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Seismic Shear Response of Diaphragms of Buildings

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Common concrete structures have concrete floor/roof diaphragms , same as steel deck diaphragms with steel structures. Diaphragms in buildings must resist lateral forces as well as vertical loads due to gravity and vertical response during earthquakes. The lateral forces developed in the plane of the diaphragm by earthquakes mainly consist of inertial forces due to mass tributary in the diaphragm and forces transferred from one vertical element of the seismic force-resisting system to another. These forces have been investigated respectively. However investigation into a combination of them had hardly been conducted. Diaphragm seismic response in elastic range of behavior of structures has been investigated previously, nevertheless no research on the seismic shear response of elasto-plastic seismic force-resisting system considering inertial forces and in-plane eccentricity has been found to be reported yet. Diaphragm failure can cause buildings to collapse due to unexpected excessive lateral lords applied to vertical elements in the seismic force-resisting system. It is significant to clarify the seismic response of diaphragms in order to determine the design force for conservative structural design of buildings. The objective of this study is to obtain fundamental characteristics of diaphragm local shear response for the distributed mass system of single-story elasto-plastic structure considering in-plane eccentricity. A series of time history analysis revealed insight into basic trends in the seismic behaviors of the diaphragm of asymmetric elasto-plastic systems with distributed mass.
Keywords: *"Diaphragms, Seismic behavior, Seismic analysis, Shear, Distributed mass"*

Introduction

Diaphragms of building structures serve a role to distribute lateral inertial forces due to tributary mass from the floor / roof systems to the other elements such as the vertical elements of the seismic force-resisting system. In addition to transferring inertial forces, diaphragms also must transfer forces from one vertical element of the seismic force-resisting system to another, generated from within the structure as a whole (Sabelli et al., 2011). Therefore diaphragms have to be designed to resist a combination of these lateral forces. It is significant to clarify the seismic response of diaphragms in order to determine the appropriate design force for conservative structural design of buildings.

Previous researches have included the following issues. Archer (1963) investigated a technique of formulation of a consistent mass matrix that accounts for the actual distribution of mass throughout the structure in a manner similar to the Rayleigh-Ritz formulation. The natural mode periods and shapes could closely approximate the solution to the exact problem. Goldberg and Herness (1965) formulated the vibration problem of multistory buildings with lumped masses at each intersection between floor and frame, considering both floor and wall deformations. The natural mode periods and shapes could be obtained by use of generalized slope deflection equations. Unemori et al. (1980) studied how the floor diaphragms stiffness affect the magnitude of the in-plane forces generated in the diaphragms for multistory building systems with lumped masses. Jain (1984) showed that for long narrow buildings with identical frames and identical floors, the modes that involve in-plane floor deformations are not excited by earthquake ground motion. Additionally it is noted that the result presupposes the acceptability of the lumping of masses of the building at the floor-frame intersections. Tremblay and Stiemer (1996) investigated the nonlinear response of a number of rectangular single-storey steel buildings subjected to historical earthquake accelerograms by means of time-history analysis. The results were examined on the fundamental period of the structures, the maximum drift, the forces and deformations in the roof diaphragm, and the ductility demand on the vertical bracings. The employed structures were symmetrical in plan with uniform mass, stiffness, and strength. Therefore, in-plane torsional effects on the seismic forces developed in the diaphragm was omitted in the study. Massarelli et al. (2012) also carried out an experimental program of some steel deck roof diaphragm specimens to assess their seismic characteristics of the diaphragm. All the specimens had evenly distributed mass, so that in-plane eccentricity was not considered. Additionally inertial forces for symmetric systems with distributed mass in the diaphragms have been also investigated and reported by Bull et al. (2010), Sadashiva et al. (2012) and other researchers.

Tremblay et al. (2000) reported on an shake table test program in which a low-rise steel building model with a flexible roof diaphragm was subjected to seismic ground motions. Eccentricity was found to affect significantly the inelastic response of vertical elements of the seismic force resisting system. Nonetheless how eccentricity can affect shear response of the diaphragm was not focused in this study. Tso and Wong (1993) conducted an investigation on the ductility demands of lateral force elements caused by torsion with asymmetrically distributed mass system assuming a rigid diaphragm. However seismic shear response of the diaphragm was not examined. Nakamura et al. (2006, 2007) have discussed and reported the behavior and the formulation of dynamic in-plane shear response to the lateral ground shaking for asymmetric lumped mass system. Some design codes introduced the accidental eccentricity of the earthquake actions induced by assumed displacement of the center of mass each way from its actual location (ASCE, 2010; Standards New Zealand, 2004).

However investigation into the seismic behavior for asymmetric structural system with distributed mass had hardly been conducted. Iihoshi et al. (2012 & 2013) previously investigated and reported dynamic in-plane diaphragm shear response for asymmetric single-story linear-elastic system with distributed mass in the diaphragm as well as its predictable formulae. To date, no research on the seismic shear force developed in the diaphragm of elasto-plastic lateral force-resisting system considering inertial forces and in-plane eccentricity has been found to be reported yet. Therefore such diaphragm shear behavior belongs to unknown field. Three dimensional time-history analyses using a model consists of finite elements with distributed mass could provide accurate seismic response of the diaphragm for a specific building, nevertheless such an analysis can increase modeling and computing efforts. Establishment of guidelines for prediction of seismic response of diaphragms might be required. Then the objective of this study is to obtain fundamental characteristics of diaphragm local shear response for the distributed mass system of single-story elasto-plastic structure considering in-plane eccentricity as a feasibility study.

A series of time history analysis of the single-story structure has been carried out to achieve insight into basic trends in the seismic behaviors of the diaphragm of asymmetric elasto-plastic system with distributed mass. This study may not be directly applicable to multi-story system. Because it is not evident whether limited study focusing on single-story system is appropriate for multi-story one. The analytical results of the seismic response are comprehensively examined and presented in representative form to provide the framework of the diaphragm design force. Obtained behavior may provide attention to diaphragm design for high seismic applications including ultimate state. Observations highlighting the dynamics of single-story system with elasto-plastic hysteretic characteristics might contribute to establish the conceptual framework for envisioning the seismic response of multi-story system with elasto-plastic characteristics.

The scope of this study includes the following:

a. Difference of peak response time between the diaphragm and the vertical elements of the seismic force-resisting system
b. Behavior of deformation and shear force distribution of diaphragm at its peak shear response

c. Effects of the fundamental period of the structure on the maximum shear force developed in the diaphragm
d. Effects of flexibility of the diaphragm on the maximum shear force developed in the diaphragm

Analytical Model

Consider a frame with 1×2 bays such as previous study (Nakamura et al., 2006 & 2007; Iihoshi et al., 2012 & 2013), according to its symmetry a simplified model used to analyze in this study consists of two bays (vertical elements) with a span L (see Figure 1). The structure has perfectly elasto-plastic hysteretic characteristics of restoring force and story drift relationships except the diaphragm with linear-elastic in-plane shear deformation hysteresis. A base shear coefficient γ defined as the base shear that causes yielding of the structure divided by the total weight of the structure is 0.25 through this study. A constant k_1 means a ratio of stiffness of bay 1, K_1, to a sum of two bays' stiffnesses, K_1 and K_2. The value of k_1 equals a ratio of strength of bay 1 to a sum of both bays' ones which means the stiffness eccentricity and the strength eccentricity are always same for each analytical model. The ratio is the following

$$K_1 = 2K_2 \qquad \therefore k_1 = \frac{K_1}{K} = \frac{2}{3} \qquad \text{where } K = K_1 + K_2$$

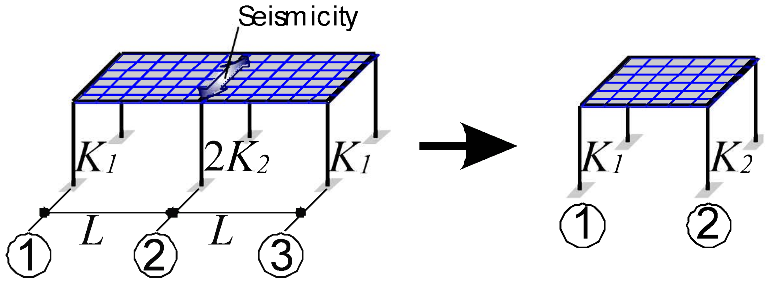
This analytical model assumes the following:

a. A 8 degree-of-freedom system with 8 masses (see Figure 1(b))
b. Uniform mass distribution in the diaphragm independent of mass of bay 1 could be expressed by Table 1 and Figure 1.
c. Each mass with a same distance can move unidirectionally same as the seismicity.
d. Each bay is represented as a mass supported by a shear spring which corresponds to its story drift.
e. Similarly the diaphragm is expressed as 6 masses connected with 7 shear springs which correspond to its in-plane shear deformation. These springs have linear-elastic hysteretic characteristics.
f. No flexural deformation of the diaphragm is considered. Therefore the span L does not have anything to do with the analytical results. This model does not incorporate the span L.

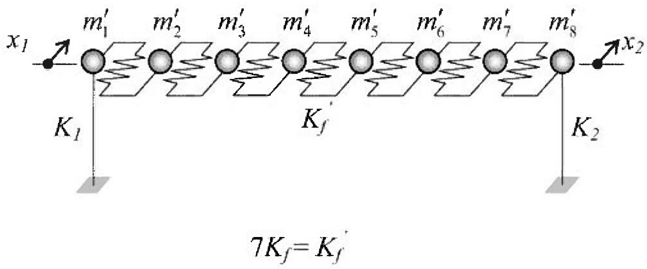
Table 1. *Mass Distributions*

m_1	0.50	2/3	0.80
M_1	0.50	2/3	0.80
M_2	0.50	1/3	0.20
m'_1	0.125	0.4225	0.65
$m'_2 \sim m'_8$	0.125	0.0825	0.05

Figure 1. *Structure and Analytical Model*



(a) Structure



(b) Analytical model

The variable structural characteristics in the analytical investigation include the following.

k_f : Diaphragm shear stiffness ratio defined as a value of the diaphragm stiffness ratio to a sum of the supporting bays' ones

$$k_f = \frac{K_f}{K} = 1,\ 10$$

where $7K_f = K'_f$

T_0 : Fundamental period assuming the diaphragm to be rigid $T_0 = 0.3,\ 0.7,\ 1.0\ (s)$

m_1 : Ratio of mass considered to be tributary for the bay 1 to a sum of masses of the system

$$m_1 = \frac{M_1}{M} = 0.50,\ 2/3,\ 0.80$$

$$\text{where } M_1 = \sum_{i=1}^{4} m_i', \qquad M = \sum_{i=1}^{8} m_i'$$

The distributed mass $m_1' \sim m_8'$ are obtained as follows (See Table 1)

$$m_1' = \frac{7m_1 - 3}{4}$$

$$m_2' \sim m_8' = \frac{1 - m_1}{4}$$

Seismic Waves

For assessment of the earthquake response by means of nonlinear time history analyses, a couple of typical unidirectional earthquake ground motions were selected. These included the Imperial Valley earthquake (EL Centro NS 1979) scaled such that its PGV (Peak Ground Velocity) matched 50 cm/s and the Building Center of Japan (BCJ) level-2 which is an artificial earthquake generated to be compatible with current Japanese seismic code with 50 cm/s of PGV (Building Center of Japan, 1994). A finite element analysis software ANSYS (Japanese version 14.5) was used in the time history analysis. The integration is performed with a time step of 0.01 seconds at most during these respective seismic wave durations with two percent of critical damping to the initial stiffness of the vertical elements.

Analytical Results

Figures 2 and 3 indicate earthquake responses of the structures with a value of diaphragm stiffness ratio of k_f = 1.0 for El Centro. They display in–plane centric and eccentric structures, respectively. The centric structures were represented by cases of m_1=2/3 which mean the mass ratio of the bay 1 to a sum of all of the masses equals the constant k_1=2/3, a stiffness (strength) ratio of the bay 1 to a sum of the two bays. Figure 4 also illustrates seismic response of the stiff diaphragm of k_f = 10. These figures include time histories of story drifts, restoring forces of the vertical elements and the diaphragm local shear forces. As for the centric system in stiffness and strength, same relative displacements of top of the vertical elements to the ground were observed in elastic and inelastic ranges of behavior. And shear response was hardly observed in the central portion of the diaphragm as shown in Figure 2(c). Meanwhile asymmetric system in Figure 3 gave slightly the gap of both bays' displacements which cause the diaphragm to be deformed into the shape of a parallelogram. Therefore each vertical element reached its yield strength at different time because of same stiffness and strength ratios of bay 1 to a sum of both bays. Maximum local shear response of the diaphragm can be thought to generate when a vertical element yielded while another remained elastic, nevertheless the maximum shear force was observed after yielding of both elements despite the gap of the displacements due to eccentricity. In a case of stiff diaphragm with k_f = 10 (see Figure 4), both vertical elements provided same displacement histories despite its in-plane eccentricity. The diaphragm can be considered to have enough stiffness to be assumed rigid. From previous study (Iihoshi et al., 2012; 2013), as for linear-elastic structures with diaphragm stiffness ratio k_f equal to or greater than 1.0, both bays' story drift displacements were always their respective approximate peak values in the cycles whenever the maximum local shear responses were observed. Meanwhile as for elasto-plastic structures, it was observed that both bays and the diaphragm did not reach their peak response at a same time for all the cases as shown in Figures 2 to 4. It can be thought because of higher mode of vibration of the structures with distributed mass in the diaphragm.

Figures 5 and 6 display deformations and shear distributions of the diaphragm (k_f = 1.0, T_0 = 0.7s) when maximum shear response occurred by El Centro and BCJ, respectively. In eccentric cases of m_1 = 0.5 and 0.8, a combination of inertial forces and transfer forces between both vertical elements was observed in the diaphragm. The deformations are not linear along the axis normal to the direction of seismic motion. And each local shear force in the central portion of the diaphragm which approximately corresponds to average one was affected by transfer forces based on in-plane stiffness and strength eccentricity of the seismic force-resisting system. The shear distributions are approximately proportional to distance from a top of the vertical element due to inertial forces applied to the evenly distributed mass in the diaphragm. This behavior is quite similar to response in a linear-elastic range (Iihoshi et al., 2012 & 2013). There was no considerable difference of diaphragm behavior between El Centro and BCJ. Maximum local shear response could be observed at either shear spring adjacent to the intersection between the diaphragm and the vertical element due to inertial forces for all the analytical cases including two different seismic waves and three different values of fundamental period with the rigid diaphragm. This behavior also coincides that of linear-elastic system.

Figure 2. *Time Histories:* T_0 = 0.7 s, m_1 = 2/3, k_f = 1.0

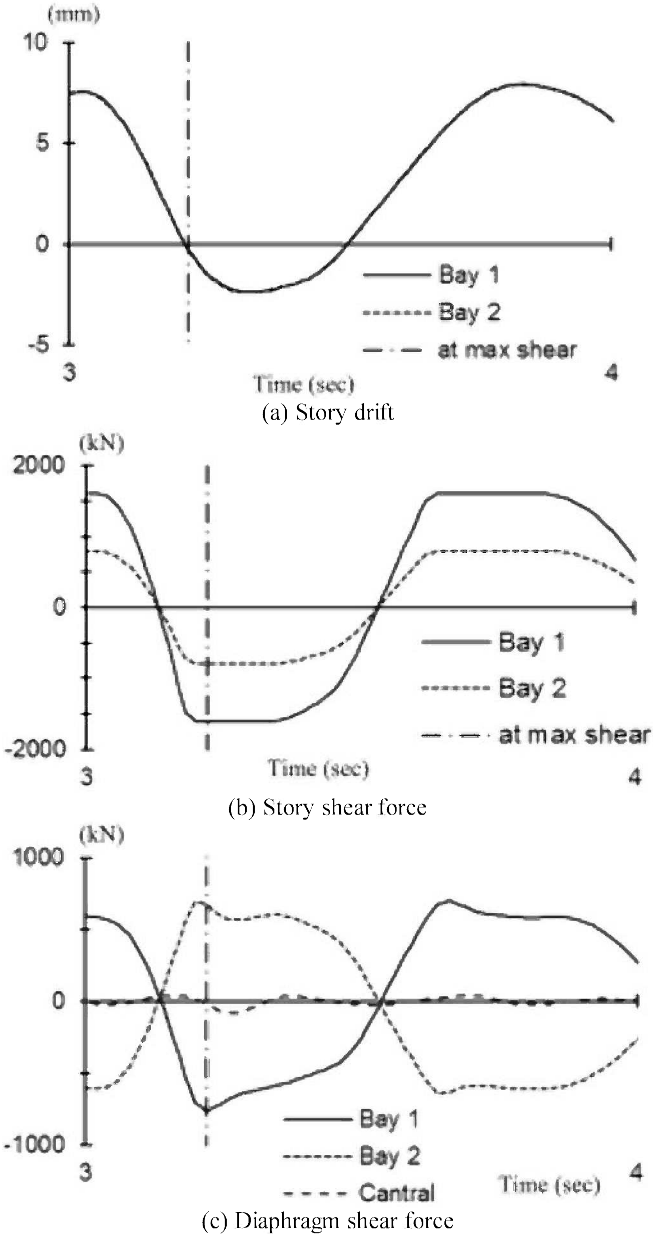


Figure 3. *Time Histories*: T_0 = 0.7 s, m_1 = 0.5, k_f = 1.0

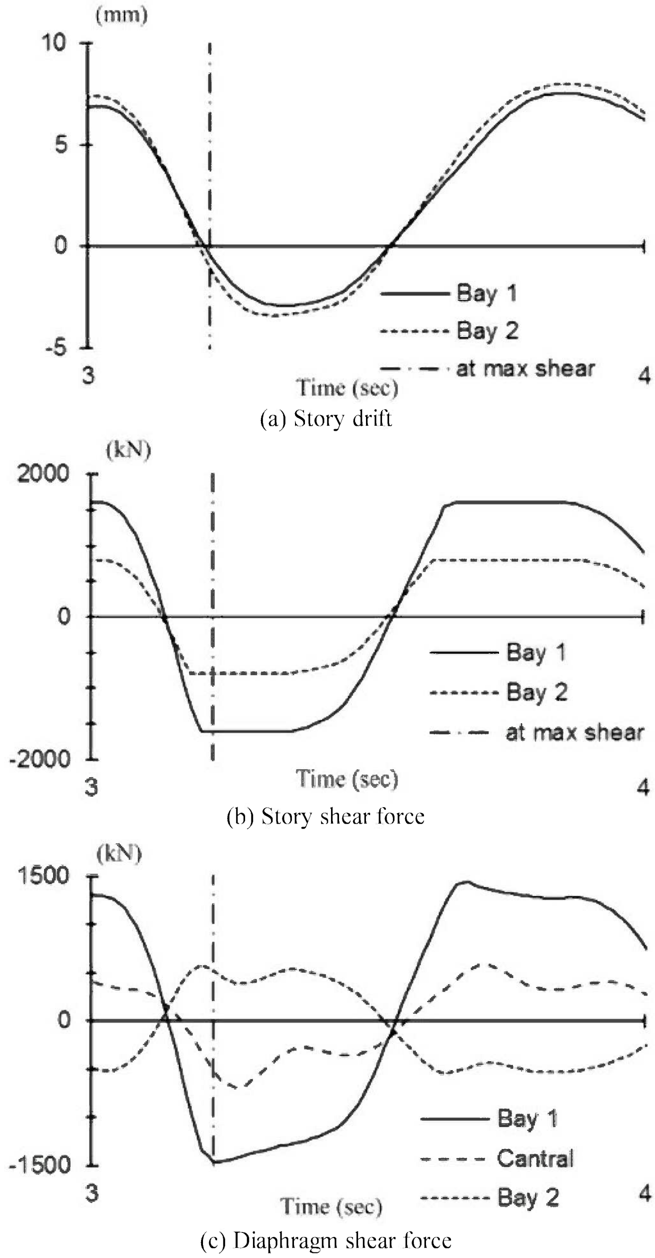
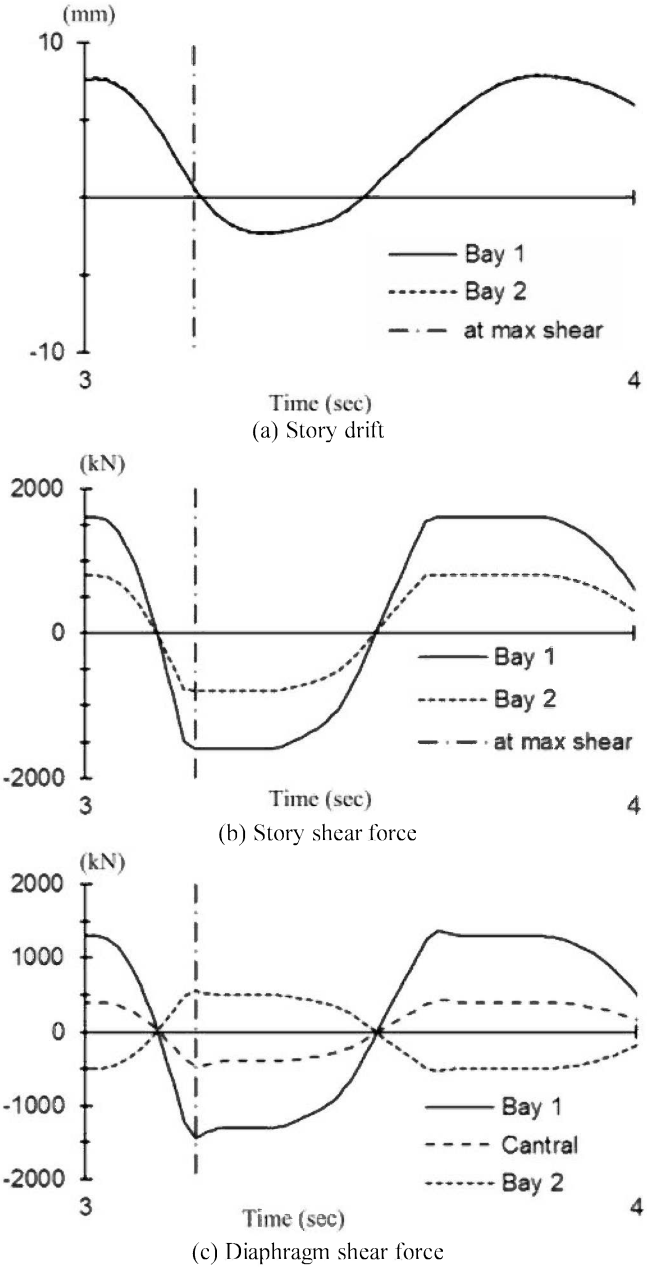
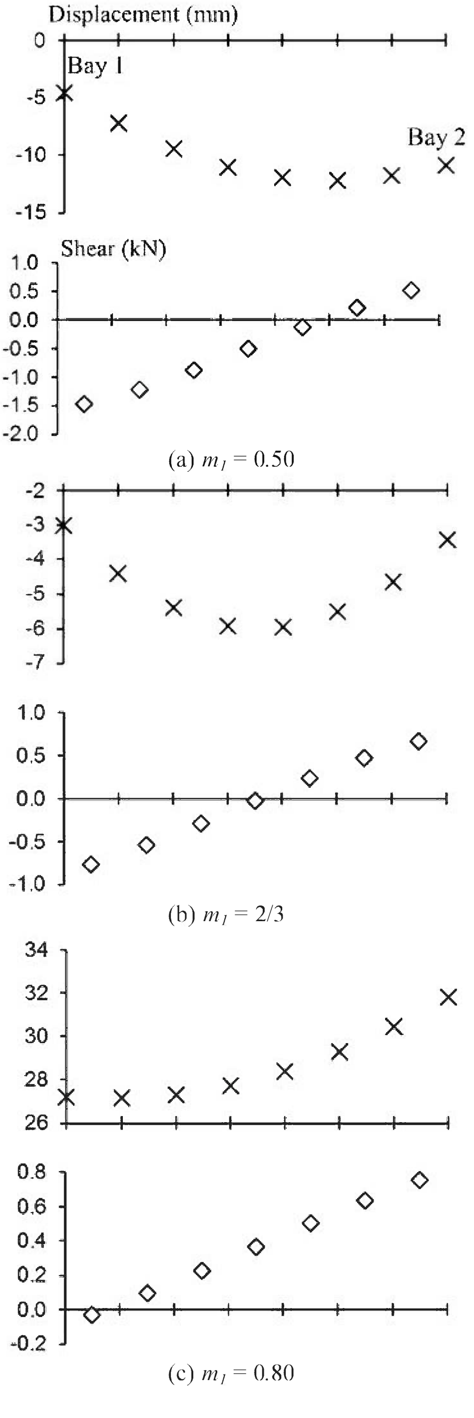


Figure 4. *Time Histories*: T_0 = 0.7 s, m_1 = 0.5, k_f = 10



Figures 7 and 8 provide normalized maximum local shear response and fundamental period relationships for k_f = 1.0 and 10, respectively. In these figures, $V_{f\max}$ designates maximum local shear, while MS_A designates a sum of yield base shear of both vertical elements of seismic force-resisting system. The diaphragm shear response for the period of 1.0 s could be slightly less than shorter other periods, to say, 0.3 and 0.7 s. However in general no correlation between the diaphragm response and the fundamental period can be seen regardless the value of diaphragm stiffness ratio, k_f.

Figure 5. *local shear response*
(*EL Centro*)

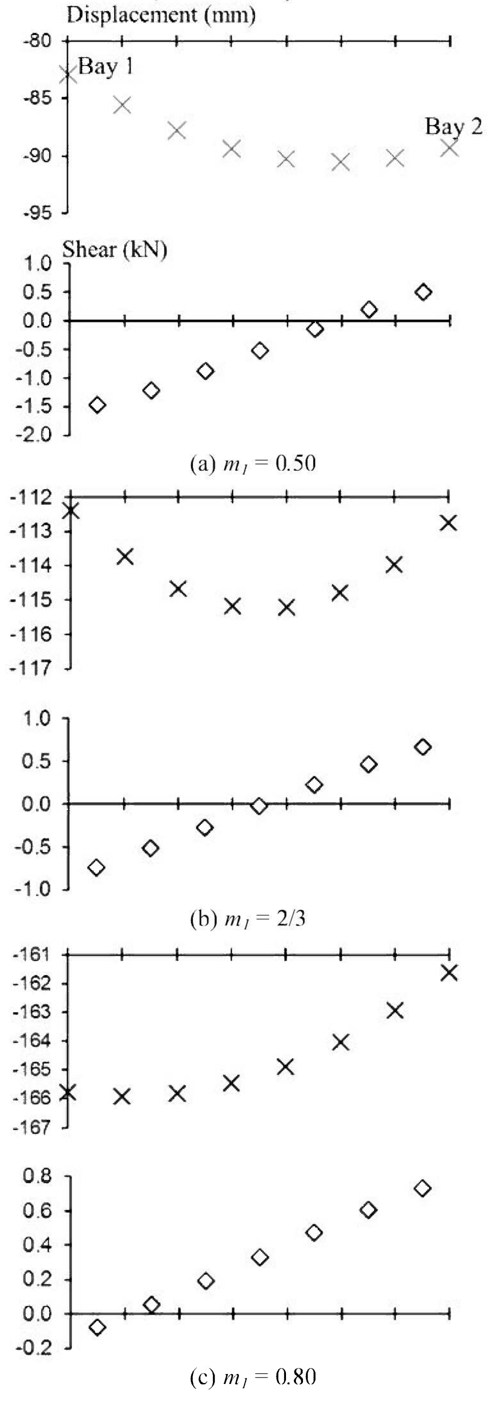


(a) $m_l = 0.50$

(b) $m_l = 2/3$

(c) $m_l = 0.80$

Figure 6. *local shear response*
(*BCJ level-2*)



(a) $m_l = 0.50$

(b) $m_l = 2/3$

(c) $m_l = 0.80$

Figure 7. *Influence of Period*: $k_f = 1.0$

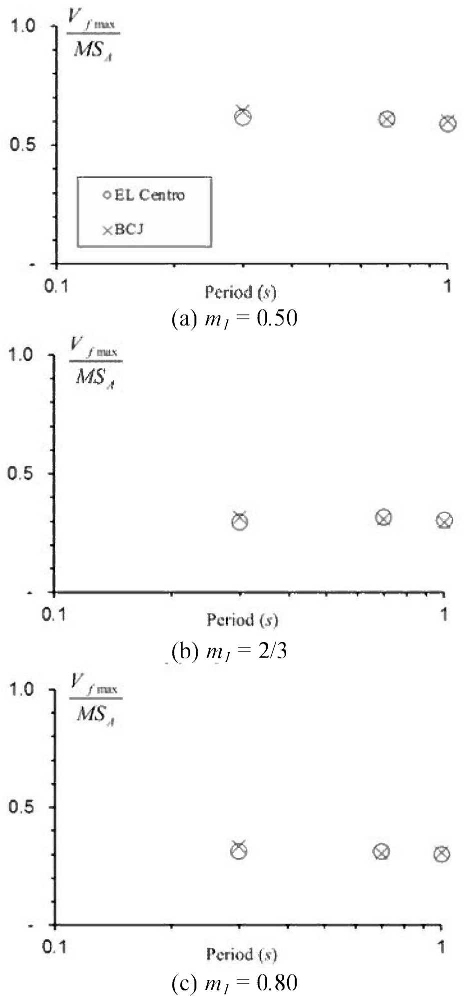
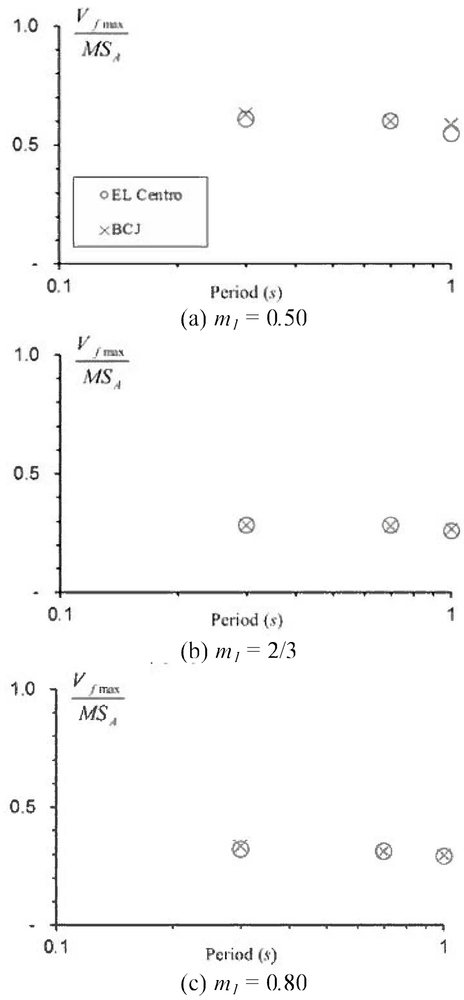
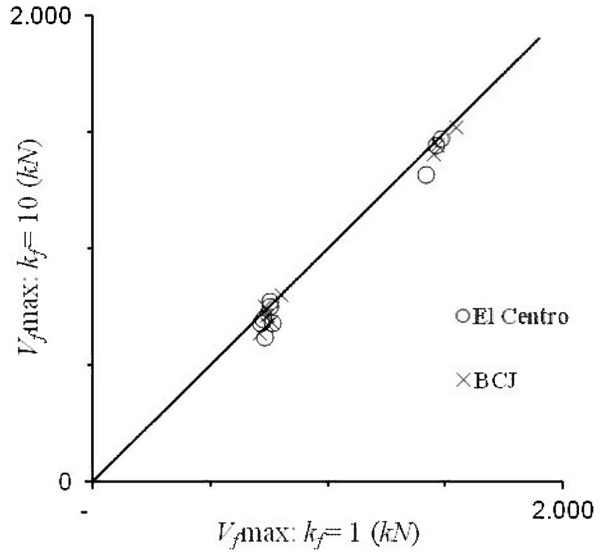


Figure 8. *Influence of Period*: $k_f = 10$



The diaphragm shear response comparison between for $k_f = 1.0$ and 10 is displayed by Figure 9. The shear force ratio of $k_f = 10$ to $k_f = 1.0$ ranged from 0.85 to 1.03. There was a tendency for the diaphragm response to decrease with increasing diaphragm stiffness.

Figure 9. *Influence of Diaphragm Stiffness on Max Shear*



Concluding Remarks

On the premise of ultimate state design criteria for severe earthquake ground motions, the elasto-plastic vertical elements of the seismic force-resisting system were employed in this study. A series of dynamic analysis was conducted in order to reveal the fundamental dynamic local shear response behavior of linear-elastic diaphragms for single story elasto-plastic restoring force and deformation hysteretic characteristic system with distributed mass considering stiffness eccentricity as well as strength one. The results and conclusions of this analytical study presented in this paper may be summarized as follows:

a. Each element such as the diaphragm and the vertical one do not reach its peak response at a same time. The fact differs from that of linear-elastic system.
b. A combination of inertial forces and transfer forces between different vertical elements resulted in shear force distribution of the diaphragm at the peak response as well as its correspondent deformation.
c. There is not great discrepancy in shear response of the diaphragm among the different fundamental periods including 0.3, 0.7 and 1.0 s.
d. There was a tendency for the induced diaphragm shear force to decrease when the diaphragm stiffness increased. However difference of the maximum shear force between the diaphragm stiffness ratios k_f = 1.0 and 10 was not so great, to say, about 15% at most.

The following issues should be mentioned as a further investigation. To avoid bias toward any particular type of ground motion, a large ensemble of earthquakes must be applied. Although three different values of the fundamental period, to say, 0.3, 0.7 and 1.0 s, were incorporated in this study, short period structures (< 0.3 s) and long period structures (>1.0 s) should be of interest in the future research. A variety of the yield base shear coefficient γ could provide comprehensive coverage on the seismic design requirements for diaphragm shear response as well as multi-story structures. This study confirmed that a diaphragm stiffness ratio $k_f = 10$ was enough to be considered rigid. However the minimum stiffness ratio enough to provide approximately same displacement histories of different vertical elements despite in-plane eccentricity should be investigated furthermore. Through the investigation, a lot of emphasis would be on how the diaphragm stiffness can affect the shear response and how the force can be predicted.

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Notation

The following symbols are used in this paper:

K = a sum of stiffnesses of 2 bays

k_1 = stiffness ratio of bay 1 (K_1/K)

K_1 = stiffness of bay 1

K_2 = stiffness of bay 2

k_f = diaphragm shear stiffness ratio to the supporting bays (K_f/K)

K_f = entire diaphragm stiffness which is a sum of K_f' (see Figure 1)

K_f' = stiffness of distributed shear springs (see Figure 1)

M = a sum of all masses

M_1 = a sum of masses deemed to be supported by bay 1

m_i' = distributed mass

S_A = absolute acceleration response

T_0 = fundamental period with the rigid diaphragm

x_1 = story drift of bay 1

x_2 = story drift of bay 2

γ = yield base shear coefficient to the total weight of the structure

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