Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (41) No. (2) April, 2019

SEISMIC PERFORMANCE OF BUILDINGS WITH DISCONTINUOUS VERTICAL ELEMENTS BY PUSHOVER ANALYSIS

R. A. HASSAN[1], M. S. GOMAA[2] AND H. EL-GHAZALY[3]

[1] MSc Student, Faculty of Engineering, Fayoum University
[2] Lecturer, Faculty of Engineering, Fayoum University
[3] Professor of Structural Engineering, Faculty of Engineering, Fayoum University

ملخص البحث:

يتناول البحث دراسة سلوك المنشآت الغير منتظمة رأسيا و ذلك عن طريق عمل دراسة على نموذجين لمنشأين خرسانيين من ثمانية أدوار باستخدام نظامين إنشائيين مختلفيين. تم استخدام نظام الفرنديل في المنشأ الأول في الدور الأول منه أما الآخر فتم استخدام نظام الكمرة في الدور الارضي وتم زراعة أعمدة عليهم. و قد تم الاخذ في الاعتبار ثلاث حالات للدراسة:- أولا بزيادة البحر للفرنديل بنسبة 33% والبحر الأكبر للكمرة بنسبة 33% في كلا المنشأين وثانيا بزيادة ارتفاع دور الفرنديل في المبنى الأول بنسبة 25% و 50% وأما في حالة المبنى الآخر فمرة بزيادة ارتفاع الدور الأرضي بنسبة 20% و 40% ومرة بزيادة ارتفاع بقية الأدوار بنسبة 33% وثالثا بالتأثير بحمل مركز كنسبة من وزن المنشأ على الأعمدة المزروعة في الدور الأخير. وقد تمت الدراسة بعمل تحليل استاتيكي لا خطي باستخدام طريقة Pushover و ذلك باستخدام برنامج ZEUS-NL. و ظهر من نتائج التحليل أن المنشآت غير المنتظمة تظهر مقاومة للزلازل أقل من المنشآت المنتظمة.

ABSTRACT

The influence of vertical irregularity on the structural response of RC structures when subjected to seismic loading is considered in a large portion of the modern urban infrastructure. Past earthquakes have shown that buildings with irregular configuration or asymmetrical distribution of structural properties examine significant increase in seismic demand, causing greater damage. Therefore, seismic codes provide elaborating empirical rules for the classification of buildings into regular, and various irregular categories as a function of asymmetries, to evaluate seismic demand. The main objective of this research is to evaluate the seismic performance of vertically irregular reinforced concrete buildings due to discontinuity of vertical elements. Two models with different structural systems are analyzed. The first has a continuous vierendeel girder at the first floor while, in the second a girder system at the ground roof floor is used. Both models are designed according to ECP201, 2012. A parametric study is performed including three distinct scenarios, changing in span, heights and, applying a concentrated mass at the top floor. This study aims to assess their effects on the seismic performance of these buildings. Non-linear static pushover analysis is employed using the Zeus-NL software (Elnashai et al, 2004). The results indicate that, the irregular buildings are more vulnerable than regular ones. Moreover, the shear capacity of the structure of vierendeel girder has been decreased by 17% when increasing the span of the vierendeel by 33%. Although, the increasing of the vierendeel story height by 25% and 50% have not significantly affected the shear capacity or the story shear. While in the structure of the transfer girder, the shear capacity has been decreased by 13% when increasing the span of the girder by 33%.

KEYWORDS: Vertical irregularity, Seismic Performance, Pushover analysis, Dicontinuity of vertical element.

1. INTRODUCTION

Researches corresponding irregular buildings have gained a wide interest in the building industry in Egypt. Irregularity in buildings can exist due to architectural, functional and economical constrains. It can occur due to discontinuity in mass, stiffness, strength, geometry or, structural form in one story with respect to adjacent stories. The mass irregularity does not affect the plastic for multistory RC frames with mass, stiffness and strength irregularity (Magliulo et al, 2002). Furthermore, the mass irregularity has the smallest effect on the seismic response, while the effect of strength irregularity is larger than the effect of the stiffness irregularity and the combined stiffness and strength irregularity is the largest (Al-Ali and Krawinkler, 1998). So, the effects of strength and stiffness irregularities on the seismic response are more dominant as compared with mass irregularity (Valmundsson and Nau, 1997). There are different types of structural irregularities such as: vertical stiffness irregularity, weight (mass) irregularity, vertical geometric irregularity, in plane discontinuity in an element of the seismic force resisting system and discontinuity in capacity (weak story) (Chintanapakdee and Chopra, 2004).

The behavior of a building during an earthquake depends on several factors such as: stiffness, lateral resistance capacity, ductility and, regular configurations. During past earthquakes, many irregular buildings showed vulnerable behavior with strong damage localized at some stories. The location of irregularity and the intensity of an earthquake have maximum influence on the seismic response (Fragiadakis et al, 2005). As per recent research, the ground motion characteristics have played an important role in determining the structural response (Baker and Cornell, 2005). Therefore, the structural engineer needs to have a thorough understanding of the seismic response of the different types and configurations of those irregular structures.

Among all types of irregularity, vertical irregularity has impressively gained a considerable attention of many researchers all over the world. As an extension to their research work, the main objective of this research is to improve the understanding of the effect of vertical stiffness irregularity on the seismic response of the structure. The present research focuses on investigating the seismic performance of vertically irregular buildings due to discontinuity of vertical elements.

Two models with eight stories have been discussed representing two different systems. The first model has a continuous vierendeel girder at the first story with 12.0 m span. The second model has a transfer girder beam at the ground story roof slab with different continuous spans 6.0 m and 12.0 m. Three scenarios have been investigated which are: (a) changing of the span, (b) changing of the height of the vierendeel girder for Model (1) and changing of all the stories heights for Model (2) and, (c) applying a concentrated mass at the top floor on the planted column. Therefore, step-by-step non-linear static pushover analysis has been employed using the well-known ZEUS-NL software to achieve this goal.

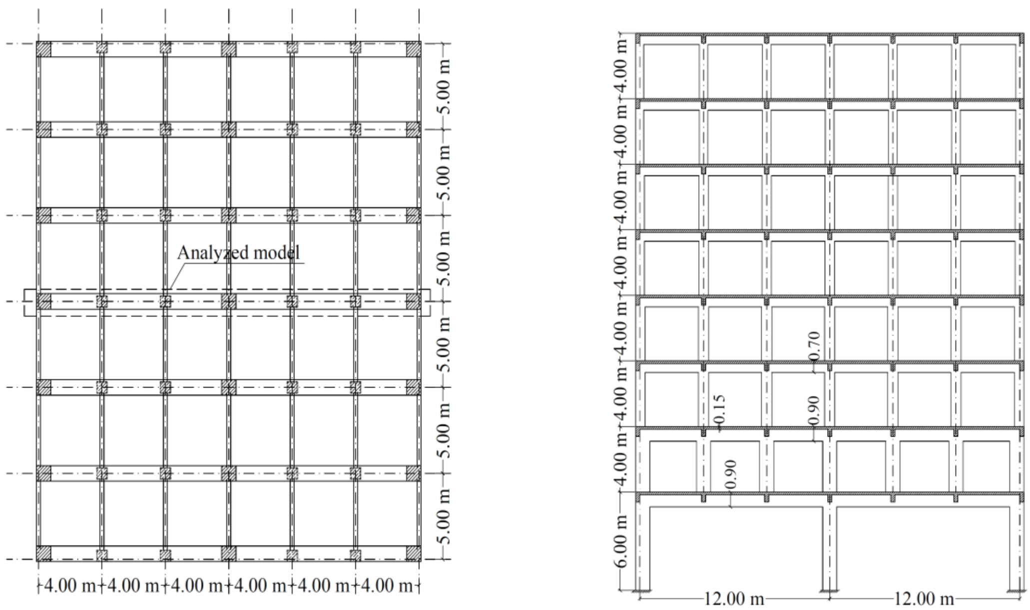
2. GEOMETRIC CONFIGURATION OF THE STUDIED MODELS

In the present study, the performance of two different models has been investigated when subjected to seismic loading. The two models represent two distinct systems that are used to allow for larger spans between columns in the lower stories comparing to upper ones. These systems are the vierendeel girder and the transfer girder. Each model has eight stories height, with 6.0 m for ground story height and 4.0 m for all other stories as shown in Figure (1) and Figure (2).

For the first investigated model, the continuous vierendeel system has been used at the first story with 12.0 m span. In the upper stories of the structure, the planted columns have been spaced at 4.0 m in X-direction and by 5.0 m in Y-direction as shown in Figure (1). Moreover, the slabs' thickness has been taken as 0.15 m, the cross sectional dimensions of the vierendeel beams are 0.9 m width and 0.9 m depth, and all other beams are 0.25 m width and 0.7 m depth. The cross sectional dimensions of the columns for Model (1) are shown in Table (1).

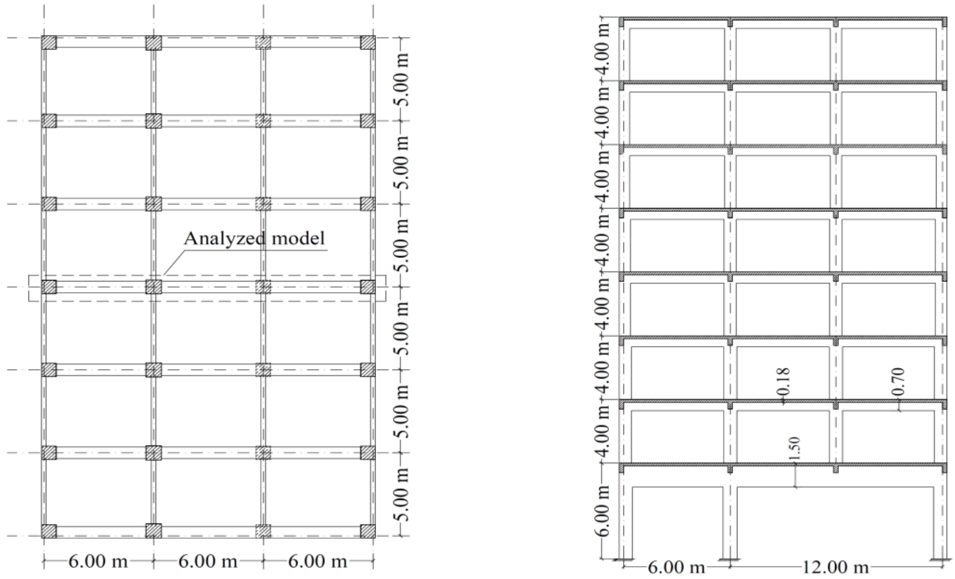
In the second investigated model, the transfer girder system has been utilized at the ground story roof slab with two spans; 6.0 m and 12.0 m, as shown in Figure (2). The planted columns have been spaced by 6.0 m in X-direction and by 5.0 m in Y-direction as shown in Figure 2. Furthermore, the slabs' thickness has been taken as 0.18 m, the girder beams are 0.7 m width and 1.5 m depth, and all other beams are 0.25 m width and 0.7 m depth. Also, the cross sectional dimensions of the columns for Model (2), are shown in Table (1).

The two proposed models have been designed according to ECP201, 2012, where comprehensive seismic design recommendations were implemented. Live load, finishes and, wall loads have been assumed to be 250, 200 and 350 kg/m^2, respectively. All models have been assumed to be founded on soil type 'C' as per ECP201, 2012. Columns have been assumed to be fixed to the foundation.



(a) Plan of first story roof slab (b) Section elevation

Figure (1) Plan and elevation of the analyzed model (1): a) Plan of ground roof slab and, b) Section elevation.



(a) Plan of first story roof slab (b) Section elevation

Figure (2) Plan and elevation of the analyzed model (2): a) Plan of ground roof slab and, b) Section elevation.

Table (1) Cross sectional dimensions and reinforcement of columns for the two models.

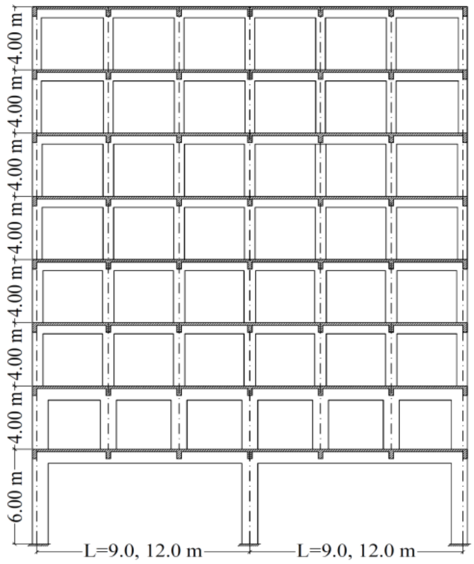
Story	Column	Model 1		Story	Column	Model 2	
		Exterior column	Interior column			Exterior column	Interior column
First &Second	dim (cm)	90X90	90X90	First	dim (cm)	75X75	80X80
	RFT (mm)	32T22	32T22		RFT (mm)	28T20	28T20
Third & Fourth	dim (cm)	60X60	65X65	Second & Third	dim (cm)	70X70	75X75
	RFT (mm)	16T18	20T18		RFT (mm)	24T18	24T20
Fifth & Sixth	dim (cm)	55X55	60X60	Fourth & Fifth	dim (cm)	65X65	70X70
	RFT (mm)	16T16	16T18		RFT (mm)	24T16	24T18
Seventh & Eighth	dim (cm)	50X50	55X55	Sixth & Seventh & Eighth	dim (cm)	60X60	65X65
	RFT (mm)	16T16	16T16		RFT (mm)	20T16	24T16

T: represents high grade steel (fy=4000 kg/cm^2)

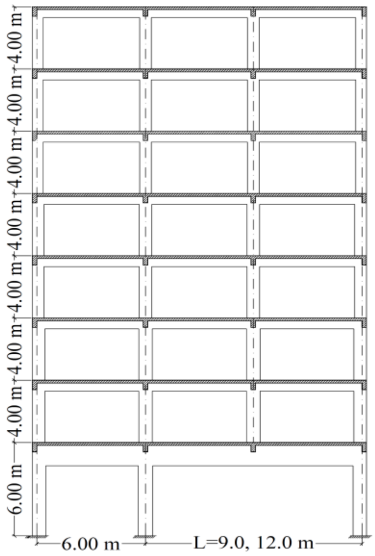
In order to evaluate the effect of vertical elements' discontinuity on the seismic performance, three distinct scenarios have been employed. In the first scenario, the span of the transfer element (i.e. the vierendeel girder or the girder beam) have been changed from 9.0 m to 12.0 m for the vierendeel (Model 1) and, from 9.0 m to 12.0 m too for the larger span of the transfer girder. The span at which the change has been applied has been referred to by "L".

In the second scenario, the vierendeel girder height (the first story height) has been set to 4.0, 5.0 and 6.0 m and the other stories heights have been kept equal to 6.0 m for ground story and 4.0 m for the upper stories. The vierendeel girder height has been referred to by "h1" in this case. While, in the second model (Model 2), the ground story height has been set to 5.0, 6.0 and 7.0 m and all other stories' heights have been set to 3.0 and 4.0 m.

Finally and for the third scenario, a concentrated mass has been applied at the roof floor at the top of the discontinuous columns. In the first model, the mass has been set to 4%, 8% and 12% of the total weight of the building. While in the second model, the mass has been set 3%, 5% and 7% of the total weight of the building. The three studied scenarios are shown in Figures (3) to (5).

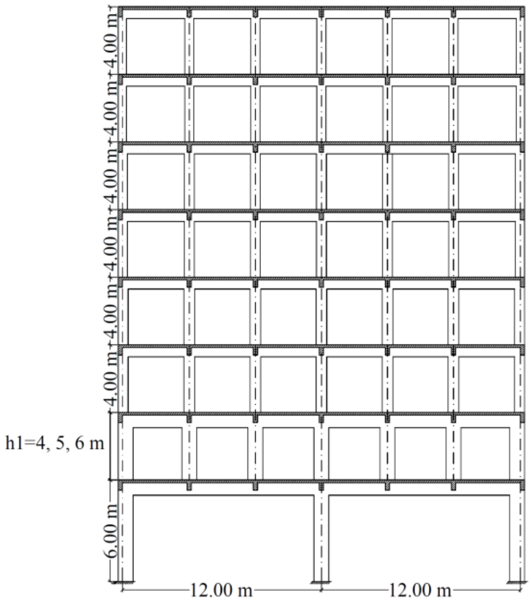


(a) Model 1

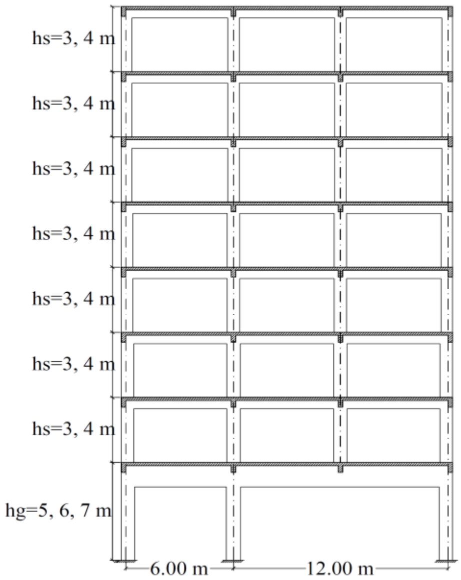


(b) Model 2

Figure (3) The first studied scenario for: a) Model 1 and, b) Model 2.

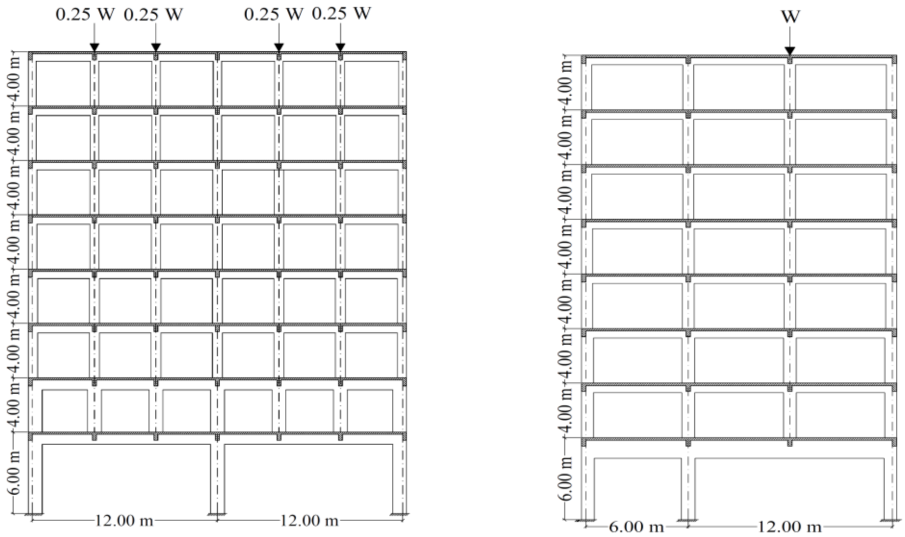


(a) Model 1



(b) Model 2

Figure (4) The second studied scenario for: a) Model 1 and, b) Model 2.

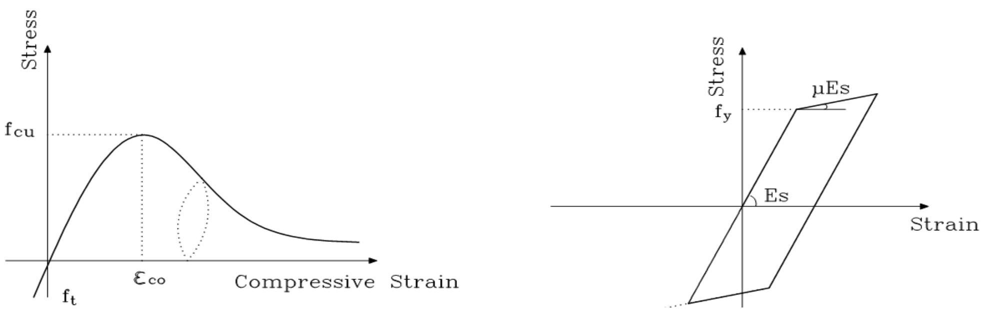


(a) Model 1 (b) Model 2

Figure (5) The third studied scenario for: a) Model 1 and, b) Model 2.

3. MATERIAL PROPERTIES

The characteristic compressive strength of concrete (Fcu) is 400 kg/cm^2; whereas, reinforcing steel yield strength (Fy) is 4000 kg/cm^2, for both models. Figure (6) shows the material models for concrete, and reinforcing steel and Table (2) and Table (3) present their properties which have been employed in Zeus-NL.



a. Material model of the concrete b. Material model of the steel

Figure (6) The material models for (a) Concrete, (b) Reinforcing steel.

Table (2) The characteristic properties of concrete

property	description	value
f_c	Compressive strength	40 MPa
f_t	Tensile strength	2.2 Mpa
ε_{co}	Crushing strain	0.002

Table (3) The properties of reinforcing steel

property	description	value
E	The Young's Modulus	$2*10^5$ MPa
f_y	Yield Strength	400 Mpa
μ	Strain-hardening parameter	0.005

4. NONLINEAR STATIC PUSHOVER ANALYSIS

In the current research work, step-by-step nonlinear static pushover analysis has been employed to investigate the performance of the studied models. The pushover analysis is an approximate analysis method consists of series of sequential elastic analyses, superimposed to approximate a force-displacement curve of the overall structure. Whereas the structure is subjected to increasing lateral force of a predetermined pattern until reaching to a target displacement that has been applied at the top floor of the building. As the load increases, some members yield. Hence, the structural model is modified to account for the reduced stiffness of the yielded members and the lateral forces are again increased until additional members yield. The process is continued until a control displacement is achieved. Hence, the target displacement may be used to estimate the expected deformation due to earthquake or the expected drift corresponding to structural collapse. Therefore, the relationship between the base shear and the top displacement, that is called capacity curve, has been determined (Papanikolaou and Elnashai, 2005). The pushover analysis has been employed by applying an inverted triangular load pattern for Model 1 and Model 2. The well-known software, Zeus-NL, has been used to perform this study (Elnashai et al, 2004).

5. RESULTS AND DISCUSSION

In this study, the capacity curve, the maximum inter-story drift ratio and the maximum story shear have been obtained and plotted for the two models as will be discussed in the following sections:

5.1 The First Studied Model

5.1.1 First scenario - capacity curve

Figure (7) depicts the relationship between the base shear versus the top displacement (capacity curve) for the first scenario for Model (1). As shown in Figure (7), when changing the span (L) from 9.0 m to 12.0 m (33% increase), the building's shear capacity decreases by about 17% for the structure with vierendeel. This is expected because the building with vierendeel with the smaller span shows higher stiffness comparing to that has the larger span.

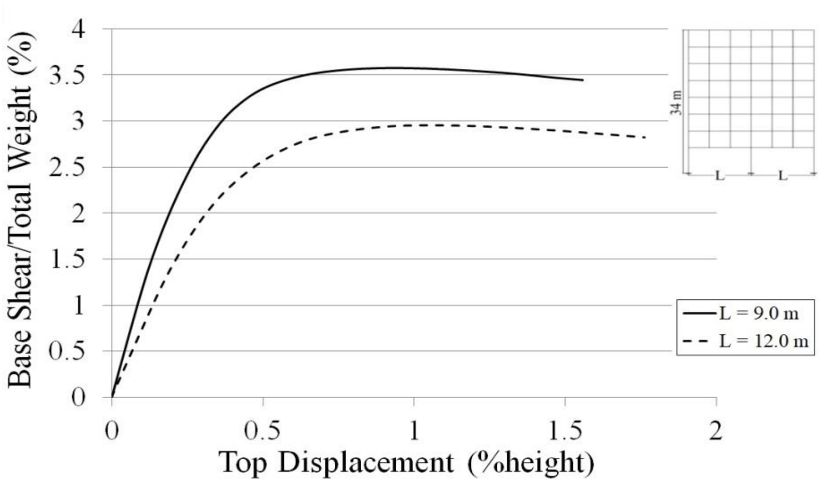


Figure (7) Capacity curve for the first scenario for Model 1.

5.1.2 First scenario - inter-story drift ratio

For the second obtained result for Model (1) in the first scenario which is the inter-story drift ratio, Figure (8) shows the inter-story drift ratio when the vierendeel span was increased by 33% (from 9.0 m to 12.0 m). According to this figure, it can be concluded that increasing the span has not significantly affected the building's behavior. However, the building which has the larger lateral stiffness, which has a span (L) of 9.0 m, shows lower story drifts by 6% to 35% comparing to the case of the larger lateral stiffness when the span (L) reaches 12.0 m. It can be also noticed that the behaviors of the two buildings are almost identical in the ground story. This is because the effect of the vierendeel system on the lateral stiffness of the ground story below the vierendeel is limited. Another notice that can be shown in the same figure is that the inter-story drift ratios of the two buildings at the top level are almost identical.

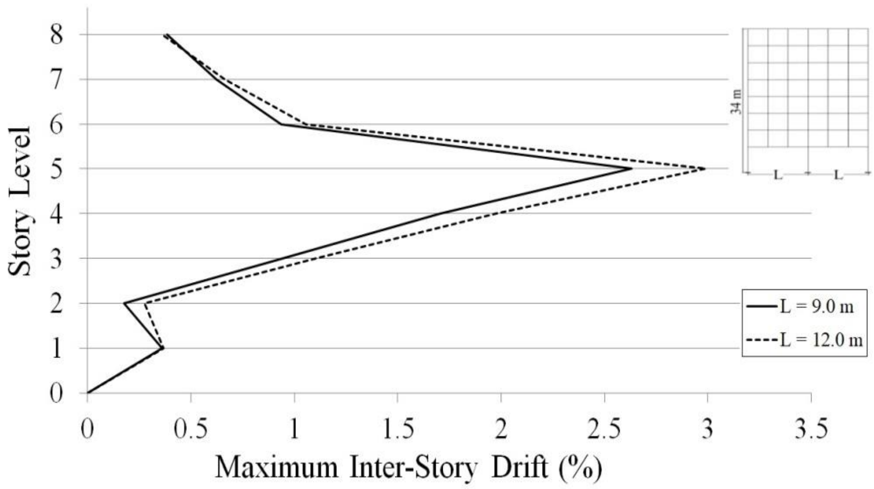


Figure (8) Maximum inter-story drift for the first scenario for Model 1.

5.1.3 First scenario - maximum story shear

The maximum story shear at each story has been obtained and then plotted for Model (1) for the first scenario as shown in Figure (9). According to this figure, it can be observed that the two buildings have the same behavior. Whereas, the maximum story shear was obviously varied at all stories due to the increase of the span from 9.0 m to 12.0 m and its values become closer at the upper stories. Consequently, the effect of the vierendeel girder on the lateral stiffness of the building in the lower story is larger than on the upper story. Besides, the columns cross sections in the upper stories are not changed. Moreover, the building which has the larger lateral stiffness, which has a span of 9.0 m, shows increase in the maximum story shears ranging between 23% and 25% comparing to those resulted from the building of the larger span and has the lower lateral stiffness.

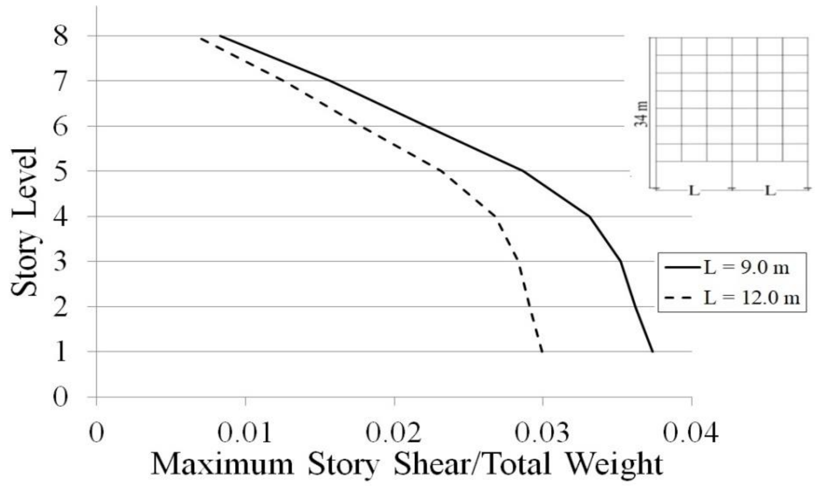


Figure (9) Maximum story shear for the first scenario for Model 1.

5.1.4 Second scenario - capacity curve

In the second scenario, it is clear that the effect of increasing the height of the first story "h1" (i.e. the story at which the vierendeel girder has been located) has not significantly affected the building's shear capacity, as shown in Figure (10). The shear capacity has been decreased by 1% and 2% when the vierendeel girder's height (h1) has increased from 4.0 m to 5.0 and 6.0 m (i.e. 25% and 50% increases), respectively. The capacity curves are almost identical for the three heights. This is due to the fact that the difference in the lateral stiffness between the vierendeel girder and the upper and lower stories has not been significantly affected by increasing the height of the vierendeel girder.

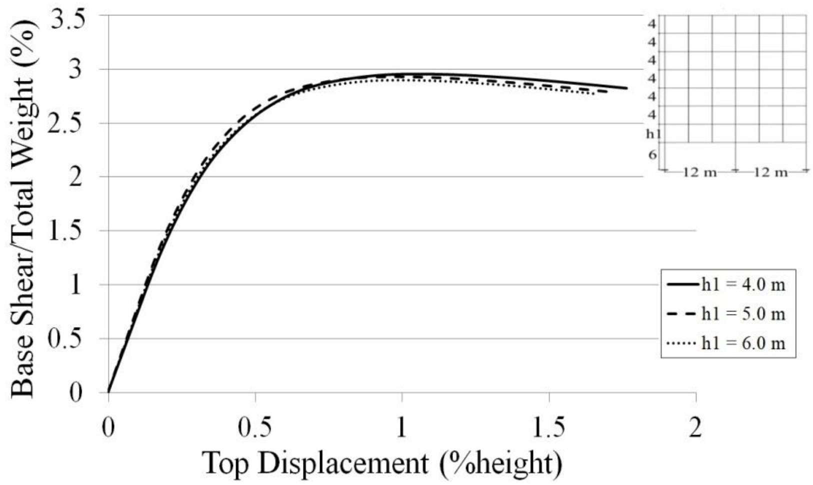


Figure (10) Capacity curve for the second scenario for Model 1.

5.1.5 Second scenario - inter-story drift ratio

Figure (11) shows the inter-story drift ratio for the second scenario for Model (1) when the vierendeel height (h1) has been increased by 25% and 50% (from 4.0 m to 5.0 m and 6.0 m, respectively). According to this figure, it can be concluded that increasing the vierendeel's height (h1) did not affect the building's behavior. However, it can be observed that increasing its height; h1, by 25% and 50%, has led to an increase in the inter-story drift ratio in the ground story by 10% and 22%, respectively. Furthermore, the major effects on the inter-story drift ratios have been noticed at the first story in which these ratios have been increased by 51% and 129% when the vierendeel girder's height has been increased by 25% and 50%, respectively. It can be also seen that another large difference in the inter-story drift ratio has been located at the middle story above the vierendeel. Finally, the inter-story ratios of the buildings at the top stories are almost identical.

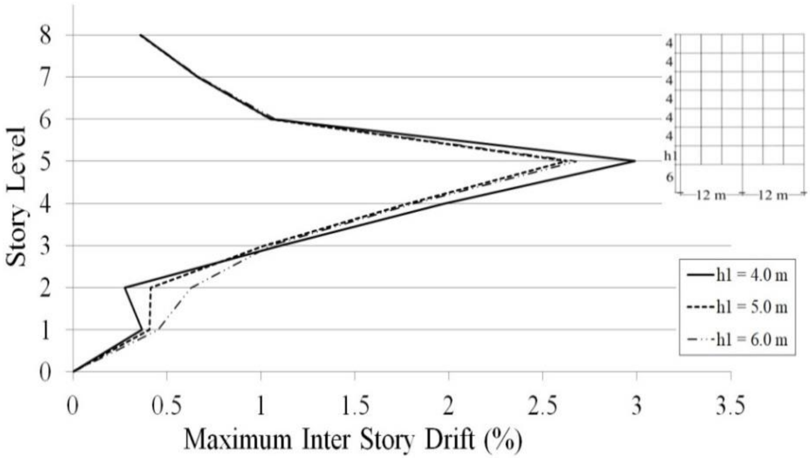


Figure (11) Maximum inter-story drift for the second scenario for Model 1.

5.1.6 Second scenario - maximum story shear

For the second scenario for Model (1), the maximum story shear has been plotted due to the change of the height of the vierendeel girder, as shown in Figure (12). As can be seen from the figure, the maximum story shears of the buildings are very close to each other at the lower stories and almost identical at the upper stories. The difference between them ranges between 0.9% and 1.8% at the lower stories and 1% and 2% at the upper stories when the vierendeel girder's height (h1) has been increased by 25% and 50%, respectively.

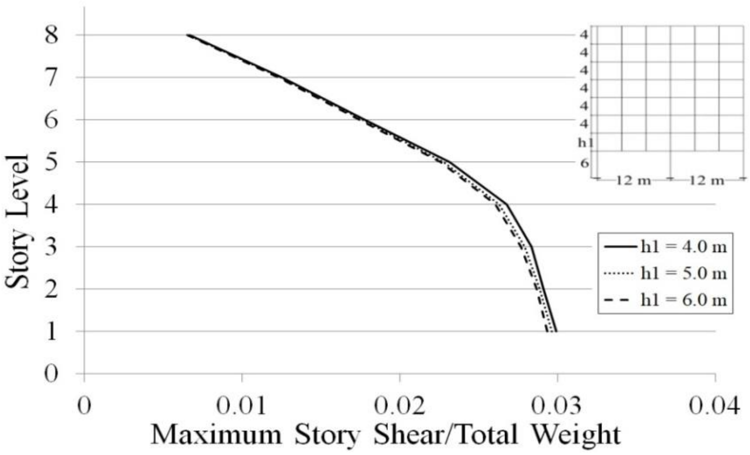


Figure (12) Maximum story shear for the second scenario for Model 1.

5.1.7 Third scenario - capacity curve

In the third scenario as shown in Figure (13), the capacity curves are illustrated for Model (1) when applying a mass with a value of 4%, 8% and 12% of the total weight of the building at the last story. The mass has been equally divided and applied at the top of the discontinuous columns. It can be seen that the behavior of the building has been drastically affected when the applied mass has been increased. As shown from the figure, the building's shear capacity has decreased by about 2%, 20% and 52% when a mass of 4%, 8% and 12% of the total weight of the building has been applied at the top level of the discontinuous columns, respectively. It is observed that the maximum shear capacities for larger masses (i.e. 8% and 12% of the total weight) occur at high top displacements, about 1.75% of the building's height.

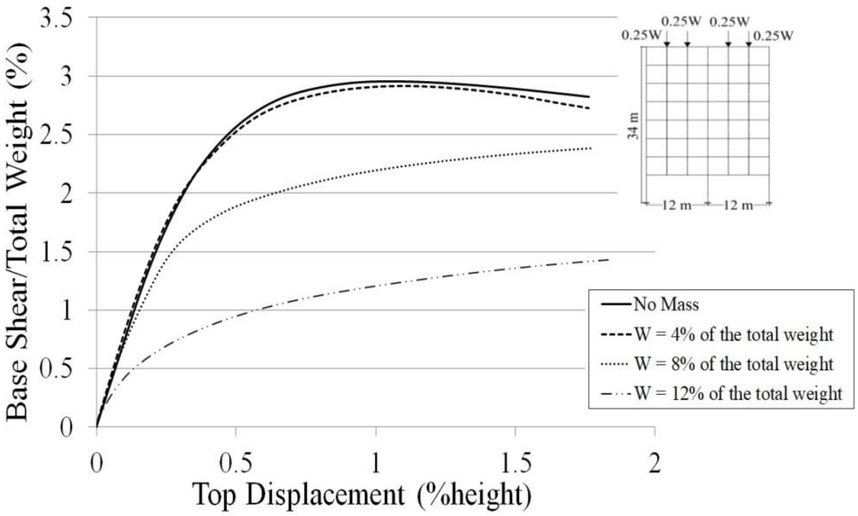


Figure (13) Capacity curve for the third scenario for Model 1.

5.1.8 Third scenario - inter-story drift ratio

Figure (14) shows the inter-story drift ratio for the third scenario for Model (1) when applying masses at the top level of the discontinuous columns. According to this figure, it can be concluded that applying a mass of 4% of the total weight of the building has not affected the building's behavior. However, sever effects have been noticed when the applied mass has been increased to represent 8% and 12% of the total building's weight. When the additional mass reached 4%, the inter-story drift ratio has been increased by a range of 15% to 84% comparing to the original building, with no mass, at the ground and first stories, respectively. While, the inter-story drift for the same buildings decreased by 21% at the middle story above the vierendeel and then increased at the upper stories. Moreover, increasing the applied mass to reach 8% and 12% produced a drastic increases range between 14% and 490% for the 8% mass and between 12% and 586% for the 12% mass.

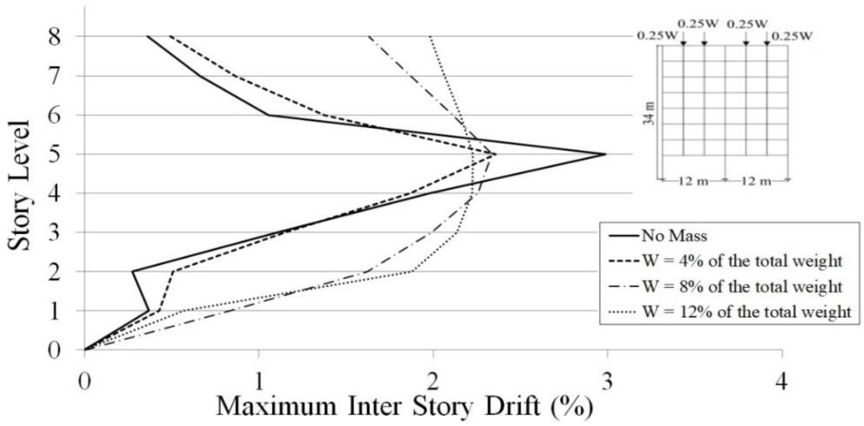


Figure (14) Maximum inter-story drift for the third scenario for Model 1.

5.1.9 Third scenario - maximum story shear

At the end, in the third scenario for Model (1), the maximum story shear is plotted as shown in Figure (15). As can be noticed from the figure, when the 4% mass has been applied, the maximum story shears of the building are almost identical to those of the original building with no mass. On the other hand, when the mass has been increased to have a value of 8%, the maximum story shear distribution has examined a large decrease ranging between 2% at the top stories and 14% at the lower stories values at the lower stories. When the mass reaches 12% of the total weight of the building, the decrease in the story shear becomes larger and ranges between 16% at the upper stories and 46% at the lower stories.

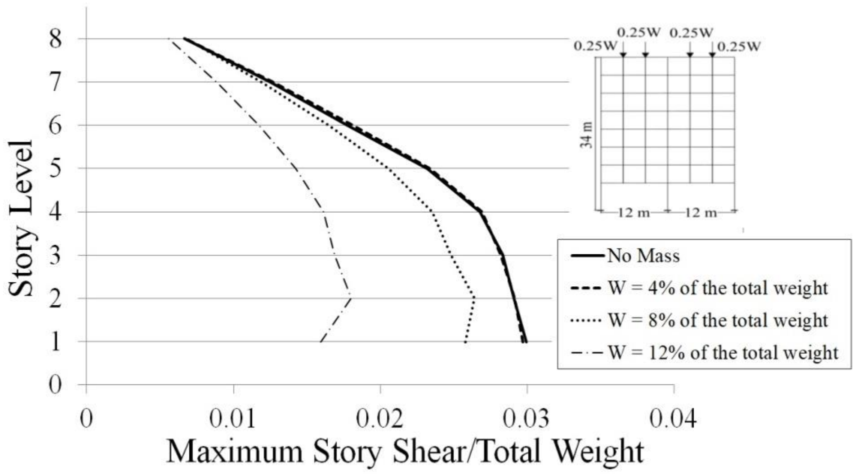


Figure (15) Maximum story shear for the third scenario for Model 1.

5.2 The Second Studied Model

5.2.1 First scenario - capacity curve

Figure (16) shows the capacity curve when changing the larger span from 9.0 m to 12.0 m (33% increase), the first scenario, for Model (2). As shown in the figure, when increasing the larger span of the transfer girder by 33%, the building shear capacity decreases by 13%. This is expected because the building with the transfer girder with the smaller spans is laterally stiffer than that has larger spans.

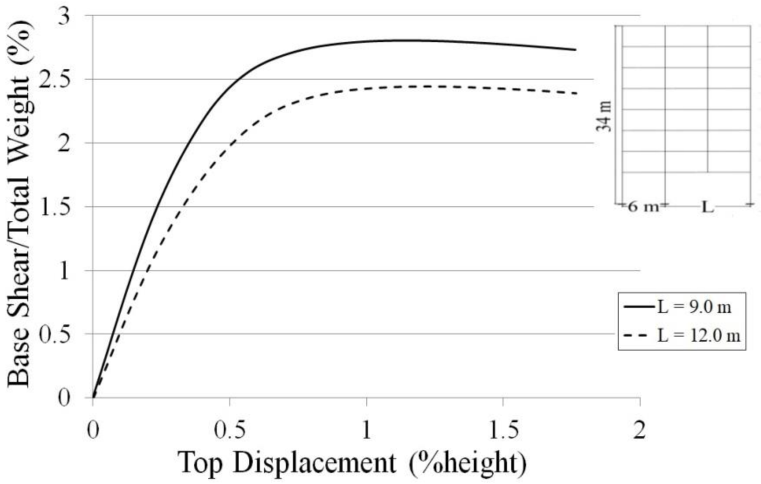


Figure (16) Capacity curve for the first scenario for Model 2.

5.2.2 First scenario - inter-story drift ratio

For the first scenario for Model (2), the inter-story drift ratio has been obtained and plotted as shown in Figure (17) when the larger span of the transfer girder has been increased by 33% (from 9.0 m to 12.0 m). According to this figure, it is obvious that increasing the span has not affected the building's behavior. However, the building which has the larger lateral stiffness, which has a span 9 m, shows lower story drift ratios by 2% to 14% comparing to that has the larger lateral stiffness. It is also observed that the behaviors of the two buildings are almost identical in the ground story. This is because the lateral stiffness of the building in the ground story mainly depends on the columns' lateral stiffness at the ground story and the contribution of the transfer girder system at this story is not as large as its contribution in the lateral stiffness of the upper story.

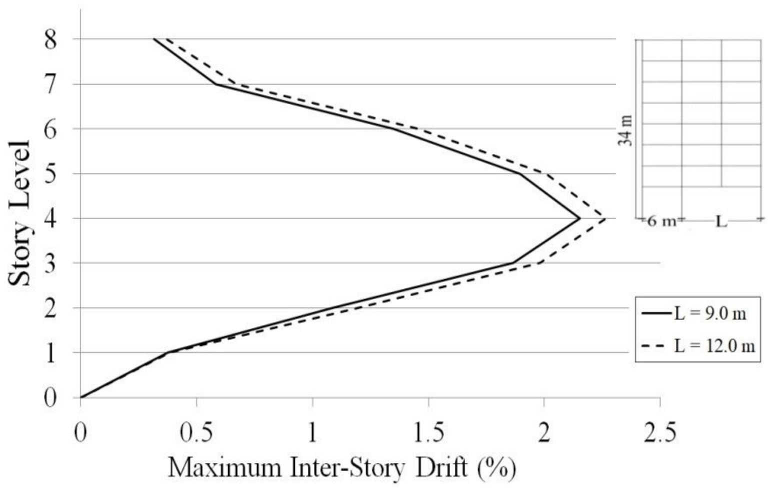


Figure (17) Maximum inter-story drift for the first scenario for Model 2.

5.2.3 First scenario - maximum story shear

The maximum story shear at each story has been plotted for Model (2) for the first scenario, as shown in Figure (18). It can be observed that the two buildings have the same behavior. While, the maximum story shear has been significantly decreased at lower stories due to increase of the span from 9.0 m to 12.0 m (33% increases) by 13%. However, this difference has been decreased to about 12% at the upper stories at which the values of the story shears become closer.

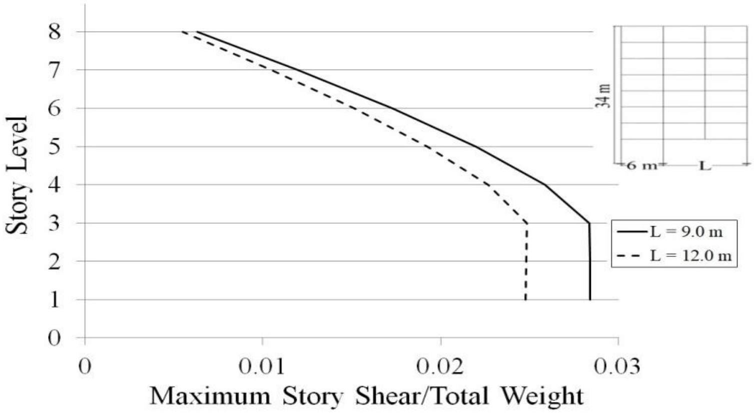


Figure (18) Maximum story shear for the first scenario for Model 2.

5.2.4 Second scenario - capacity curve

For the second scenario for Model (2), Figure (19) shows the capacity curves for the building when changing the height of its ground story (hg) firstly from 5.0m to 6.0m and 7.0m, then changing all stories' heights (hs) from 3.0 m to 4.0 m. In the first case, i.e. changing the ground story height (hg) to 5.0 and 6.0 m and the all other stories' heights have been kept equal to 3.0 m, the shear capacity decrease by 5% and 20% when increasing the ground story height only by 20% and 40%, respectively. While, in the second case, i.e. the ground story height has been increased from 5.0 m to 6.0 and 7.0 m and all other stories have been increased from 3.0 m to 4.0 m, the shear capacities for the building are almost identical. This is because the difference of the lateral stiffness between the ground story and the above story is larger in the first case than the second case. It is also observed that the effect of changing of height of all stories significantly affect the building shear capacity with a more obvious manner comparing to the case in which only the ground story height has been changed.

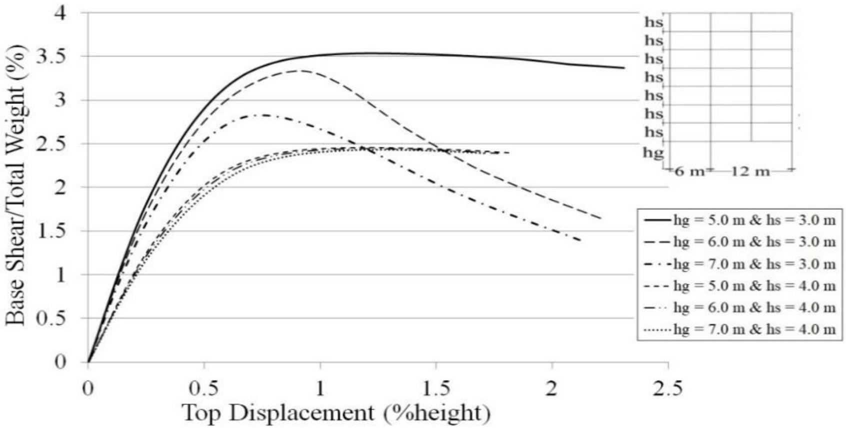


Figure (19) Capacity curve for the second scenario for Model 2.

5.2.5 Second scenario - inter-story drift ratio

Figure (20) shows the inter-story drift ratio for the second scenario for Model (2) when changing the height of its ground story (hg) firstly from 5.0m to 6.0m and 7.0m, then changing all stories' heights (hs) from 3.0 m to 4.0 m. In the first case, i.e. changing the ground story height (hg) to 5.0 and 6.0 m and the all other stories' heights have been kept equal to 3.0 m, a soft story mechanism has been occurred at the ground story. This can be due to the large difference in the lateral stiffness between the ground story and the above story. However, in the second case, i.e. when the ground story height has been increased from 5.0 m to 6.0 and 7.0 m and all other stories have been increased from 3.0 m to 4.0 m, the building shows a similar behavior to that of the original heights but with some differences in the drift ratios. The inter-story drift ratio at the ground story has decreased by 46% when increasing the upper stories' heights above the transfer girder from 3.0 m to 4.0 m (33% increase) and the ground story height has been kept unchanged. Besides, increasing the ground story by 20% and 40% (from 5.0m to 6.0m and 7.0m) and increasing all other stories by 33% (from 3.0m to 4.0m) has led to increase the inter-story drift ratio at the ground story by 2% and 98%, respectively.

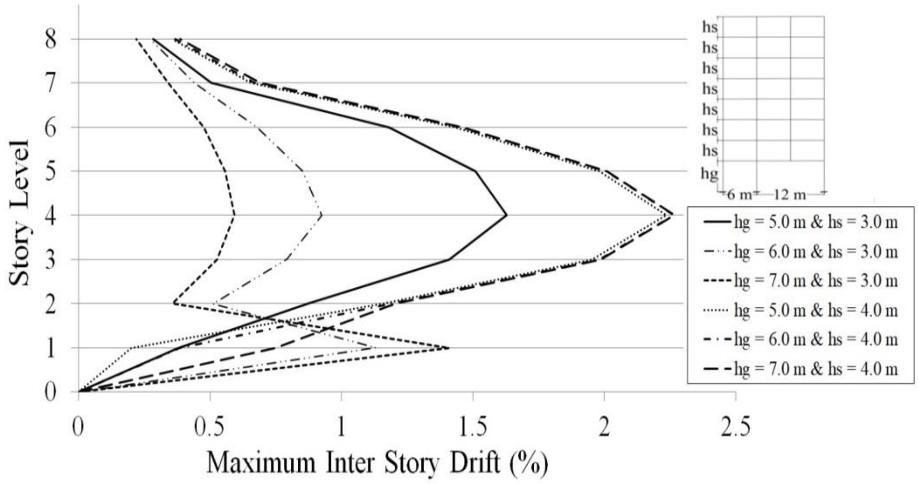


Figure (20) Maximum inter-story drift for the second scenario for Model 2.

5.2.6 Second scenario - maximum story shear

For the second scenario for Model (2), the maximum story shear has been obtained and plotted as shown in Figure (21) due to change the height of the ground story firstly, then all the stories' heights. According to this figure, it can be shown that the overall building's behavior has not been significantly changed although some differences can be seen in the story shear comparing the building with the original story heights. In the first case when increasing the ground story height from 5.0 m to 6.0 and 7.0 m significant decreases in the maximum story shear at the lower stories can be observed. This decrease ranges between 3% and 8% when the ground story height has been increased by 20% to reach 6.0m. Furthermore, the decrease ranges between 17% and 23% when the ground story height has been increased by 40% to reach 7.0m. On the other hand, in the second case when the ground story height has been increased from 5.0 m to 6.0 and 7.0 m and all other stories have been increased from 3.0 m to 4.0 m, the behavior of the three building's cases are almost identical.

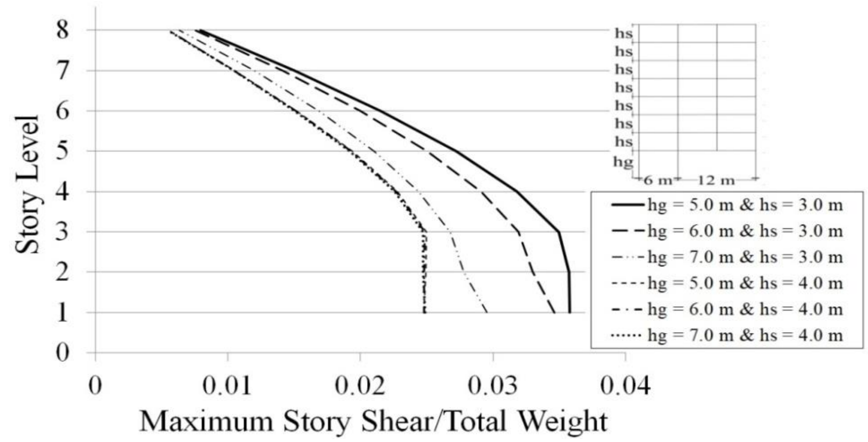


Figure (21) Maximum story shear for the second scenario for Model 2.

5.2.7 Third scenario - capacity curve

In the third scenario as shown in Figure (22), the capacity curve has been depicted for Model (2) when a mass with a value of 3%, 5% and 7% of the total weight of the building at the last story. The mass has been applied at the top level of the discontinuous columns. It can be seen that the behavior of the building has been significantly affected when the applied mass has been increased. The building shear capacity has decreased by about 14%, 36% and 60% when the applied mass has reached 3%, 5% and, 7% of the total weight of the building, respectively. Moreover, it is observed that the lateral stiffness of the building is decreasing by increasing the applied mass.

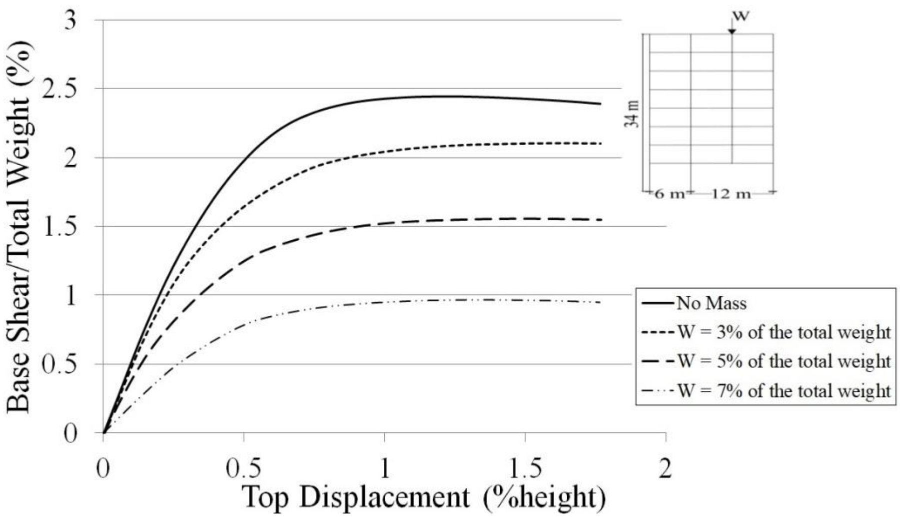


Figure (22) Capacity curve for the third scenario for Model 2.

5.2.8 Third scenario - inter-story drift ratio

The inter-story drift ratio for the third scenario for Model (2) has been plotted as shown in Figure (23). According to this figure, it can be seen that applying any mass at the top of the discontinuous column significantly affects the building's behavior. The inter-story drift at the transfer girder level, the ground story, increases by 2%, 73% and 115% by applying a mass of a value of by 3%, 5% and 7% of the total weight of the building, respectively. Moreover, at the fourth story level when the mass equals 3%, the inter-story drift is almost identical to the original case with no mass. On the contrary, when the mass has been increased to 5% and 7% the inter-story drift has decreased by 12% and 17%, respectively. Finally, the inter-story drift of the three cases are almost identical at the upper stories but with a large difference with the original case in which no mass has been applied.

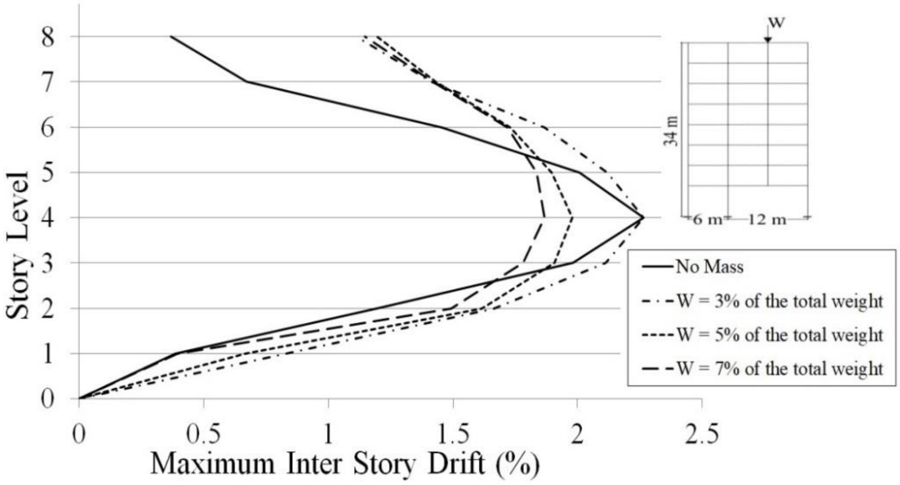


Figure (23) Maximum inter-story drift for the third scenario for Model 2.

5.2.9 Third scenario - maximum story shear

At the end, in the third scenario for Model (2), the maximum story shear has been plotted as shown in Figure (24). The figure shows that applying a mass at the top level of the discontinuous column with values of 3%, 5% and 7% of the total weight of the building has resulted in decreasing the story shears. This can be due to the increased total mass of the building without increasing its lateral stiffness. From Figure (24), it is clear that the maximum story shear has been decreased by 11%, 34% and, 58% at lower stories when the applied mass has increased to 3%, 5% and, 7%, respectively. However, the decrease at the upper stories reaches 4%, 21% and, 41% for the 3%, 5% and 7% masses, respectively.

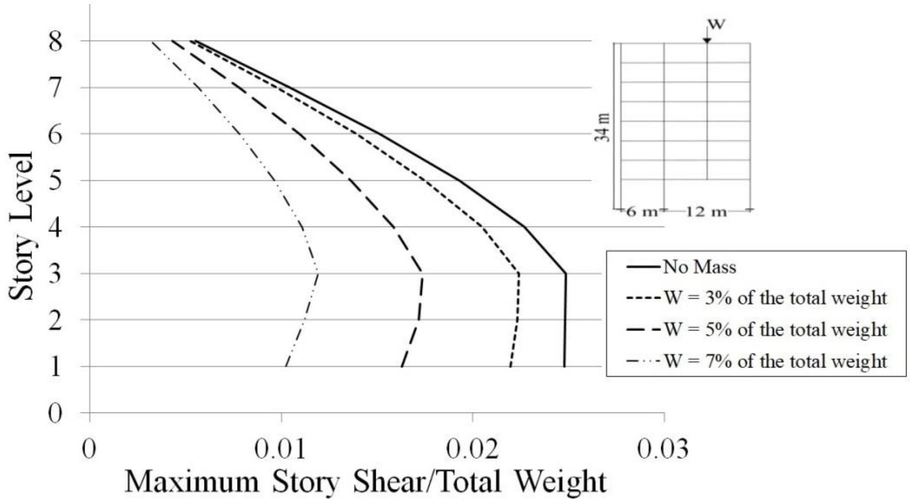


Figure (24) Maximum story shear for the third scenario for Model 2.

6. CONCLUSIONS

The current research work represents a comprehensive study on the effects of the discontinuity of the vertical elements on the seismic performance of RC buildings. Two models with eight stories were analyzed. The two models have two different systems to transfer the loads of the discontinuous columns to the ground. The first one has a continuous vierendeel girder at the first floor and in the other; a transfer beam girder at the ground story roof slab has been used. Three different scenarios were investigated which are: (a) changing of the span, (b) changing of the height of the vierendeel girder for Model (1) and changing of all the stories heights for Model (2) and, (c) applying a concentrated mass at the top floor on the planted column. Non-linear static pushover analysis was employed using the ZEUS-NL software. The following conclusions are drawn:

- The vertically irregular buildings are more vulnerable to than regular ones.
- At the structure with vierendeel girder the shear capacity has been decreased by 17% when increasing the span of the vierendeel by 33%. Increasing the vierendeel story height by 25% and 50% has not significantly affected the shear capacity or the story shear. However, the lateral stiffness of the vierendeel had been significantly affected by increasing its span contrarily increasing of its height.
- In the structure of the transfer girder, the shear capacity has been decreased by 13% when increasing the span of the girder by 33%. However, increasing the height of the ground story only by 20% and 40% resulted in decreasing the shear capacity by 5% and 20%, respectively. Contrarily, increasing of all stories' heights (ground story by 20% and 40% and other stories by 33%) led to a similar behavior. This is because of the difference of the lateral stiffness between the ground story and the above story is larger in the first case than the second case. It is worth to mention that a soft story mechanism has occurred at the ground story at the first case.
- For both models with the vierendeel girder and with the transfer girder, increasing their span or their heights did not affect the building behavior from the inter-story drift and maximum story shear point of views. However, applying a mass at the top level of the discontinuous columns led to a drastic change in the building's behavior.
- It is not preferable to apply any additional mass at the top level of the discontinuous vertical elements to avoid the unexpected drastic changes in the building's behavior. However, a maximum mass of 4% and 3% of the building total weight can be applied without making this drastic change in the building behavior.
- Emphasizing the importance of implementing a design methodology in which inelastic deformation demands and capacities are explicitly incorporated in the design process.

REFERENCES

1. ECP-201, “Egyptian code for calculating loads and forces in structures and building works”, Housing and Building Research Center (HBRC), Egypt, 2012.
2. FEMA302, “NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures”, Federal Emergency Management Agency, Washington D.C., 1997.

3. Valmundsson E. V., and Nau J. M., “Seismic Response of Building Frames with Vertical Structural Irregularities”, Journal of Structural Engineering, Vol. 123, NO. 1, pp. 30–41, 1997.
4. Al-Ali A. K., and Krawinkler H., “Effects of vertical irregularities on seismic behavior of building structures”, Report No. 130, The John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, USA, 1998.
5. Magliulo G., Ramasco R., and Realfonzo R., “A critical review of seismic code provisions for vertically irregular frames”, In Proceedings of the Third European Workshop on the Seismic Behavior of Irregular and Complex Structures, CD ROM, Florence, 2002.
6. Elnashai A. S., Papanikolaou V., and Lee D. H., “Zeus-NL - A Program for Inelastic Dynamic Analysis of Structures – User Manual”, Mid-America Earthquake Center, University of Illinois at Urbana- Champaign, 2004.
7. Chintanapakdee C., and Chopra A. k., “Seismic Response of Vertically Irregular Frames: Response History and Modal Pushover Analyses”, Journal of Structural Engineering, Vol. 130, NO. 8, pp. 1177- 1185, 2004.
8. Papanikolaou V. K., and Elnashai A. S., “Limits of Applicability of Conventional and Adaptive Pushover Analysis for Seismic Response Assessment”, Civil and Environmental Engineering Department, University of Illinois, 2005.
9. Oguz S., “Evaluation of pushover analysis procedures for frame structures”, Master thesis, Middle East Technical University, 2005.
10. Fragiadakis M., Vamvatsikos D., and Papadrakakis M., “Evaluation of the influence of vertical Stiffness irregularities on the seismic response of a 9-story steel frame”, In Proceedings of the 4th European workshop on the seismic behavior of irregular and complex structures, CD ROM, Thessaloniki, 2005.
11. Baker J. W., and Cornell C. A., “A vector-valued ground motion intensity measure consisting of spectral acceleration and epsilon”. Earthquake Engineering and Structural Dynamics, Vol. 34, NO. 10, pp. 1193–217, 2005.