a) shows the displacement, acceleration, and first mode time period of the rectangular floor plan model (rectangularity ratio 2.5) with Y-direction rectangular columns, where for a column stiffness reduction by 60% the top displacement decreased by 20% more than in the control case (rectangular building with square columns), but displacement in the combination case (20% column stiffness + 60% beam stiffness) increased by more than 50%, with respect to the control case. Figure 8(b) represents the X-direction orientation of rectangular columns, where the displacement in the X direction increased by more than 35%, and when slab stiffness decreased by 90%, displacement increased by nearly 70%. Figure 8(c) represents the effect of the reciprocal arrangement of rectangular columns, where the top displacement and top acceleration are not affected significantly, but a combination of a decrease in stiffness (60% columns + 60% beams + 90% slabs) increased top displacement and top acceleration by nearly 60%.



a) Y-direction rectangular columns



b) X-direction rectangular columns



c) Reciprocal arrangement of rectangular columns

Fig. 8. Percentage ratios of displacement, acceleration, and first mode time period for the rectangular (ratio 2.5) building with rectangular column cross sections

Figure 9 shows the effect of stiffness reduction for different model elements; 20% column stiffness reduction does not have a significant effect on shear and bending capacities of the model, reducing the stiffness of the columns by 40% decreased the base shear and bending of the model by more than

15% and 30%, respectively, and reducing column stiffness by 60% decreased the shear and bending capacities by more than 30% and 40%, respectively. Decreasing slab stiffness by 90% almost does not affect the model shear and bending capacities. The combination of reduced column and beam stiffness (each 60%) reduced the shear and bending capacities by more than 45%.

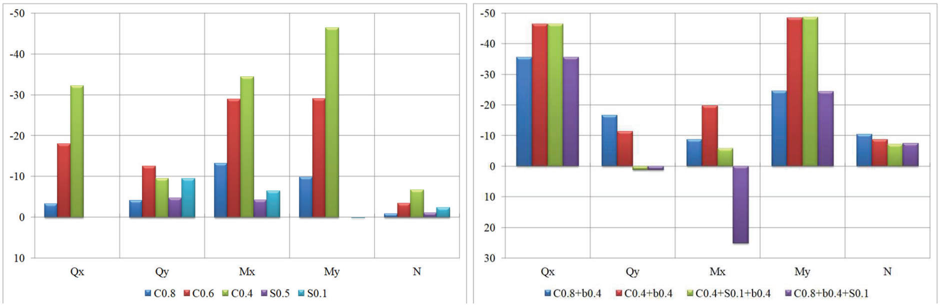
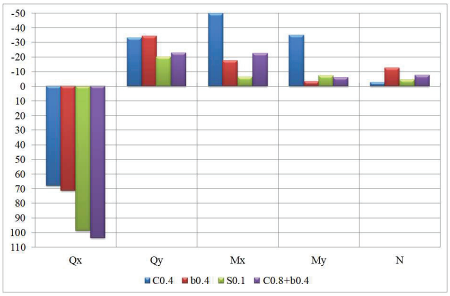
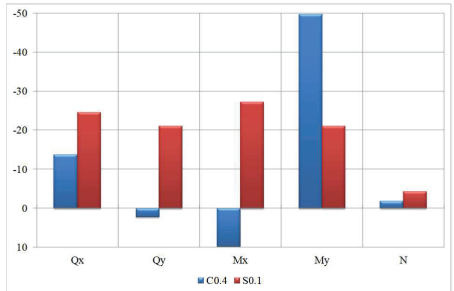


Fig. 9. Percentage ratios of base shear force, base bending moment, and base normal force for the rectangular building (ratio 2.5) with square column cross sections

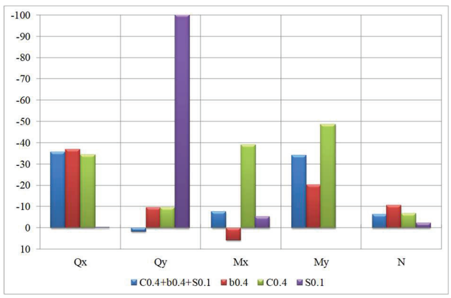
Figure 10 represents the percentage ratios of straining actions of the rectangular floor plan model (rectangularity ratio 2.5). Figure 10(a) shows base shear, bending, and normal capacities of the rectangular floor plan with Y-direction rectangular columns, where base shear capacity increased by more than 70% in the X-direction for a stiffness reduction of columns, beams, and slabs (60%, 60%, 90%), and stiffness reduction in a combination of columns and beams, by 20%+60% respectively, but in the Y-direction shear capacity reduced by more than 30%. Figure 10(b) shows the straining actions of columns, beams, and slabs for the X-direction orientation of rectangular columns, where base shear and bending capacities decreased by more than 10% and 20% for columns stiffness reduction by 60%, and slab stiffness reduction to 10%, respectively. In the X-direction of the columns, the capacity of base shear in the Y-direction increased. Figure 10(c) shows a reciprocal arrangement of rectangular columns in the rectangular floor plan model, where reduction of slab stiffness to 10% reduced the shear capacity in the Y-direction by 100%, with respect to the control case. Normal force capacity for all cases was almost not affected by the variation (reduction) of the stiffness of different RC elements.



a) Y-direction rectangular columns



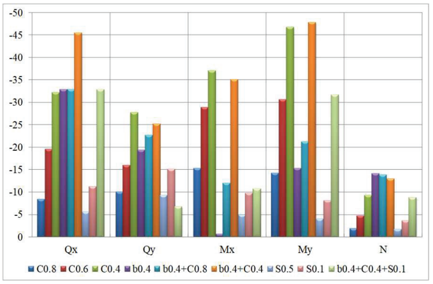
b) X-direction rectangular columns



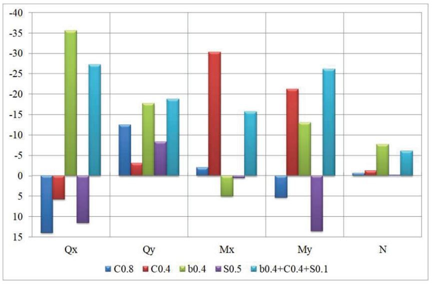
c) Reciprocal arrangement of rectangular columns

Fig. 10. Percentage ratios of base shear force, base bending moment, and base normal force for the rectangular (ratio 2.5) building with rectangular column cross sections

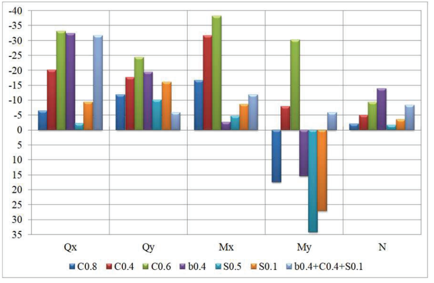
Figure 11 shows the effect of the reduction of stiffness of different structural elements on the straining actions with a rectangularity ratio of 1.5. Figure 11(a) shows that a reduction of column stiffness by 20% decreased the shear capacity by nearly 7% and the bending moment by nearly 15%. The effect of horizontal rectangular columns (in the direction of the rectangularity of the structure) is shown in Figure 11(b), where the shear capacity in the X-direction increased due to the inverse direction of the columns to the direction of the earthquake wave. Reduction of beam stiffness by 60% decreased shear capacity by nearly 35% and 17% in the X- and Y-directions, respectively. A slab stiffness reduction to 10% is not significant in the response of the rectangular floor plan model - as shown in Figure 11(c) - for reciprocal distribution of rectangular columns. The combination of a stiffness reduction of the columns, beams, and slabs has the most impact on the lack of the model's capacities in both shear forces and bending moments, but normal force capacity for all cases is almost not affected by a reduction in column, beam, and slab stiffness.



a) Square columns



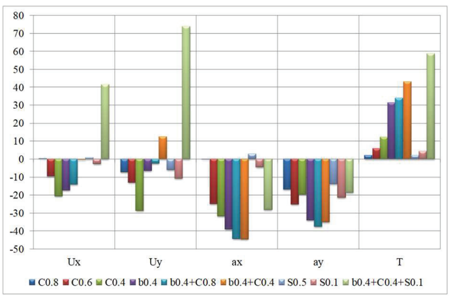
b) Rectangular X-direction columns



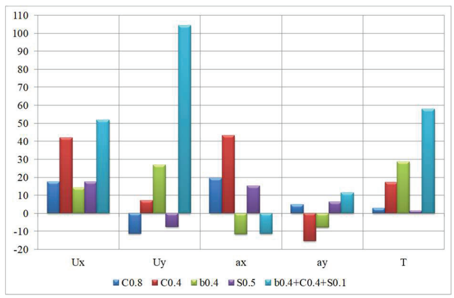
c) Reciprocal arrangement of rectangular columns

Fig. 11. Percentage ratios of base shear force, base bending moment, and base normal force for the rectangular (ratio 1.5) building

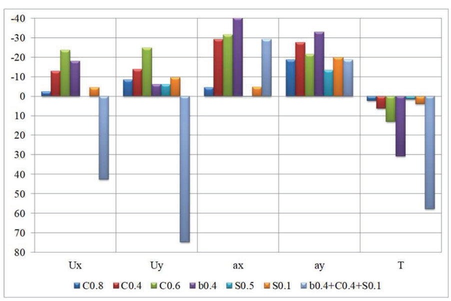
Figure 12 shows the seismic response of the rectangular building model (rectangularity ratio 1.5). Figure 12(a) shows the rectangular building with square columns, where nearly no trend is obvious in the displacements in the X- and Y-directions with respect to the control case, but displacements increased by 70% and 40% in the Y- and X-directions, respectively, in the case of a decrease in column stiffness by 60% from full column stiffness. The accelerations in the X- and Y-directions for almost all studied cases decreased with a maximum reduction of about 40% when compared to the control case. The first mode time period increased with a reduction in the stiffness of the structural elements, especially in the combination of stiffness reduction of the beams, columns, and slabs by 60%, 60%, and 90% respectively. Figure 12(b) shows the seismic response of the rectangular building with an X-direction of the rectangular columns. The displacements in the X- and Y-directions increased for almost all cases, especially in the case of a combination stiffness reduction of the beams, columns, and slabs by 60%, 60%, and 90%, respectively, then, the next effective case is the stiffness reduction of columns by 60%, and, finally, the first mode time period increased in all cases, especially in the combination-reduction case. Figure 12(c) represents the high-rise building with a rectangular floor plan and a reciprocal arrangement of rectangular columns (see Figure 2(c)), where displacements and accelerations in the X- and Y-directions decreased, especially when column stiffness decreased by 60% comparing to the original full column stiffness, but the displacements in X- and Y-directions increased by nearly 43% and 75% in the case of a combination stiffness reduction of beams, columns, and slabs by 60%, 60%, and 90%, respectively. The first mode time period increased, especially in this combination-reduction case, by nearly 60%.



a) Square columns



b) Rectangular X-direction columns



c) Reciprocal arrangement of rectangular columns

Fig. 12. Percentage ratios of top displacements, top accelerations, and first mode time period for the rectangular (ratio 1.5) building

4. Conclusions

The present study aims to show the effects of the stiffness of different structural elements (columns, beams, and slabs) of an H.R.B., and the impact of floor plan shape (square or rectangular) and column cross sections (square or rectangular) on the capacity of its earthquake resistance (shear forces, bending moments, and normal forces). The control models for both square and rectangular floor plan models were those with square cross-section columns, and the various models presented herein were analyzed to investigate their performance under seismic loads. From the present study it can be concluded that:

- For H.R.B.s subjected to earthquakes, columns, beams, and slabs participate in the overall stiffness of the structure in varying percentages.
- Column stiffness is a more influential factor (over beam and slab stiffness) on the straining actions of an H.R.B. The minimum stiffness values of columns are no less than 40% of the original column stiffness values, which decrease the shear and moment capacities of the building by about 25% and 33%, respectively, for the square floor plan and square columns cross sections, so from the point of view of retrofitting and strengthening high-rise buildings it will be useless to retrofit or strengthen the building if the stiffness of its columns is less than 40%, in spite of the high stiffness of its beams and slabs.
- The stiffness of the beams indemnifies the reduction of slab stiffness and vice versa; this is noticeable in the reduction of shear and moment capacities when beam and slab stiffness are reduced together.
- For the square floor plan building, when the stiffness of the columns decreased by 60%, in a special (col(1)) arrangement and a reciprocal arrangement of the rectangular columns, the displacements decreased by about 20% and 25%, respectively, and the shear and bending capacities decreased by about 25% and 40%, respectively.
- In the case of the rectangular floor plan, the most influential stiffness contributions were those of the columns and beams. For the H.R.B. with a high rectangularity floor plan ratio, the shear and moment capacities increased in the long direction (compared to the short direction) of the building by different ratios in spite of the stiffness reductions of the structural elements of the building. Accelerations also increased in the long direction. The shear capacities in the long X-direction increased by nearly 2.3 times the corresponding values in the short Y-direction. The short direction was most affected by the lack of stiffness of the structural elements.
- The most resistant floor plan of the H.R.B. was the square floor plan and the square cross-section columns for bidirectional earthquake forces, where the straining actions were equal in both directions.
- The shear capacity of the H.R.B. with a square floor plan and square column cross sections decreased by about 20% when column cross sections changed from square to rectangular (for reciprocal and special column arrangements) in the case of a 60% column stiffness reduction (i.e., 40% column stiffness), but the direction of rectangularity of the columns in the square floor

plan building changed the shear and moment capacities (i.e., increased capacities in the direction of the columns' length, and vice versa).

- If the rectangularity ratio of the building is high, the effect of the direction of the rectangular columns is larger.
- When the column stiffness is higher, the natural period of the building is low.
- There is evidence supporting the effects of the stiffness of beams and columns in the overall RC H.R.B. stiffness and its retrofit technique decisions.

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Fig. 11. Percentage ratios of base shear force, base bending moment and base normal force for rectangular (ratio 1.5) building

Rys. 11. Stosunki procentowe podstawowej siły ścinającej, podstawowego momentu zginającego oraz podstawowej standardowej siły dla prostokątnego budynku (stosunek 1,5)

Fig. 12. Percentage ratios of top displacements, top accelerations and first mode time period for rectangular (ratio 1.5) building

Rys. 12. Stosunki procentowe górnych przesunięć, górnych przyspieszeń oraz okresu pierwszego trybu dla prostokątnego budynku (stosunek 1,5)

Table 1. Dimensions and reinforcements of structural elements (Column, Beam and Slab)

Tabela 1. Wymiary i wzmocnienia elementów konstrukcyjnych (Słupy, Belki i Płyty)

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WPŁYW SZTYWNOŚCI ELEMENTÓW KONSTRUKCYJNYCH NA REAKCJĘ SEJSMICZNĄ WIEŻOWCÓW Z ŻELBETU

Słowa kluczowe: Elementy konstrukcyjne, żelbet (RC), sztywność, reakcja sejsmiczna, wieżowce.

STRESZCZENIE:

Aby zbadać, jaki procent każdego rodzaju elementów (słupów, belek i płyt) wpływa na ogólną sztywność i wydajność wieżowców (H.R.B.) pod obciążeniem sejsmicznym, sztywność każdego elementu jest zmniejszana o 10% do 90%. Analiza historyczna przeprowadzona przez SAP2000 obejmowała trzynaście modeli 3D 12-piętrowych wieżowców w celu zobrazowania wpływu sztywności i przekrojów słupa (prostokątnego lub kwadratowego), planu pięter budynku (kwadratowego lub prostokątnego), sztywności belki oraz sztywności płyty, na odporność budynku na trzęsienie ziemi. Sztywność słupa miała większy wpływ niż sztywność belki i płyty na odporność wieżowca na trzęsienie ziemi.
Z niniejszego badania można wywnioskować, że:

- Sztywność słupa jest bardziej efektywnym czynnikiem wpływającym na przeciążenie wieżowca niż sztywność belki i płyty. Minimalne wartości sztywności słupów są nie mniejsze niż 40% pierwotnych wartości sztywności słupów, co zmniejsza nośność na siły ścinające budynku o około 25% i 33%, odpowiednio dla kwadratowych przekrojów pięter i słupów, a zatem z punktu widzenia modernizacji i wzmocnienia wieżowców, bezużyteczne będzie zmodernizowanie lub wzmocnienie budynku, jeśli sztywność słupów jest mniejsza niż 40%, pomimo dużej sztywności belek i płyt. Jeśli sztywność słupa jest większa, standardowy okres przydatności budynku jest krótki.
- Sztywność belek zabezpiecza przed zmniejszeniem sztywności płyt i na odwrót, takie zjawisko występuje podczas zmniejszania nośności na siły ścinające, gdy sztywność belek i płyt jest jednocześnie zmniejszana.
- W przypadku prostokątnego planu pięter, najskuteczniejszą sztywnością była sztywność słupów i belek. W przypadku wieżowca o wysokim współczynniku prostokątności, nośność na siły ścinające została znacznie zwiększona (w porównaniu do nieznacznego zwiększenia) w budynku z wykorzystaniem różnych współczynników, pomimo zmniejszenia sztywności elementów konstrukcyjnych budynku. Również przyspieszenia zostały znacznie zwiększone. Nośność na siły ścinające przy znacznym zwiększeniu wzrosła prawie 2,3 razy w stosunku do odpowiednich wartości przy nieznacznym zwiększeniu. Nieznaczne zwiększenie charakteryzowało się brakiem sztywności elementów konstrukcyjnych.
- Najbardziej odpornym planem pięter w wieżowcu był kwadratowy plan pięter i kwadratowe słupy o przekroju poprzecznym dla dwukierunkowych sił trzęsień ziemi, gdzie przeciążenie było równe przy obu zwiększeniach.
- Nośność na siły ścinające wieżowca z kwadratowym planem pięter i kwadratowymi słupami o przekroju poprzecznym zmniejszyła się o około 20%, gdy przekroje poprzeczne słupów zmieniły się z kwadratowych na prostokątne (w odniesieniu do wzajemnych i specjalnych układów słupów) w przypadku 60% zmniejszenia sztywności słupa (tj. 40% sztywności słupa), lecz kierunek prostokątności słupów w budynku z kwadratowym planem pięter zmienił nośność na siły ścinające (tj. zwiększył ją w kierunku długości słupów i odwrotnie).
- Słupy o prostokątnym przekroju muszą być odpowiednio ustawione, aby otrzymać wieżowiec i smukłe budynki w celu osiągnięcia maksymalnej odporności na trzęsienie ziemi.
- Jeśli współczynnik prostokątności budynku jest duży, wówczas wpływ kierunku prostokątnych słupów jest wysoki.
- Istnieją dowody na wpływ sztywności belek i słupów na ogólną sztywność zbrojonego wieżowca oraz decyzje dotyczące technik modernizacji.