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Towards Seismic Performance of Tall Buildingswith Transfer Floors

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Abstract:This paper studies the seismic performance of tall buildings with transfer girders or slab. These transfer systems are oftenused to transfer vertical and lateral loads from the upper superstructure to the lower substructure. Two case studies were analyzed using the response spectrum and pushover analysis methods. The analyses were carried out using ETABS computer software. The selected case studies have either transfer girders or transfer slab. Seismic response parameters such as; base shear, story shear distribution, bending moment distribution, top displacement, story drift, time period and response modification factor are obtained for each study case. Moreover, pushover analysis (POA) is done to evaluate the capacity of the existing building to resist the anticipatedearthquake loads. The results of the studied cases indicated that, the base shear obtained using POA is about 65% to 83% of that calculated using the response spectrum. On the other hand, the base shear calculated using the response spectrum of Saudi building code (SBC 301) is considerably lower than that obtained using POA. Also, the response modification factor is very sensitive to both horizontal and vertical irregularity.

KEYWORDS: Tall buildings, Transfer girder, Transfer slab, Response spectrum, Pushover analysis.

1. INTRODUCTION

Discontinued vertical elements within tall buildings are needed to satisfy the innovative architectural demands in which columns may have different arrangement between floors. At the present time, several tall buildings are constructed with transfer elements to transmit vertical and lateral loads from discontinuous columns and shear walls to the below elements. Types of transfer elements include girders, slabs, arches, trusses, inclined columns, etc.

Several studies addressed the structural performance of high-rise buildings with transfer elements. Su*et al.*[1] determined the appropriateseismic assessment methodology for tall buildings with transfer slab. They discussed the main factors influencingthe response of transfer structures and provided the designation of their seismic sensitivity. Londhe[2] made an experimental work to study the shear capacity of reinforced concrete (RC) transfer girders. The author proposed an analytical model to design transfer girders in high-rise buildings. Elawady*et al.*[3] gave a comparative study for the seismic performance of tall buildings with transfer slabs and girders. The vertical location of the transfer system with respect to the building height was investigated. The analysis showed that the position of damage was in the regionof the transfer floor, as well as the first floor. Abdelbasset*et al.*[4] investigated the effect of transfer plates on the drift of the building. The analytical results of models showed that stiffness reduction of the vertical and horizontal elements had remarkablyaffected the drift. Osman and Abel Azim [5] studied the behavior of tall buildings with thick transfer slab. In this study, the interaction between the transfer slab and the supporting floors during the analysis process was examined, as well as the span of transfer slab to its thickness and stiffness on the structural behavior of the building. Yacoubian *et al.*[6] investigated the seismic shear demands on shear walls supporting tall buildings. This work tackled the displacement incompatibility between connected walls that imposed high in-plane strains in the slabs and beams connecting the tower wall above the podium interface level. Elassaly and Nabil [7] investigated seismic behavior of 2-D RC structures using transfer slab models. The aim was to determine the seismic damage of these types of structures compared to regular ones. Abdul Sameer and Azeem [8] investigated the seismic behavior of tall building with transfer floor. Models of three buildings using moment resisting frame and shear wall frame were studied. Ayash*et al.*[9] studied the seismic behavior of high-rise buildings with two transfer slabs and compared it with standard model without transfer slabs.

2. PUSHOVER ANALYSIS METHODS

Pushover analysis (POA) is a method of static-nonlinear analysis where a structure subjected to gravity loading and the lateral load pattern is controlled by monotonic displacement which continuously increased until an ultimate condition is reached by elastic and inelastic behavior FEMA 440 [10]. Pushover analysis methods are classified into three broad categories: conventional POA methods, adaptive POA methods and energy based POA methods. The conventional POA methods that used in this research are as follows: Capacity Spectrum Method (CSM), N2 Method and Displacement Coefficient Method (DCM).

2.1 Capacity-Spectrum Method

Capacity Spectrum Method (CSM) is a rapid seismic assessment and design tool for buildings. A form of equivalent linearization known as the CSM was documented in ATC 40 [11]. The basic assumption in equivalent linearization techniques is that the maximum total deformation of a nonlinear SDOF system can be approximated from the maximum deformation of a linear elastic SDOF system that has a period and a damping ratio that are larger than the initial values of those for the nonlinear system.

2.2 N_2 Method

The N2 method is adopted by the Eurocode 8 [12] and represents a modified version of the CSM. In the N2 method, the evaluation of the seismic demand is based on the use of inelastic spectra, instead of highly damped elastic spectra, as done through the CSM.

2.3 Displacement Coefficient Method

Displacement Coefficient Method (DCM) was described in FEMA 273 [13] and FEMA 356 [14]. The model incorporating inelastic material response is displaced to a target displacement and the resulting internal deformations and forces are determined.

3. PERFORMANCE LEVEL

Performance-based design is important to assess the performance level of building, which is used by designers of the structures. Four levels of seismic performance were chosen as a basis for design as given in FEMA 356 [14], including Operational (O), Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Figure 1 shows the performance level of structures description along with a force-displacement curve which shows the behavior of global structure against lateral load.

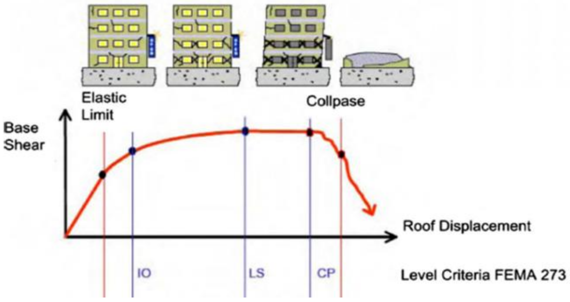

Fig. 1. Structures Performance Levels [13]

4. CASE STUDIES

Two buildings with transfer girders or transfer slab which have already been constructed in Egypt and United Arab Emirates are selected as case studies. The 3D finite element models for each building is developed using ETABS 2018. First, each building is investigated using the response spectrum method. After that, pushover analysis method is used to evaluate the capacity of existing buildings to resist expected earthquakes.

4.1 Case Study No. 1 (Transfer Girders)

4.1.1 Building Description

This case study is a RC building with 15 stories and total height of 51.10 m that was constructed in Cairo, Egypt. The developed 3D model is shown in Figure 2. The transfer girders are located at sixth story level. The width and depth of transfer girders are 1500 mm and 2000 mm, respectively. The cross-sectional elevation as well as columns below and above transfer girder are shown in Figures 3-5. The concrete grade for horizontal and vertical elements is C40. The yield stresses for steel reinforcement and stirrups are 400 MPa and 240 MPa, respectively. In the pushover analysis, the concrete and steel reinforcement materials are modeled using the isotropic unconfined axial stress-strain relationship and uniaxial stress-strain relationships, respectively. Deformation controlled behavior are used for beam, frame and wall elements with types moment M3, interaction P-M2-M3 and Fiber P-M3, respectively. The soil classification type was C.

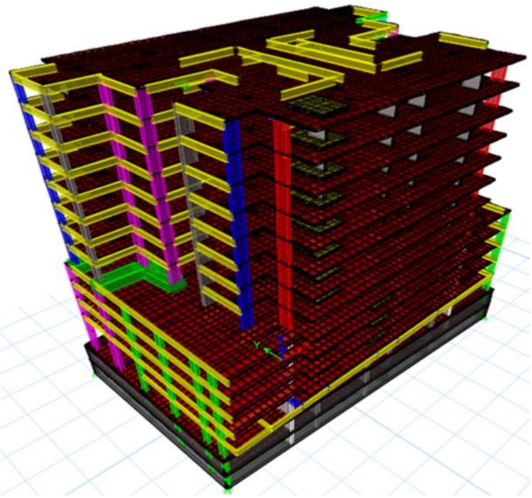

Fig. 2. 3D Model for Case Study No. 1 [This Work]

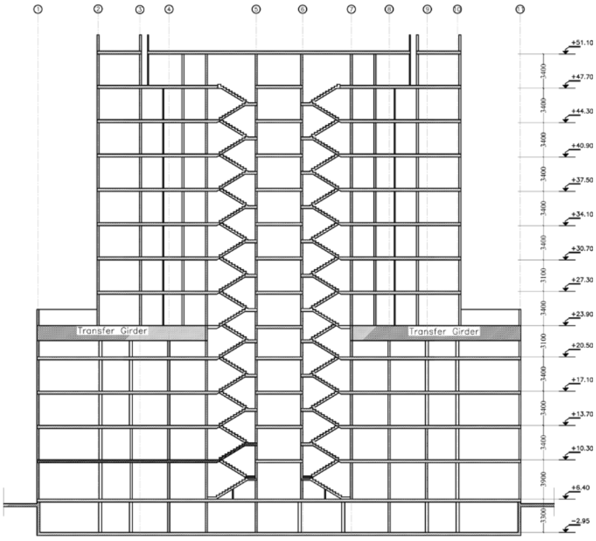

Fig. 3. Cross-Sectional Elevation

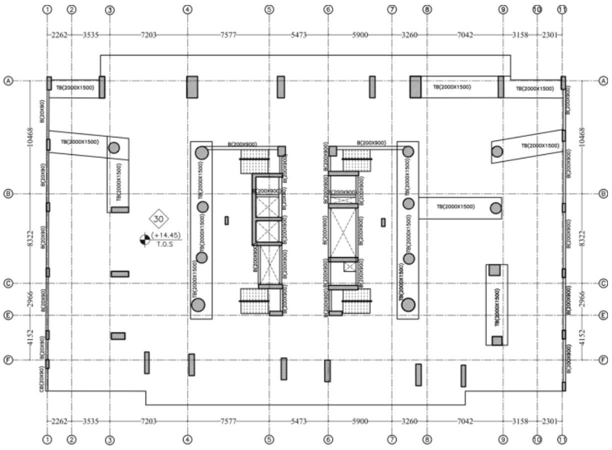

Fig.4. Layout of Transfer Girders and Below Columns

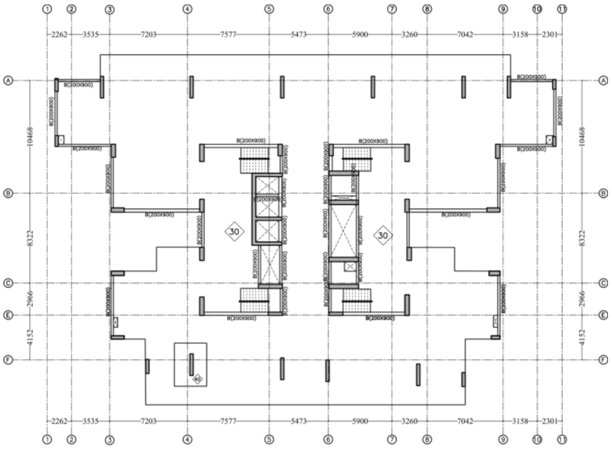

Fig. 5. Layout of Columns above Transfer Girders

4.1.2 Output Results

Figures 6-8 show the results of the global performance of the building.

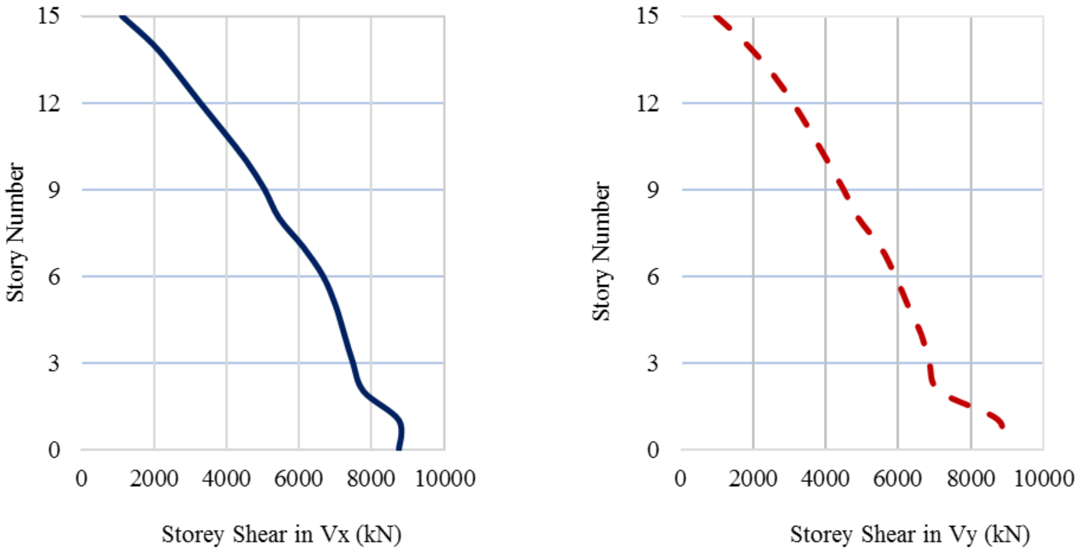

Fig. 6. Story Shear in X -and Y-Directions

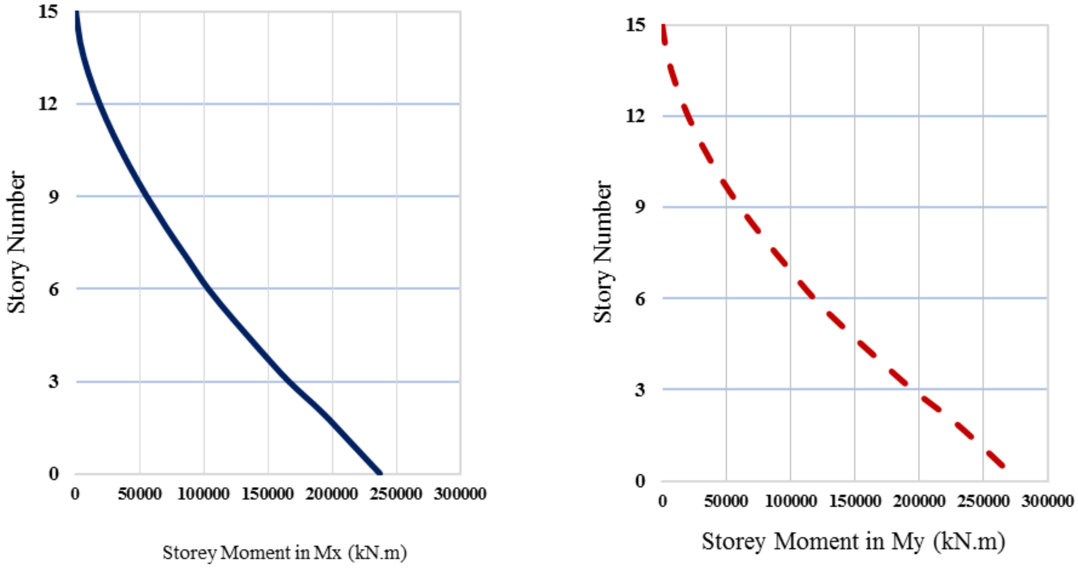

Fig. 7. Story Moment in X- and Y-Directions

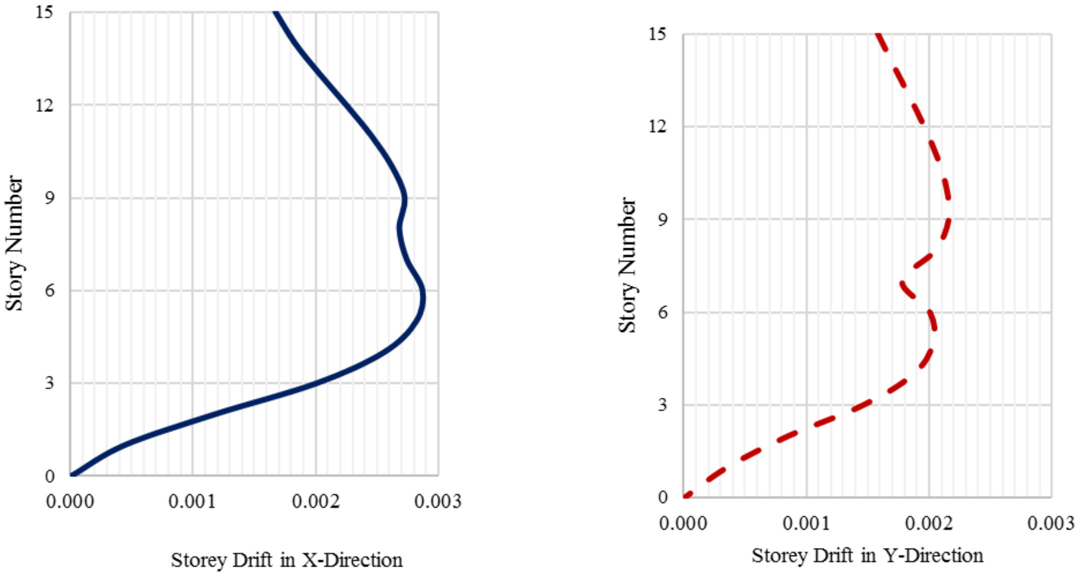

Fig. 8. Story Drift in X-and Y-Directions

4.1.3 Performance Points

The performance points calculated using Eurocode 8 [12] target displacement method (N2 method) are shown in Figures 9-10.

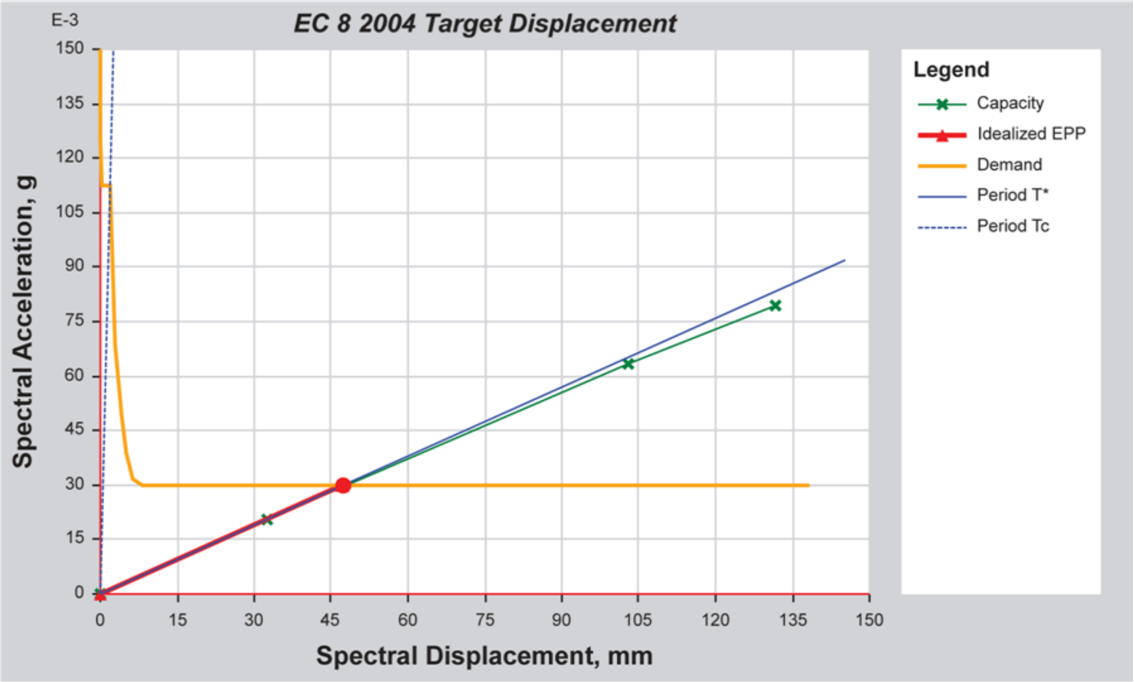

Fig. 9. Performance Point in X-Direction

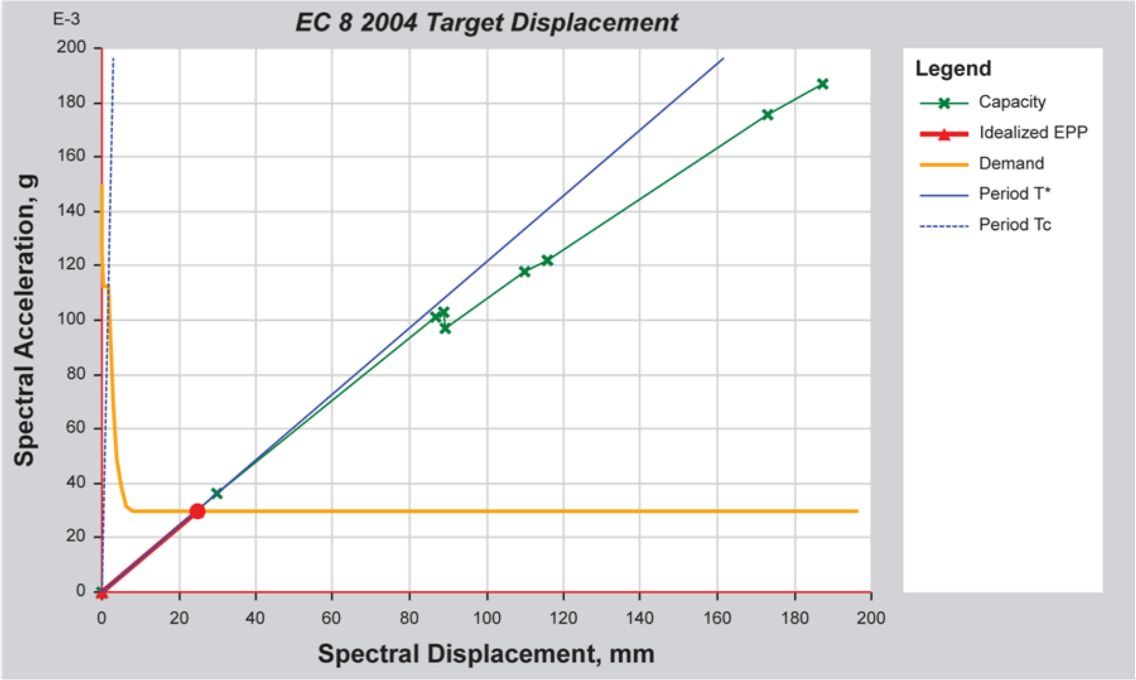

Fig. 10. Performance Point in Y-Direction

4.1.4 Comparison Between Pushover and Response Spectrum Results

The numerically calculated base shear, displacement and time period values of the building are shown in Table 1. It can be noted that, the base shear obtained using POA is about 70% of that calculated using response spectrum analysis. The number of modes to reach 90% participation of mass in both principal directions is fifteen. The elapsed time to run the model is 6 hours and number of formed plastic hinges is 3730.

Table 1. Building Response Results

Building response	Pushover		Response spectrum	
	X-Direction	Y-Direction	X-Direction	Y-Direction
Base shear (kN)	6074	6241.2	8755	
Displacement (mm)	69.2	44.06	112	87
Time period (Sec.)	2.52	1.82	3.16	

4.2 Case Study No. 2 (Transfer Slab)

4.2.1 Building Description

This case study is a RC building located in Dubai, UAE with 53 stories and total height 193.70m. The developed 3D model is shown in Figure 11. The prestressed concrete transfer slab thickness is 2800m and is located at 12th story level. The cross-sectional elevation and columns below and above transfer slab are shown in Figs. 12-14. The concrete grades for horizontal and vertical elements are C50 and C70, respectively. The yield stress for steel reinforcement is 460 MPa. The building was designed according to uniform building code (UBC97) [15]. The materials and element types used in pushover analysis are like those in case study No. 1. The soil classification type was S_c.

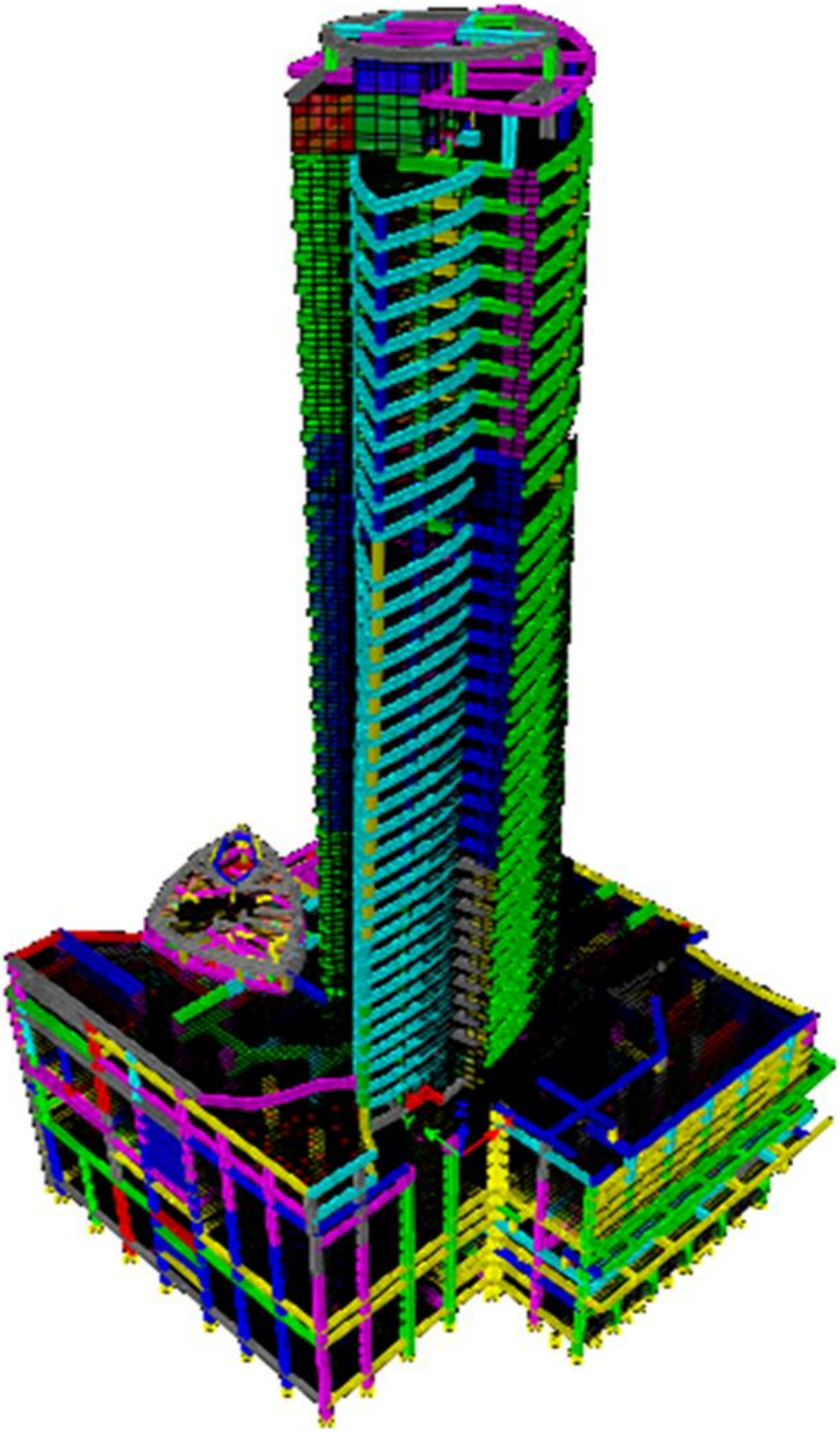

Fig. 11. 3D Model for Case Study No. 2 [This Work]

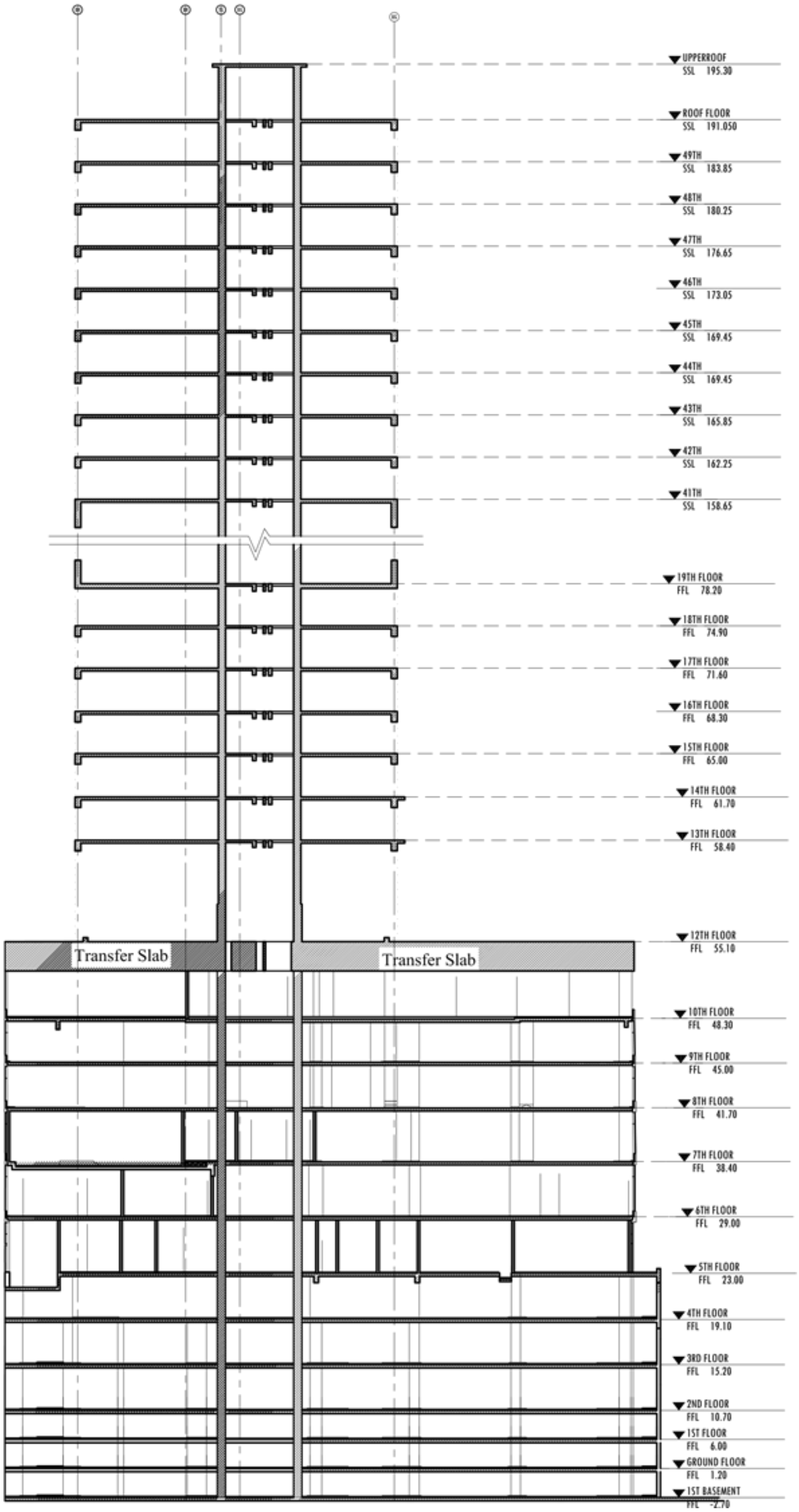

Fig. 12. Cross-Sectional Elevation

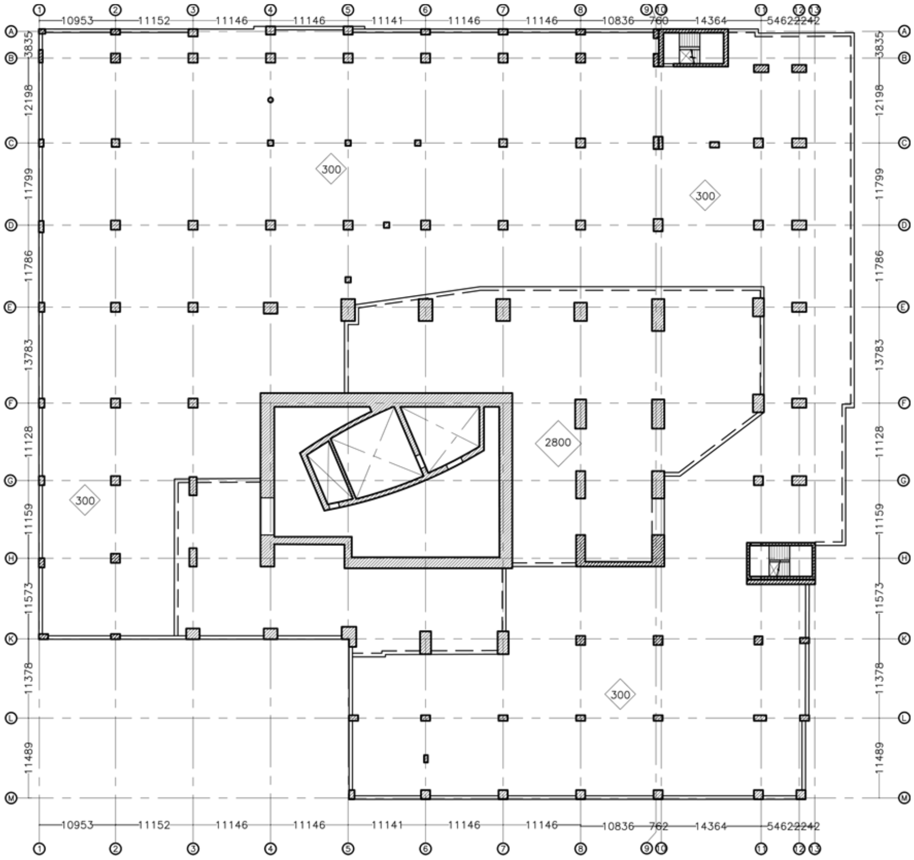

Fig. 13. Layout of Transfer Slab and Below Columns

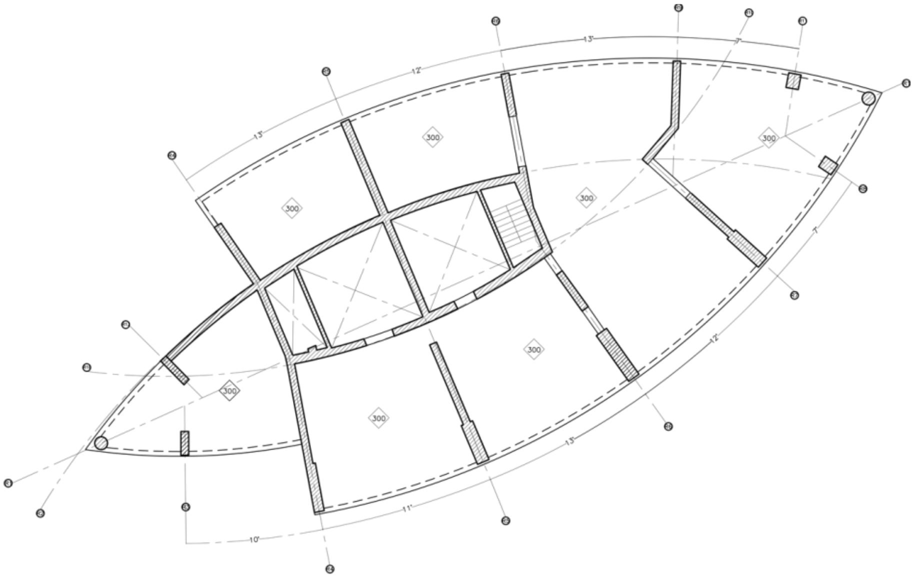

Fig. 14. Layout of Columns above Transfer Slab

4.2.2 Output Results

Figures 15-17 show the results of shear distribution, moment distribution, story drift and story displacement.

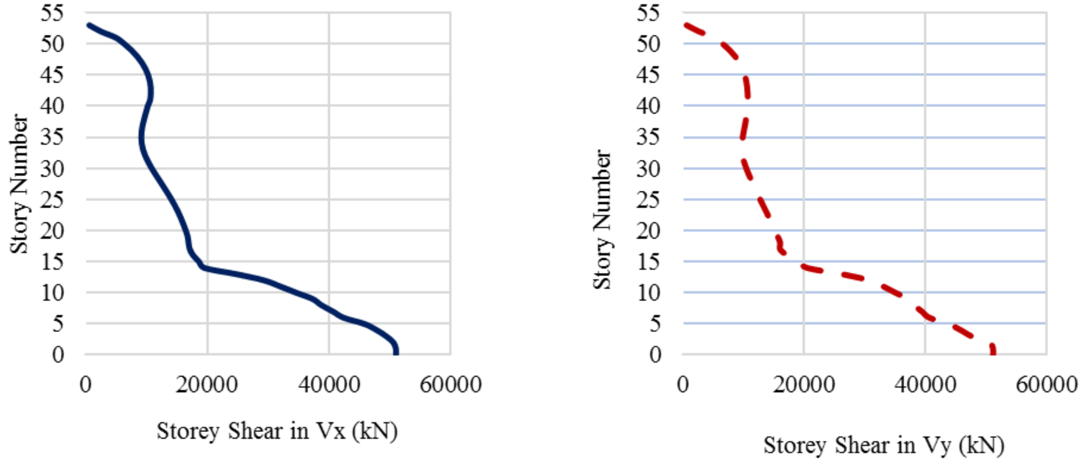

Fig. 15. Story Shear in X-and Y-Directions

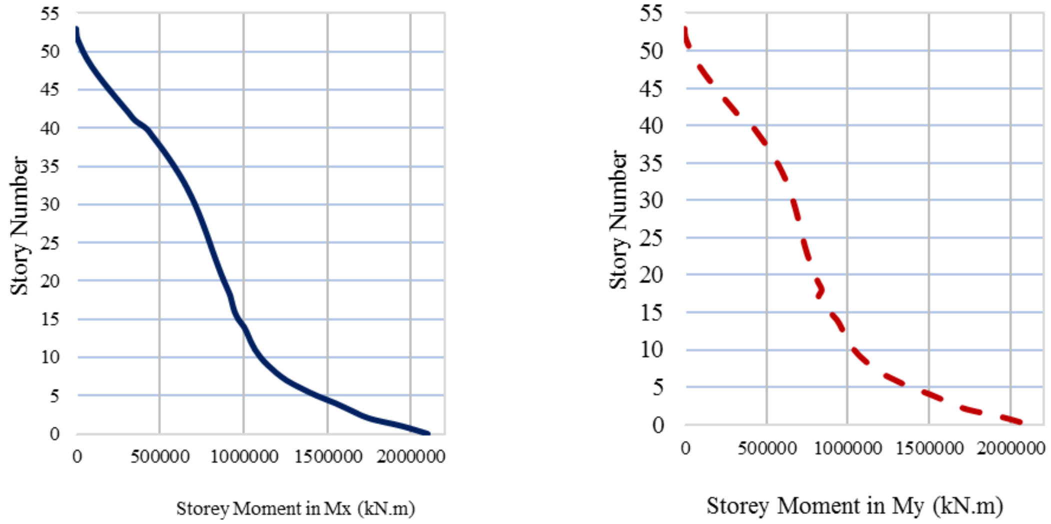

Fig. 16. Story Moment in X-and Y-Directions

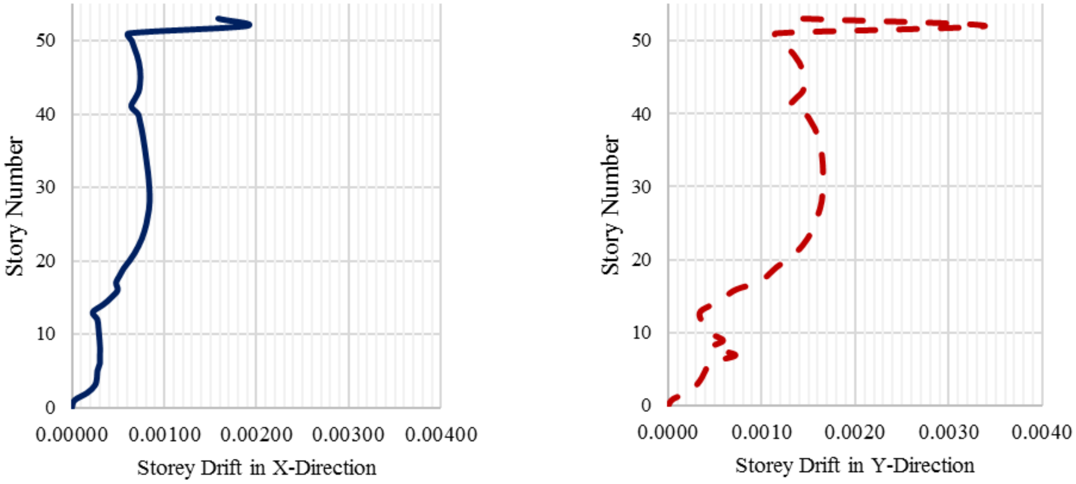

Fig. 17. Story Drift in X-and Y-Directions

4.2.3 Performance Points

The analysis of pushover analysis is conducted using ASCE41-13 [16] with displacement modification method mentioned in section 2.3. The calculated performance points in X- and Y directions are shown in Figures 18-19.

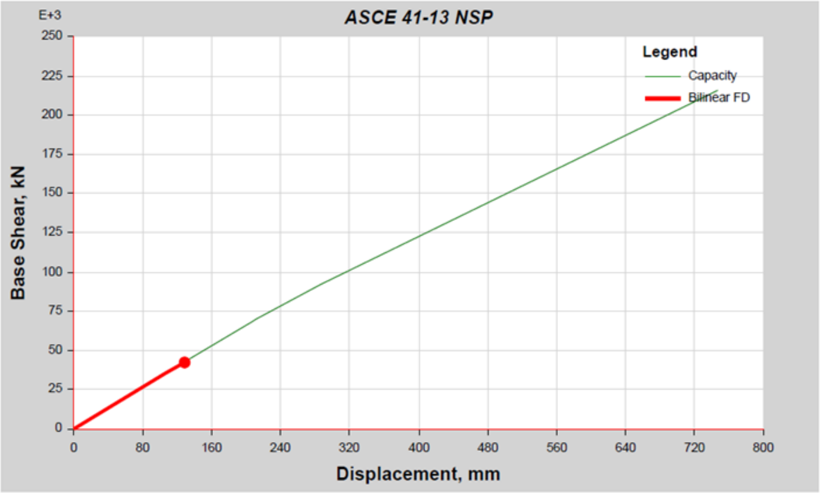

Fig. 18. Performance Point in X-Direction

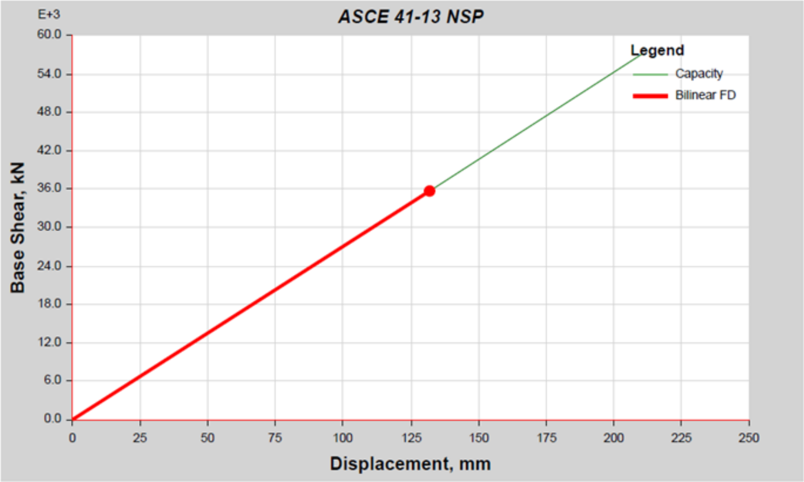

Fig. 19. Performance Point in Y-Direction

4.2.4 Comparison Between Pushover and Response Spectrum Analysis Results

The numerical calculated base shear, displacement and time period values of the building are shown in Table 2. It can be noted that, the base shear obtained using POA is about 83% and 70% of that calculated using response spectrum analysis in X- and Y-directions, respectively. The number of modes to reach 90% participation of mass in both principal directions is ninety. The elapsed time to run the model is 300 hours and number of formed plastic hinge is 22385.

Table 2. Building Response Results

Building response	Pushover		Response Spectrum	
	X-Direction	Y-Direction	X-Direction	Y-Direction
Base shear (kN)	42353.70	35780	51046	
Displacement (mm)	55.46	132	93	191
Time period (Sec.)	2.70	3.72	6.30	

5. RESPONSE MODIFICATION FACTOR

Evaluation of response modification factor (R) is based on the idealized-pushover curve to obtain the values of design shear (V_d), yield shear (V_y), ultimate shear (V_u), yield displacement (Δ_y) and ultimate displacement (Δ_u). The R values for the two studied cases are calculated using the ATC-63 and FEMA 356 methods. Table 3 shows the allocated R values in different building codes.

Table 3. R Values Allocated in Different Building Codes for Reinforced Concrete (RC)Seismic Force-Resisting Systems

Seismic Force-Resisting System		R-Value		
		ASCE7-16 [17]	Eurocode 8 [12]	ECP 2012 [18]
Bearing Wall Systems	Special RC shear wall	5.0	$4\,V_u/V_y$	-
	Ordinary RC shear wall	4.0	$3.0\,V_u/V_y$	4.5
Building Frame systems	Special RC shear wall	6.0	$4\,V_u/V_y$	-
	Ordinary RC shear wall	5.0	$3.0\,V_u/V_y$	5.0
Moment-Resisting Frame Systems	Special RC moment frames	8.0	$4\,V_u/V_y$	7.0
	Intermediate RC moment frames	5.0	-	5.0
	Ordinary RC moment frames	3.0	$3.0\,V_u/V_y$	-
Dual Systems with Special RC Moment Frames	Special RC shear wall	7.0	$4\,V_u/V_y$	-
	Ordinary RC shear wall	6.0	$3.0\,V_u/V_y$	6.0
Dual Systems with Intermediate RC Moment Frames	Special RC shear wall	6.5	$4\,V_u/V_y$	-
	Ordinary RC shear wall	3.0	$3.0\,V_u/V_y$	5.0
Shear Wall-Frame Interactive Systems	Ordinary RC shear wall and moment frames	4.5	-	-

5.1 ATC-63 Method

ATC-63 [19] proposed the Equation 1 to calculate the value of R (Figure 20).

$$R = \Omega . R_{\mu} . R_{R} . R_{\xi} \tag{1}$$

Where $\Omega = V_y/V_d$ is the over strength factor, $R_\mu = V_e/V_y$ is the ductility factor, R_ζ is the damping factor and R_R is the redundancy factor. Tables 4-5 show the calculated values of response reduction factor. Where T is the fundamental time period and $R\mu$ is function of μ depends on time period, as per Newmark and Hall [20].

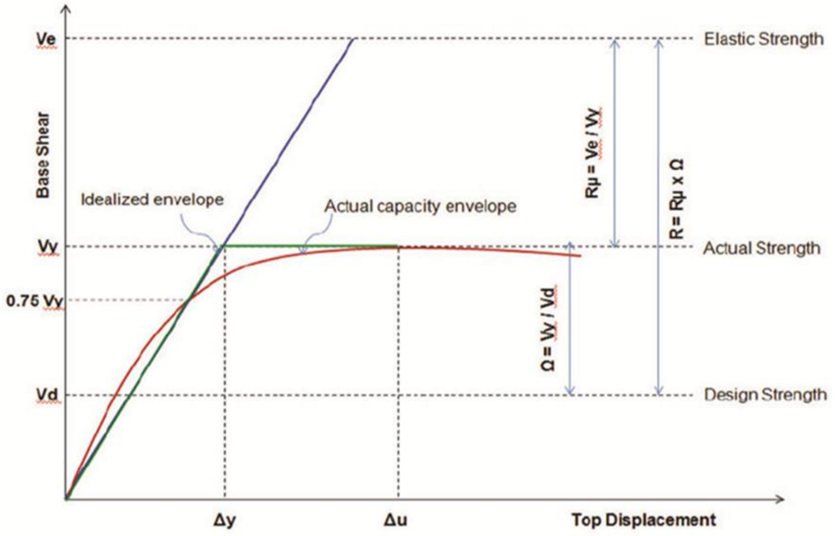

Fig. 20. Relation Between Response Reduction Factor, Over-Strength and Ductility Reduction Factor [21]

$$R_\mu = \begin{cases} 1 & if T < 0.2 \\ \sqrt{2\mu - 1} & 0.2 < T < 0.5 \\ & \mu T > 0.5 \end{cases} \quad (2)$$

Table 4. Response Reduction Factor in X-Direction

Case study No.	V_u (kN)	V_d (kN)	T (sec)	$\Omega = \boldsymbol{V_u/V_y}$	$\boldsymbol{\Delta_u}$(mm)	$\boldsymbol{\Delta_y}$(mm)	$\mu = \boldsymbol{\Delta_u/\Delta_y}$	$\boldsymbol{R_\mu}$	R
1	16340	8755	3.16	1.87	192	75	2.56	2.56	4.78
2	215617	51046	6.30	4.22	747	108	6.92	6.92	29.22

Table 5. Response Reduction Factor in Y-Direction

Case study No.	Vu (kN)	V_d (kN)	T (sec)	$\Omega = \boldsymbol{V_u/V_y}$	$\boldsymbol{\Delta_u}$(mm)	$\boldsymbol{\Delta_y}$(mm)	$\mu = \boldsymbol{\Delta_u/\Delta_y}$	$\boldsymbol{R_\mu}$	R
1	40428	8755	3.16	4.62	334	152	2.20	2.20	10.15
2	57154	51046	6.30	1.12	211	45	4.69	4.69	5.25

5.2 FEMA 356 Method

The response reduction factor is also calculated using the Eq. (3) proposed by FEMA 356 [14]. Figure 21 shows the nonlinear force-displacement relationship between base shear and displacement of the control node that shall be replaced with an idealized relationship to calculate the effective lateral stiffness (K_e), effective yield strength (V_y), post-yield slope (α) and elastic lateral stiffness (K_i).

$$R = \frac{S_a}{V_y/W} C_m \quad (3)$$

Tables 6-7 show the calculated values of response reduction factor. Where W is the effective seismic weight, S_a is the response spectrum acceleration at the fundamental period and damping ratio of the building in the direction under consideration and C_m is the effective mass factor.

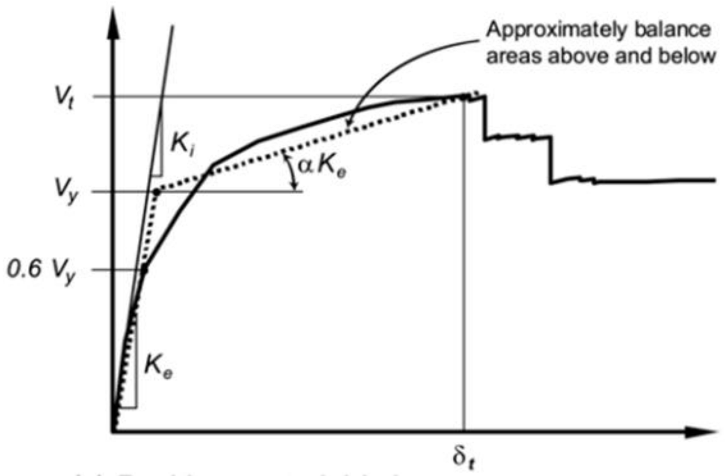

Fig. 21. Idealized force-displacement curve [14]

Table 6. Response Reduction Factor in X-Direction

Case study No.	S_a (g)	W (kN)	T_i (sec)	K_i (kN/m)	K_e (kN/m)	$T_e = T_i\sqrt{\frac{K_i}{K_e}}$ (sec)	V_y	C_m	R
1	0.17	296236	2.52	89051	89051	2.52	6689	1	7.53
2	0.038	5189829	2.69	330851	330851	2.69	35574	1	5.54

Table 7. Response Reduction Factor in Y-Direction

Case study No.	S_a (g)	W (kN)	T_i (sec)	K_i (kN/m)	K_e (kN/m)	$T_e = T_i\sqrt{\frac{K_i}{K_e}}$ (sec)	V_y	C_m	R
1	0.23	296236	1.82	141762	138732	1.84	21044	1	3.24
2	0.031	5189829	3.27	271991	271991	3.27	12174	1	13.22

6. CONCLUSIONS

Based on the obtained results, the following conclusions may be drawn:

1. The presence of transfer floor increases the base shear value for all building heights.

2. In both case studies, the story shear force is significantly reduced above the transfer floor location due to the sudden decrease in mass.
3. To obtain the required participation mass ratios, buildings with transfer elements at lower level should be analyzed using a greater number of modes to reach the required mass participation.
4. Transfer elements attract considerable lateral loads and therefore, must be designed accordingly.
5. To consider the deformations effect of transfer slabs in the seismic behavior of the buildings, it is recommended to model the transfer slab using thick shell elements or three-dimensional solid elements instead of considering it as a rigid diaphragm.
6. The presence of transfer floors in buildings makes the curves of story drift ratio to become nonuniform particularly when transfer floor is at the critical height location.
7. There is an abrupt change in their lateral stiffness at the vicinity of the transfer floor. Therefore, the transfer floor location controls the maximum location for the story drift. This is an important issue, so designers can take appropriate precautions to satisfy the serviceability requirements.
8. It is advisable to locate the transfer floor in the range of 20% to 30% building height. This, however, may be governed by architectural constraints, the location of the mechanical levels, speed of construction and economy.
9. The pushover analysis (POA) can predict the degradation of structure stiffness, the formation and locations of plastic hinges as lateral loads are increased. Also, POA identify members that are likely to reach critical states during an earthquake and evaluate the building's performance to the considered earthquake.
10. Using POA could save about 20% to 35% in the RC concrete dimensions and reinforcement of the buildings. This finding emphasizes the importance of performing POA in the evaluation of buildings with transfer system especially in high seismic hazards regions.
11. For the case studies presented in this research, the base shear obtained using POA is about 65% to 83% of that calculated using the response spectrum. On the other hand, the base shear calculated using the response spectrum of Saudi building code (SBC 301) is considerably lower than that obtained using POA.
12. Damage of the studied buildings is still limited because the worst elements yield at the IO to LS level.
13. The response modification factor is very sensitive to both horizontal and vertical irregularity. Only for the studied cases, the building codes R values may be overestimated.

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