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STUDY OF THE SEISMIC RESPONSE OF R. C. HIGH-RISE BUILDINGS WITH DOUBLE TRANSFER FLOORS

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ABSTRACT

In multifunctional high rise buildings; the transfer systems are introduced to redistribute vertical and lateral loads from the discontinued columns in the upper floors to the lower levels of the building. Only high-rise buildings with single level of transfer floor were mostly studied. However, in some cases the architect may require two or more levels of transfer and it is expected to vary the building response; therefore further studies must be focused on these cases. A number of buildings with different altitudes of double transfer floors were analyzed using nonlinear time history technique using 3D finite element models. The global seismic responses of the buildings were evaluated. In addition, the optimum vertical position of the double transfer was investigated to minimize the bad effect of the transfer floor existence. It can be concluded that the worst seismic performance is in case of buildings with the lower altitude and nearer spacing of the double transfer floors also the irregularity arising from the soft story phenomenon is more pronounced. Additionally, as the distance between the double transfer floors increased, the building stiffness was reduced and therefore the soft story irregularity probability was increased.

KEYWORDS: Double transfer floor, Soft story mechanism, P-delta effect, Time history analysis.

1. INTRODUCTION

In many high-rise buildings, architectural requirements may result in a variable configuration for the vertical structural elements (columns and shear walls) between stories. To accommodate this vertical elements' discontinuity, a transfer floor must be introduced as shown in Fig. 1. A transfer floor (transfer thick slabs, trusses or transfer deep girders) causes the sudden change in the building's lateral stiffness at its level and the structure becomes susceptible to the formation of a soft story mechanism

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under earthquakes. Previous studies focused on the seismic behavior of high-rise buildings with only one level of transfer floor with different systems and different vertical positions. As the transfer floors are needed in more than one level in many of multifunction high-rise buildings; it is expected that these will change the building response. The seismic behavior of high-rise buildings with multiple transfer levels should thus be examined.

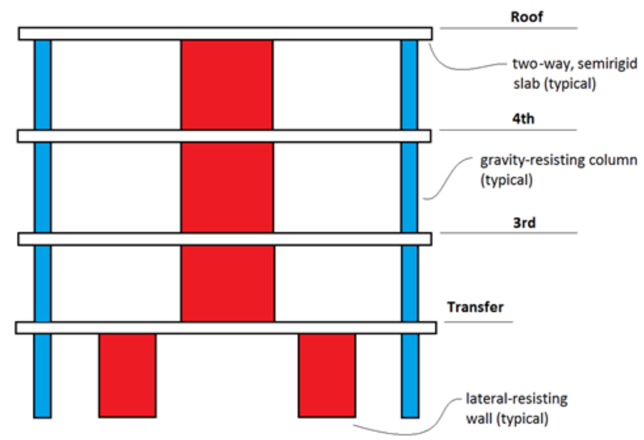

Fig. 1. Concept of the transfer systems in buildings.

2. LITERATURE REVIEW

Yousef et al. studied the nonlinear seismic behavior of vertically irregular reinforced concrete moment-resisting building frames [1]. Seismic analysis of 82 ductile moment-resisting regular and vertically irregular multistory buildings has been carried out. The reliability of the criteria provided by different codes, in order to distinguish the regular from irregular building frames has been verified. The results showed that the limits in UBC-97 and ECL-08 aimed to identify the lateral stiffness are satisfactory and can be relaxed by about 10%. The limit of story mass irregularity recommended by UBC-97 leads to severe "non-conservative" results; and therefore, it needs to be modified. The limit identifying setback irregularity of frames at the lower 15% of the total height of the frame gives poor results and it is proposed to change this limit to become 30% of the total height of the frame. Abdlebasset et al. presented a state of the art review on recent publications dealing with the seismic behavior of high rise buildings with transfer floor [2]. The transfer system deformation is still ignored and assumption of rigid diaphragm is adopted in design, this concept is not quite correct and simulation in 3-D model should be done using solid element which will lead to stiff transfer system with high shear and flexural stiffness which reduces the deformation of the transfer system under lateral loads. Irregularity in upper stories would have a little effect on the floor displacements, while, irregularity in lower stories would have a significant effect on the height-wise distribution of floor displacements. Vertical location of transfer floors with respect to total height of the building has a significant effect on high rise buildings performance; introduction of the transfer floor in the lower part of the structure (20-30% of the total height of the structure from its foundation) is better than having it in a higher location. Abdlebasset et al. constructed the 3-D numerical model for a high-rise building with transfer floor and analyzed using response spectrum and nonlinear time-history analysis techniques [3]. The effect of the transfer floors on the buildings' drift and internal forces is investigated using a full or reduced stiffness for the vertical elements. They concluded that for drift and lateral displacement checks, gross inertia may be used in the analysis. For strength design, cracked inertia of sections can be used. Elawady et al. performed a comparative study for the seismic response of high-rise buildings with transfer floors [4]. 3-D finite element models were analyzed using elastic linear response spectrum and inelastic nonlinear time history techniques. The comparative studies are investigated for different systems and different vertical position for transfer floor. The results showed the localization of damage at both the level of the transfer floor and the first floor. The location of the transfer floor affected the global seismic response of the structure. The transfer girders system is a preferred more than the slab system. Gang Li et al. proposed an integrated seismic optimum design approach for the high-rise buildings with girder transfer floor, including topology optimum design of the transfer floor and size optimum design of beams and columns [5]. First, the girder transfer floor is optimized to obtain the optimum topological form of the transfer floor. Then the size optimum design of beams and columns is performed. The initial cost and life cycle cost are employed as the objective function in the seismic design, respectively. Finally, a numerical example of 23-story high-rise building is calculated. Li et al.

aimed to study the behavior of high-rise building with transfer slab, Micro-concrete shaking table test 1:20 was constructed [6]. The prototype consisted of 34 stories in addition to three parking floors and a 2.7 m transfer slab. The numerical analysis was carried out using ETABS. It observed that the largest story drifts occurred at the stories above the transfer plate and the upper stories. The transfer slab was responsible of almost 76% of the of the stiffness drop in the floors near the transfer level. Wu et al. carried out Shaking-table tests of three scaled models of tall buildings with a transfer story at story five, seven or nine, respectively [7]. The experimental results showed that with increasing transfer story level the natural frequencies of the structures show little change and the change of mode shapes is not significant. Elastic and elasto-plastic time history analyses of tall buildings were performed. The analytical results showed that for tall buildings with a high-level transfer story the maximum elastic interstory drift ratios become small at the transfer story. Reducing the stiffness below the transfer story will increase the interstory drift ratio. Abdul Sameer et al. investigated the seismic performance of the buildings with transfer plate provided in two different building models shear wall frame (SWF) and moment resisting frame (MRF), which further divided into two conditions in which the height of the building and the height of transfer floor itself is taken as variable [8]. Different buildings with story conditions are modelled using SAP 2000. Transfer Plates with depths ranging from 1m to 3m are used. In SWF models, shifting the transfer slab position to seventh floor level increased the performance, whereas in MRF models the transfer slab located at the lower level gave good results. Osman et al. examined the structural behavior of high-rise buildings utilizing thick transfer plate slabs between their tower and podium floors [9]. The effects of different design aspects such as transfer slabs span to thickness ratio and stiffness on the structural behavior of such structures are investigated. It was concluded that interaction between the transfer plate slabs and supporting tower can significantly affect the calculated straining actions within tower structural elements and consequently should be accounted for during analyzing the structure. Lande et al. constructed a number of proto-type models of high rise building and were analyzed using linear response spectrum analysis [10].

The models were analyzed using ETABS. The analyzed models have transfer slab system at different floor levels in high rise building. The seismic response of high rise building such as story shear, story moment, and story displacement, inter-story were numerically evaluated. They concluded that vertical location of transfer floors with respect to total height of the building has a significant effect on buildings performance. Also, introduction of the transfer floor in the lower part of the structure (20-30% of the total height of the building from its foundation) is better than having it in a higher location.

3. OBJECTIVE

The main objective of this paper is to examine the seismic behavior of high-rise buildings with double transfer floors compared to standard building with no-transfer floors. The optimum location of double transfer floor to minimize the bad effect of the transfer floor existence is then investigated.

4. MODELLING AND ANALYSIS

4.1 Building Description and Modeling

The building considered is a 45 story, 135 m high-rise reinforced concrete (RC) building. The plan area of the structure is 25m × 25m with columns spaced at 5m from center to center. The height of each story is 3m. The buildings was modeled as three-dimensional multi– story concrete frames with a 5% damping ratio. The slab thickness was chosen to be 250 mm to keep the slab safe against the vertical loads, punching load, and deflection. The columns sizes are considered as 300×1200 mm with steel reinforcement 20φ20 and shear wall is considered as 300×3000 mm. Grade 30 concrete (compressive strength 30 N/mm²) is considered throughout the height of the building. Figure 2 shows the typical plan with the locations of the planted columns. The analyses are based on the assumptions that the building's models were assumed regular in plan; neglecting soil-structure interactions (fixed supports) for all columns and walls. Columns were modeled using frame element while the slabs and shear walls were modeled using shell-thin element. The transfer slabs were also modeled using shell-thick element. The sectional properties of the walls and columns are uniform throughout the height.

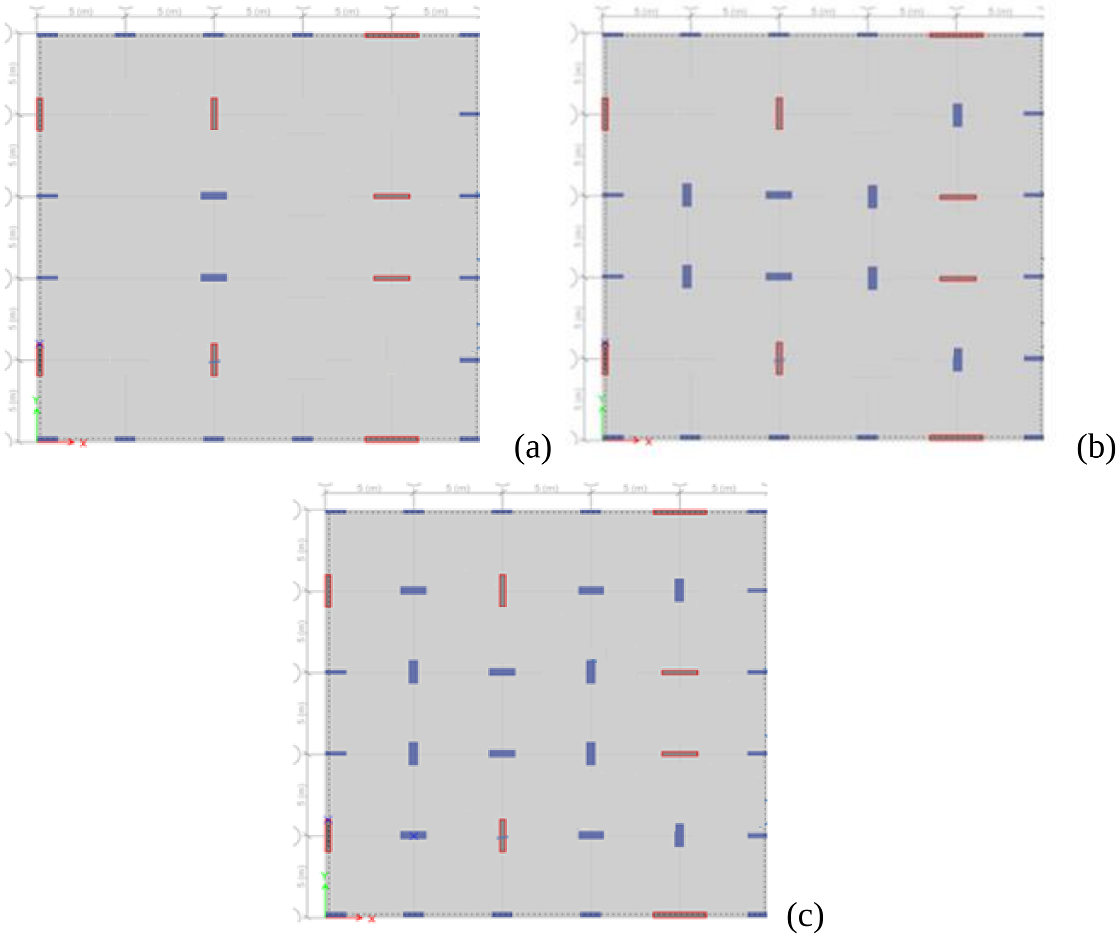

Fig. 2. Typical Plans with the locations of the planted columns (a) from ground to 1st transfer level (b) between 1st and 2nd transfer levels (c) from 2nd transfer level to roof.

As shown in Fig. 3, there are six cases of transfer slab types represented at variable heights. These 6 cases are (20%+80%H), (20%+60% H), (20%+40% H), (40%+80% H), (40%+60% H) and (60%+80% H) where H is the total height of the building measured from its foundation. The case of (60%+80% H) is the empirical case for comparisons only. The designed transfer slabs have variable dimensions depending on their vertical position. Table 1 lists the dimensions of the transfer slabs at different levels in the building.

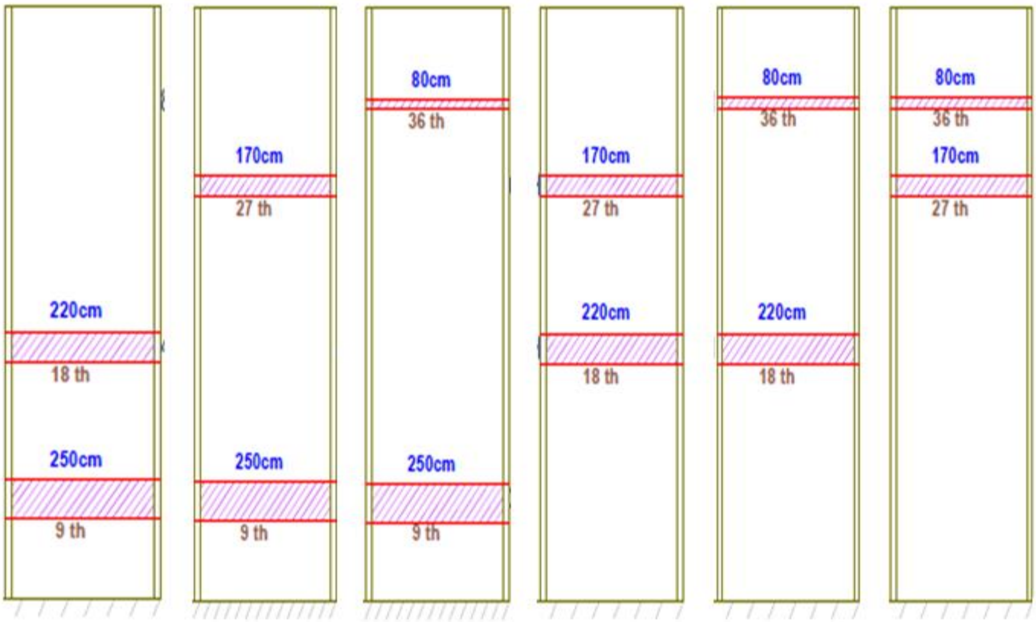

Fig. 3. Six combinations for double transfer floor showing the different levels and different transfer slab thickness.

Table 1. Dimensions of the transfer slabs for the six combinations

Case	Position of the transfer floor	Floor @ level	Transfer Slab thickness, m
1	20% + 40%	9	2.50
		18	2.10
2	20% + 60%	9	2.50
		27	1.70
3	20% + 80%	9	2.50
		36	0.80
4	40% + 60%	18	2.20
		27	1.70
5	40% + 80%	18	2.20
		36	0.80
6	60% + 80%	27	1.80
		36	0.80

4.2 Description of Loadings

The dead load is the building own weight. Flooring covering load and live load are considered distributed on the slabs at 1.5 kN/m^2 and 2 kN/m^2, respectively. The selected earthquakes were Northridge 1994, Kobe 1995 and El Centro 1940 with low, moderate and high peak ground accelerations (PGA) and these are scaled to be 0.3g for comparisons. Table 2 and Fig. 4 show the different characteristics of the earthquakes used in the study (a) Kobe 1995, (b) El-Centro 1940 and (c) North Ridge 1994, respectively.

Table 2. Different characteristics of the earthquakes used in the study.

Earthquake	Mw	Station	PGA (m/s$^{2)}$	PGV (m/s)	EPD (km)
El Centro	6.1	El Centro	0.32 g	9.26	11
Kobe	6.7	Nishi-AKashi	0.82 g	11.2	9
North Ridge	6.9	California	0.15 g	3.1	15

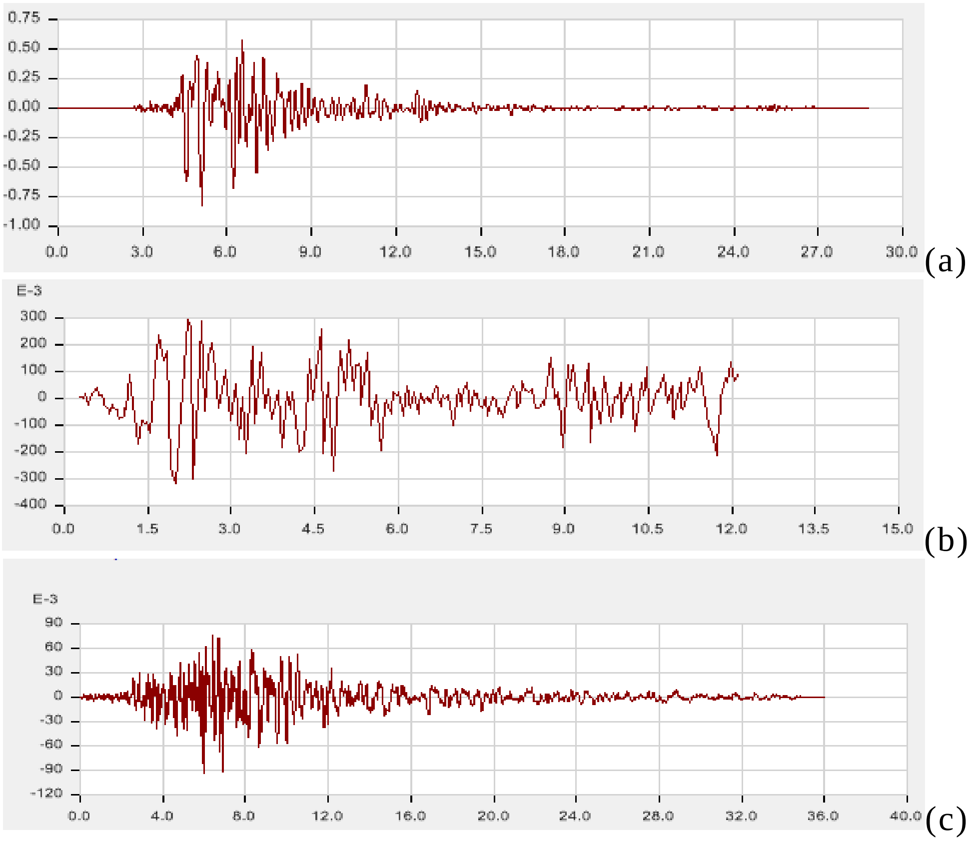

Fig. 4. Acceleration records of the selected earthquakes
(a) Kobe, (b) El Centro and (c) Northridge.

4.3 Analysis Types

The analyses were carried out using the software package ETABS. The material nonlinearity associated with the inelastic behavior of reinforced concrete has been neglected is this study. Only the geometric nonlinearity is considered based on P-Delta effect based on mass source. Mass source is a mass multiplier for live load taken at 0.25. This means that only 25% of live load is to be considered for calculation of seismic weight. The structural members were assumed to be cracked, the effective inertia for the slabs (I_{eff}) equals 25%, while the effective inertia is taken as 50% for beams and 70% for both columns and shear walls of gross inertia (I_g).

5. RESULTS

The results are obtained from the three earthquake records with different intensities on the six building combinations. The maximum values of the results from the three responses resulting from three scaled earthquakes are taken and compared according to the Egyptian Code for Loads and Forces in Structural Works, 2012 [11]. The comparative studies have been carried out to observe the change in parameters such as lateral story displacements, story drifts and story and base shear and time period. The soft story formations due to existence of transfer slabs are also investigated.

5.1 Building Responses

Figures 5-7 and Table 3 show the story displacement, drift and shear force for the six combinations for building with double transfer floors with various locations of transfer floors, and standard building without transfer floor.

In the buildings with double transfer floors, there are three regions; the first and second regions have a fixed – fixed behavior while the third part has a fixed – free behavior. As the altitude of upper transfer floor increased with respect to lower transfer floor; its mass is reduced and the effect of fixed free behavior is reduced as shown when comparing the cases 20%-40%, 20%-60% and 20%80%. As the separation distance in the second part increased; the effect of double fixation is reduced as shown when comparing the cases 20%-40%, 20%-60% and 20%-80% and the cases 40%-60% and 40%80%. As the separation distance in the first part increased; the effect of double fixation is reduced as shown in cases 20%-80%, 40%-80% and 60%-80% and cases 40%-80% and 60%80%.

The maximum drift in the first part of the building (i.e. below the first transfer floor) occurred at mid height between base and first transfer floor level. This amplification in drift is reduced as the altitude of first transfer floor increased. In the second part of the building (i.e. between the first and the second transfer floors); it is noted that the maximum drift value occurred at mid height between first and second transfer floor level. The closer distance caused de-amplification in story drift. As the separation distance increased; the amplification in drift is reduced. For the third part (i.e. above second transfer floor); the story drift was reduced when compared to the standard case as the upper part decreased due to the cantilever action in this part is reduced.

Regarding the shear force distribution, existence of transfer floor caused abrupt reduction in shear above transfer floor level due to large mass. This abrupt reduction is diminished as the altitude of transfer floor is increased due to reduction of transfer floor mass. As the altitude of first transfer floor level is reduced; the shear force is amplified. When the distance of the second part increased the amplification in shear was reduced. On the other hand; the shear force is reduced for higher altitude of first transfer floor level from the base and as this altitude increased as the de-amplification increased. For cases 20%-40%, 40%-60% and 60%-80% (the closed double transfer level) the shear force between them is converted from amplification to de-amplification as their altitude is increased measured from the base.

The graphs showed that the building with transfer floors at 20% + 40% had the maximum values for the story displacement, drift and shear due to the large masses of transfer floors as designed accordingly to sustain vertical loads and caused amplifications in building responses when compared with the standard case. On the other hand, the minimum values of the lateral displacement, drift and shear were found in the building with transfer floors at 60% + 80% where the transfer floors placed at higher altitude with small masses according to their design and caused reductions in building responses when compared with the standard case.

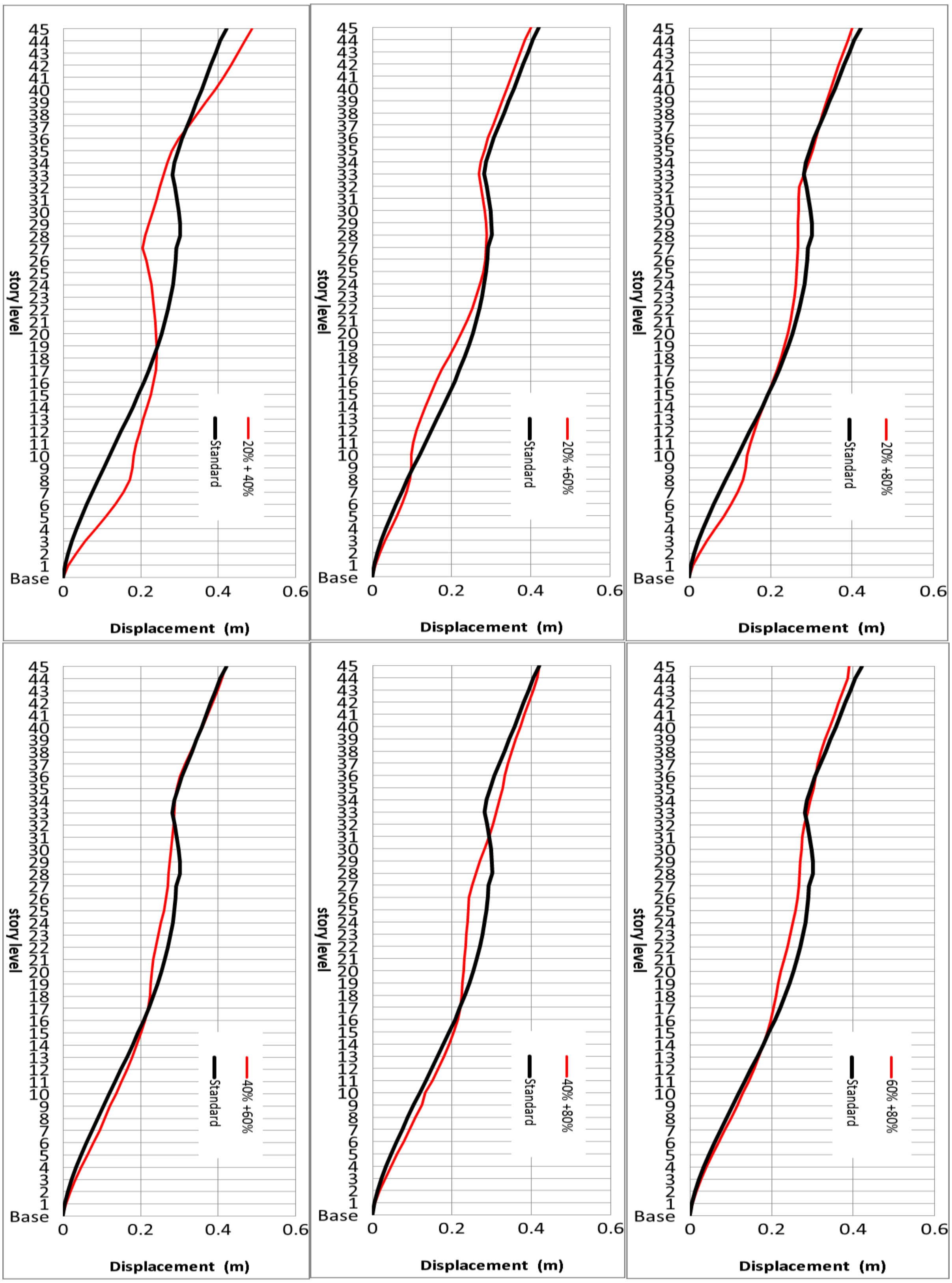

Fig. 5. Story displacements for the six combinations
for building with double transfer floors.

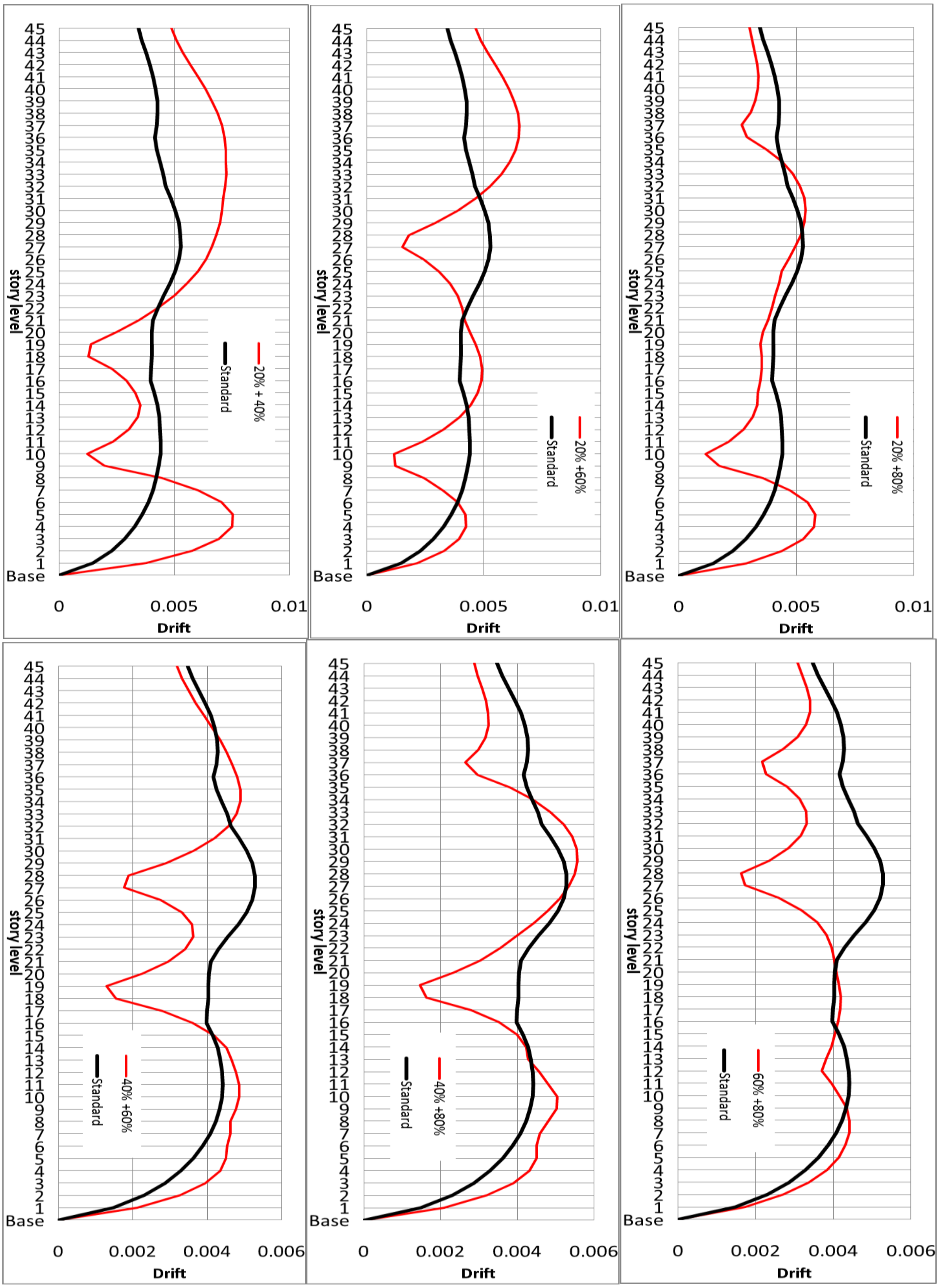

Fig. 6. Story drift for the six combinations for building with double transfer floors.

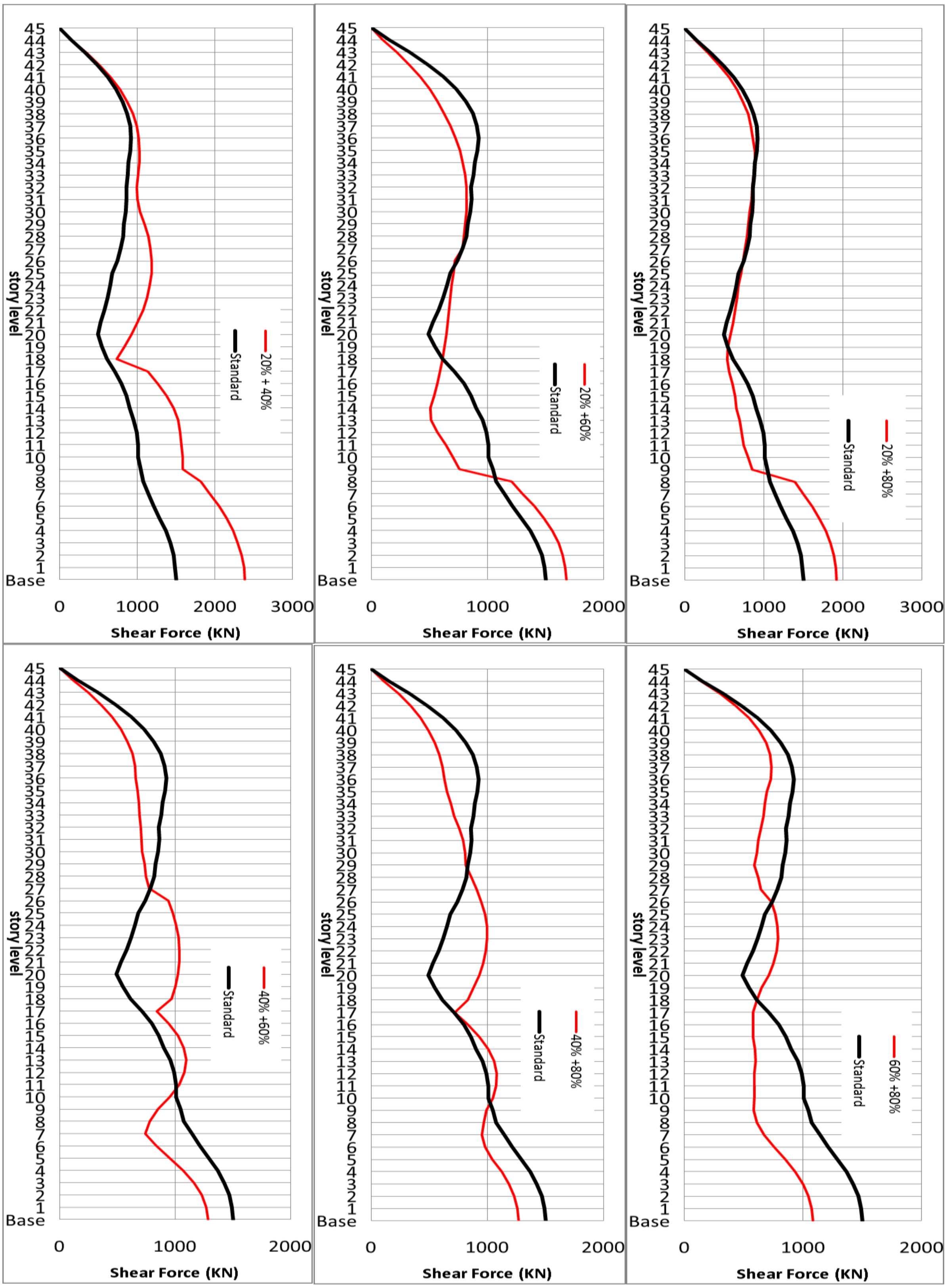

Fig. 7. Story shear for the six combinations for building with double transfer floors.

Table 3. Story displacements, drift and shear force for six combinations of buildings with double transfer floors and standard building without transfer floor.

Levels of H%	20% +40%	20% +60%	20% +80%	40% +60%	40% +80%	60% +80%	Standard
Displacement, m	0.487	0.401	0.400	0.421	0.420	0.390	0.421
Ratio	115.7%	95.2%	95.1%	99.9%	99.8%	92.7%	------
Drift	0.0075	0.0065	0.0058	0.0049	0.0056	0.0044	0.0053
Ratio	143%	124%	110%	93%	105%	83%	-------
Shear force, kN	2393	1681	1921	1289	1271	1086	1502
Ratio	159%	112%	128%	86%	85%	72%	-------

It is seen that the buildings, where the transfer floors were at highest altitude from the base and closer to each other, had smoother drift profile and shear profile and were closer to the standard profiles. This is observed in the case of building with transfer floors at 60 % + 80%. Therefore, the closer distance between the two transfer floors, did not cause the better the performance of the structure and produced rougher response profiles especially in cases of lower altitude of transfer floors.

5.2 Building Time Period

Table 4 presents the time period for the six studied buildings with double transfer floors various locations compared with the case of the standard building without transfer floor. It is known that reducing the time period will decrease the serviceability parameters such as the lateral displacement. However, it will increase the straining actions of the buildings such as the story shear.

It was noted that the existence of transfer floors decreased the fundamental period of the buildings. The large mass of the transfer floors caused more reduction in the periodical time of the buildings. The building with lower altitude of double transfer floors with closer spacing between them (20%-40% case) had smaller time period. This is due to heavier transfer floor i.e. increased building stiffness and this led to increase the seismic response of the building. On the other hand, the building with higher altitude and closer distance of double transfer floors i.e. (60%-80%) case; had larger time period due to lighter weight of transfer floors that caused smaller increases in building stiffness and this led to reduce the seismic response of the building. When compared with the cases of building with double transfer floors at (20%-40%), (20%-60%), and (20%-80%), it is noted that as the distance between the double transfer floors increased the time period increased i.e. the building stiffness is reduced. This observation could be reach when compared with the cases of buildings with double transfer floors at (40%-60%) and (40%-80%). This is also seen with the previous reduction in buildings shear response and increased displacement and drift responses when compared with the standard case.

Table 4. Time period for the six combinations for building with double transfer floors and the standard buildings.

Levels	20%+ 40%	20%+ 60%	20%+ 80%	40%+ 60%	40%+ 80%	60%+ 80%	Standard
Time Period, sec.	6.145	6.537	6.962	6.941	7.276	7.76	8.075
Ratio W.R.T standard	76%	81%	86%	86%	90%	96%	------

5.3 Soft story formation

There were two major types of irregularities in buildings; the plan irregularities and vertical irregularities. Vertical irregularities were associated with the dynamic forces distribution, load path and force transfer. The irregular structures form localized force concentrations that require special measurements to rectify the expected extra forces effect. The transfer floors, made irregularly, changed the load path as a result of huge load concentrations and stiffness variations which are expected to occur at the vicinity of the transfer floors.

The soft story failure is the main cause of vertical irregularities. This phenomenon happened when one or multiple floors had significant change in stiffness. These kinds of structures exhibited a less safe behavior more than the similar regular structures. This was due to the concentration of damage at the soft story level and to the corresponding excessive inter-story drift. According to Chinese National Specification (2010) [12], a soft story, irregularity in lateral stiffness, is defined as:

1. Criteria A: If the story stiffness of the questioned story is less than 70% of the story above.

2. Criteria B: If the story stiffness of the questioned story is less than 80% of the average stiffness of the upper three stories.

Figure 8 illustrates the soft story vertical irregularity check. If the structure is more than five stories and the total height of the structure is more than 19.5 m, it is subject to this type of irregularity. If one of the two tests criteria were met, then the floor is considered as soft story.

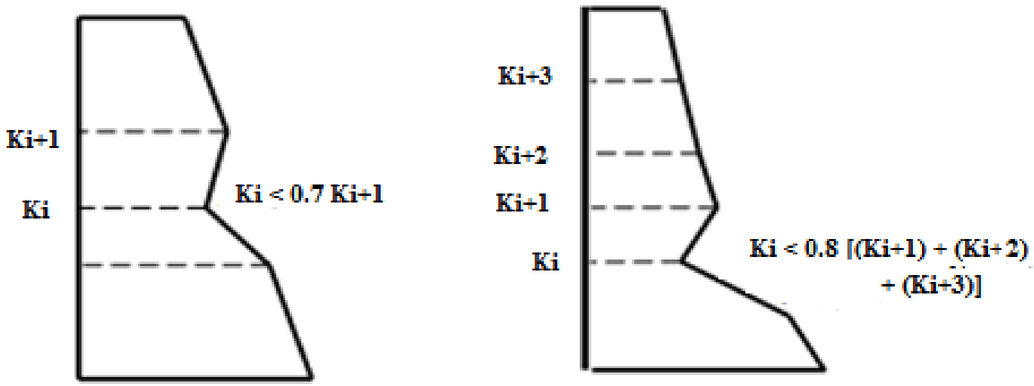

Fig. 8. Soft story checks according to Chinese national specification [12].

Figure 9 and Table 5 show the soft story analysis for the buildings with double transfer floors at different levels combinations according to criteria A and criteria B. It was noted that the building with lower altitude of double transfer floors with closer spacing between them (20%+40% case) were more vulnerable towards soft story stiffness irregularity due to high masses of both transfer floors. On the other hand, the building with higher altitude of double transfer floors and also closer spacing of double transfer floor (60%+80%) had less soft story failure ability due to lighter masses of both transfer floors. For buildings with closer transfer floors, as their altitudes increased from the base; the irregularity raised from soft story mechanism was diminished. This was observed in (20%+40%), (40%+60%) and (60%+80%) cases. As the spacing between both transfer floors increased, the soft story irregularity increased. This is because the high variation of both transfer floors masses.

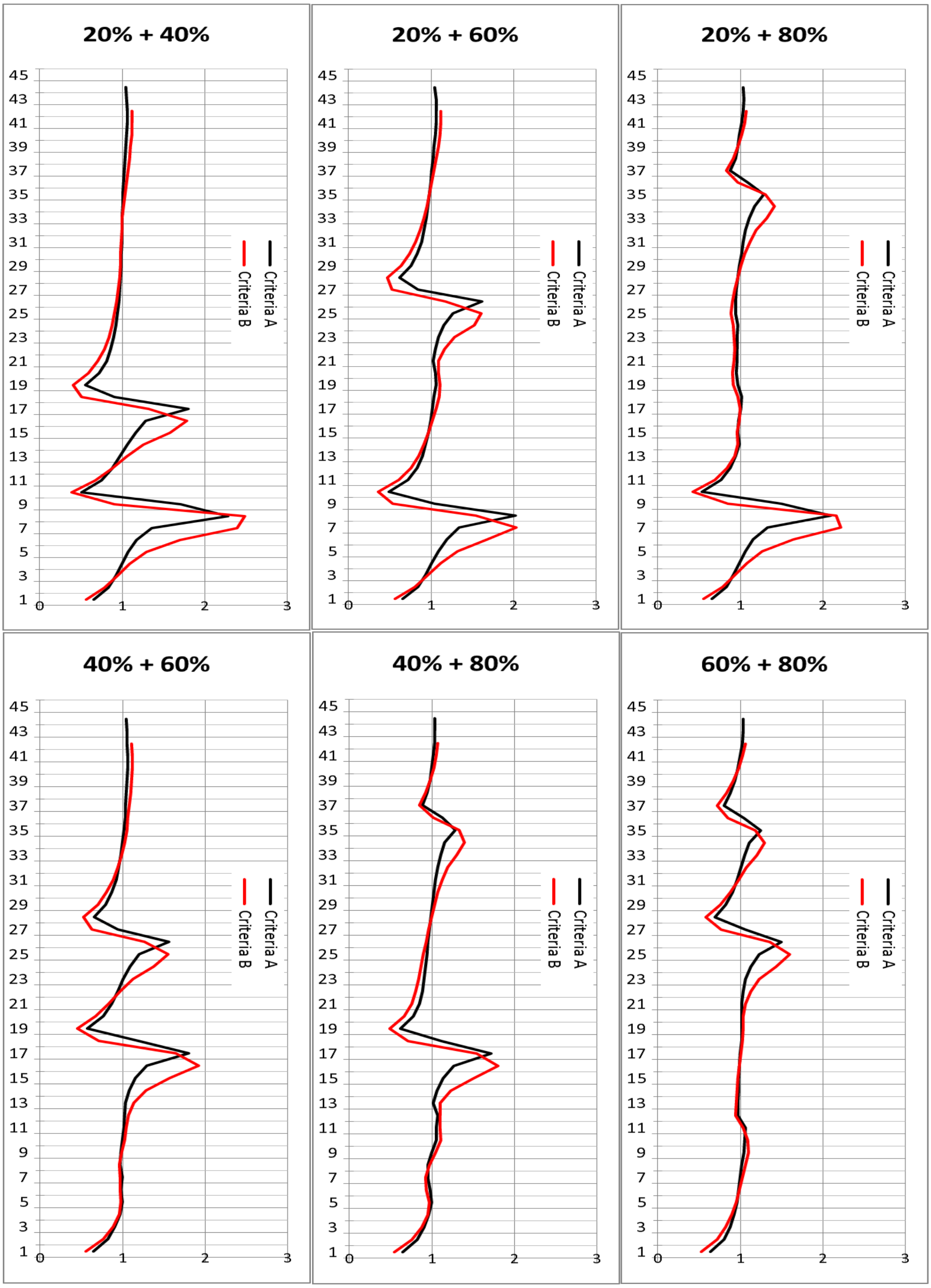

Fig. 9. Soft story analysis for the buildings with double transfer floors at different levels combinations according to criteria A and criteria B.

Table 5. Soft story analysis for the buildings with double transfer floors at different levels combinations according to criteria A and criteria B.

Reduction value	Criteria	20%+ 40%	20%+ 60%	20%+ 80%	40%+ 60%	40%+ 80%	60%+ 80%
T.F @ Level 1	A	0.554	0.614	-	0.650	-	-
	B	0.405	0.472	-	0.526	-	0.716
T.F @ Level 2	A	0.504	0.489	0.538	0.575	0.621	0.693
	B	0.390	0.362	0.426	0.452	0.489	0.584

6. CONCLUSIONS

Based on the above results, the following conclusions can be drawn:

1. The building with lower altitude of double transfer floors and closer distance between them had smaller time period. This was due to heavier transfer floor i.e. increased building stiffness and this led to increase the seismic response of the building; and the soft story irregularity is pronounced.
2. As the distance between the double transfer floors increased, the time period increased i.e. the building stiffness reduced and this caused a reduction in buildings shear response but increased in displacement and drift responses when compared with standard case; in addition, the soft story irregularity increased due to high variation of both transfer floors masses.
3. As the distance between the double transfer floors increased, the time period increased i.e. the building stiffness reduced and this caused a reduction in buildings shear response but increased in displacement and drift responses when compared with standard case; in addition, the soft story irregularity increased due to high variation of both transfer floors masses.
4. The shorter the distance between the double transfer floors with higher altitudes with respect to building height, the better the performance of the structure and the smoother the response profiles. This is due to lighter weight of transfer floors that caused smaller increases in building stiffness and this led to reduce the seismic response of building; and the soft story irregularity is diminished.
5. The case of tall buildings having the lower altitude of double transfer floors with nearer spacing between is considered to be the worst in seismic performance.

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DECLARATION OF CONFLICT OF INTERESTS

The authors have declared no conflict of interests.

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دراسة الاستجابة الزلزالية للمباني الخرسانية العالية ذات ادوار انتقالية مزدوجة

تم في البحث اجراء دراسة تحليلية لتقييم الاستجابات الزلزالية غير الخطية لعدد من المباني العالية ذات ادوار انتقالية مزدوجة بمستويات مختلفة باستخدام نماذج عناصر محددة ثلاثية الأبعاد من خلال تقنية التاريخ الزمني الغير الخطي وتحديد الوضع الرأسي المثالي للأنظمة الانتقالية المزدوجة لتقليل تأثيرها السلبي على السلوك الزلزالي للمبنى وتمت ملاحظة أن أسوأ أداء زلزالي يحدث في المباني ذات الأدوار الانتقالية في المستويات المنخفضة والمتقاربة من بعضها البعض و بالإضافة إلى ذلك وجد انه مع زيادة المسافة بين الانظمة الانتقالية المزدوجة تقل جساءة المبنى وتزداد احتمالية عدم الانتظام الناتجة من تأثير الدور اللين.