Inelastic Seismic Response of Reinforced Concrete Buildings with Symmetric and Unsymmetric Floor Diaphragm Openings

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SUMMARY:

Floor and roof diaphragms play a key role in distributing earthquake-induced loads to the lateral load resisting systems. The in-plane flexibility of the diaphragms was often ignored for simplicity in practical design, until recently where building standards such as ASCE7 (2005) acknowledged that this assumption can result in considerable errors when predicting the seismic response of RC buildings with diaphragm plan aspect ratio greater than 3:1. However, the influence of floor diaphragm openings has not been directly considered. In this paper, the inelastic seismic response of five 3-story reinforced concrete buildings with end shear walls and plan aspect ratio of 4:1 with symmetric and unsymmetric floor openings within the middle two-thirds of the building using an enhanced version of IDARC2 are presented. It is concluded that the influence of “inelastic” in-plane diaphragm deformations due to floor openings may not be overlooked when openings are present irrespective of where they are located.

Keywords: Inelastic, Response, Diaphragm, Concrete, Buildings.

1. INTRODUCTION

Roof and floor systems play an important role in distributing lateral loads by exhibiting diaphragm-like behavior, but they are only designed to carry gravity loads and transfer these loads to supporting beams, columns or walls. Because horizontal diaphragms which typically function as deep beams having very high stiffness and strength in comparison to other structural components, they are often considered to be infinitely rigid in reinforced concrete buildings. In the case of rigid floor diaphragms, the floor plate is assumed to translate in plan and rotate about a vertical axis as a rigid body, the basic assumption being that there is no in-plane deformation in the floor plate. However, this assumption has serious limitations for buildings with considerable in-plane diaphragm deformation (Panahshahi, 1988). For diaphragms assumed to be infinitely stiff (rigid), the force distribution depends only on the relative stiffness between the vertical resisting elements. With advances in numerical methods and computer technology, it is important in some cases that floor systems be modeled as elastic and/or inelastic diaphragms (Panahshahi, 1991 & Kunnath, 1991) so that diaphragm in-plane deformations are included in the analysis. The inelastic deformations are important not only for proper evaluation of the lateral load distribution to vertical resisting frames and walls but also to determine the ductility demand of floor diaphragms and frames. In this paper all three types of diaphragms (elastic, inelastic and rigid) are addressed in order to evaluate the effect of in-plane deformations for reinforced concrete floors with and without openings on the seismic performance of buildings with frames and end shear walls. The inelastic dynamic response of the buildings was evaluated by means of an enhanced computer program IDARC2 (Panahshahi, 1988) to account for unsymmetric floor slab cross-sections due to floor openings. The program uses macro-modeling schemes to account for diaphragm in-plane deformations due to shear and flexure while taking into account stiffness deterioration and strength degradation of the reinforced concrete beams, columns, shear walls and slabs due to inelastic cyclic loadings caused by ground motion.

2. RESEARCH SIGNIFICANCE

Openings in diaphragms are often unavoidable and their presence can significantly modify the behavior of the diaphragm. At present, the designer assumes that the reinforced concrete floor diaphragms are rigid and elastic when diaphragm aspect ratios are 3:1 and 4:1, respectively. This assumption may lead to erroneous results particularly in reinforced concrete buildings with floor openings. This issue is considered important, as it is the least understood subject in this area, since there is no quantification of the error in diaphragm ductility demand and frame shear forces as a result of ignoring openings. Therefore, in this study, inelastic diaphragm deformations are incorporated in the analysis in order to capture the "real" behavior of the structural members as opposed to the "assumed" one in low-rise rectangular buildings. The latter will yield a better understanding of the structural behavior and hence design of reinforced concrete buildings with floor diaphragm openings when subjected to strong ground motion.

3. OBJECTIVE

The main goal of this research project was to gain in-depth understanding of the seismic response of low-rise rectangular reinforced concrete buildings with symmetric and unsymmetric floor diaphragm openings. This is achieved by investigating the applicability of rigid, elastic and inelastic floor assumptions to floor diaphragm models with aspect ratio of 4:1 when openings are present. Floor openings of various sizes are placed in symmetric and asymmetric plan locations in order to investigate the influence of floor diaphragm flexibility on the distribution of lateral loads to frames and shear walls. By capturing the true behavior of reinforced concrete buildings with diaphragm openings, the results of this study will lead to valuable information.

4. DESCRIPTION OF STRUCTURES AND SEISMIC DESIGN PARAMETERS

In this present study, five 3-story, 39 ft high (i.e., 13 ft story height) reinforced concrete buildings are investigated. The structure's plan is twelve 20 ft bays in length (240 ft total) and three 20 ft bays in depth (60 ft total), with 8 in. thick shear walls placed symmetrically at the end frame as shown in Figures 1 thru 5. The columns are 14 in. x 14 in. and the girders are 14 in. x 24 in. Floor diaphragm is a one-way 5 in. slab spanning across the frames with intermediate 14 in. x 14 in. supporting beams, i.e., 10 ft span. All elements were designed and detailed to meet ACI 318-08 and IBC 2009 prescribed forces. The lateral force resisting system in the N-S direction (short direction) consists of "Building Frame System" in which the shear walls will resist the entire seismic load, and intermediate moment resisting frames (IMRF) are used in the E-W direction (long direction). The equivalent lateral forces generated were based on a site class C, seismic design category (SDC) C and seismic use group I. Diaphragm openings were placed in the middle two-thirds of the building plan.

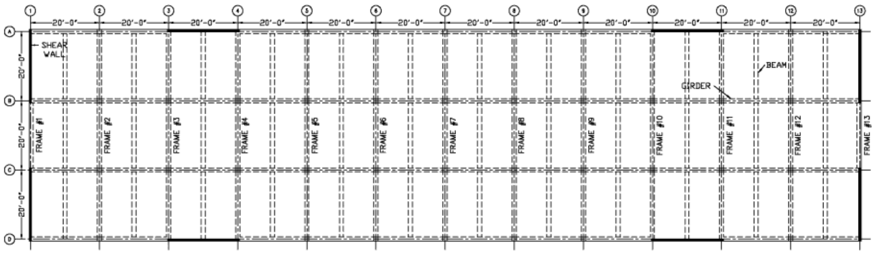

Figure 1. Solid diaphragm plan with end walls (Case 1)

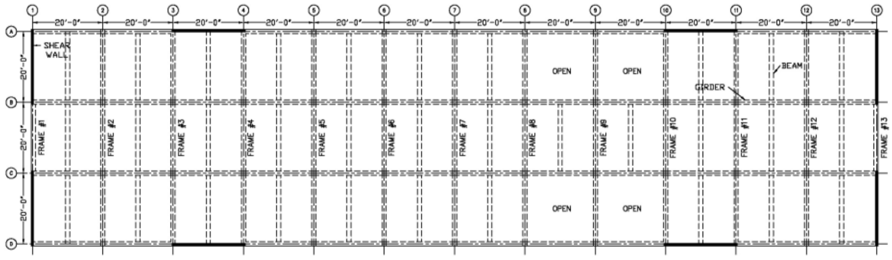

Figure 2. Open diaphragm plan with end walls (Case 2)

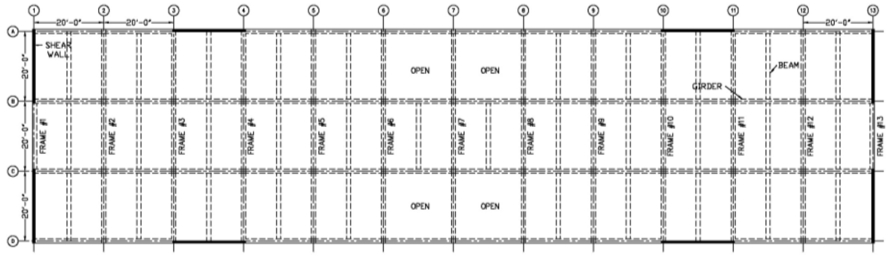

Figure 3. Open diaphragm plan with end walls (Case 3)

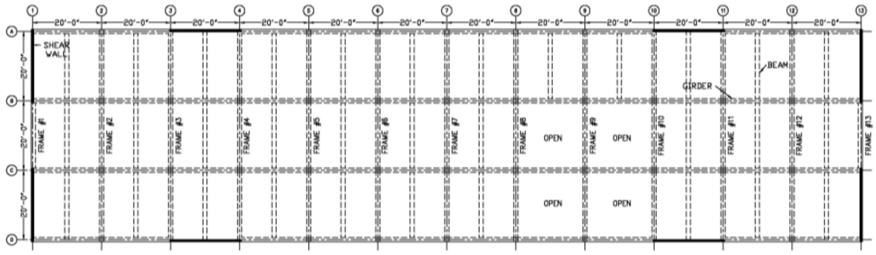

Figure 4. Open diaphragm plan with end walls (Case 4)

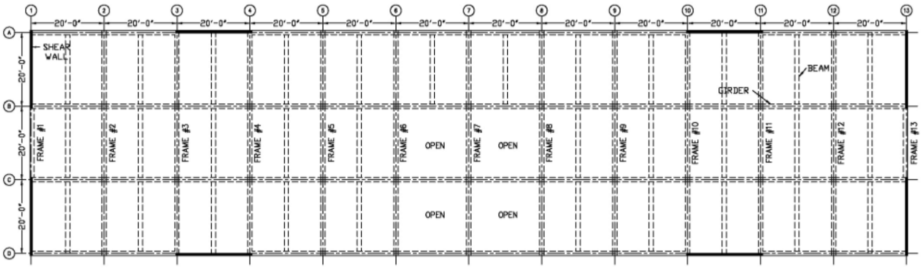

Figure 5. Open diaphragm plan with end walls (Case 5)

All buildings were assumed to be in Saint Louis, Missouri, and hence are designed and detailed accordingly with the seismic parameters shown in Table 1. All elements were designed using concrete compressive strength of 4000 psi and grade 60 reinforcing steel with an applied uniform live load of 50 psf and super imposed dead load of 20 psf. Members' structural reinforcing details are given in Table 2.

Table 1. Seismic parameters per IBC 2009

Parameter	**Value**
Short Period Acceleration, S_s	0.57
Long Period Acceleration, S_l	0.19
Short Period Site Coefficient, Fa	1.17
Long Period Site Coefficient, Fv	1.59
Short Period Spectral Response Acceleration Parameter, S_{DS}	0.45
Long Period Spectral Response Acceleration Parameter, S_{Dl}	0.20
Response Modification Factor, $R_{N\text{-}S}$ & $R_{E\text{-}W}$	5.00
Over-strength Factor, $\Omega_{o,\, N\text{-}S}$ & $\Omega_{o,\, E\text{-}W}$	2.50
Deflection Amplification Factor, $C_{d,\, N\text{-}S}$ & $C_{d,\, E\text{-}W}$	4.50
Fundamental Period of Structure, $T_{a,\, N\text{-}S}$	0.31 sec.
Fundamental Period of Structure, $T_{a,\, E\text{-}W}$	0.43 sec.
Base Shear Seismic Coefficient, Cs	8.9 %

Table 2. Reinforced concrete elements details per ACI 318-08

Element Type	**Element Size**	**Steel Reinforcing**
Slab	5 in.	#3 @ 12 in. one-way
Columns	14 in. x 14 in.	8-#6 verticals w/#3 @ 6 in. ties
Walls	8 in.	#6 @ 12 in. each way vertical & horizontal
Girders	14 in. x 24 in	3-#5 top & bottom w/#3 @ 10 in. stirrups – next to solid slab. 2-#5 top & bottom w/#3 @ 10 in. stirrups – next to open slab.
Beams	14 in. x 14 in.	6-#5 top & bottom w/#3 @ 6 in. stirrups

5. ANALYTICAL MODELING USING ENHANCED IDARC2

IDARC2 is a computer program for two-dimensional analysis of 3D building systems in which a set of frames parallel to the loading direction is interconnected by transverse elements to permit flexural-torsional coupling. The details of the analytical schemes may be found in Panahshahi, et al. (1988). In IDARC2, a reinforced concrete building is idealized as a series of plane frames linked together by floor slabs and transverse beams. Each frame must lie in the same vertical plane. Consequently, a building is modeled using the following element types: floor slabs, beam-columns, shear walls, shear wall edge columns, and transverse beams. All components of the building, except transverse beams, are modeled as tri-linear, inelastic elements with concentrated plasticity at member ends with a distributed flexibility rule to account for the spread of plasticity. A linear variation of flexibility is assumed in deriving the flexibility matrix. A typical floor slab is modeled using two degrees of freedom (DOF) per node: one lateral and one rotational. Two inelastic springs are used to model shear and flexure independently. In this study, IDARC2 was enhanced to include unsymmetric slab diaphragm cross-sections with typical idealized moment-curvature diagrams for such element shown in Figure 6.

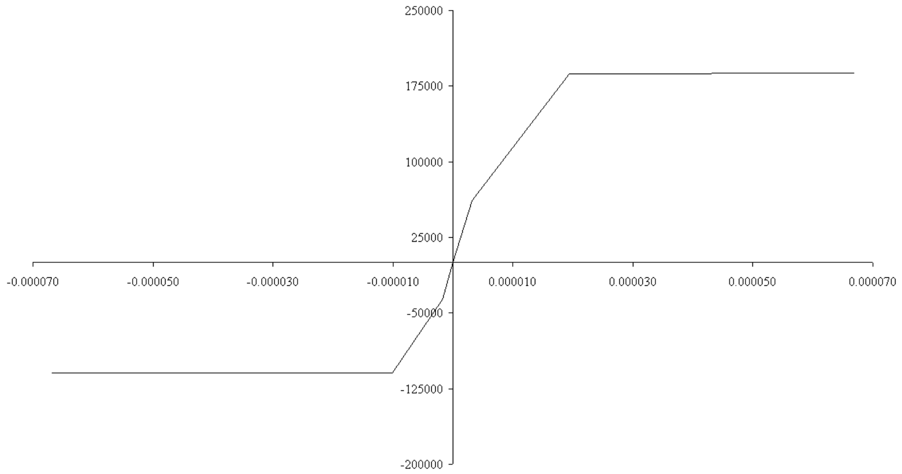

Figure 6. Idealized moment-curvature curve of unsymmetric slab diaphragm cross-section (kip-in/radian)

Also, main beam-column elements and/or shear wall form a vertical plane in the direction of earthquake loading. They are modeled as continuous inelastic shear-flexure springs in which shear-deformation effects have been coupled by an equivalent spring. The modeling of shear wall elements is similar to that for floor slabs except for the inclusion of axial effects and the incorporation of edge columns at the ends of the wall. Walls may, however, be modeled with or without edge columns. To incorporate the effects of transverse elements to account for their restraining action due to the axial movements of vertical elements, especially edge columns in shear walls, and permit flexural-torsional coupling with the main elements, each transverse T-beam is modeled using elastic springs with one vertical and one rotational DOF. As for the nonlinear dynamic analysis; IDARC2 follows the Newmark-Beta algorithm for the step-by-step solution of the dynamic equation of motion. The hysteretic model used for the analysis incorporates three parameters (stiffness degradation (α), strength deterioration (β) and pinching effect (γ)) in conjunction with a nonsymmetric trilinear curve to establish the rules under which inelastic loading reversals take place. These hysteretic parameters are combined in various ways to achieve a range of hysteresis behavior patterns typical to reinforced concrete sections. Details of significance and the general effects of these parameters can be found in Panahshahi, et al. (1988).

The enhanced IDARC2 was used to conduct inelastic static (push-over) and dynamic (time-history) analyses for the five reinforced concrete buildings in this study. All three different diaphragm types (elastic, inelastic and rigid) were investigated for every case. For comparison purpose, the building without diaphragm openings was included (Case 1). As for the diaphragms with openings four types of building plans were selected (as shown in Figures 2 through 5): symmetric with respect to both longitudinal and transverse axes (Case 3), unsymmetric with respect to only transverse axes (Case 2), unsymmetric with respect to only longitudinal direction (Case 5), and unsymmetric with respect to both longitudinal and transverse directions (Case 4). Since there are no available records of any severe earthquakes for the Saint Louis area, a suite of three well-known earthquakes is chosen with periods close to that of the buildings in question. This preference was made to maximize any resonance that may take place during an earthquake. Since the peak ground acceleration (PGA) recorded is higher than that of the site at 0.27g, the seismic input for the dynamic analysis was scaled accordingly, as shown in Table 3.

Table 3. Earthquakes characteristics used in the analysis

Earthquake	**PGA, g**	**T_g, sec.**	**Scale**
Loma Prieta - Corralitos - 1989	0.41	0.34 sec.	0.659
San Fernando - Pacoima Dam -1971	1.15	0.40 sec.	0.235
Parkfield - Cholane -1966	0.48	0.40 sec.	0.563

6. RESULTS

For all the five buildings considered, the investigation proceeds by the pushover analysis (inelastic static) and then is completed with the inelastic dynamic analysis. From the pushover analysis, it is observed that the behavior of this type of buildings is primarily controlled by the yielding sequence of wall elements and then slab elements. In buildings with solid diaphragms (Case 1), the slab elements yielded after the wall elements at base shear coefficients of 0.42 and 0.18, respectively. Introducing the diaphragm openings symmetrically with respect to the longitudinal axis (Case 3) reduced the base shear coefficients at which the slab elements yielded from 0.42 to 0.24. However, a drastic change in pushover results is observed when diaphragm openings are placed unsymmetrically with respect to the longitudinal axis, the slab elements yielded simultaneously with the wall elements at a base shear coefficient of 0.17 (Cases 4 and 5). A less pronounced change was noticed when diaphragm openings are placed unsymmetrically with respect to the transverse axis (Case2). The summary of the pushover analysis results is given in Table 4.

Table 4. Pushover results summary

Building	**Base Shear Coefficient**	
	Wall Yielding	**Slab Yielding**
Case 1	0.180	0.420
Case 2	0.170	0.250
Case 3	0.180	0.240
Case 4	0.170	0.170
Case 5	0.170	0.170

Results of dynamic (time-history) indicate that significant inplane deformations occur when the scaled Loma Prieta earthquake is used since its dominant period was the closest to the fundamental period of the buildings. Thus, the summary of dynamic analyses results for all the cases subjected to the scaled Loma Prieta earthquake, where the maximum floor deformations were observed, is given in Table 5. Examination of the maximum in-plane diaphragm deflection (which occurred at the third level) indicates that the results obtained using the inelastic slab model are 2.87 to 4.59 times greater than the values obtained using elastic slab model. Consequently, the frame shear redistribution due to inelastic slab deformations increased the frame shear in these buildings, particularly, in buildings with floor diaphragm openings. For example, the percentage of base shear load resisted by the interior frames in building with symmetric openings (Case 3) was as high as 30.86%, 1.40 and 1.18 times the values obtained from rigid and elastic diaphragm assumptions, respectively. Similar results were obtained for buildings with unsymmetric openings regardless of the type of unsymmetry (Cases 2, 4 and 5). Thus, using elastic (or rigid) diaphragm assumption in evaluation of seismic response of the RC buildings with diaphragm openings resulted in a non-conservative estimation of the floor deformations and frame shears.

Table 5. Results summary of dynamic analysis using Loma Prieta earthquake

Loma Prieta Earthquake															
Output	Case 1			Case 2			Case 3			Case 4			Case 5		
	Solid Diaphragm			Open Diaphragm			Open Diaphragm			Open Diaphragm			Open Diaphragm		
	Inelastic	Elastic	Rigid	Inelastic	Elastic	Rigid	Inelastic	Elastic	Rigid	Inelastic	Elastic	Rigid	Inelastic	Elastic	Rigid
Diaph. Max. Inplane Defl., in.	0.592	0.183	0.000	1.061	0.231	0.000	0.826	0.223	0.000	0.894	0.312	0.000	0.825	0.223	0.000
Base Shear, V kips	1599.6	1732.6	1708.8	1533.8	1737.4	1700.0	1545.5	1800.5	1593.0	1568.4	1803.8	1739.7	1508.7	1775.5	1631.2
%V to Walls	71.38	73.47	77.38	69.07	72.82	78.10	69.14	73.88	77.90	70.72	75.12	79.48	69.97	74.68	78.70
%V to Frames	28.62	26.53	22.62	30.93	27.18	21.90	30.86	26.12	22.10	29.28	24.88	20.52	30.03	25.32	21.30
Period, T sec.	0.286	0.286	0.247	0.284	0.284	0.237	0.285	0.285	0.237	0.279	0.279	0.237	0.279	0.279	0.236
Bldg. Max. Top Displ., in.	1.204	1.118	0.823	1.323	1.061	0.750	1.274	1.066	0.719	1.241	1.045	0.740	1.292	1.051	0.725

Typical plots of the normalized floor displacements obtained from the dynamic analyses for rigid, elastic, and inelastic slab models are compared in Figure 7, 8, and 9 for buildings with solid diaphragms (Case 1) and diaphragms with unsymmetric openings about longitudinal or transverse axis (Cases 2 and 5) for the scaled Loma Prieta earthquake.

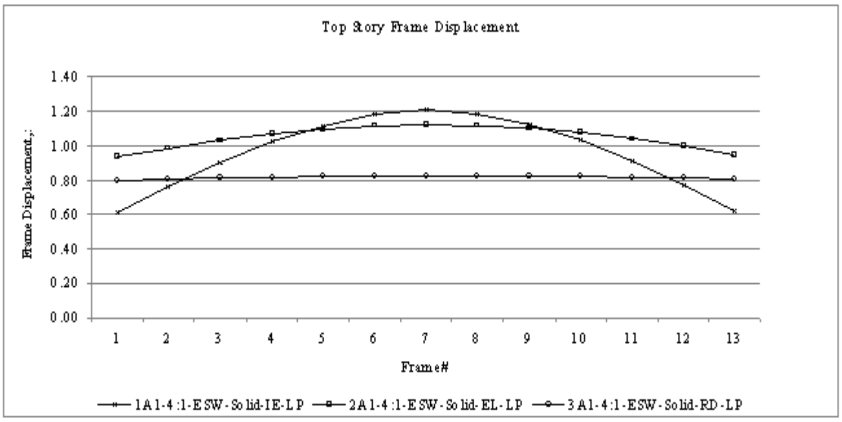

Figure 7. Loma Prieta-Solid Diaphragm top story normalized frames displacements (Case 1)

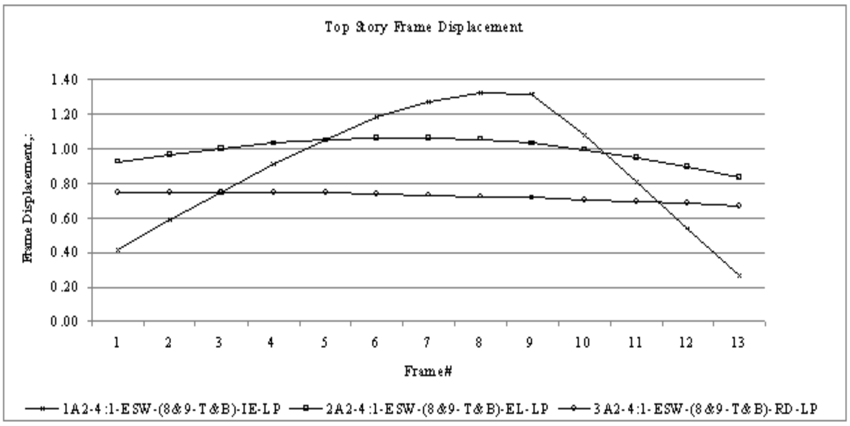

Figure 8. Loma Prieta-Open Diaphragm top story normalized frames displacements (Case 2)

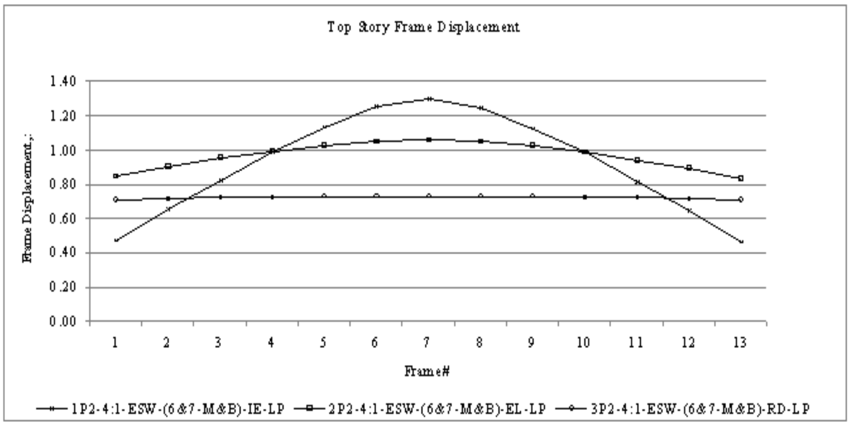

Figure 9. Loma Prieta-Open Diaphragm top story normalized frames displacements (Case 5)

7. CONCLUSION

The investigation of the inelastic seismic response of 3-story reinforced concrete rectangular buildings with end shearwalls and diaphragm plan aspect ratio of 4:1 with symmetric and unsymmetric diaphragm openings placed within the middle two-thirds of the building floor plan, indicates that ignoring the inelastic diaphragm deformations can result in an incorrect assessment of the structure nonlinear seismic response (floor deformations and frame shear distributions), irrespective of the location of the openings relative to the building plan axes. Hence, the influence of floor openings should not be overlooked in such buildings. Finally, all cases investigated in this study gave insight into the influence of diaphragm rigidity assumptions (inelastic, elastic and rigid) on the nonlinear seismic response of the buildings with floor diaphragm openings.

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