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Seismic Behaviour of High-Rise Buildings with Transfer Floors

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ABSTRACT: A comparative analytical study for the seismic response of high-rise buildings with transfer floors is presented. A number of prototype models were analyzed using elastic linear response spectrum and inelastic nonlinear time history techniques using three-dimensional finite element models. The analyzed models had different transfer floor system: transfer slabs and transfer girders. The vertical position of the transfer system with respect to the building height was investigated. Global seismic response of the buildings such as storey shear and bending moment distribution, and inter-storey drift were numerically evaluated. The results showed the localization of damage in the vicinity of the transfer floor in addition to the first floor; the location of the transfer floor influenced the global seismic response of the structure. The numerical analysis revealed that the transfer girders system is a competitive alternative to the slab system in terms of reducing the seismic weights as well as the material cost with a slight change in the global seismic behaviour of the building. Transfer girders system is more flexible compared to slab system and generate lower straining actions on the structural vertical elements.

1 INTRODUCTION

In large and populated cities, the need to have buildings with various operational demands has been increased. To accommodate the multiple architectural requirements, the location, orientation, and dimensions of the vertical and lateral load resisting elements vary every certain number of stories. In such cases, a transfer floor is commonly used to solve this persistent structural-architectural conflict. A transfer floor is the floor system which supports a system of vertical and lateral load resisting elements and transfers its straining action to a different underneath system. Transfer systems are generally used in multi-function structures, in which the lower stories of the building usually are used as open public areas, while floors above that transfer system could accommodate typical residential or office spaces. Several structural systems could be used for such buildings as the lateral resisting system below/above the transfer floor may be moment-resisting frames, core walls and structural walls. The transfer structures may be in form of transfer girders or transfer solid or voided slabs.

Yoshimura (1997) and Li et al. (2006) argued that the immense change in the lateral stiffness at the transfer floor from a stiff shear wall system above to a relatively flexible column-girder system below may create a soft (or weak) storey and violates the seismic design concept of "*strong column weak beam*". Yoshimura (1997) also concluded that "*if first storey mechanism might occur, the collapse could be unavoidable even for buildings with base shear strength of as much as 60% of the total weight*".

Therefore, Yong et al. (1999) recommended that if this irregularity is not taken into consideration during design stages, the structural irregularity may become a major source of building damage during strong earthquakes.

Paulay and Priestley (1992) argued earlier that it is preferable to consider forces generated by earthquake induced displacements rather than traditional loads in structural design for earthquake resistance. Furthermore, in ductile response of buildings to earthquakes, high compression strains are expected in vertical elements due to the combined effect of the axial force and bending moment. Thus, unless adequate, closely spaced and well detailed transverse reinforcement is placed in the potential plastic hinge region, spalling of concrete followed by instability of the compression reinforcement will take place especially in cases of vertical irregularity where the theory of strong column-weak beam does not stand. That is why designers should seek to dissipate seismic energy primarily in well confined beam plastic hinges.

Paulay and Priestley (1992) also recommended that analytical models should be able to capture the localization of straining actions in the vicinity of (and at) the level(s) of discontinuity. The models should also be able to predict the magnitudes of such actions which are developed due to the seismic excitation.

In this paper, linear response spectrum and non-linear time history analyses are presented to provide a comparison of the seismic behaviour of two types of transfer floor systems: transfer girders and transfer slabs. The various positioning of the transfer floor with respect to the building's height is scrutinized. The analyses present the global seismic response of the structures: shear force distribution, base shear, storey moment distribution, and inter-storey drift distribution. High-rise buildings with different number of stories are considered in the comparative investigation.

2 PROTOTYPE BUILDING DESCRIPTION

A prototype building model was selected to be analyzed in the course of this study. The building has a footprint of 20.0 x 48.0 m as shown in Figure 1.

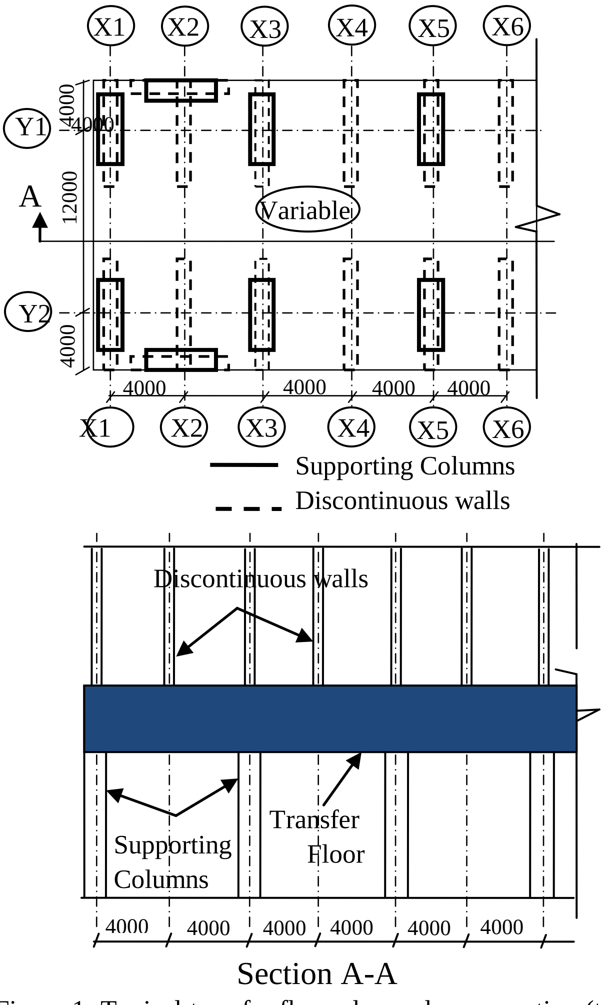

Figure 1. Typical transfer floor plan and cross section (transfer slab system).

Two groups of models were analyzed. The first one incorporates solid transfer slabs (plates) while the second group has transfer girders. The building plan was chosen to be biaxially symmetric to eliminate any torsional effect. The floor height above and below the transfer floor was taken to be 3.50 meters center-to-center of the floor slabs. Tables 1 and 2 show the models' matrix for all the analyzed models. Full details of the models are given by Elawady (2012). For each building height, four different transfer floor locations were studied. In case of adopting transfer girders system, all the slab thickness in the transfer floor was considered to be 0.16 m. These four locations of the transfer floors were chosen to cover all possible levels of the transfer floors which are 10% *H*, 20% *H*, 30% *H*, and 50% *H*; with *H* being the total height of the building measured from its foundation.

Table 1. Description of buildings models and dimensions

No. of Stories and model ID	Total Building Height	Transfer Type	Transfer Floor Dimensions: Slab Thickness	Transfer Floor Dimensions: Girders dimensions bxt
	m		m	m
75 storey tower	262.5	Slab	2.50	N/A
		Girder	0.16	G(1.7x3.5)
50 storey tower	175.0	Slab	2.00	N/A
		Girder	0.16	G(1.5x3.0)
25 storey tower	87.5	Slab	1.50	N/A
		Girder	0.16	G(1.0x2.0)
10 storey tower	35.0	Slab	1.00	N/A
		Girder	0.16	G(0.5x1.5)

Table 2. Description of buildings models and dimensions.

No. of Stories and model ID	Walls dims. above transfer floor	Walls dims. below transfer floor	Slabs thickness above/below transfer floor
	m	m	m
75 storey tower	0.35x9.0	1.25x5.0	0.2/0.4
50 storey tower	0.30x8.0	1.00x4.0	0.2/0.4
25 storey tower	0.225x6.0	0.70x3.0	0.2/0.4
10 storey tower	0.15x4.0	0.50x2.0	0.2/0.4

Figure 2 shows the finite element model adopted for one of buildings: the 25 storey high building with transfer floor at 25% of the height.

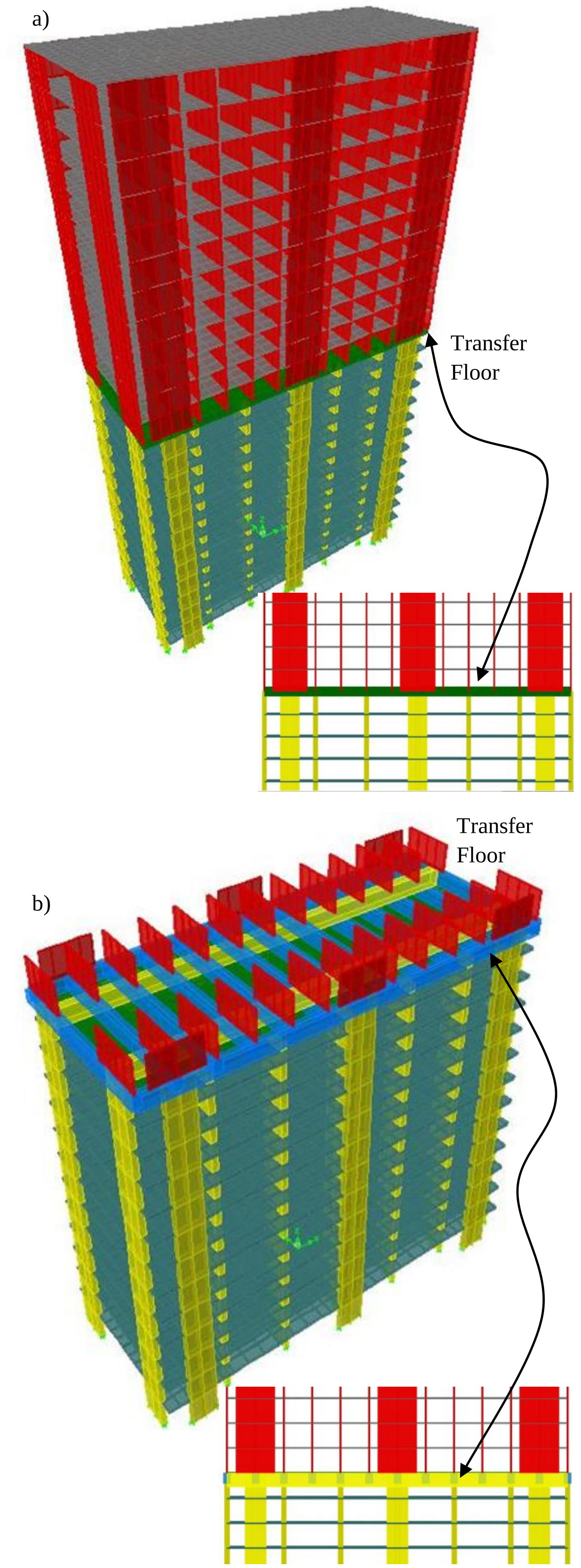

Figure 2. Finite element model for the 25 stories building model with transfer system at 50%H: a) transfer slab and b) transfer girder system with floors above the transfer level removed for purpose of illustration.

3 LINEAR NUMERICAL ANALYSIS

3.1 *Response Spectrum Function*

Response spectrum analysis was conducted on the models to evaluate the behaviour of the building. The modal analysis incorporated the first twelve vibrational modes using CQC combining sequence.

Figure 3 shows the design and maximum considered response spectra chosen for the conducted analyses. Cairo (Egypt), the location chosen for this study, falls under seismic zone 2A according to UBC 97. Soil type is selected to be SC (very dense soil and soft rock) for the underlying soil strata. The ductility reduction factor R of the lateral force-resisting system, was taken as 5.50. The live load seismic mass reduction factor was taken to be 0.50. The building floors were loaded such that for all typical floors above the transfer floor level and at the transfer floor, the super imposed dead load (floor cover is chosen to be 3 kN/m^2 and the live load is considered to be 2 kN/m^2. For all typical floors below the transfer floor level, the super imposed dead load and the live load are considered to be 4.5 kN/m^2 and 5 kN/m^2, respectively.

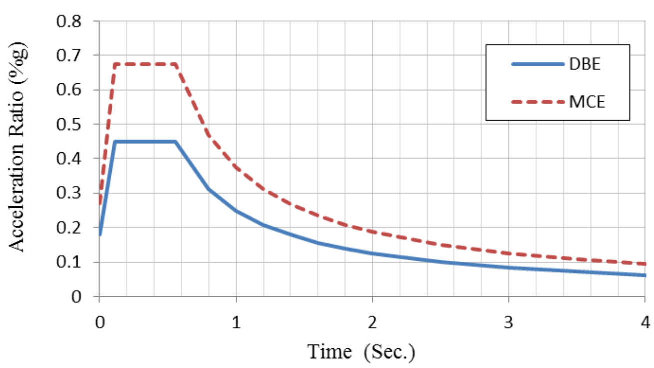

Figure 3. Response spectrum according to UBC 97 code of practice.

3.2 *Finite Element Simulation*

Ye et al. (2003) argued that a 3-D elastic analysis of a building's model for frequent earthquakes produces discrepancy in the natural frequencies of the first and second modes from those experimentally recorded by about 10%. As such, the accuracy of the finite element programs for these types of buildings is accepted.

A three-dimensional linear elastic model is constructed for each one of the 32 models shown in Table 1 and analyzed for various transfer floor locations. The finite element software package ETABS was used for the analyses. For slabs and walls, shell elements were used while for beams and girders, frame elements were adopted.

4 LINEAR ANALYSIS RESULTS

In this section a comparison between both girders and slab types of the transfer floor is presented for the 25 storey building. A more detailed comparative study is given for the rest of the buildings models elsewhere (Elawady 2012).

4.1 *Transfer Floor Level*

For the sake of evaluation of the effect of the transfer floor location within the building height, the building model with 25 stories was found to be most representative case; thus, only its results will be presented herein. Complete analyses and results for the rest of the buildings models (Table 1) are given elsewhere (Elawady 2012). The shear and bending moment distributions along the buildings height are shown in Figure 4. It is evident from this figure that a significant increase in the base shear is observed in the tower with the lowest transfer system located at 10% of the total building height. It should be noted that the storey shear force experience a significant reduction above the transfer location in all cases due to the abrupt reduction in the mobilized mass.

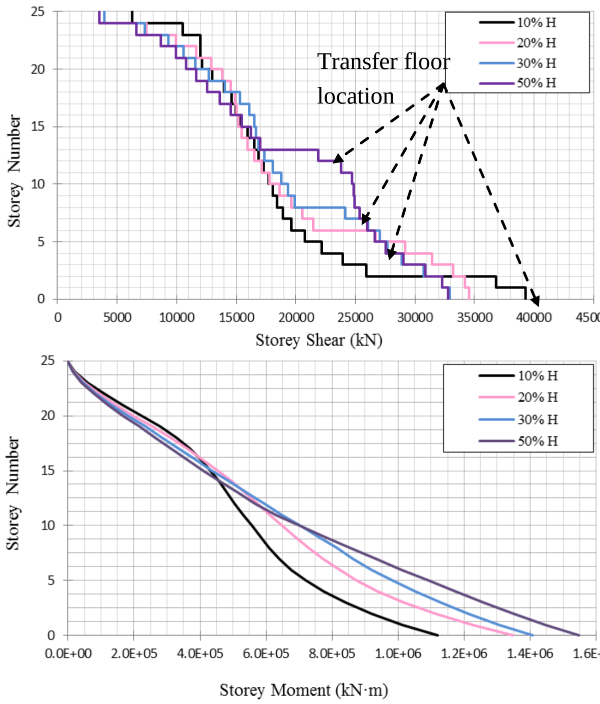

Figure 4. Storey shear (above) and storey moment (below) distributions for the 25 storey building model resulting from linear response spectrum analysis.

Chopra (2001) revealed that the contributions of higher modes are known to be significant, even in elastic systems. In this respect, the storey shear diagram suggests that the higher modes effect is significant especially in the buildings with lower transfer floor location (Elawady 2012). This may be viewed as a consequence of the tendency of the building with higher transfer floor to act as a single-degree-of-freedom system. Figure 4 shows that when the transfer floor lies at higher position, the total base moment increases and vice versa. This may be attributed to the huge seismic mass located at high location for higher transfer locations.

Figure 5 shows a plot of the inter-storey drift and displacement distribution over the building height. The figure reveals that the drift below the transfer floor reach a maximum value midway between the foundation and transfer floor level and then decreases gradually up to the transfer floor location. Above the transfer floor, the drift begins to increase till it reaches a maximum value in the vicinity of the roof level. For higher transfer floors, the abrupt change in the inter-storey drift above and below the transfer structure becomes more severe. It is noted that for buildings having a transfer floor at or above 50% of the total height, the maximum drift, affecting the response of the non-structural components and partitions as well as imposing high ductility demands on the structural elements, occurs under the transfer floor. This was observed via the analysis of the drift results of four different buildings with different heights for the investigated two types of transfer floors (Elawady 2012).

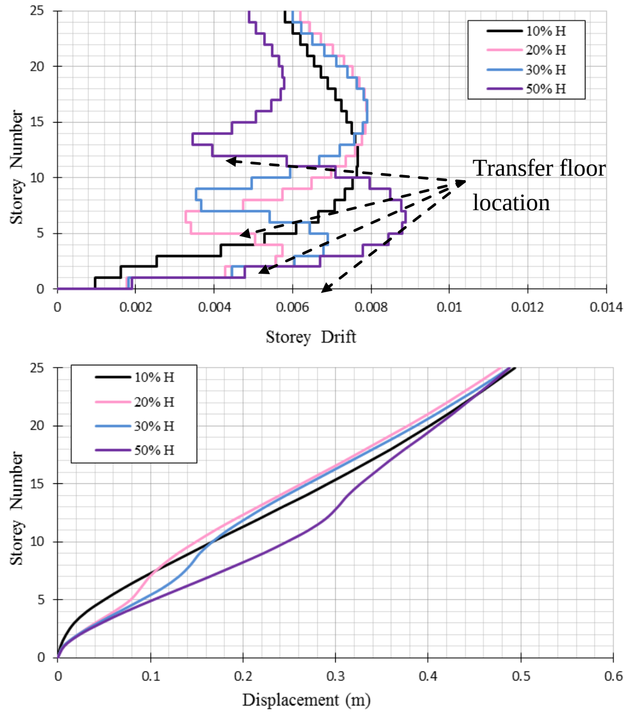

Figure 5. Storey drift (above) and displacement distribution (below) for the 25 storey building model resulting from linear response spectrum analysis.

Li et al. (2006) argued that drift ratio increases with the increase in the seismic load as well as the existence of irregularity in a building. The exact location of the damage due to vertical irregularities was thought to be below the transfer floor level; i.e. the location of the soft-storey mechanism. However, the current buildings models revealed that comparing the story drifts at the typical floors under moderate and major earthquakes reveals a 3.3 folds increase in the storey drifts above the transfer floor level and about 1.2 folds drift increment below it (Elawady 2012): this conclusion agrees with the argument raised by Li et al. (2006). Thus, it is argued that the majority of the damage would occur at the floors above the transfer floor level. This conclusion is pronounced for buildings with transfer floors located at lower levels; it is not applicable for buildings with transfer floors at or above 50% of the buildings height (Elawady 2012).

The displacement distribution shown in Figure 5 reveals that every building has a flexural behaviour mode up to its transfer floor level. At this level, a large inertial force hit the building due to the significant mass of the transfer level which results a large displacement. Due to the seismic energy dissipation which takes place at the location of the discontinuity, the drift decreases above this location.

This behaviour observed in the analysis and explicitly recorded by Elawady (2012) agrees with Yong et al. (1999) argument which states that above the transfer floor level, the building *almost* acts as a free cantilever with its fixation located at the transfer floor level with the rest of the building under the transfer floor *approximately* acts like a fixed-fixed flexural member.

4.2 *Transfer Floor Systems*

Figure 6 shows the effect of changing the transfer floor system on the values and distribution of the storey shear. The figure suggests that this change in the transfer floor system does not affect the distribution but results-in lower storey shear values for girders type transfer system.

It is evident from Figure 6 that the overall seismic response is not affected by changing the transfer system from slab type to girder type. However, this change significantly affects the design economy especially in the floors below the transfer floor level. This result is in an agreement with Su (2008) concepts which state that a deeper (or stiffer) transfer structure with higher flexural and shear stiffness can help decreasing the abrupt change in the shear forces in the exterior vertical elements. Such a deep element will eliminate transfer floor rotation effect which increases the straining actions on the external vertical elements due to the deferential rotations between the top and bottom of the wall.

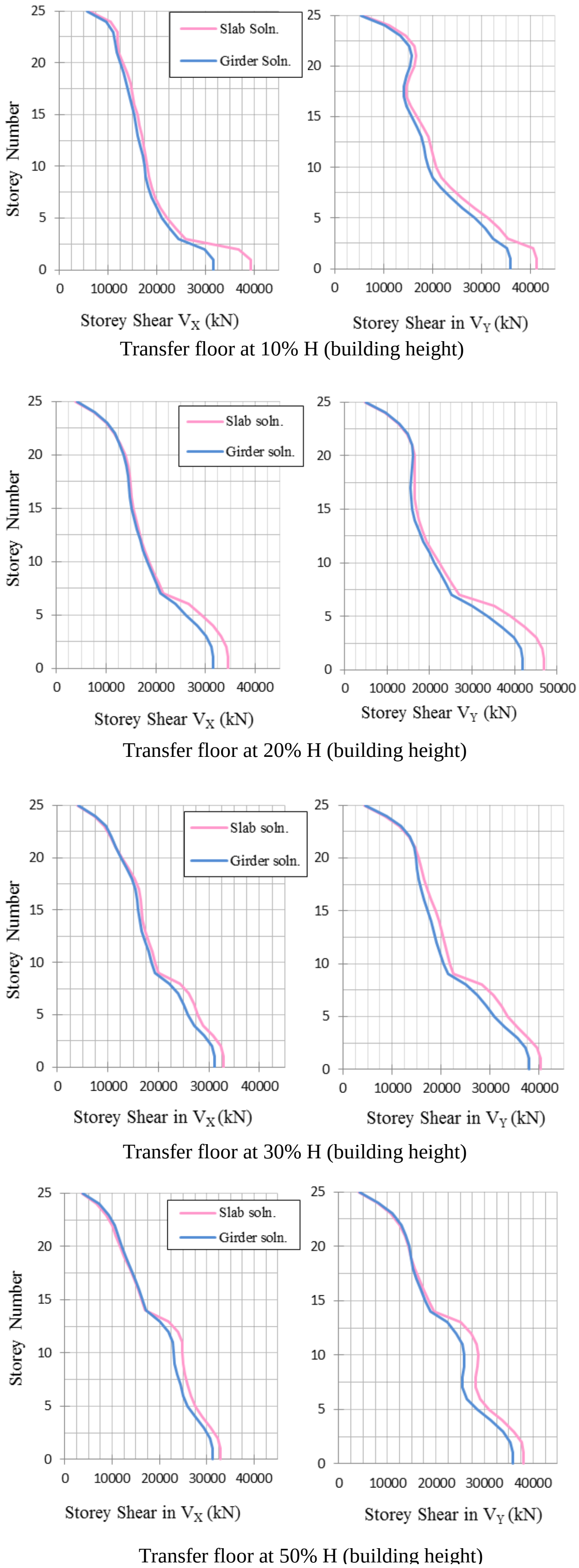

Figure 6. Storey shear distributions for buildings models resulting from linear spectral analysis.

The same response is also reflected in the storey moment distribution which as shown in Figure 7.

As shown in Figure 8 (drift plots), girders type transfer system shows a more flexible behaviour than slab type especially at the transfer floor level and above it. The drift values are affected by the flexibility of the girders system which affects the zones in the vicinity of the transfer floor.

Yong et al. (1999) argued that seismic energy dissipation occurring at the discontinuity location causing the displacement to continue to decrease above the transfer floor. Thus, roof displacement by itself is not a suitable serviceability measure for the structure as the behaviour changes through the height of the structure.

However, if this displacement is used, for instance, to prevent the pounding of the structure with a neighboring one, it should be indicated that all the buildings with the same height experienced approximately the same roof displacement.

This conclusion is not suitable for taller buildings especially in case of higher-level transfer floor.

All the previous results are summarized numerically in Table 3 which also reveals the percentage of reduction in both base shear and moment when adopting transfer girders instead of transfer slab.

5 NONLINEAR NUMERICAL ANALYSIS

The importance of performing a nonlinear time history dynamic analysis was argued by many researchers (e.g. Elnashai 2002) particularly for high-rise buildings with vertical irregularities such as transfer systems. This kind of analysis would as well take into consideration the strong-motion characteristics, especially duration, frequency content and near-source features. Despite its simplicity, it was also argued that the currently adopted spectrum scaling technique is unjustifiable and basically incorrect particularly for buildings with vertical irregularities.

The numerical investigation presented herein is intended to investigate the material nonlinear seismic behaviour of high-rise buildings with transfer floors. The analysis considers only the girder type transfer system as its seismic behaviour was found to be similar the transfer slab system (Elawady 2012). A parametric study was conducted on the building models which have 25 storey as it is found to be the most representative model among all the linearly analyzed models. Four different levels for the transfer floor were adopted: at 10%, 20%, 30% and 50% of the total building height. The time history record Chi-Chi (Figure 9) was chosen to be the major record for all models.

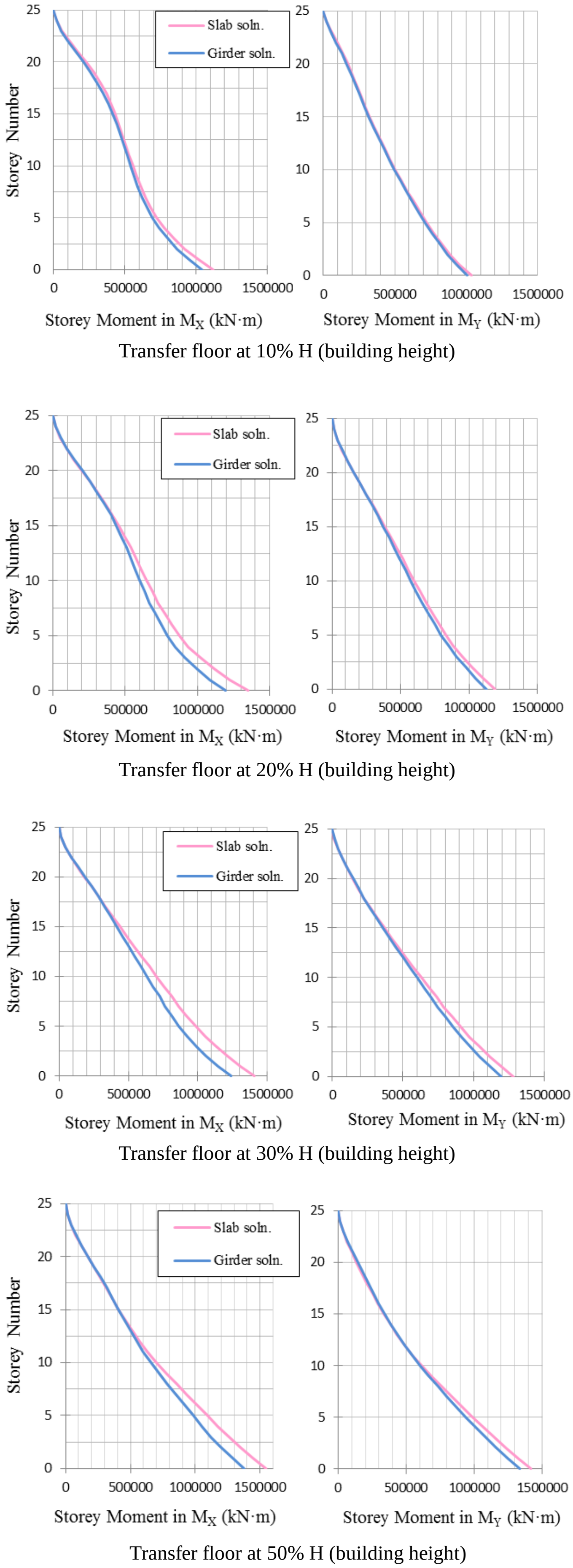

Figure 7. Storey moment distributions for buildings models resulting from linear spectral analysis.

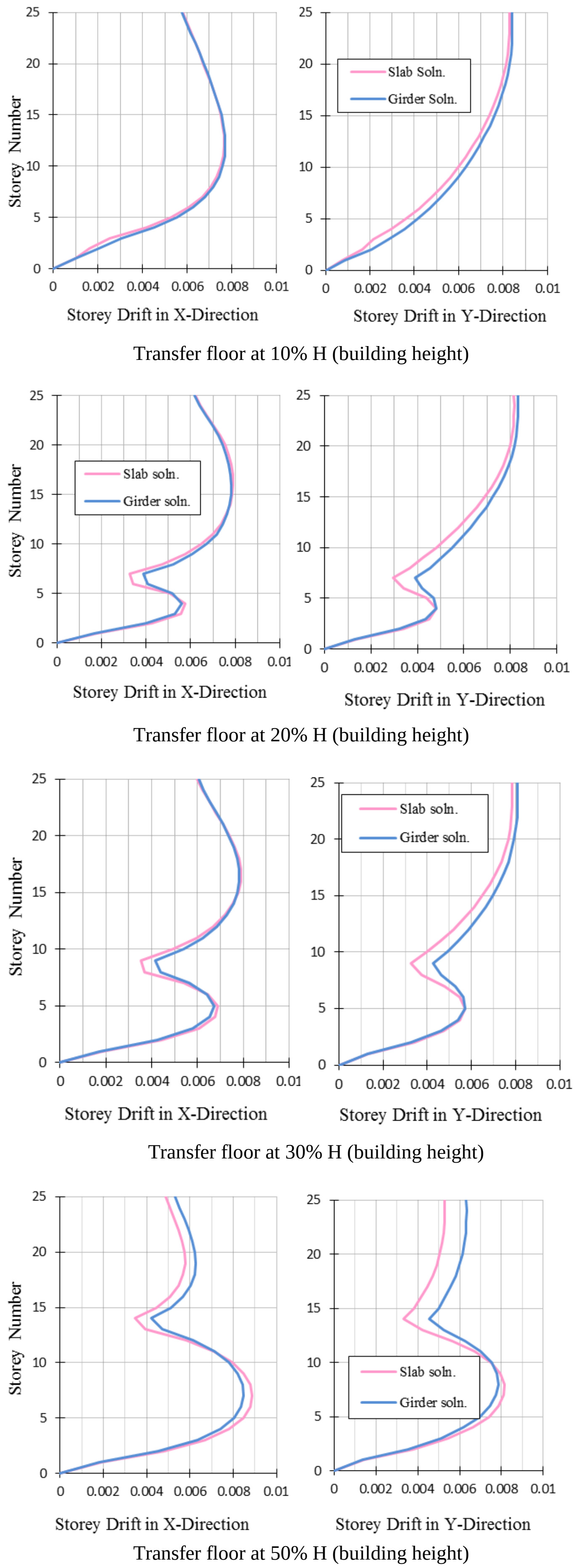

Figure 8. Storey drift for buildings models resulting from linear spectral analysis.

Table 3: Base shear and moment resulting from linear spectral analyses for all buildings models (MN, m units).

Bldg	Action	Transf. Type	Transfer level with respect to *H* 10%*H*	20%*H*	30%*H*	50%*H*
75-Storey	Base Shear V_x	Slab	69	54	54	59
		Girder	66	53	53	58
		% diff	*5.1%*	*2.3%*	*2.5%*	*1.2%*
	Base Mom. $M_x x10^3$	Slab	6.8	6.9	7.3	8.3
		Girder	6.8	6.8	7.3	8.3
		% diff	*0.6%*	*0.3%*	*0.2%*	*0.7%*
	Base Shear V_y	Slab	86	63	60	60
		Girder	82	62	59	59
		% diff	*5.3%*	*2.6%*	*1.2%*	*0.7%*
	Base Mom. $M_y x10^3$	Slab	6.6	6.8	7.5	8.4
		Girder	6.5	6.8	7.5	8.4
		% diff	*0.2%*	*0.1%*	*0.5%*	*0.8%*
50-Storey	Base Shear V_x	Slab	59	48	41	40
		Girder	55	42	39	39
		% diff	*8.8%*	*14%*	*3.2%*	*1.5%*
	Base Mom. $M_x x10^3$	Slab	3.0	3.1	3.3	3.5
		Girder	2.8	2.9	3.1	3.4
		% diff	6.2	6.2	5.9	4.8
	Base Shear V_y	Slab	76	55	52	45
		Girder	68	51	49	44
		% diff	*12%*	*6.7%*	*3.7%*	*2.8%*
	Base Mom. $M_y x10^3$	Slab	2.8	2.9	3.1	3.4
		Girder	2.7	2.7	2.9	3.3
		% diff	2.0%	5.1%	6.3%	2.5%
25-Storey	Base Shear V_x	Slab	39	36	33	33
		Girder	32	32	31	32
		% diff	*24%*	*9.3%*	*5.9%*	*5.3%*
	Base Mom. $M_x x10^3$	Slab	1.1	1.3	1.4	1.5
		Girder	1.0	1.2	1.2	1.4
		% diff	*7.7%*	*3.1%*	*13%*	*12%*
	Base Shear V_y	Slab	41	47	40	38
		Girder	36	42	38	36
		% diff	*15%*	*12%*	*6.2%*	*6.3%*
	Base Mom. $M_y x10^3$	Slab	1.0	1.2	1.3	1.4
		Girder	1.0	1.1	1.2	1.3
		% diff	*2.9%*	*5.5%*	*6.9%*	*6.3%*
10-Storey	Base Shear V_x	Slab	22	30	29	24
		Girder	16	19	24	22
		% diff	*39%*	*54%*	*22%*	*15%*
	Base Mom. $M_x x10^3$	Slab	0.4	0.5	0.6	0.6
		Girder	0.4	0.4	0.5	0.5
		% diff	*13%*	*27%*	*16%*	*15%*
	Base Shear V_y	Slab	26	38	39	32
		Girder	21	25	31	29
		% diff	*29%*	*49%*	*25%*	*11%*
	Base Mom. $M_y x10^3$	Slab	0.3	0.3	0.4	0.5
		Girder	0.3	0.3	0.3	0.4
		% diff	*10%*	*23%*	*16%*	*17%*

5.1 *Finite Element Simulation*

A three-dimensional material nonlinear model is constructed for the 25 storey building models with each model presenting a different level for the transfer floor. The finite element software package SeismoStruct was used in the analysis which is capable of considering large displacement behaviour of space frames under static or dynamic loading, taking into account both geometric nonlinearity and material inelasticity.

Frame elements were adopted to model the buildings and the transfer floor. To present the structural member cross-section behaviour, fiber approach is adopted where each cross section fiber is associated with a uniaxial stress-strain relationship. The sectional stress-strain state of a structural element is then obtained through the integration of the nonlinear uniaxial stress-strain response of the individual fibers. Typically a cross section of an element is discretized into 300 to 400 fibres: a typical reinforced concrete section is depicted in Figure 9.

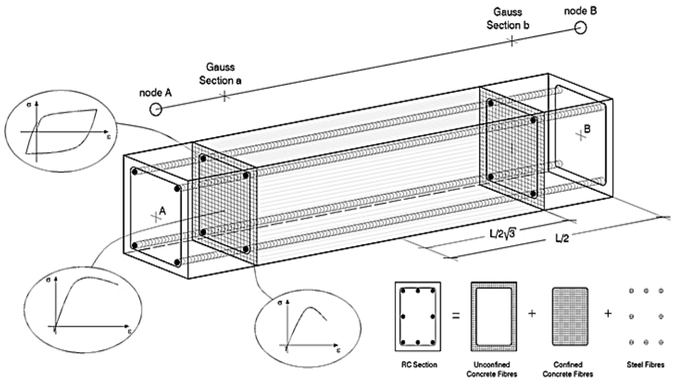

Figure 9. SeismoStruct program simulation of material nonlinearity in a frame element.

The constitutive model adopted for the confined concrete material is the modified Mander et al. (1989) nonlinear concrete model which is a nonlinear concrete model with a uniaxial nonlinear constant confinement model (Martlnez-Rueda and Elnashai 1997). The confinement effects provided by the lateral transverse reinforcement are incorporated through the rules proposed whereby constant confining pressure is assumed throughout the entire stress-strain range. The proposed concrete model exhibits unconditional numerical stability and predicts increasing strength and stiffness degradation under cyclic loading for any level of strain. As such, a good agreement, for these models, is observed between analysis and experiments, confirming the ability of the model to predict the cyclic and dynamic behaviour of reinforced concrete members with mixed axial-flexural response characteristics (Mander et al. 1989).

Five model calibrating parameters are defined in order to fully describe the mechanical characteristics of the material which are concrete compressive strength (40 MPa), concrete tensile strength (4 MPa), maximum concrete strain (0.002), confinement factor (1.2) and concrete specific weight (24 kN/m^3).

As SeismoStruct program does not simulate shell elements, additional mass was calculated to represent the flooring and live load. For podium floors, the additional mass was found to be 28 kN/m while for typical floors it was found to be 14 kN/m.

To adjust earthquake accelerograms records, SeismoMatch package is used in order to match it with the specific target response spectrum adopted in the linear elastic analysis; thus, guarantees a realistic comparison between linear and nonlinear analyses. Figure 10 shows the Chi-Chi record and adjusted one adopted in the analysis.

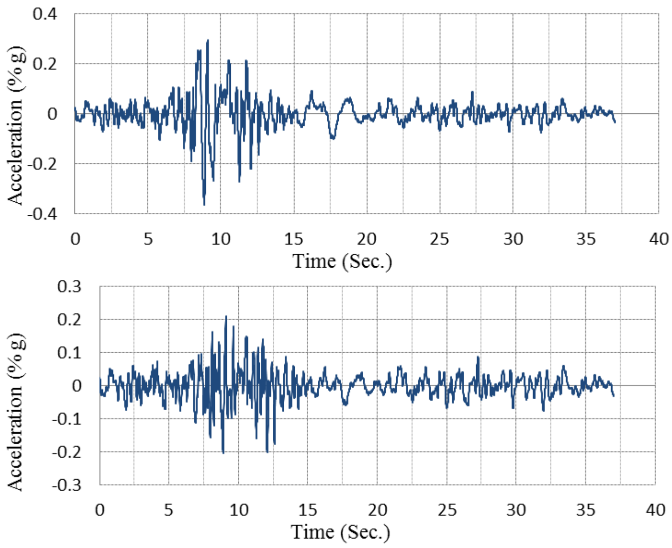

Figure 10. Chi-Chi record (above) and scaled Chi-Chi record (below).

Furthermore, to validate that the modified time history represents the best fit to the target response spectrum Siesmosignal package is adopted as it is a familiar package used to analyze signal processing of strong motion. Figure 11 shows that the matched time history response spectrum which was coincided on the previous linear analysis target and the modified Chi-Chi response spectrum function at the average periodic time of the structures.

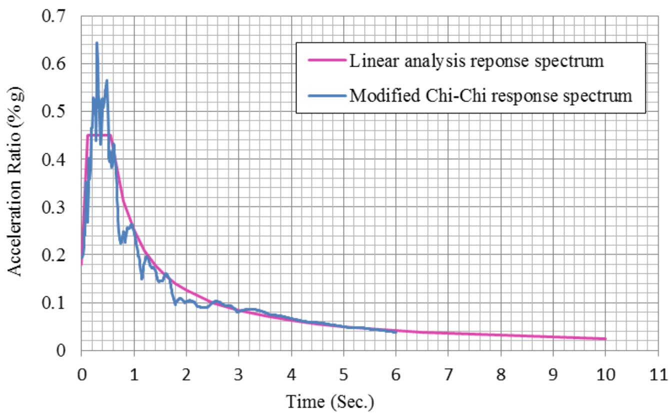

Figure 11. Modified time history response spectrum and the target linear response spectrum function.

6 NONLINEAR ANALYSIS RESULTS

The plastic hinge map (Figure 12) shows that a stress concentration, due to the vertical irregularity, occurred in the vicinity of the transfer floor in addition to the first floor vertical elements.

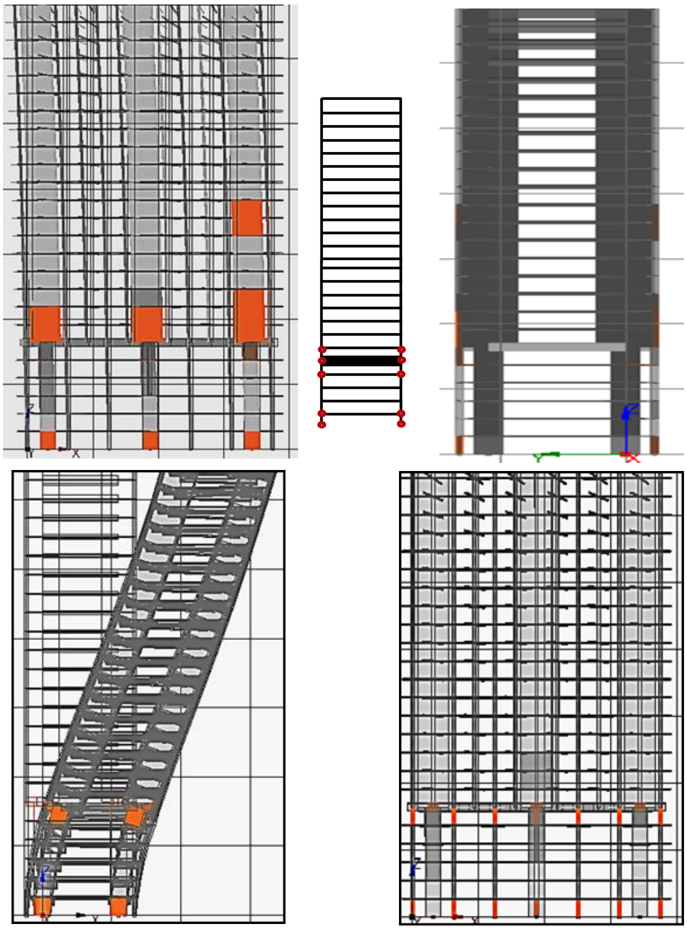

Figure 12a. Plastic hinges map in the X-direction (above) and in the Y-direction (below) for 25 storey building model with transfer floor at 20%H.

Furthermore, the analysis revealed that buildings with transfer system at 20%H experience a failure during the analysis time.

6.1 *Storey Shear and Storey Moment Distributions*

The inelastic analysis results are plotted in Figures 13 to 16 for the 25 storey building.

The analysis revealed a strength demand increasing in the areas of the stress concentration like the first floor and the floors in the vicinity of the transfer floor (the vicinity of the vertical irregularities): this is evident in Figures 13 to 16 for the 25 storey building model plotted for different levels of the transfer floors.

Despite this fact, the previously performed linear spectral analysis provided a reasonable behaviour for these models compared to the behaviour resulted from the nonlinear time history analysis. As such, it is concluded that linear spectral analysis underestimates the response at the regions of stress concentration which agrees with previous conclusions made by Ali and Krawinkler (1998).

This conclusion is pronounced when several modes contribute to the building response in similar amount (Elawady 2012).

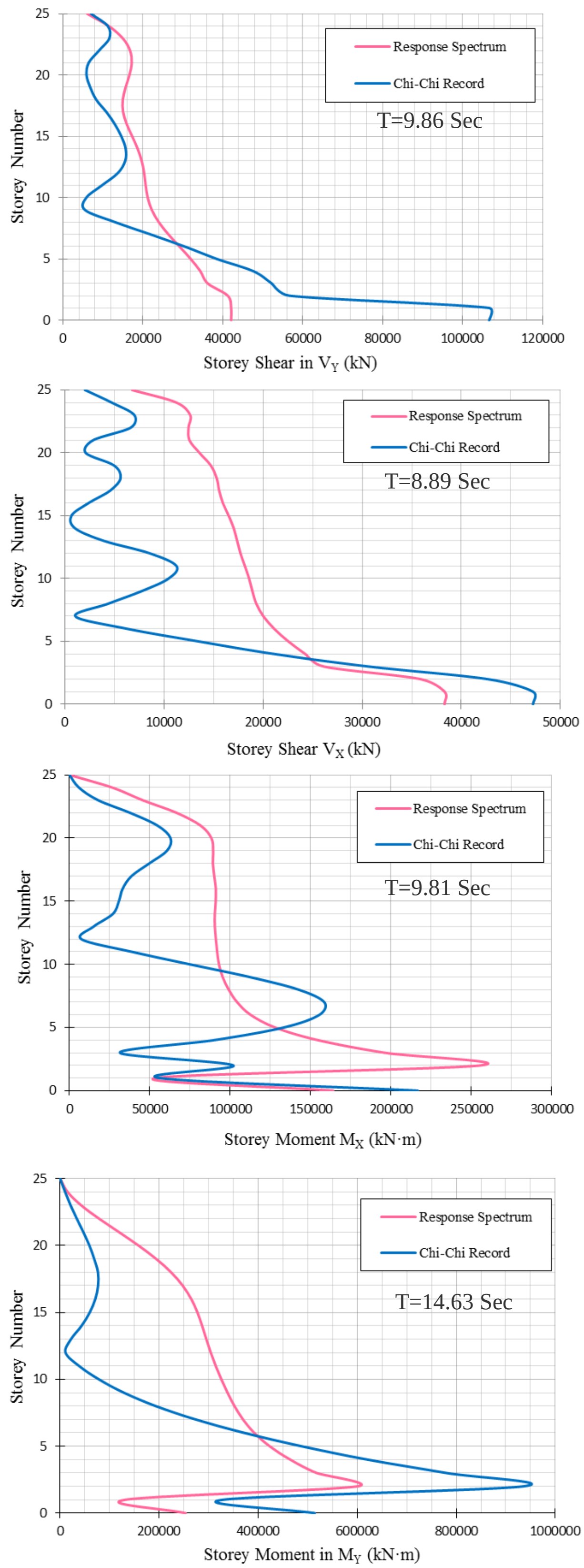

Figure13. 25 storey building response - transfer floor at 10%H.

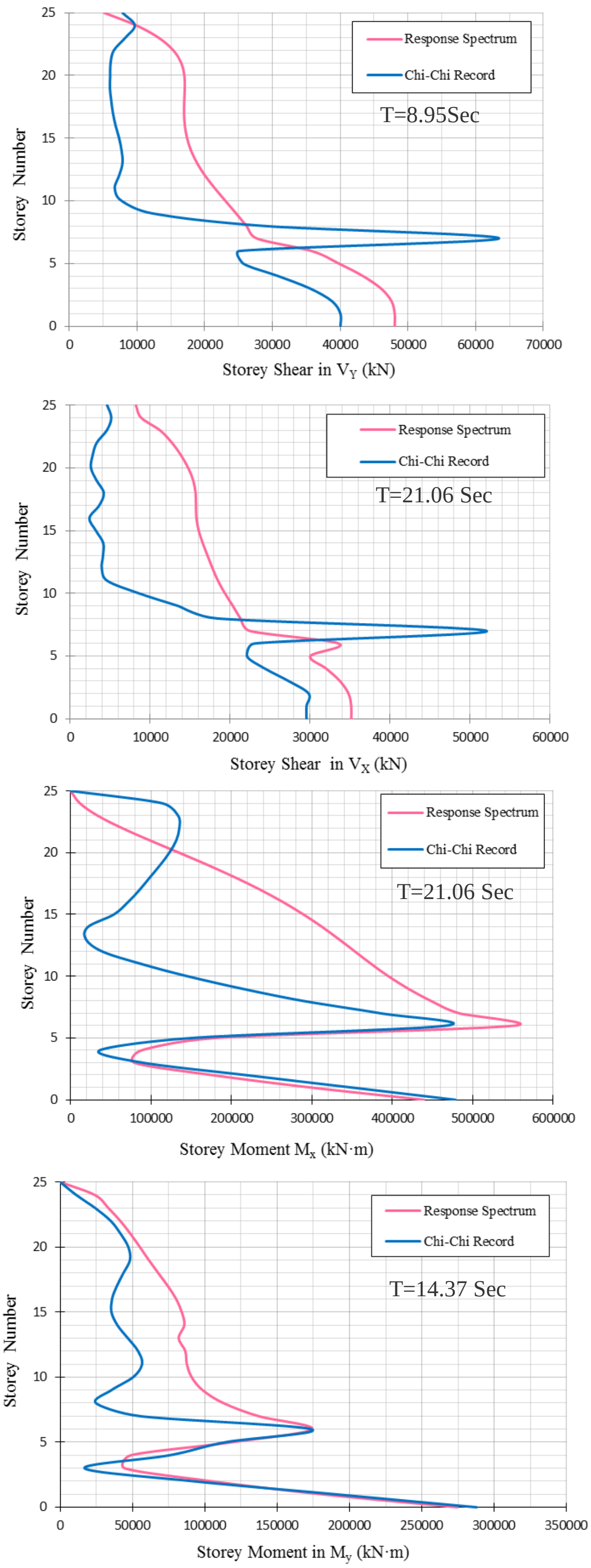

Figure 14. 25 storey building response - transfer floor at 20%H.

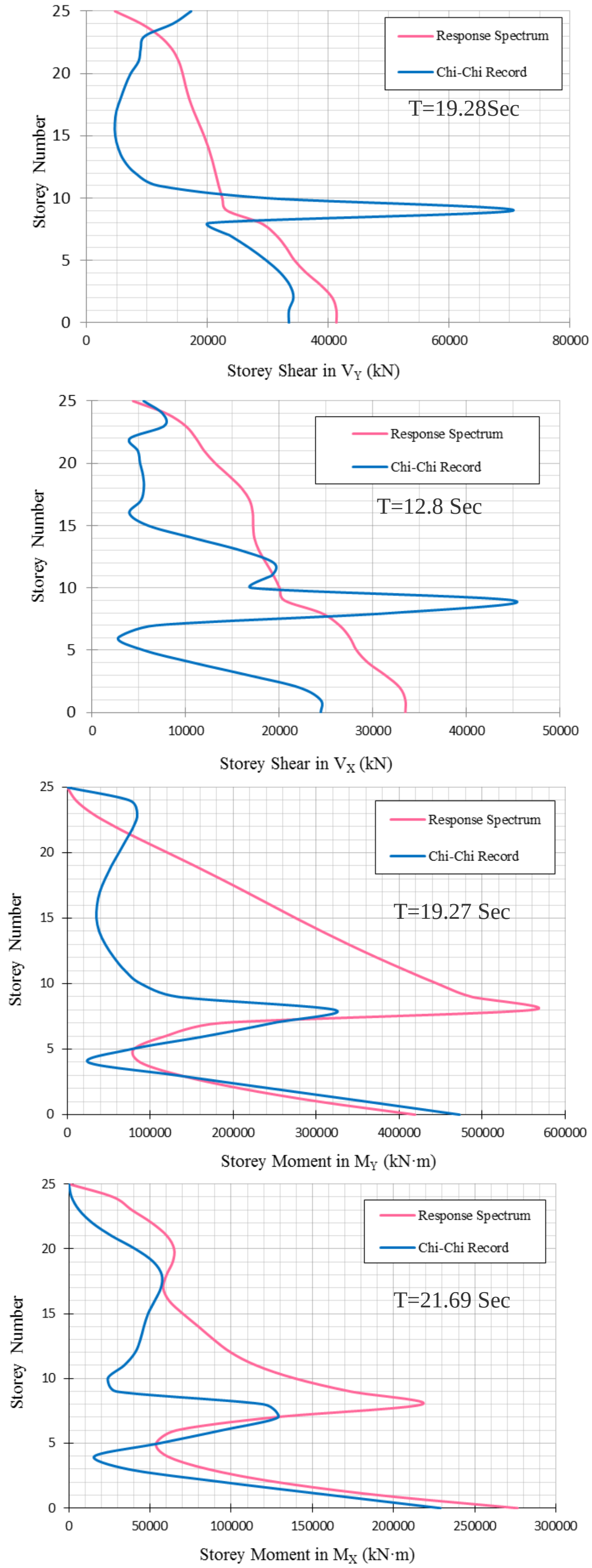

Figure 15. 25 storey building response-transfer floor at 30%H.

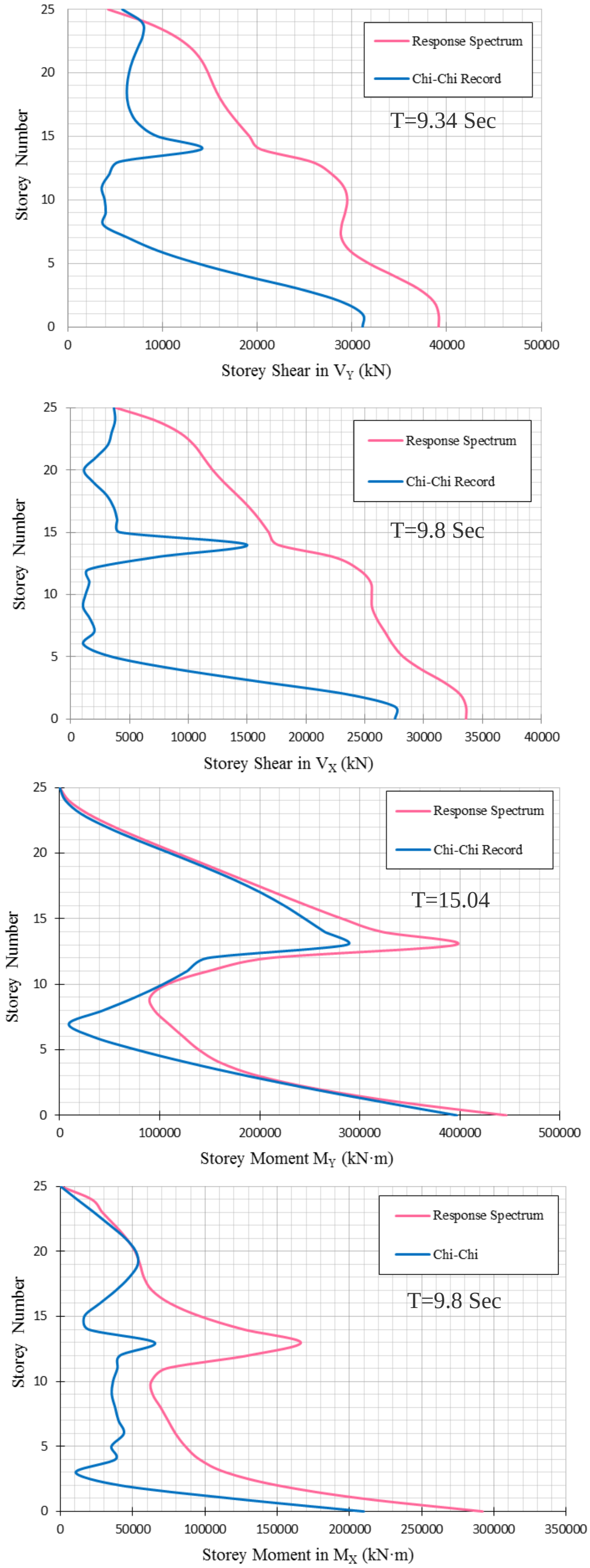

Figure 16. 25 storey building response-transfer floor at 50%H.

The analyses also revealed that in case of higher-level transfer floor (compare Figures 13 to 16) where the first mode dominates building response, the building tends to have single degree of freedom behaviour and the linear response spectrum analysis overestimates the building response.

6.2 *Storey Drift and Storey Displacement Distributions*

As shown in Figures 17 and 18, the increase in ductility demands occurs when the transfer floor lies in the mid-height of the building.

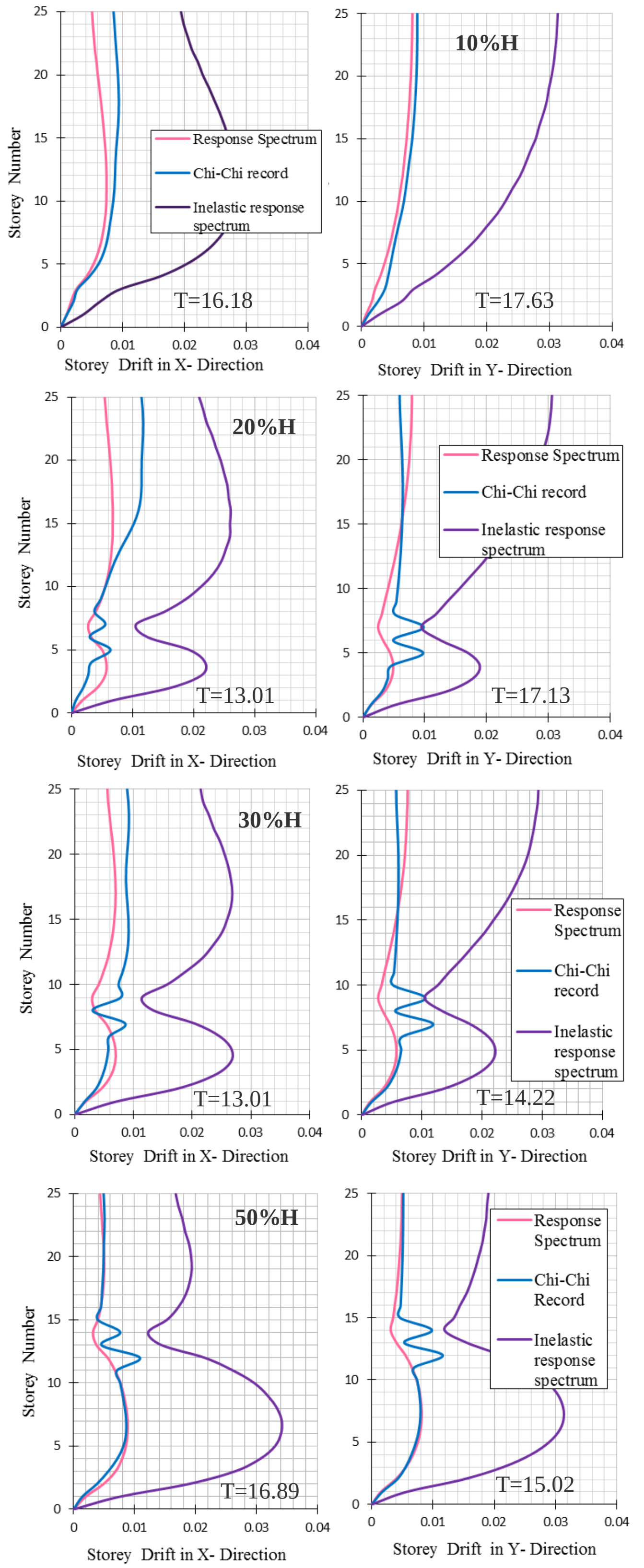

Figure 17. 25 storey building drift for different levels of the transfer floor.

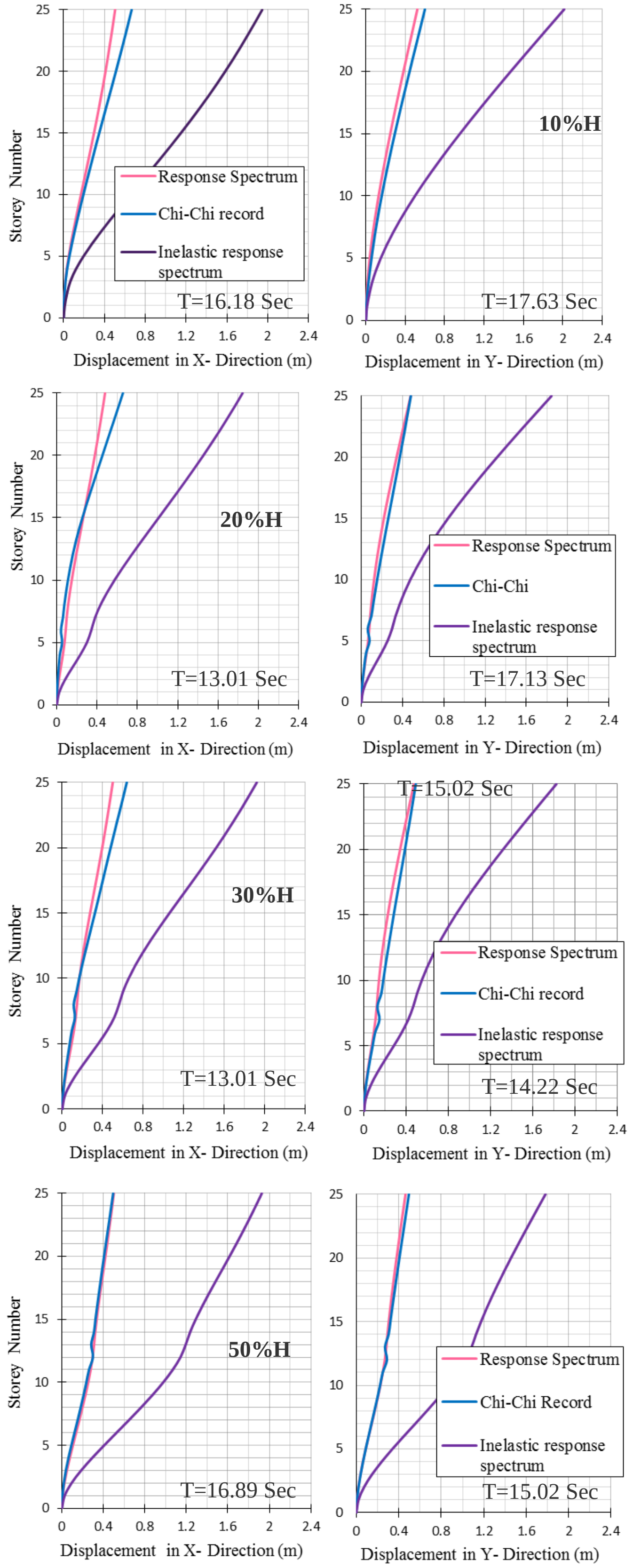

Figure 18. 25 storey building displacements for different levels of the transfer floor.

In addition, it is evident from the drift distributions that linear response spectrum analysis underestimates the drift demands in the vicinity of the transfer floor compared drift values obtained from the non-linear analysis.

It is worth mentioning that the UBC97 code (as a typical example for code provisions) uses a magnification factor of *0.7xR* for the drift and displacement calculations where

$$\Delta_M = 0.7 \cdot R \cdot \Delta_s \quad (1)$$

where Δ_M is the maximum inelastic response displacement which is the total drift or total storey drift that occurs when the structure is subjected to the Design Basis Ground Motion, including estimated elastic and inelastic contributions to the total value, Δ_s is the design level response displacement which is the total drift or total storey drift that occurs when the structure is subjected to the design seismic forces and R is a numerical coefficient considering the inherent over-strength and global ductility capacity of lateral force-resisting systems.

This approach is presented in Figures 17 and 18 as the “inelastic response spectrum” and compared to the results of both the linear and non-linear analysis. It is evident form the figures that code approach is very conservative even in the buildings with vertical irregularities like the ones investigated herein.

Although the same ductility behaviour is ensured as per Figures 17 and 18, the distribution of the storey ductility demands over the height is found to be non-uniform for all the studied cases. In general, storey drift demands increase in the soft storey and decrease in the most of other stories.

It is also evident from Figures 17 and 18 that in most the studied cases, the roof drift obtained from the nonlinear analysis is larger than that obtained from the linear elastic analysis.

7 CONCLUSIONS

An analytical study was conducted to investigate the seismic behaviour of high-rise buildings with transfer floors. A number of buildings models were analyzed using elastic response spectrum in addition to inelastic nonlinear time history analysis. Two transfer systems were considered: slab and girders types. Different level for the transfer floor with respect to the building height was scrutinized.

It was shown that girder type transfer system improves the global behaviour of the structure and reduces the total weight of the structure which provides further reduction in the straining actions below the transfer floor level. A reduction in the base shear and base moment was recorded for girders type transfer floor system compared to the solid slab one. This conclusion is valid for higher-level transfer floors as well as for lower level ones.

Buildings with transfer floors at higher levels tend to deform and respond primarily as a single-degree-of-freedom structure with the fundamental mode dominating the seismic response of the structure. On the other hand, buildings with lower level transfer floors need to be analyzed using more modes contributions to obtain the required participation ratios.

Buildings with lower level transfer floor have a higher base shear compared to similar buildings with transfer floor at higher level due to the higher stiffness of the lower part of the structure. On the other hand buildings with higher level transfer floor have a higher base moment compared to buildings with lower level transfer floor.

Location of the transfer floor within the building height also controls the maximum drift location. This is an important issue which will enable designers to take the suitable precautions to have a safe design from the serviceability point of view. Roof drift of buildings with a lower level transfer floor is higher than that for buildings with transfer floor located at higher level. This is due to the huge mass above the transfer floor in case of lower level transfer floor relative to the small mass above the transfer floor level in case of higher level transfer floor. As such, lower level transfer system would produce higher roof drift regardless of the transfer system type (slab or girders).

Codes of practice adopt magnification factors to convert the elastic response spectrum displacement and drift to inelastic response spectrum. It was shown that this approach overestimates the value of the displacement and the drift.

The lateral stiffness ratio adopted to check the existence of a soft storey may not be a good indicative for the location of the maximum drift or the shear force distribution along the building height: the linear elastic numerical analysis performed here preliminary indicates that damage and failure may not occur at the storey in the vicinity of the transfer system and the soft storey mechanism may not be observed.

The performed investigation revealed the importance of performing nonlinear seismic analysis for buildings with transfer floors especially in high seismic hazards regions. It was shown via the inelastic analysis that the strength demands increase in the areas of the stress concentration like the first floor and the floors in the vicinity of the transfer floor, i.e. the vicinity of the irregularity. However, linear spectral analysis does not provide the same trend as that of that of the nonlinear time history analysis. Another example is the roof drift where the drift obtained from the nonlinear analysis is larger than that obtained from the linear spectral analysis. Linear analysis yielded acceptable results for buildings with transfer floors at higher level (50% of the building height) where the first mode contributes the highest ratio in the response parameters.

The data presented in the current study tackled high-rise buildings with only one level of transfer floor. In few buildings the Architect may require two (or more) levels of transfer; it is expected that this will change the building response compared to buildings with one level of transfer analyzed herein. As such, conclusion drawn here to one level of transfer should be cautiously applied when the building contain more than one level of transfer floors.

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