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THE EFFECTS OF EXISTENCE OF TRANSFER SLAB SYSTEM ON THE SEISMIC BEHAVIOR OF RC BUILDING

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Abstract: A comparative analytical study for the structural dynamic behavior of multi-story R.C. building that implies a transfer slab system in one of its floor slabs, is presented. The study aims to improve the general understanding of the effects of transfer slab system in the R.C. buildings on their seismic behavior. The vertical position of transfer slab system with respect to the building height, is investigated. A plane frame model of R.C building, subjected to different ground motions, is studied. The ground motion is simulated through sets of natural accelerograms used in time history analyses. The change in the behavior of R.C. building models is evaluated by comparing results of maximum story drift ratios, maximum shear story and local damage distribution along the height of the building for different models. The damage indices are obtained through time history analyses for different plane frame models by using modified Park-Ang damage index indication. The time history analysis is performed in computer code (IDARC2D, 2006). The output based on analyzing and comparing the results of different models to infer some of the principles that should be taken into account when designing this kind of buildings.

1 INTRODUCTION

The need to have a building with various operational demands has been increased. Transfer slab system is commonly used to solve this persistent structural–architectural conflict. The building that implies a transfer slab system involves three structural parts: a podium, a transfer system and a tower. A podium structure is located below the transfer system. It is allotted as functional areas such as a shopping mall, parking, commercial markets, multi-purpose halls….etc. Thus, columns are required in longer span design. The transfer system lies between podium and tower parts; it supports a varying system of vertical and lateral load resisting elements. For the tower, located in the upper part of the structure, it is often used as an office and residential units using more economical shorter span design. Shear walls may not exist in the stories below transfer system, due to an architectural demand. Several researches studied experimentally and numerically the effects of existence of the transfer slab. Yong et al. (1999) argument states that above the transfer floor level, the building almost acts as a free cantilever with its fixation located at the transfer floor level; whereas the rest of the building under the transfer floor approximately acts like a fixed-fixed flexural member. Xu et al. (2000) investigated the effects of the vertical positioning of the transfer structure system on the seismic response behavior of the frame-supported shear wall structures. They found that the most onerous soft story behavior phenomenon is expected when the transfer floor is located at a level close to 40% of the height of the building, in which case, the maximum inter-story drift is expected at the transfer floor level. Ye et al. (2003) confirmed 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 may be accepted. Li et al. (2006) investigated the seismic behavior of an R.C residential building that had 34 typical floors above a 2.7 m thick transfer plate and a three-level podium. After major earthquakes; tension failure was found on the end shear walls in the vicinity of the transfer plate. Floor slabs and beam-wall joints were also cracked. The majority of the damage would occur at the floors above the transfer floor level. Elassaly and Nabil (2017) investigated the expected change on the structural dynamic behavior of multi-story R.C. building that implies a transfer slab system in one of its floor slabs and resists seismic forces by frame system. The existence of transfer slab system causes an increase in the shear story in podium part stories. The first story following the floor containing transfer slab may experience excessive drift ratios and local damage; hence, it may be subjected to soft story mechanism. The increase of the transfer system elevation level reduces building resistance for ground motions. It was concluded that the existence of shear walls above the transfer system would improve its dynamic behavior. Geng and Xu (2002), Rong and Wang (2004), and Wu et al. (2007), performed a hypothetical tube structures and real coupled shear wall-core wall buildings with transfer stories at various levels under earthquake loads. They confirmed that soft-story phenomenon was found to be more dominant with increasing the difference in the equivalent lateral stiffness between the superstructures above and below the transfer floor, in addition to the effects of the above mentioned higher position of the transfer floor. Gomez-Bernal et al. (2013), performed a 3D numerical analysis to investigate the interaction between shear walls and transfer-slabs subjected to lateral and vertical loading. In their investigation, they checked the behavior of shear wall/slab buildings and they argued that further investigations are still needed to investigate the behavior of buildings with transfer systems to cover variables such as the slab type (solid waffle, plane), the walls' position on slab, the anchor between slab and wall, etc. This paper discusses the effects of the existence of transfer slab system as well its elevation level on the seismic behavior of the RC building. The worst location of the transfer slab (as a percentage of total height of the building height) is investigated. The lateral resisting system below transfer floor is represented by moment–resisting frames. While the lateral resisting system upper transfer slab system is a moment–resisting frames, in addition to structural shear walls. Five parameters are assessed to achieve the objective of the study; the fundamental periods, shear story, inter-story drift ratios, local damage as well as the overall damage indices. The comparative analysis of those parameters of models b to those of model A, would highlight the influence of transfer slab system as well as its elevation level on the seismic behaviour of RC buildings.

2 HYPOTHETICAL STRUCTURE AND MATHEMATICAL MODELING

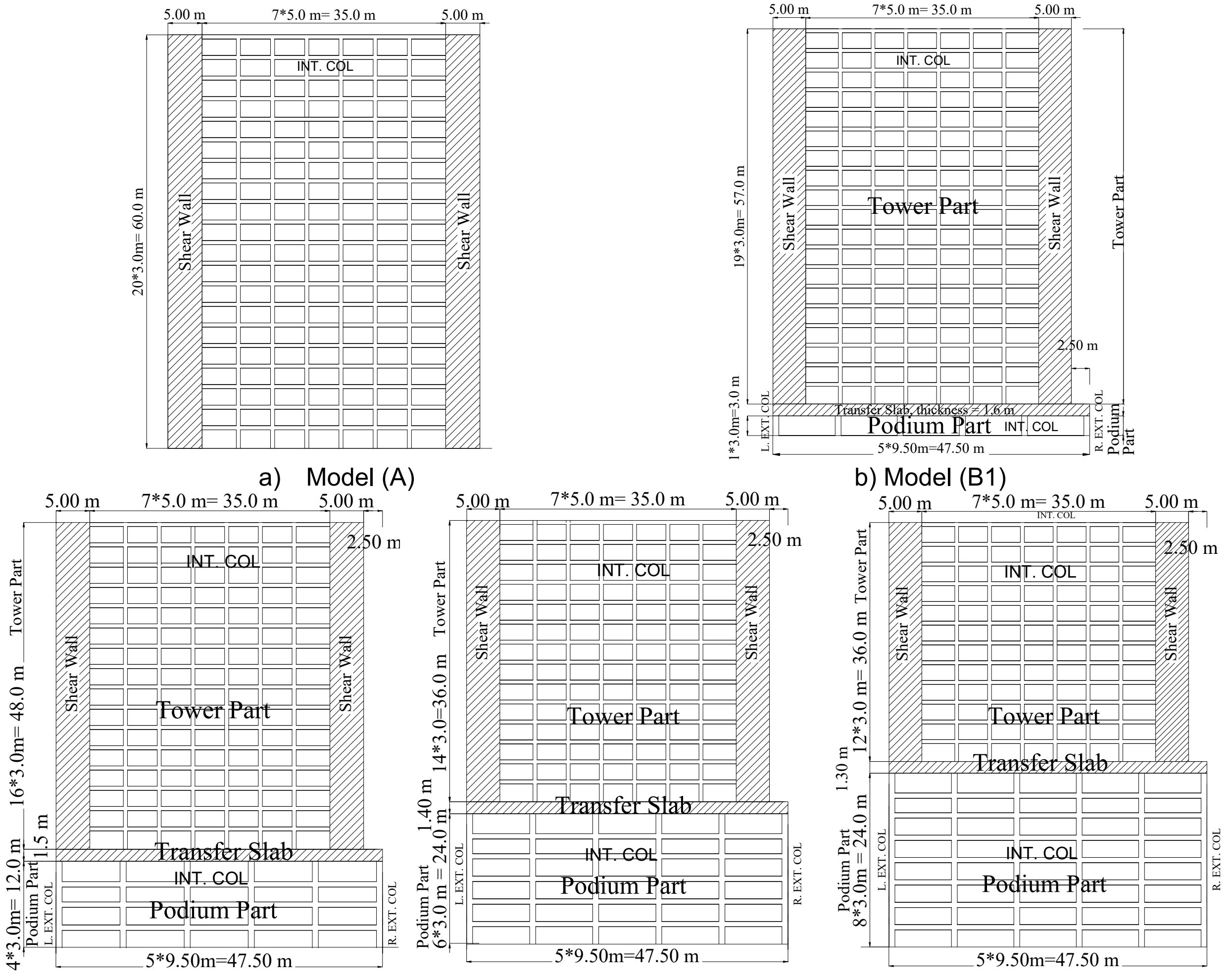
Figure 1 presents an elevation view of the considered hypothetical 20-story plane frame which has a floor height of 3.0 m. The RC model can be visualized as subdivided into three zone parts, the first part is the podium part, the second is the floor containing the transfer slab system and the last one is the tower part. The transfer slab system exists either in the first, fourth, sixth or eighth floor, for model B1, B2, B3 and B4, respectively. RC frames is selected for the podium part; whereas, a dual system of R.C frames and shear walls is utilized in tower part. Frame spacing are assumed to be 5.0 m for all building models. Columns axes are set to 9.5m and 5.0m apart for podium and tower, respectively. Solid slab with thickness of 160 mm and 120 mm, are chosen for podium and tower slabs, respectively. Beam dimensions are 250*600 mm for tower slabs and 250*900 mm for podium slabs. Transfer slab is represented by thick slab transferring the loads from tower to podium columns; it is modeled as a beam, having width of 2.0m. Model A presents a regular plane frame without transfer slab; it is considered as the reference model. Building models are designed in accordance to ACI 318-14 (2014). Table 1 summarizes the configurations of columns assumed for different models. Table 2 presents depth, D, and reinforcement details of transfer beam for each model.

3 NONLINEAR TIME HISTORY ANALYSIS

Two finite element programs ETABS (2015) and IDARC2D (2006) are employed. Frame elements are assumed for columns, beams and transfer system; whereas, shell elements are considered for shear walls. Since all sample buildings are assumed to fulfill regularity conditions in-plane, torsion effects are expected to be insignificant; thus, two-dimensional models of interior frames of sample buildings, are investigated. Computer code ETABS (2015) is used to perform static design, as well as obtaining modal shapes and frequencies of each model. For the nonlinear dynamic analysis of models subjected to ground motions (Table 3), the program IDARC2D (2006) is used. A time step of 0.001s and a 5% Rayleigh proportional damping are selected. The analysis takes into account P-delta effects; whereas, effects of infill walls on the system stiffness, are neglected. A smooth hysteretic model is used to simulate the elastic-yield transition and the shape of unloading; it incorporates stiffness degradation, strength deterioration, non-symmetric response, slip-lock and a tri-linear monotonic envelope. Significant structural features, including damage indices, inter-story drift ratios and base shear, are calculated using IDARC2D (2006) analysis. The damage indicator, implemented in the computer program IDARC2D (2006), is the Park and Ang damage index. The Park and Ang damage index is defined as a mathematical model for quantitative description of the damage state of the structures; it is expressed as the linear combination of normalized maximum deformation and hysteretic energy dissipation, Park et al. (1987):

$$[1] \qquad DI = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u P_y} \int dE_h$$

Where δ_m and δ_u are the maximum and ultimate deformation of element; β is a model constant parameter. $\int dE_h$ is the hysteretic energy absorbed by element during earthquake; P_y is the yield strength of element.



a) Model (A)

b) Model (B1)

c) Model (B2)

d) Model (B3)

e) Model (B4)

Figure 1: Configurations of used models of R.C. building

Table 1: Configurations and RFT details of model columns

Building model	Podium part			Tower part		
	Column section	Cross section (mm)	RFT (mm2)	Column section	Cross section (mm)	RFT (mm2)
A				CE & CI	600*600 & 700*700	5628 & 7683
B1	CE & CI	650*650 & 950*950	10802 & 23568	CI	650*650	7734
B2	CE & CI	650*650 & 950*950	10802 & 23568	CI	600*600	6580
B3	CE & CI	650*650 & 950*950	10802 & 23568	CI	550*550	5626
B4	CE & CI	650*650 & 1000*1000	10802 & 25532	CI	550*550	5778

CE: External column section; CI: Internal column section.

Table 2: Configurations and RFT of transfer slab sections with 2 meter width

Building model	Transfer slab			Building model	Transfer slab		
	Section	D (mm)	RFT(mm2),Top & Bot		Section	D (mm)	RFT(mm2),Top & Bot
B1	BL&BI&BR	1600	15750&12300&11300	B3	BL&BI&BR	1400	10100&9500&8500
B2	BL&BI&BR	1500	13900&11100&10100	B4	BL&BI&BR	1300	11930&9500&8500

BL: Left external beam section; BR: Right external beam section; BI: internal beam section.

Table 3: Characteristics of the used Ground Motions (PEER, Strong Motion Database 2000).

EQ	ID	Earthquake/ Component	Date	M	PGA (g)	PGV (m/s)	a/v ratio (g/ms-1)
EQ.1	P0030	Parkfield / PARKF/C02065	28/06/1966	6.1	0.476	75.1	0.63
EQ.2	P0998	Northridge / NORTHR/PAR--L	17/01/1994	6.7	0.657	75.2	0.87
EQ.3	P0082	San Fernando / SFERN/PCD164	09/02/1971	6.6	1.226	112.5	1.09
EQ.4	P0934	Northridge / NORTHR/SYL360	17/01/1994	6.7	0.843	129.6	0.65
EQ.5	P0890	Northridge / NORTHR/MUL279	17/01/1994	6.7	0.516	62.8	0.82
EQ.6	P0127	Gazli, USSR / GAZLI/GAZ090	17/05/1976	6.8	0.718	71.6	1.00

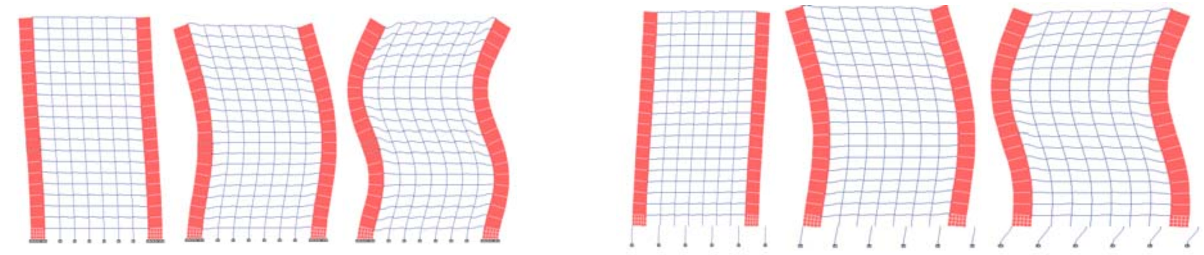
4 DISCUSSION OF ANALYSIS RESULTS

Developing the general concepts regarding the effects of the existence of transfer slab and its elevation level on the seismic behaviour of RC buildings, are the main objectives of the current study. Designers must have well visualization about the critical zones that experiences higher stress distribution along the building height. The dynamic behaviour of such type of building is investigated by comparing the results of maximum story drift ratios, shear story and local damage along the height of the building, as well as the overall damage of models #B with those of model A. Thus, a comprehensive picture of the effects of transfer slab system as well as its elevation effects, are well examined. The dynamic behavior of building models is investigated through examining their mode shapes and fundamental frequencies. Figure 2 demonstrates the mode shapes as well as the corresponding periods of the first three mode shapes of model A, B1, B2 and B3. The fundamental period of model B1 is prolonged by 1.80% compared with that of model A. For the other models, the increase varies from 9.83% to 14.75% for models B2 and B3, respectively.

Figure 3 shows the variation of story shear, presented as a percentage of the total building weight (WT), of models A, B1, B3, and B4. All models are subjected to six different ground motions (Table 3). For model A, the figure shows a typical variation of story shear, where the highest value exists at the base. Then, it gradually decreases towards the top of the model. According to the applied ground motion excitation, the maximum base shear varies from 6% to 11% of total model weight, for all investigated models, except for model B1, where the maximum base shear almost reached up to 18% of total model weight. However, transfer slab existence does not affect the distribution shape of the shear story along building models. In order to demonstrate the expected variation of maximum story shear for different models due to the transfer system, a plot of the maximum change of story shear of Model B, compared to that of Model A, is depicted in Figure 4. The maximum change in story shear of a particular floor of model B is represented as:

(Max. SSB# - Max. SSA) / Max. SSA (represented as percentage value)

Where, SSB# is story shear in a particular floor of models B; SSA is the corresponding value of Model A. The presence of transfer system has significant effects on story shear distribution. The story shear is reduced in the tower part of B models relative to those of model A due to the abrupt reduction in the mobilized mass between transfer slab floor and its neighbour stories. The amount of decrease in story shear of tower part increases with the increasing of transfer slab position level. For different applied earthquake motion, story shear of tower part stories decreases almost by 20% to 40%, 30% to 70%, 60% to 70% and up to 90% in cases of model B1, B2, B3 and B4, respectively, compared with model A. It should be noted that story shear increases significantly in transfer slab floor. This increase is reduced by increasing the elevation level of transfer slab system. The increase in story shear may reach as high as 80%, 50%, 40% and 15% for models B1, B2, B3 and B4, respectively. The columns beneath the transfer system; experience significantly high values of story shear; thus, it may lead to plastic hinge generation.

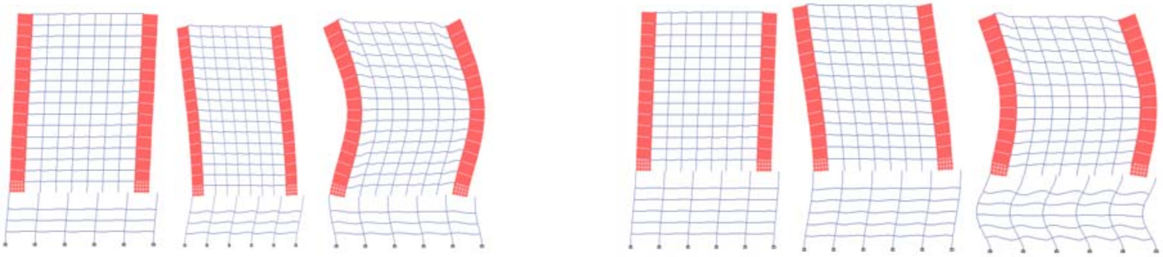


T1 = 2.094 s T2 =0.557 s T3 = 0.246 s

a) Model A

T1= 2.132 s T2 =0.575 s T3 = 0.291 s

b) Model B1



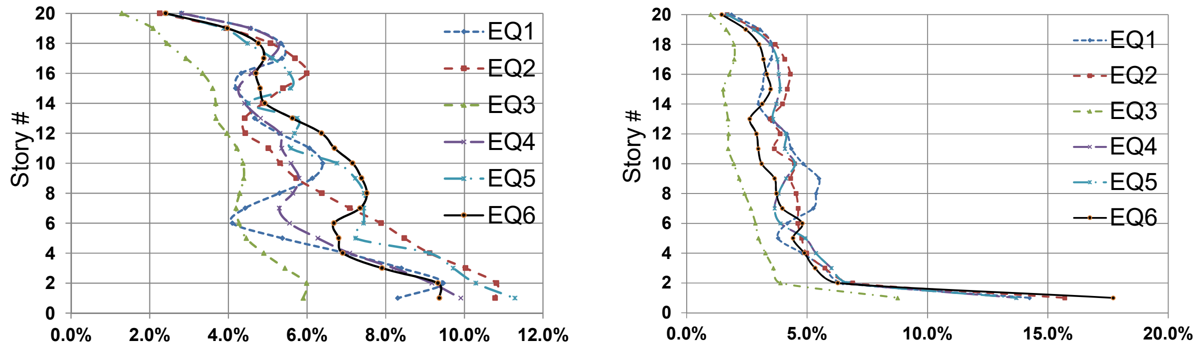
T1 = 2.30 s T2 =0.891 s T3 = 0.373 s

c) Model B2

T1 = 2.403 s T2 =0.933s T3 = 0.353 s

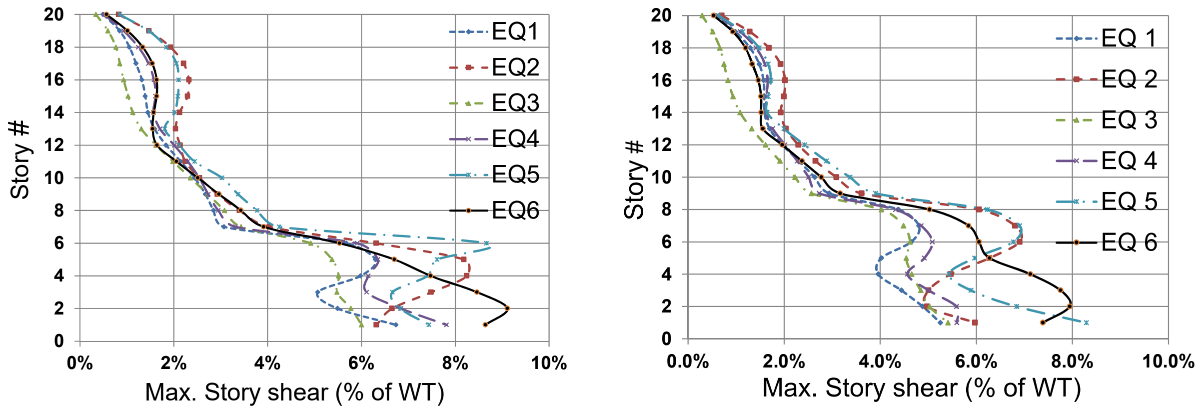
d) Model B3

Figure 2: First three mode shapes of models A, B1, B2 and B3



a) Model A

b) Model B1



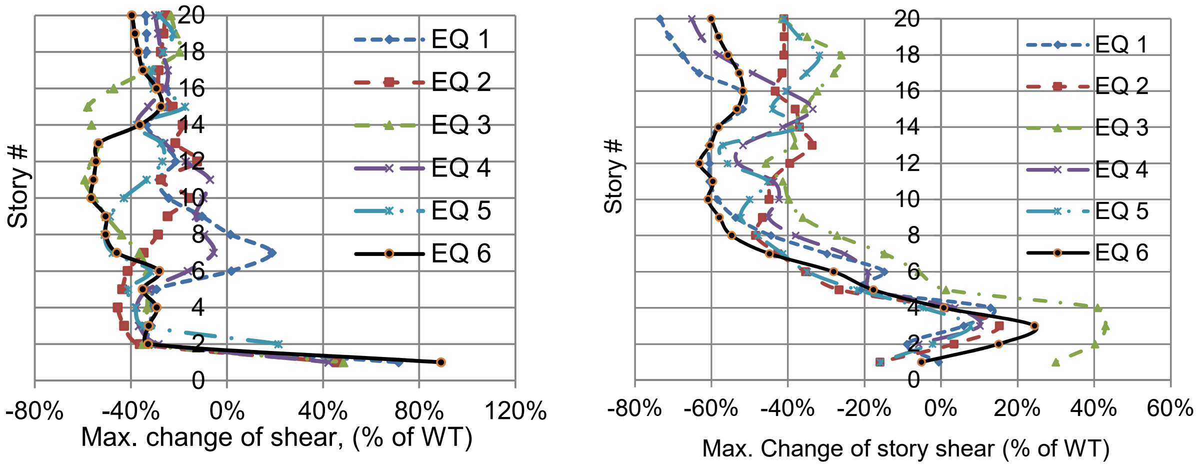
c) Model B3 d) Model B4

Figure 3: Variation of story shear as a percentage of total building weight for models A, B1, B3, and B4

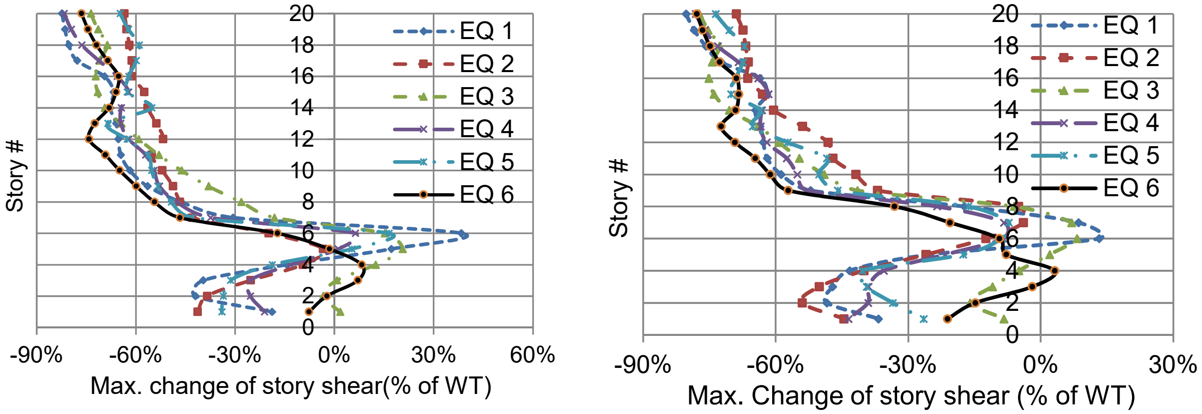
Figure 5 shows the variation of story drift of models A and B4 under the effects of six different ground motions. Figure 5a depicts a typical cantilever behaviour of model A. It should be noted that model A has two external shear walls which dominate its behaviour. Thus, the upper stories, of model A, experience the highest values of drift ratios. For model B4, transfer system existence has significant influence on the story drift distribution. Figure 5b shows a typical behaviour of RC building with transfer slab, where it may be visualized as if the building is composed of two buildings, with distinctive behaviour, on top of each other. The upper part represents a cantilever type building, similar to that of model A. The lower part represents a typical distribution of story shear of framed structure [6], where the middle stories of podium part experience the highest drift ratios. Figure 6 demonstrates the changes of story drift ratios along the height of B models in comparison to those similar stories of model A. The maximum change in story drift of a particular floor of models B, is represented as:

(Max. SDB# - Max. SDA) / Max. SDA (represented as percentage value)

Where, SDB# is the story drift in a particular floor of Models B; SDA is the corresponding value for Model A. The inter-story drift of transfer floor, is decreased in range of 30% to 70%, in comparison to similar stories of Model A. The drift ratio of first story above transfer slab increases in comparison to comparable floor of model A; this increase may reach 100%. The drift ratios of tower part decrease for B models when compared to those of model A. This decrease increases with the increase of vertical level position of the transfer system. For the lower stories of model A, drift ratios have small and insignificant values, for different seismic input excitations. The similar stories of the podium part of B models, are expected to have higher values than those of model A. Finally, it could be concluded that story drift at tower part and transfer system floor decreases significantly; whereas it increases for the podium part. Figure 7 depicts the typical distribution of local damage along the height of model A as well as those of Models B, when subjected to different input ground motions. For model A, it is noticed that top stories experience the highest local damage. Comparing parts a, b, c and d of Figure 7, it is clearly obvious that local damage distribution is greatly affected by transfer system existence and its position level. For B models, top stories and transfer slab floor, experience low values of local damage. The lower story of tower part; that is the floor follows the transfer system, often experiences an increase in local damage.

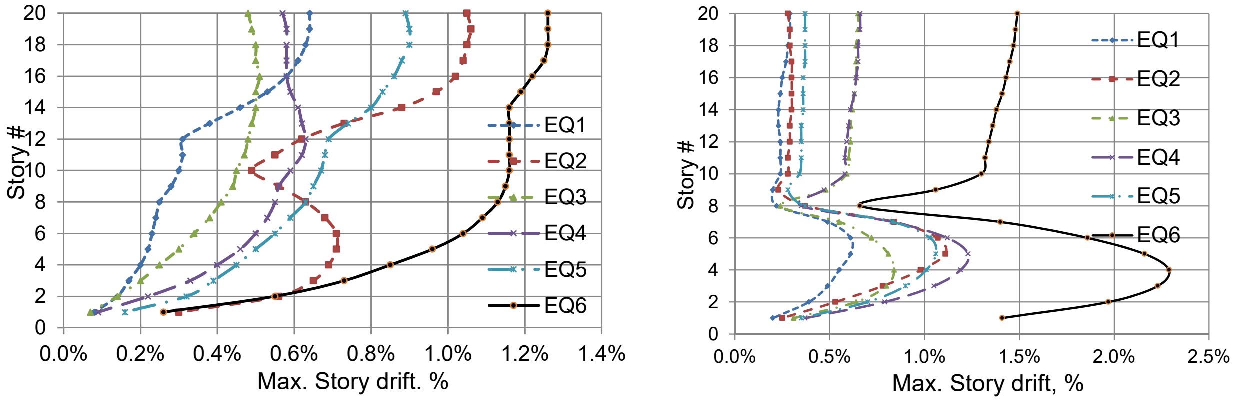


a) Model B1 b) Model B2



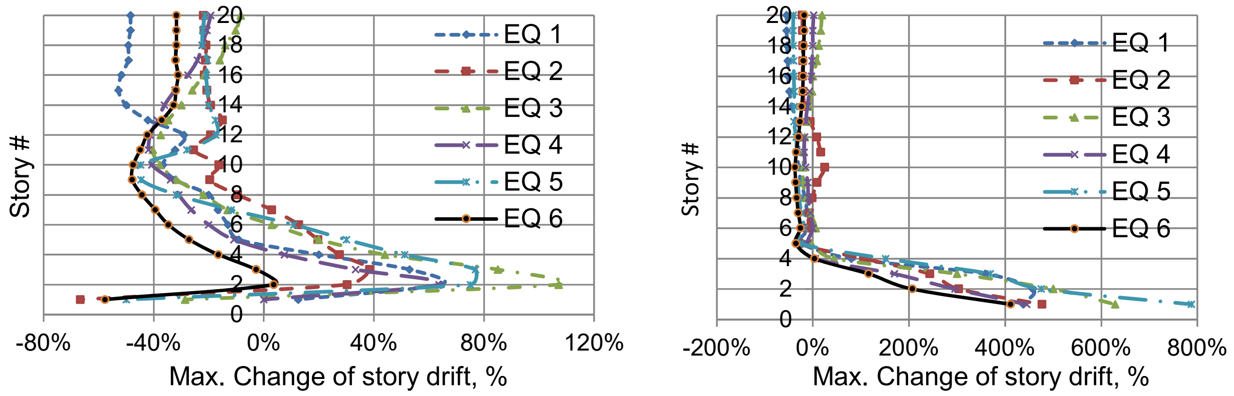
c) Model B3 d) Model B4

Figure 4: Variation along height of models, of the maximum change of story shear, when subjected to six different input excitations

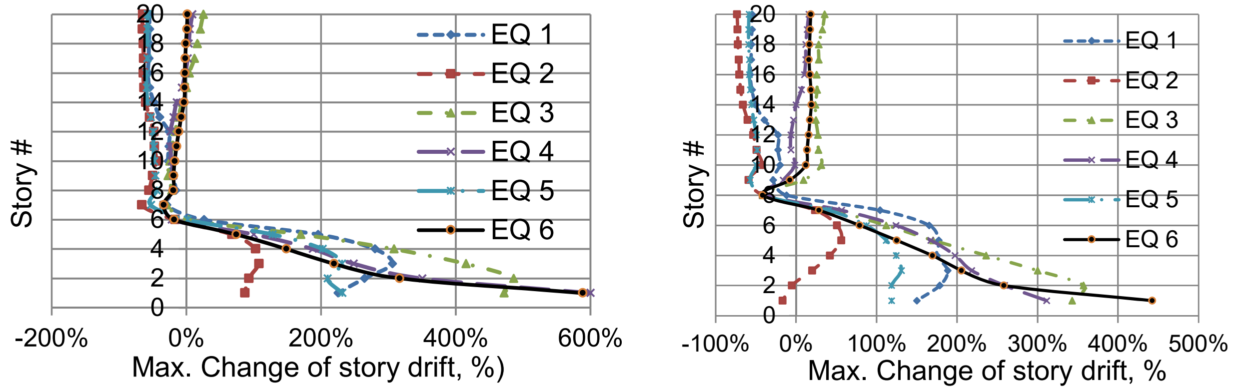


a) Model A b) Model B4

Figure 5: Variation of max. Story drift ratio along the height of model A and B4



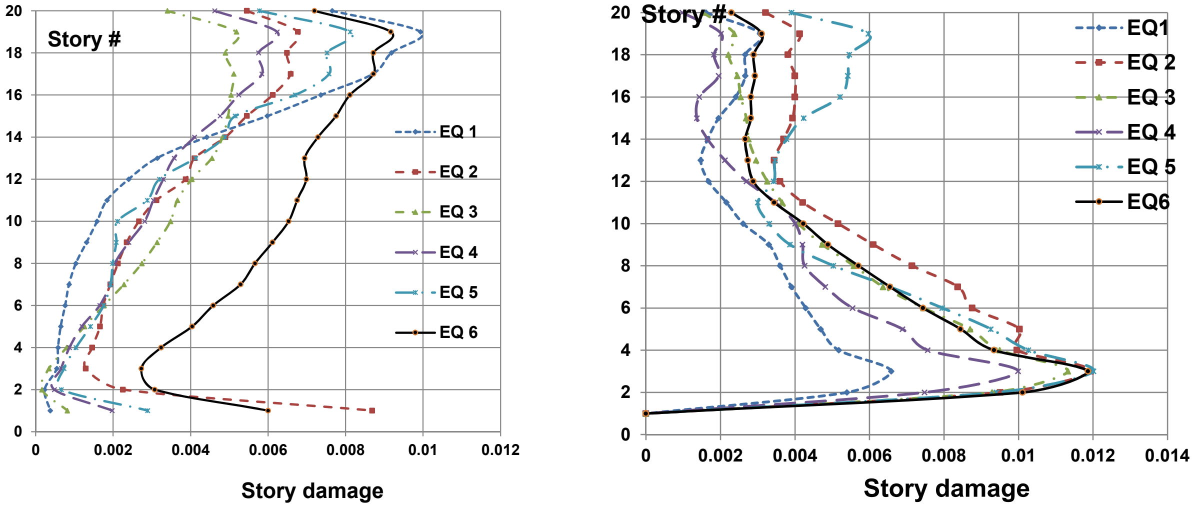
a) Model B1 b) Model B2



c) Model B3 d) Model B 4

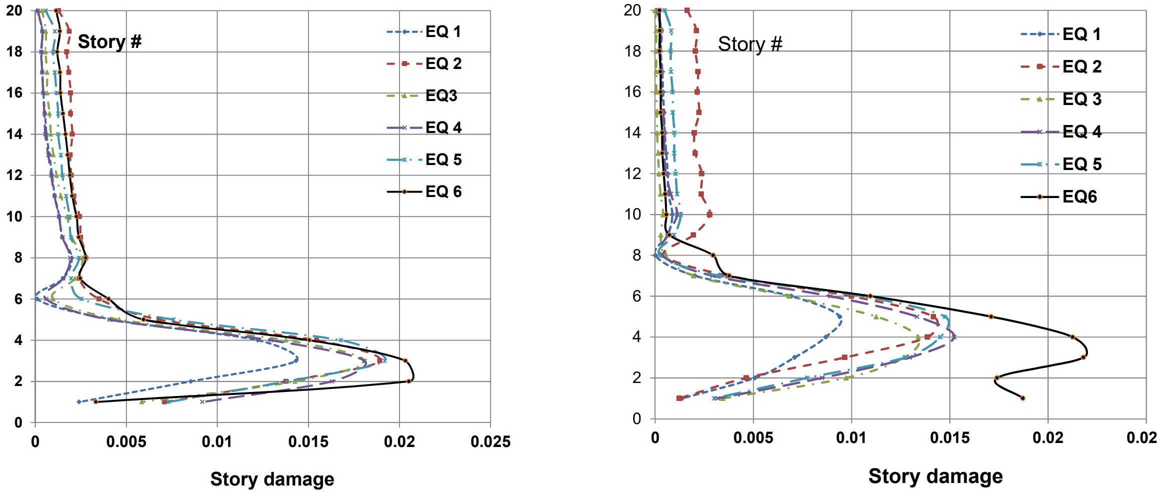
Figure 6: Variation of change of max. Story drift ratio for B models

For models B2, B3 and B4; where transfer slab is located at height equals to or greater than 20% of total height, the maximum damage almost occur in the middle stories of podium part. The accumulative damage of the story that implied transfer slab is noticed to experience less levels of damage indices, compared to those occurring at middle stories of podium part. Columns carrying transfer slab experience the higher damage indices compared to other columns all over building stories. Transfer floor experiences high shear forces because of its great mass. Hence, high shear forces usually lead to cracks appearance in the slab–column connections of transfer slab story. During earthquakes, this cracks may develop to form plastic hinges. Table 4 presents the status of different studied models under the effects of EQ6 (Table 3). It is noted that during the first 4 seconds of the seismic period, almost no cracks occurs in all models. No plastic hinges appear in column connections of model B1 during the first 10 s of EQ6. Model B2 is considered the first model to experience formation of plastic hinges compared to the other models. Model B2 shows less efficiency to resist seismic forces compared to other models. Plastic hinges are generated in the lower story of podium part and in transfer slab after 9 seconds of start of earthquake event. of seismic event. Model B4 has better efficiency than B2 and B3 to resist seismic forces. It is noted that model A has the most efficiency to resist the seismic compared to B models. It should be noted that building efficiency decreases significantly by the existence of transfer slab system.Figure 8 presents bar charts representing the variation of overall damage index of different models, when subjected to different applied earthquake ground motions. The figure shows that Model B2 experiences the highest overall damage indices in comparison to other models. It should be noted that transfer slab of model B2 exists at height of 20% of building total height (TH). Models B1 (5% of TH), B3 (30% of TH) and B4 (40% of TH) lead to less values of overall damage indices; thus, they are considered to have relatively accepted seismic performance. Thus, it could be concluded that existence of transfer slab system at level about 20% of building total height, is expected to lead to the worst case of all studied cases. Figure 9 depicts the variation of maximum base shear, represented as % of total weight of building (WT), with transfer slab levels (% of TH) of models B. The figure shows that the maximum base shear occurs for case of transfer system at height of 5% of TH (model B1); the base shear decreases with the increase of transfer slab elevation. It should be noted that the base shear of model A, under different applied earthquakes vary from 7% to 13% of WT.



a) Model A

b) Model B1



c) Model B3

d) Model B4

Figure 7: Variation of story damage for A and B models, when subjected to different seismic

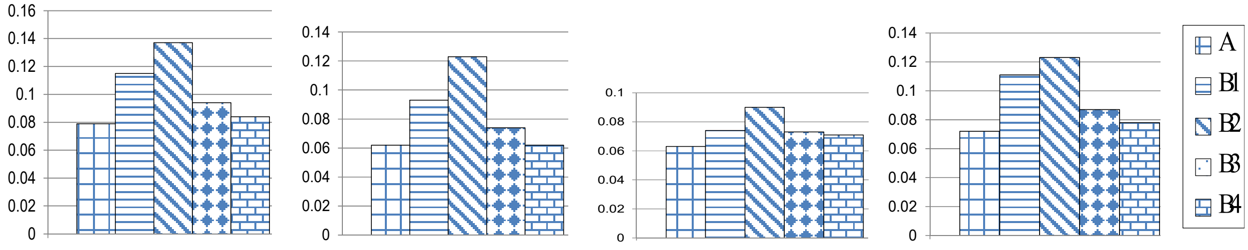
Table 4: Status of different studied models under the effects of EQ6

Time span t*, s	Model A	Model B1	Model B2	Model B3	Model B4
4	Zone 1: SC				
5	Zone 2: SC	Zone 2: SC	Zone 3: C Zone 4: C		
6			Zone 1: SC Zone 4: Ph	Zone 1: SC Zone 3: C Zone 4: C	Zone 1: SC
7				Zone 4: Ph	Zone 3: C Zone 4: C
8		Zone 3: C			
9			Zone 2: SC Zone 3: Ph	Zone 3: Ph	Zone 4: Ph
10				Zone 2: SC	Zone 3: Ph

*t: time span, s, from start of earthquake event.

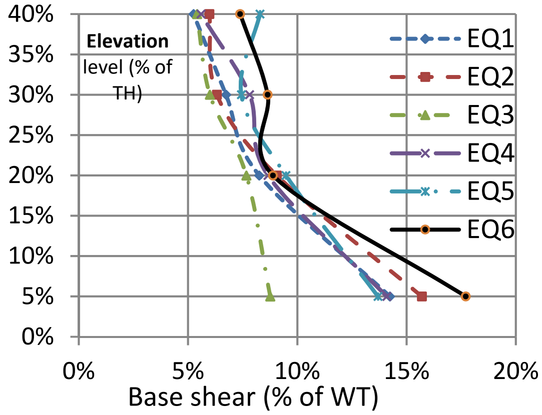
Sc: Slight cracks, C: Cracks, Ph: Plastic hinges, Zone 1; upper stories of tower part; Zone 2; Lower stories of tower part; Zone 3; Transfer slab columns; Zone 4; Lower story of podium part.

Figure 10 depicts the variation of overall damage indices, with the level of transfer slab levels, represented as % of TH. The figure shows that the building models experience highest overall damage indices in cases where transfer slab is located at 15% to 30% of total building height (TH). In other words, the worst elevation level for transfer slab is closed to 20% of total building.



a) EQ2 b) EQ3 c) EQ4 d) EQ5

Figure 8: Variation of overall damage index for all models, under different ground motions



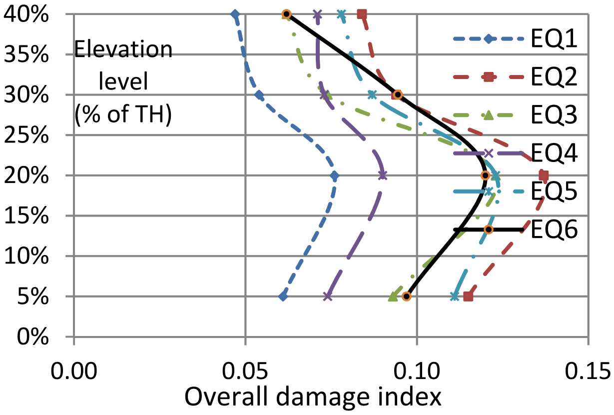


Figure 9: Variation of max base shear (% of WT), with different transfer slab levels (% of TH)

Figure 10: Variation of overall damage index, with different transfer slab levels (% of TH)

5 CONCLUSIONS

The effects of transfer slab system existence as well as its elevation level on the seismic behaviour of RC building, have been investigated. The outcomes of the study are limited to the RC models investigated. The followings represents the expected behaviour of RC building with transfer system (B models), compared to that without transfer system (A model):

- The fundamental periods of RC B models, are expected to lengthen by 2 to 14%.
- RC building with transfer slab, behaves as if the building is composed of two buildings, with distinctive behaviour, on top of each other. For the present study, the upper part (tower) represents a cantilever

type building, similar to that of model A; whereas, the lower part (podium) represents a typical framed structure.

- Tower stories may experience less values of story shear and inter story drift ratios; this reduction increases with the increase of transfer slab level.
- Podium stories are expected to experience higher values of drift ratios and story damage.
- Columns beneath the transfer floor experience significantly high values of story shear; thus, it may lead to plastic hinge generation and soft story mechanism.
- Local damage distribution is greatly affected by transfer system existence and its position level.
- The maximum overall damage almost occurs in the middle stories of podium part.
- Plastic hinges are more likely to be generated in RC building with transfer system than that without it.
- Existence of transfer slab system at level about 20% of building total height, is expected to lead to the highest values of overall damage indices.
- Base shear decreases with the increase of transfer system elevation.

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