Research Article Open Access

Seismic Response of Buildings with Soft Story

S ElRefaie[1] and M Saif[2]

[1]Civil Engineering Department, Faculty of Engineering and Islamic Architecture, Umm Al-Qura University, Saudi Arabia
[2]Civil Engineering Department, Faculty of Engineering and Islamic Architecture, Umm Al-Qura University, Saudi Arabia

***Corresponding author:** Dr. ElRefaie, Associate Professor, Civil Engineering Department, Faculty of Engineering and Islamic Architecture, Umm Al-Qura University, Saudi Arabia, E-mail: sarefaie@uqu.edu.sa*

Citation: ElRefaie S and Saif M (2020) Seismic Response of Buildings with Soft Story, J Civil Engg ID 1(1): 25-33.
https://doi.org/10.47890/JCEID/2020/SElRefaie/12045783

Received Date: May 05, 2020; **Accepted Date:** May 16, 2020; **Published Date:** May 20, 2020

Abstract

Extending lifts` reinforced concrete cores to foundations usually restricts services and lobby functions of a building. A core supported on columns at core`s corners is considered a good alternative for sorting out this problem. However, this will cause an abrupt reduction in the lateral stiffness of the building below the cores level i.e. soft story vertical irregularity. Hence, large lateral displacement of the building is expected causing its instability and potentially results in its collapse. No caution at seismic response parameters (for instance, lateral story drift ratio) is found in the current codes for buildings having soft stories. The ratio between the lateral stiffness of a given story and that of a story / three stories above is the only parameter found in current codes, for example UBC and ASCE7 codes, to identify a soft story criterion. In this paper, the seismic response of a building due to change in the level at which the central core is planted and the distribution of the columns supporting it is investigated. Partial support of reinforced concrete cores via underneath columns is found to be an effective means of enhancing the lateral stiffness of the building and reducing its lateral side sway. This effect is extremely dependent on the level of the soft story i.e. the level at which the cores are planted. The phenomena of the UBC and ASCE7 codes for identifying the soft story in a building needs to be revised.

Keywords: Soft Story; Seismic Loads; Vertical Irregularity; Drift Ratio; Concrete; Cores

Introduction

Reinforced concrete high-rise buildings become popular in many countries such as USA, Dubai, and China [1, 2]. When open areas are needed, such as in parking, malls and reception areas, the reinforced concrete cores and shear walls, are stopped from continuity through these areas and are planted on columns, beams or transfer slabs [3, 4]. This abrupt change in the lateral stiffness from a story with high stiffness shear walls to a story with low stiffness columns, results in weak and soft story problems [5-7]. Having a soft story in a building changes the lateral load distribution mechanism and thus may induce changes in phenomena like lateral displacement and inter-story drift ratio. A static pushover analysis is utilized by others [8, 9] to determine the performance of the building under different irregularity conditions.

As far as the authors are aware, there are no specific provisions for limiting structure response parameters such as lateral stiffness, drift ratio and lateral displacement of buildings having soft stories and subjected to seismic loading. In this research, 3D analysis of buildings with reinforced concrete cores directly supported over columns at cores` corners was carried out. General purpose finite element software program, namely ETABS [10] has been employed to study the behaviour of a reinforced concrete building with a soft story at different floor levels and with variation in the supporting columns locations.

Building Description

Geometry

The building under consideration is a 10 floors administration building. The building includes central two cores and square columns as vertical elements. In order to obtain different levels at which soft story exists, the following cases are considered:

Case no. 1: a building includes columns only i.e. no cores (Figure 1-a);

Case no. 2: a building with discontinued cores at the level of the first floor and supported by four columns at the corners of the cores as depicted in Figure 1-b;

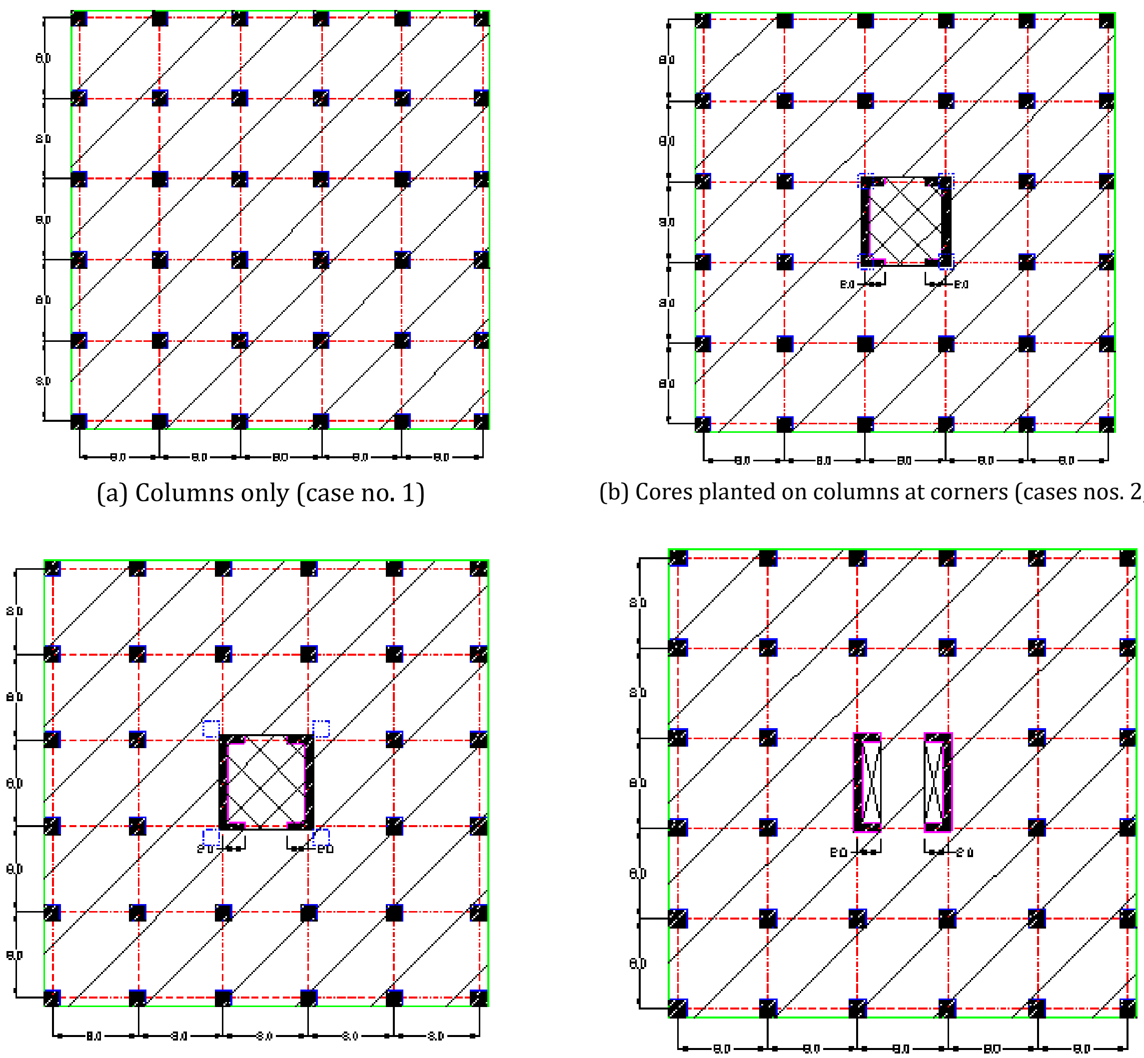
Case no. 3: a building with discontinuous cores at the level of the second floor. Four columns are extended underneath the four corners of the core (see Figure 1-b);

Case no. 4: same as cases number 1 and 2 but the cores are discontinued at the level of the third floor as illustrated in Figure 1-b;

Case no. 5: similar to case number 1 but the columns underneath the cores` corners are shifted out 1m from the cores corners as can be seen from Figure 1-c; and

Case no. 6: the cores are extended down till the foundation level as shown in Figure 1-d.

The building is deliberately kept symmetric in X and Y-directions in order to avoid torsional effects. Furthermore, all columns of the building are square to keep the discussion focused only on the soft story effect, without being distracted by the issues like orientation of columns. Typical span is 8.0m in X and Y-directions and typical floor height is 3.5m. The slab is a traditional reinforced concrete flat slab with a 280 mm thickness. All columns are typical in cross-section with 600x600mm cross-section dimensions. The thickness of the wall of the central cores is 800mm throughout the height of the cores with cross-section dimensions as shown in Figure 1. All flexural modifiers are adopted for slabs, columns and cores according to ACI318 standard code of practice [11].



(a) Columns only (case no. 1)

(b) Cores planted on columns at corners (cases nos. 2, 3 and 4)

(c) Cores planted on columns shifted from corners (case no. 5)

(d) Cores extended to the foundation (case no. 6)

Figure 1: Building geometry

Material Properties

The concrete cylinder compressive strength considered in this study is 50 N/mm2. The concrete is a normal weight concrete with a density of 25kN/m3. The Young`s modulus of the concrete is 4700√f'c [11]. The yield strength of the steel reinforcement is 420N/mm2.

Gravity and Seismic Loads

Apart from a building self-weight, the gravity loads considered in this research are: the floor cover load of 2.0 kN/m^2, walls load of 3.5 kN/m2 and live load of 2.5kN/m2. The UBC code provisions [6] are considered in this research. The specified building is in seismic zone 2A with a standard occupancy category number 4. Hence, both static and dynamic lateral force procedures can be adopted for either regular or irregular structures (see Section 1629.8.3 and Item 2 in Section 1629.8.4 in the UBC code [6]. In this research, only static force procedure is adopted in both X and Y-directions. The soil is a soft rock with SC soil profile. Building importance factor, I, Seismic coefficients, Ca and Cv, seismic zone factor, z, and the seismic coefficient Ct are considered, 1.0, 0.18, 0.25, 0.15 and 0.02, respectively. The over strength factor, R, equals to 5.5 as the lateral resistant system considered for the specified building is a building frame system with reinforced concrete shear walls. Mass of the dead load (self-weight, floor cover and walls loads) is the only mass utilized for seismic loading. A damping ratio of 0.05 is adopted.

Soft Story

A soft story is defined in the UBC code [6] as that story with lateral stiffness less than 70 per cent of that of the story above or less than 80 per cent of the average stiffness of the three stories above. As the lateral stiffness of a story is function of the moments of inertias of the vertical elements of that story, it may be expected that comparing the moments of inertias of the vertical elements of two subsequent stories can be used for identifying a soft story. This is unfortunately incorrect as going to be approved in this paper. For the proposed building, the moments of inertias of the columns which the only vertical elements found at the expected soft story (cases from 2-5 as depicted in Figure 1) is 2419.6 m4 either in X or Y-directions as the columns are squares. Above the soft story, where the cores appeared, the moments of inertias for both the cores and columns together is 2569.6 m4 and 2663.8 m4 in X and Y-directions, respectively. Hence, the ratio between the moments of inertias of the columns of the expected soft story to that of the cores and columns of the story above is 94% and 91% in X and Y-directions, respectively. This is of course is not satisfying the UBC code limit for identifying the soft story as mentioned above. Therefore, simple calculations cannot be implemented to capture the soft story and a more rigorous analysis should be carried out. A nonlinear finite element program, namely ETABS [10] is employed for studying the seismic performance of buildings with soft stories.

Figures 2 and 3 give the relationship between the story stiffness ratio (the stiffness of a lower floor / stiffness of the subsequent upper floor) and the story number in X and Y-directions, respectively. As the stiffness ratio is defined as the ratio between the stiffness's of two subsequent floors, its value plotted in Figures 2 and 3 is at the number of the upper floor. For instance, the stiffness ratio between first and second floors is plotted at the second floor i.e. story number 2 as shown in Figures 2 and 3.

In X-direction, for all buildings with discontinuous cores i.e. cases from 2 to 5, Figure 2 illustrates that the soft story criterion that is the stiffness ratio, defined above, is less than 70% [6] is not valid. Conversely, in Y-direction, the soft story criterion is satisfied for the story just below the discontinued cores as depicted in Figure 3. For example, in case no. 3, the second story is found to satisfy the soft story criterion when the cores are planted over the columns of the second story (see Figure 3). Expectedly, shifting the columns supporting the cores 1.0m out from the cores` corners causes more severe building vertical irregularity compared with planting the cores over the columns at cores corners. However, identifying the existence of a soft story in the building of case no. 5, using the criteria of the UBC [6], is not valid (Figures 2 and 3). Therefore, the phenomena of the UBC [6] and ASCE7 [7] codes for identifying the soft story in a building needs to be revised.

From the above check of existence of a soft story, it can be confirmed that wherever the greater moments of inertias of the cores are discontinued in a direction, a soft story can be expected in that direction (as in Y-direction in the specified building). Therefore, in the subsequent sections, the influence of the core's discontinuity on structure response parameters such as maximum story displacement, story stiffness, story drift ratio is studied.

Maximum Story Displacement

Figures 4 and 5 give the maximum lateral story displacement for cases 1 to 6 reported above against the story number in the X and Y-directions, respectively. Figures 4 and 5 show that the building without cores as in case no. 1 (with columns only), has the largest story lateral displacement compared to the other buildings with continuous or discontinuous cores. On the other hand, the building with continuous cores to the foundation as in case no. 6 yielded the least lateral story displacement. Of course, the buildings with cores planted are not as stiff as the building with cores extended to the foundation. In Y-direction, where the moments of inertias of the cores are high, the influence of the core's continuity on the lateral story displacement is significant for stories just below the discontinuation level of the cores as illustrated in Figure 5. When the cores are planted over columns (see cases from 2 to 4), the lateral story displacement is less than the corresponding displacement of the building without cores (see case no. 1). Furthermore, raising the level at which the cores are planted as in cases from 2 to 4 resulted in an increase in the lateral story displacement as depicted in Figures 4 and 5. Moreover, shifting the columns supporting the planted cores at first floor as in case no. 5 caused larger lateral displacements compared to the corresponding displacements obtained from case no. 2 where the columns were exactly at the corners of the cores.

Table 1 gives the maximum lateral story displacement for the first and the 10th stories under static earthquake loads in X and Y-directions. Although the ratio of the moment of inertia of the cores relative to the total moment of inertia of the cores and columns in a specified story is less than 7% (= 173.1 / 2569.6) in X-direction and less than 9% (= 221.1168 / 2663.8) in Y-direction,

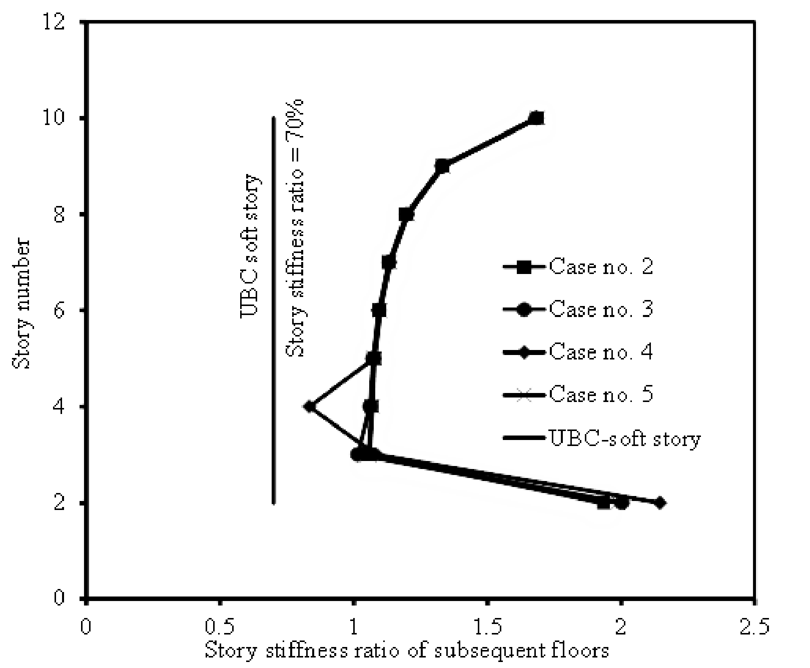


Figure 2: Story stiffness ratio of subsequent floors in X-direction

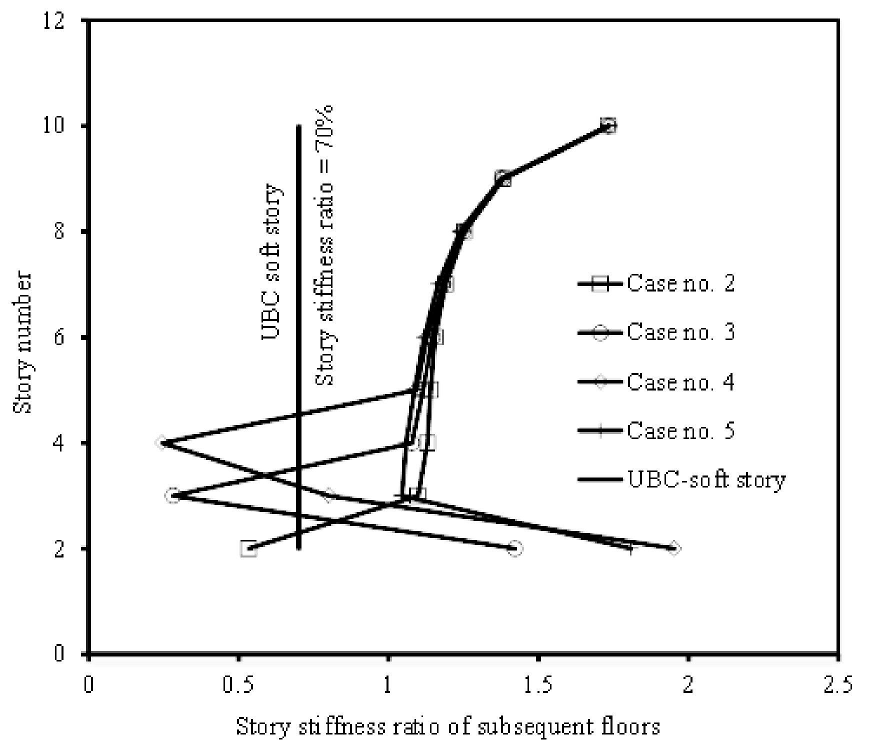


Figure 3: Story stiffness ratio of subsequent floors in Y-direction

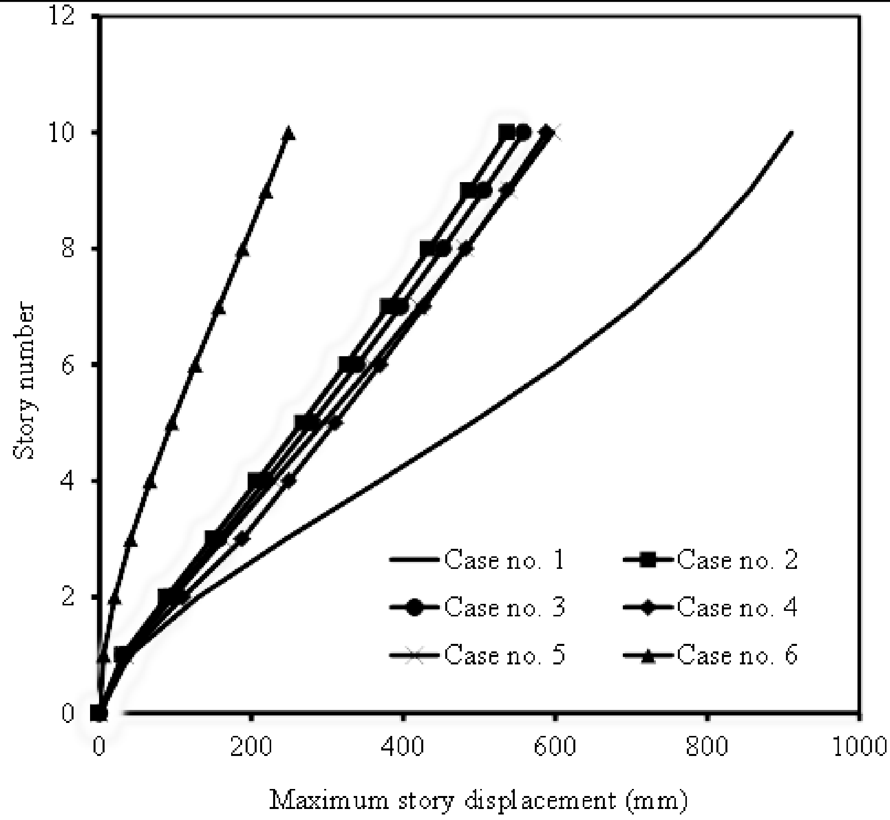


Figure 4: Maximum story displacement in X-direction

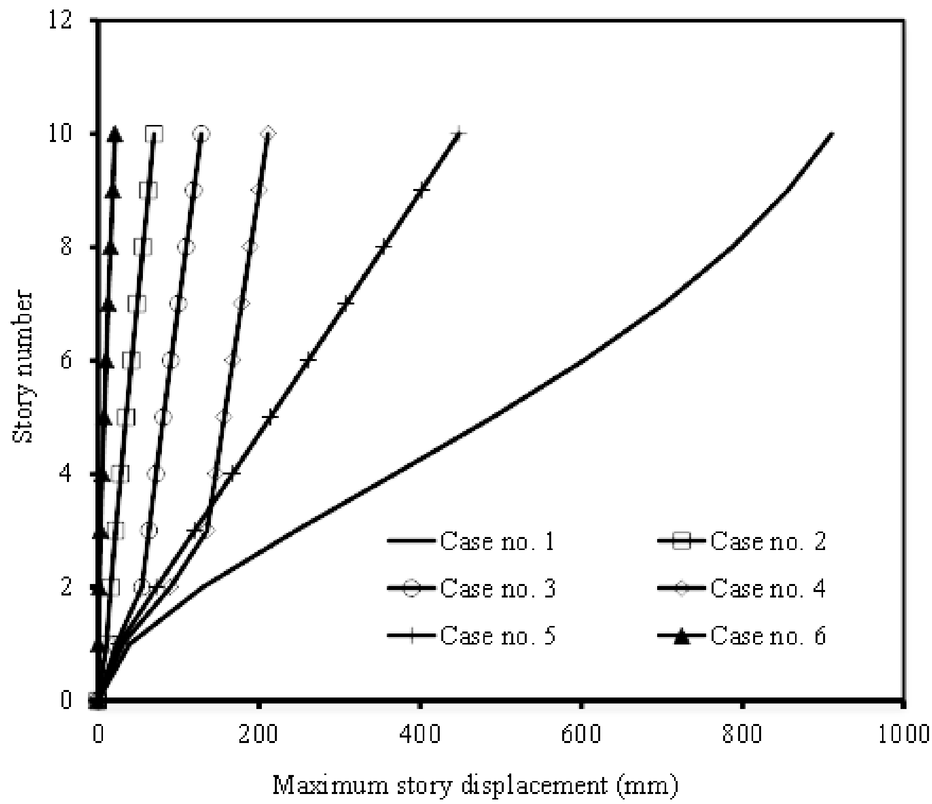


Figure 5: Story displacement in Y-direction

Table 1: Influence of core continuity on the maximum story displacement

Case no.	Core status	Maximum story displacement (mm) in x and y-directions			
		1st story		10th story	
		x	y	x	y
1	Columns only (without cores)	39.4	39.4	910.7	911.1
2	Cores planted on the 1st floor	30.4	10.5	536.6	69.7
3	Cores planted on the 2nd floor	32.0	22.8	557.8	128.4
4	Cores planted on the 3rd floor	35.3	30.7	587.7	211.2
5	Cores planted on shifted columns	33.0	26.3	596.4	448
6	Cores extended to foundation	11.2	1.1	272.5	23.8

the cores have great influence on the lateral story displacement. This can be noticed from Table 1, where the lateral displacements in X-direction of the 1st and 10th stories in case no. 6 (the case with cores extended to foundation) reduced dramatically to less than one third of those in case no. 1, (the case without cores, i.e. columns only).

In Y-direction, where the cores have great moment of inertia, the level at which the cores are discontinued highly affects the maximum story displacement as can be noticed in Table 1. Shifting the columns that support the cores` corners 1m out, as in case no. 5, lead to a dramatic increase in the lateral story displacement of the 10th story in Y-direction as shown in Table 1. Hence, it can be concluded that shifting the supporting columns out of the cores` corners as in case no. 5, has greater influence on the story lateral displacement than the cases at which the cores were discontinued at different levels as in cases 2 to 4.

Story Stiffness

Table 2 presents the stiffness ratio of 1st, 2nd, 3rd and 10th stories that is the ratio between the story stiffness in cases nos. 2 to 5 to the corresponding story stiffness in case no. 5. The least loss in story stiffness due to the discontinuity of the cores appears in case no. 2 in X-direction for the 10th story where the stiffness ratio reaches about 60% as can be seen in Table 2. The story stiffness ratio decreases as the level at which the cores is discontinued increases as can be seen for cases 2-4 in Table 2. It can also be noticed from Table 2 that the stiffness ratio in Y-direction is smaller than that in X-direction. This is attributed to the great moment of inertia of the cores and hence its great contribution towards the building stiffness in Y-direction compared with that in X-direction. Therefore, discontinuity of the cores has more influence on the building stiffness in Y-direction than its influence on the building stiffness in X-direction (see Table2). Furthermore, the discontinuity

Table 2: Influence of core continuity on the story stiffness

Story no.	%Stiffness ratio +									
	X-direction					Y-direction				
	1	2	3	4	5	1	2	3	4	5
1st story	13.92	19.21	18.17	16.38	17.74	1.44	5.74	2.63	1.94	2.30
2nd story	12.38	20.76	18.92	15.93	18.61	1.05	18.50	3.18	1.71	2.18
3rd story	15.79	32.95	31.3	24.66	29.65	1.25	26.40	17.70	3.35	3.28
10th story	54.05	60.53	58.68	58.62	53.98	4.86	40.00	29.40	25.3	5.97

of the cores has more influence on the stiffness ratio of low-level stories as illustrated in Table 2. Shifting the supporting columns for the cores by slightly distance resulted in a significant reduction in the story stiffness ratio throughout all floors of the building (see case 5 in Table 2).

Figures 6 and 7 show the story stiffness for all cases studied 2-5 (see Table 2) throughout the whole building height. Case number 1, that is columns only without cores, is not shown in Figures 6 and 7 as its story stiffness ratio values are negligible compared with those of cases 2-5. The story stiffness decreases when approaching higher stories levels (Figures 6 and 7). The lateral stiffness in X-direction where the cores have small moment of inertia is slightly affected by the status of the core's continuity (Figure 6).

Conversely, the lateral stiffness of the building in Y-direction with great inertia of the cores is significantly affected by the level at which the cores are planted and the location of the supporting columns of the cores as can be seen from Figure 7. In a building with discontinuous cores, for instance, case no. 3 with cores planted over story number 2, the lateral stiffness of story number 3 where cores

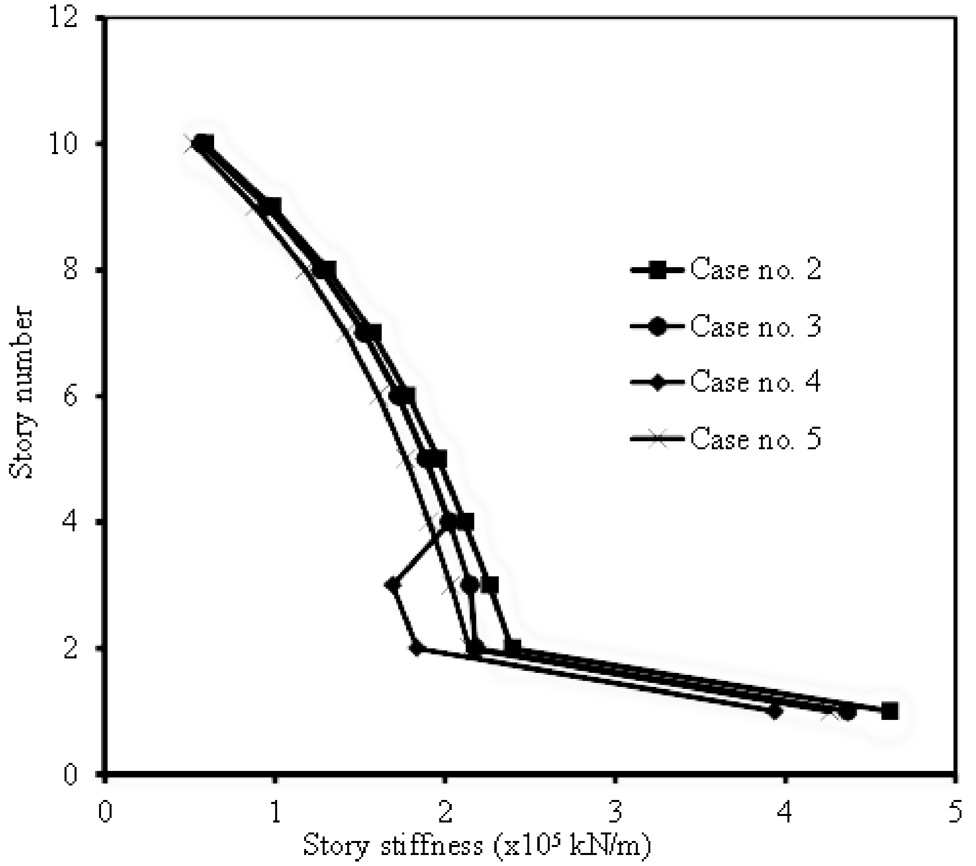


Figure 6: Story stiffness in X-direction

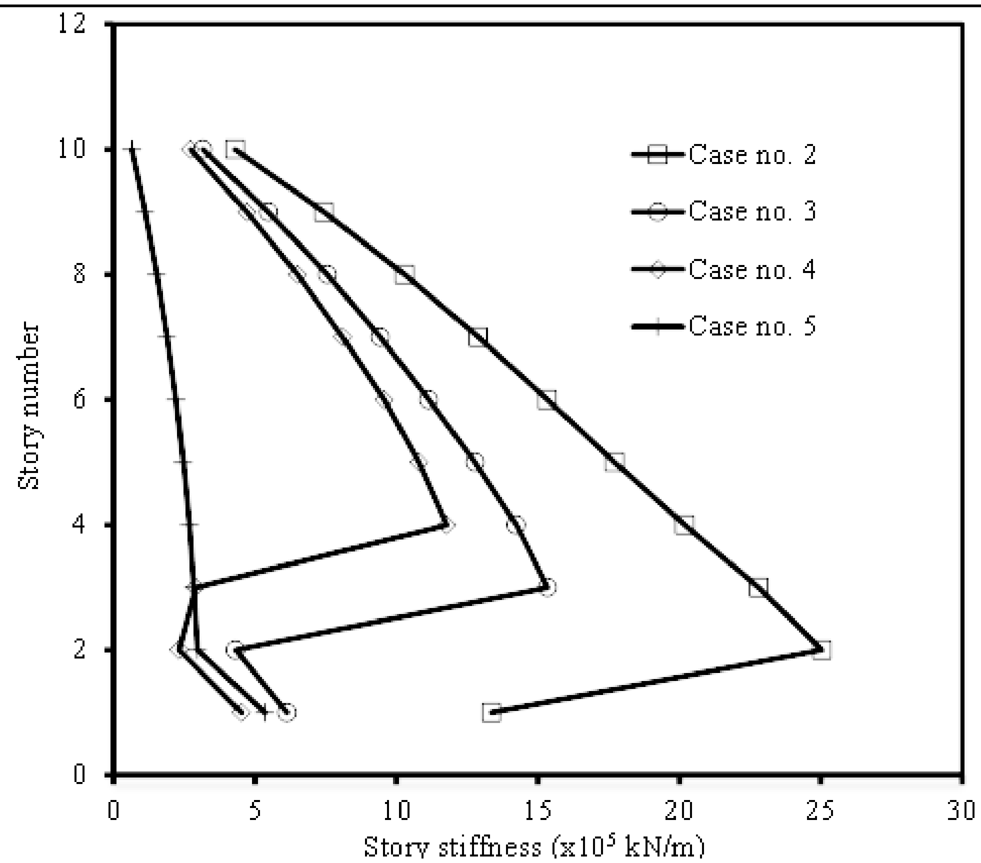


Figure 7: Story stiffness in Y-direction

are found, is greater than that of story number 2 where columns only are found (Figure 7). Shifting the columns supporting the cores` corners, case no. 5, leads to weak building lateral stiffness compared with that when the cores are directly supported on cores corners as depicted from Figure 7.

Drift Ratio

Story drift ratio is the story drift divided by the story height. Figures 8 and 9 show the inelastic story drift ratio in X and Y-directions, respectively. The limit of the story drift ratio assigned in the UBC code is 0.02 and is plotted in Figures 8 and 9. Of course, continuing the cores to the foundation level (case no. 6) resulted in the least story drift ratio. The influence of the level at which the cores are planted on the maximum story drift ratio is insignificant in X-direction as a result of the small moment of inertia of the cores (Figure 8). The story drift ratios for different cases (cases 2-5) become close from each other when approaching roof floor. In case no. 1 where columns only are found in the building, the maximum story drift ratio is located at the building mid-height, whereas it appears at the discontinuation level of the cores for cases 2-5 (Figures 8 and 9). Similar result was obtained by other researchers [12]. Above the cores discontinuation level, the story drift ratio decreases for one floor and then it becomes unchanged up to

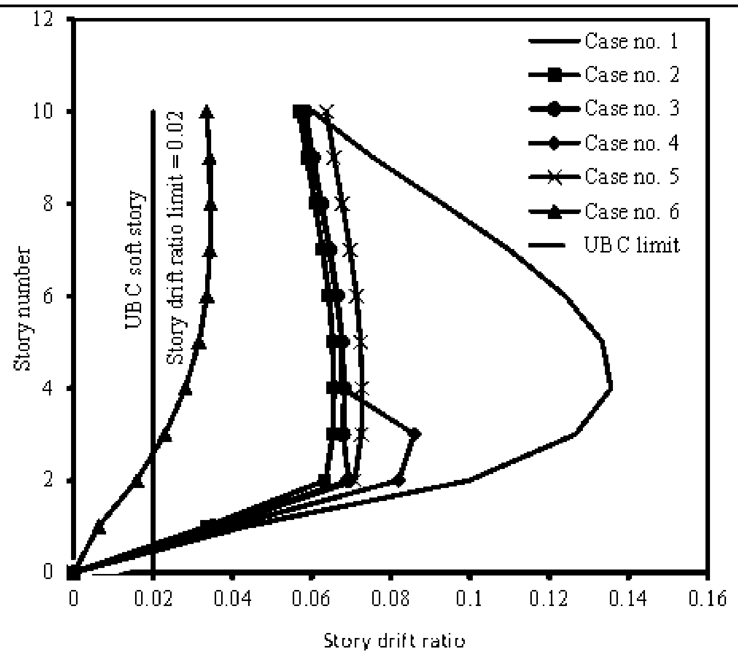


Figure 8: Story inelastic drift ratio in X-direction

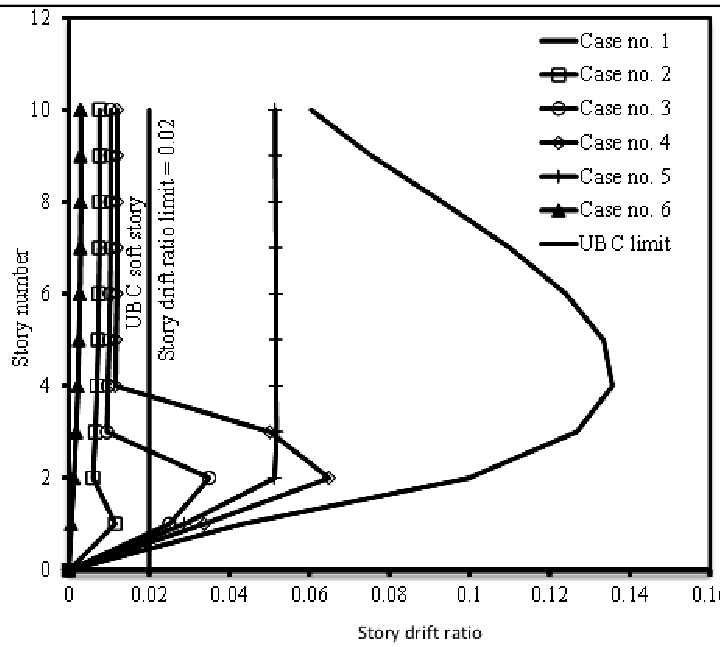


Figure 9: Story inelastic drift ratio in Y-direction

the roof floor level (Figures 8 and 9). Figure 8 illustrates that the story drift ratio limit specified in the UBC code, 0.02, is violated in X-direction although the building has continuous cores. Conversely, the maximum story drift ratio in Y-direction is less than 0.02 in case no. 2 (see Figure 9) although the building has a soft story (see Figure 3).

This means there is no specific caution is proposed in the UBC code [6] for buildings with soft stories from story drift ratio limit point of view. The authors suggest a limit for the story drift ratio of 0.01 for buildings with soft stories. Similarly, more restrictive drift limit for longer-period structures in the 1997 UBC is unwarranted [13]. Further research is needed to investigate the impact of the revised earthquake drift provisions on design and construction of reinforced concrete buildings [14].

Conclusions

In this research, seismic structural response parameters for buildings with soft stories subjected to equivalent static earthquake loading are studied. ETABS nonlinear software program is employed. Parameters such as the level at which the soft story exists and the location of the columns supporting the central cores are investigated. The following conclusions are drawn:

- Simple calculations for identifying the presence of a soft story in a building via calculating the moment of inertia of two subsequent floors are not accurate. Rigorous analysis should be carried out in order to check the presence of a soft story.
- The criteria adopted in the UBC code [6] and ASCE7 [7] for identifying the soft story vertical irregularity in a building are not applicable for all buildings.
- Existence of reinforced concrete cores either continued or planted eventually enhances the stiffness and reduces the lateral story displacement of a building compared with a building without cores.
- The higher the level at which the cores are planted the larger the lateral story displacement and the smaller the lateral stiffness of the building.
- Shifting the supporting columns out from the cores` corners produces weak lateral stiffness of the building and increases the lateral story displacement compared with the building with cores directly supported on columns.
- The lateral stiffness of a building in a direction is significantly dependent on the direction at which the cores produce large moment of inertia.
- Story drift ratio reaches its maximum value almost at mid-height of the building without cores, whereas it reaches its maximum value at the planting level of the cores.
- The story drift ratio becomes unchanged above the story at which the cores are discontinued.
- Story drift ratio limit of 0.01 is suggested for buildings with soft stories.

References

1. Standard AA. August. Building Code Requirements for Structural Concrete (ACI 318-11). American Concrete Institute. 2011.
2. Code UB. Uniform building code. International Conference of Building Officials, Whittier, CA. 1997.
3. Amin MR, Hasan P, Islam BKMA. Effect of soft storey on multi storied reinforced concrete building frame. 4th Annual Paper Meet and 1st Civil Engineering Congress. 2011:22-24.
4. Searer GR, Freeman SA. Design drift requirements for long-period structures. 13th World conference on earthquake engineering, Vancouver, BC. 2004.
5. Hejazi F, Jilani S, Noorzaei J, Chieng CY, Jaafar MS, Ali AA. Effect of soft story on structural response of high rise buildings. IOP Conference Series: Materials Science and Engineering. IOP Publishing. 2011;17(1):012034.
6. Guevara-Perez LT. Soft story and weak story in earthquake resistant design: A multidisciplinary approach. 15WCEE. Lisboa. 2012.
7. Dya AFC, Oretaa AWC. Seismic vulnerability assessment of soft story irregular buildings using pushover analysis. Procedia Engineering. 2015;125:925-932.
8. Yi Z, Burton HV, Shokrabadi M, Issa O. Multi-scale cost-benefit analysis of the Los Angeles Soft-Story Ordinance. Engineering Structures. 2020;214:110652.
9. ASCE7-10. Minimum design loads for buildings and other structures (The American Society of Civil Engineers (ASCE)). 2010.
10. Fintel M, Khan FR. Shock-absorbing soft story concept for multistory earthquake structures. Journal Proceedings. 1969;66(5):381-390.
11. Abdlebasset YM, Sayed-Ahmed EY, Mourad SA. High-Rise Buildings with Transfer Floors: Construction Stages Analysis. Journal of Al-Azhar University Engineering Sector. 2016;11(40):927-942.
12. Mohod MV. Pushover analysis of structures with plan Irregularity. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE). 2015:46-45.
13. CSI (Computers and Structures, Inc.). ETABS Extended 3D Analysis of Building Systems Software, Nonlinear Version 13.0.0; 2005.
14. ACI Committee 318. Building Code Requirements for Structural Concrete (ACI 318-14) [and] Commentary on Building Code Requirements for Structural Concrete (ACI 318R-14). 2014.