Seismic Behavior of Flanged Shear Wall Buildings Subjected to Near-Fault Earthquakes Having Forward Directivity

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SUMMARY:
Flanged shear walls are used extensively in moderate- and high-rise buildings to resist lateral loads induced by earthquakes. The seismic performance of many buildings is, therefore, closely linked to the behaviour of the reinforced concrete walls. They must be carefully designed to provide not only adequate strength, but also sufficient ductility to avoid brittle failure under strong lateral loads, especially during an earthquake. Recordings from recent earthquakes have provided evidence that ground motions in the near field of a rupturing fault can contain a large energy, or "directivity," pulse. A directivity pulse occurs when the propagation of the fault proceeds at nearly the same rate as the shear wave velocity. This pulse is seen in the forward direction of the rupture, and can cause considerable damage during an earthquake, especially to structures with natural periods that are close to those of the pulse. In the present paper, 126 inelastic time-history analyses have been performed to predict the nonlinear behaviour of RC Flanged shear wall buildings under both far-fault and near-fault ground motions. The analyses show that buildings with fanged walls under the near-fault records will incur less structural damage than corresponding buildings under the far-fault records. On the other hand, major earthquakes that impose large ductility demands may cause significantly more structural damage in fanged walls under the far-fault records. Non-structural damage in fanged-wall buildings is greater than that in buildings under the far-fault records. The increase in non-structural damage is also greater when there are large ductility demands.

Keywords: Flanged shear wall; near-fault earthquake; forward directivity; seismic behavior.

1. INTRODUCTION

The lateral and gravity load-resisting system consists of reinforced concrete shear walls and reinforced concrete slabs. Shear walls are the main vertical structural elements with a dual role of resisting both the gravity and lateral loads. Among the shear wall structures, flanged shear walls typically have different strength, stiffness and ductility capacities in the two opposite directions when loading is parallel to the web. Ekwueme *et al.* (1997) studied the effect of flanged walls on the seismic performance of tall buildings. Their evaluation showed that buildings with flanged walls will incur less structural damage from moderate earthquakes than corresponding buildings without flanged walls.

Considerable debate has occurred on the effect of ground motions on structural systems. As distinguished from ground motions recorded at moderate distances from the causative fault, these motions contain intense, relatively long duration pulses corresponding to the fault rupture process. Impulsive type motions can cause considerable damage during an earthquake, especially to structures with natural periods close to those of the pulse.

Near fault effects can be broken down into three types depending on the pulses whether they are of acceleration, velocity, or displacement type. The velocity pulse motion, sometimes referred to as "fling," represents the cumulative effect of almost all of the seismic radiation from the fault (Somerville 1997). From a seismological perspective, the velocity pulse is more commonly found in earthquake records compared to acceleration and displacement pulses. Although from an engineer's perspective, the velocity pulse is a better indicator of damage than the acceleration pulse, the damage potential is also dependent on the peak displacement during the pulse (Hall et al. 1995).

The displacement pulse without the high velocity pulse does not have a high damage potential because the structure has time to react to the displacements. After the 1971 San Fernando earthquake, engineers and seismologists realized the potential damage that may occur due to the effects of near fault ground motions on structures. The damage observed during the 1994 Northridge, California, the 1995 Kobe, Japan, the 1999 Izmit, Turkey, and the 2003 Bam, Iran earthquakes proved the engineer's hypothesis that structures located within the near fault area had more severe damage than structures located outside of this zone. These earthquakes provided a wealth of new information about the behavior of engineered structures because the respective epicenters were in urban settings. Based on the data collected, building designers started studying the near fault effects on buildings. Their research and findings led to implementing design factors in the 1997 Uniform Building Code that began to account for near fault motions. Additional design factors to more accurately model near fault effects were implemented in the 2000 International Building Code.

The objective of this paper is to use the wealth of recent ground motion data to improve the understanding of the response of flanged RC shear wall buildings to pulse-type ground motions that result from forward-directivity effects.

2. CHARACTERISTICS OF NEAR-FAULT GROUND MOTIONS

The near fault of an earthquake can be defined as any area in the close vicinity of the fault rupture surface. In the near fault, the ground shaking is influenced by a number of factors. Besides strong shaking, the characteristics of near-fault ground motions are linked to the fault geometry and the orientation of the traveling seismic waves (Somerville 2000). Vertical strike-slip faults can produce a directivity effect, and dip-slip faults can produce directivity effects as well as hanging wall effects. Hanging wall effects are felt on the hanging wall of a fault (the earth above a vertically dipping fault), and are due to the proximity of much of the fault to hanging wall sites. Directivity effects can be classified as forward, reverse, and neutral. Forward directivity is when the direction of the rupture propagates toward the site, while reverse directivity is when the rupture progresses away from the site. Neutral directivity is when the site is perpendicular to the ruptured fault (Orozco and Ashford 2002). Within the research community, the term "directivity effects" has come to mean "forward directivity effects" because forward directivity is more likely to be responsible for the ground motions that cause damage. Figure 1 portrays the three zones of directivity, with the star representing the epicenter and the black line indicating the fault.

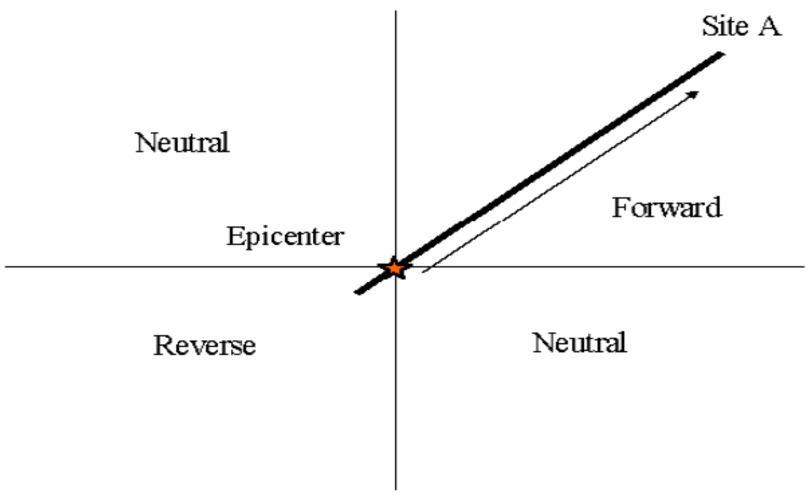


Figure 1. Zones of directivity (Orozco and Ashford 2002)

When a fault rupture propagates toward a site at a velocity close to that of the shear wave velocity, an accumulation of most of the energy of the seismic radiation of the fault can arrive at the site as a single long-period pulse. This is called a directivity pulse (Somerville 2000). The rupture is broken into sub-faults; beginning at the epicenter, the rupture propagates along the fault in the direction of the arrow toward Site A. Because the velocity of the shear waves is close to the rupture velocity, the energy of the forward direction arrives within a short time period. Forward directivity effects only occur when the rupture propagates toward the site, and the direction of slip on the fault is aligned with the site. Not all near-fault locations will experience forward rupture directivity effects in a given event.

Forward directivity effects can be felt for both strike-slip faults and dip-slip faults. On a strike-slip fault, the directivity effects are mostly concentrated away from the hypocenter because the energy builds up as the shear waves travel away from the point of dislocation toward the site. A dip-slip fault produces forward directivity effects at the sites located around the surface exposure of the fault (Orozco and Ashford 2002). Although the geometry of a fault is usually well known, the direction of rupture is unpredictable. Therefore it is recommended that all buildings that fall within the near fault of an active fault be designed for a possible velocity pulse.

3. DESCRIPTION OF BUILDINGS USED FOR EVALUATION

Three existing flanged RC shear wall buildings of 13, 16 and 19 stories were selected as representative case studies to evaluate their seismic demands when subjected to near-fault ground motions with forward directivity, and to compare the respective responses to typical far-fault ground motions. These buildings were designed in compliance to the Iranian Code of Practice for Seismic Resistant Design of Buildings (2005). The rectangular plan of all buildings measures 30m × 25m that is shown in Figure 2.

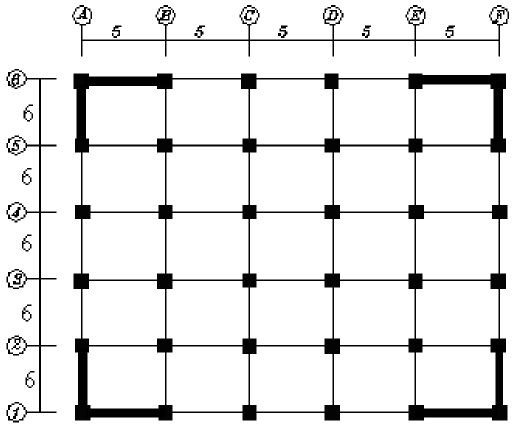


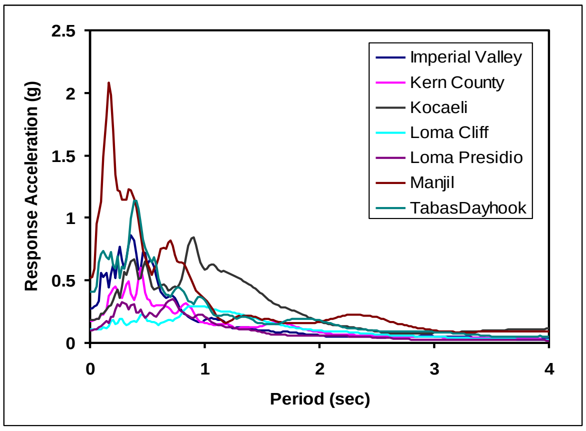
Figure 2. Structural configuration of studied buildings (units: meter)

The columns are embedded into grade beams and anchored to the top of the pile cap, essentially restraining displacements and rotations in all directions. The buildings are assumed to be fixed at the base with a damping ratio of 5% in all modes, and the floors as rigid diaphragms with infinite in-plane stiffness. The sections of structural elements are square and rectangular and their dimensions are changed at different stories. The slab thickness is 10 cm. Storey heights of buildings are assumed to be constant with the exception of the ground storey. The modulus of elasticity (Young's modulus) E = 30 kN/mm^2, Poisson's ratio $\nu = 0.20$ and the mass density $\rho = 24\ kN/m^3$ are assumed in all models. The uniaxial strength for nonlinear modeling of the concrete is considered to be 35 MPa. The rebar is modeled as steel with yield strength of 400 MPa and an ultimate strength of 600 MPa.

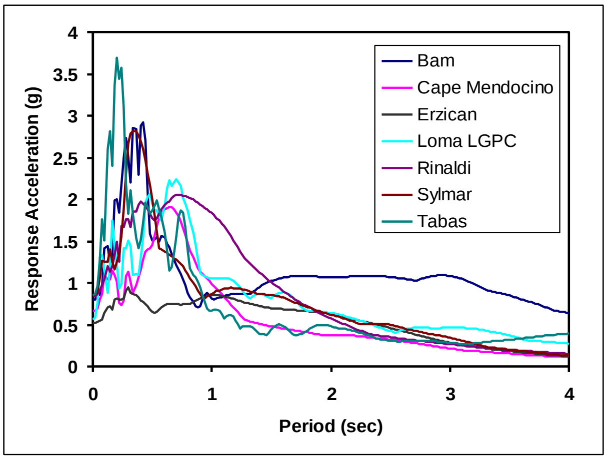
Permanent and imposed loads are assumed to be: dead load of storey level, 5.5 KPa; dead load of roof, 6 KPa; dead load of partitions, 1 KPa; dead load of external walls, 2.5 KPa; live load of storey levels, 2 KPa; and live load of roof, 1.5 KPa.

4. GROUND MOTION DATABASE

The ground motion database compiled for nonlinear time-history (NTH) analyses constitutes a representative number of far-fault and near-fault ground motions from a variety of tectonic environments. A total of 14 records were selected to cover a range of frequency content, duration and amplitude. Near-fault records were chosen so as to consider the presence of forward-directivity effects. Hence the assembled database can be investigated in two sub-data sets. The first set contains seven ordinary far-fault ground motions recorded within 90 km of the causative fault plane from earthquakes in the magnitude (M_W) range of 6.5 to 7.4. The second set includes seven near-fault ground motions characterized with forward-directivity effect. These records are from earthquakes having a magnitude (M_W) range of 6.5 to 7.4, and recorded at closest fault distance of 0.0 to 10 km. Information pertinent to the ground motion data sets including station, component of earthquake and peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD) of records are presented in Tables 1 and 2 and their elastic acceleration response spectra are shown in Figures 3.



(a)



(b)

Figure 3. Elastic acceleration response spectra of (a) far-fault and (b) near-fault ground motion recordings used in the evaluation of each building

Table 1. Far-fault ground motion database

NO.	Earthquake	Year	Station	Comp.	Mw	Distance (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	Kern County	1952	Taft	111	7.4	81	0.17	17.47	8.83
2	Tabas	1978	Dayhook	TR	7.4	107	0.4	26.17	9.1
3	Imperial Valley	1979	Calexico	225	6.5	90.6	0.27	21.23	8.98
4	Loma Prieta	1989	Presidio	000	6.9	83.1	0.099	12.91	4.32
5	Loma Prieta	1989	Cliff House	90	6.9	84.4	0.107	19.78	5.06
6	Manjil	1990	Abbar	L	7.3	74	0.51	42.46	14.92
7	Kocaeli	1999	Ambarli	90	7.4	78.9	0.18	33.22	25.84

Table 2. Near-fault ground motion database

NO.	Earthquake	Year	Station	Comp.	Mw	Distance (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	Tabas	1978	Tabas	TR	7.4	3	0.85	121.22	95.06
2	Loma Prieta	1989	LGPC	00	7.0	1.3	0.56	94.71	41.13
3	Cape Mendocino	1992	Petrolia	90	7.1	9.5	0.66	89.68	28.99
4	Erzincan	1992	Erzincan	NS	6.9	2	0.51	83.95	27.66
5	Northridge	1994	Rinaldi	228	6.7	7.1	0.83	166.03	28.15
6	Northridge	1994	Sylmar	360	6.7	6.4	0.84	129.3	31.92
7	Bam	2003	Bam	L1	6.5	7	1.09	131.26	89.24

Data source: PEER (http://peer.berkeley.edu/smcat)

Utilised in this study is a data processing technique proposed in Iwan *et al.* (1985) and refined in Iwan and Chen (1994) to recover the long period components from near-fault accelerograms. This process has been extensively elaborated in Boore (2001) and Boore *et al.* (2002).

6. SEISMIC RESPONSE EVALUATION OF BUILDINGS

In total, 126 nonlinear time history (NTH) analyses were conducted on the three buildings. Inter-story drift ratio (IDR), defined as the relative displacement between two consecutive story levels, displacements at different story levels, base shear force, base bending moment and shear forces at different story levels are used as the primary measure of seismic demand. Additional demand measures, such as component and story ductility were also investigated.

On the other hand, buildings are evaluated for damage expected during the various levels of ground motions. To standardize damage within this behaviour state, a damage parameter was defined that compared the ductility demand to the ductility capacity of a wall or column. Thus, if the yield curvature of a wall is ϕ_y and the curvature demand and curvature capacity at the ultimate limit state are given by ϕ_{dem} and ϕ_u, respectively, then the `Ductility Demand Ratio' (DDR) is given by

$$DDR = \frac{\phi_{dem} - \phi_y}{\phi_u - \phi_y} \tag{1}$$

The definition of the parameter in this form provides insight into how close a wall or column is to failure. A value of 0.5 means that a wall has used up to 50% of its available ductility, while values greater than 1.0 imply failure. The parameter is also independent of the deformation response variable used for calculating ductility. It yields the same result whether it is calculated using curvature, rotation or displacement. For behaviour states prior to the yield limit state, the ductility demand ratio is used to determine how close the element is to yielding. Thus, negative values indicate that the wall or column has not yielded, and the ductility demand ratio is calculated by (Mortezaei and Ronagh 2011)

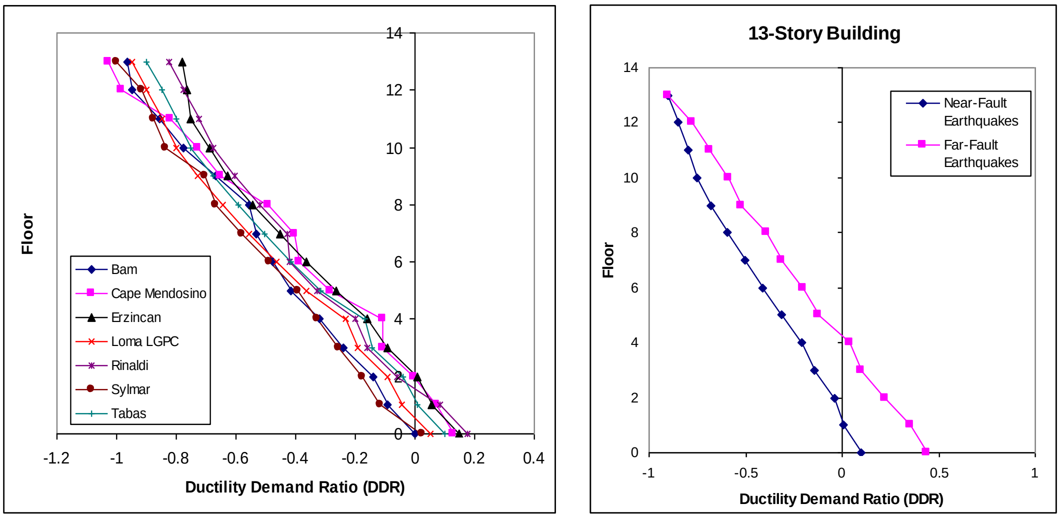
$$DDR = -\left(1 - \frac{\phi_{dem}}{\phi_y}\right); \qquad \phi_{dem} < \phi_y \tag{2}$$

The ductility demand ratio is an effective parameter for evaluating damage because it can be used as a statistical variable, as well as a parameter for comparing responses of various buildings. The mean ductility demand ratio from the 14 ground motions for near-fault and far-fault records was calculated for the buildings.

Figures 4-6 show the mean ductility demand ratios for 13, 16 and 19-story buildings. As expected, the structural damage increases with ground motion intensity.

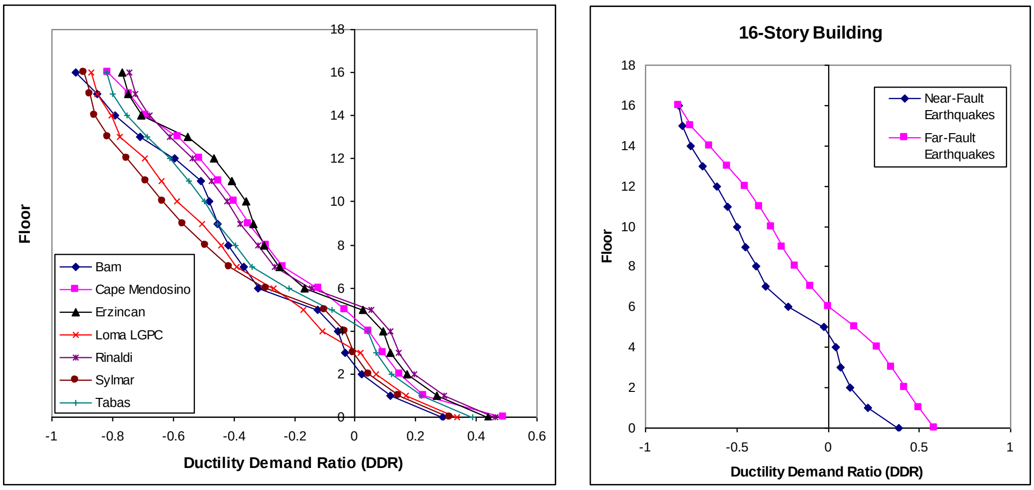
For the 13-story building, there was practically no yielding in the walls except level one, although the cracking limit state was attained in all levels. Thus, one can conclude that for a 13-story building with flanged shear walls after a near-fault earthquake minor structural repairs would be expected. The damage to the building subjected to far-fault earthquakes is slightly larger than that of the building subjected to far-fault earthquakes.

Significantly more damage is expected in the 16 and 19-story buildings. Figure 4 shows that severe damage to buildings subjected to far-fault earthquake is likely. A significant amount of yielding in the bottom of 16 and 19-story buildings is expected. Once again, there is slightly more damage to the building under the far-fault records. However, at the second, third and forth levels, which has large ductility demands, the building subjected to far-fault earthquakes is slightly less damaged.



(a) (b)

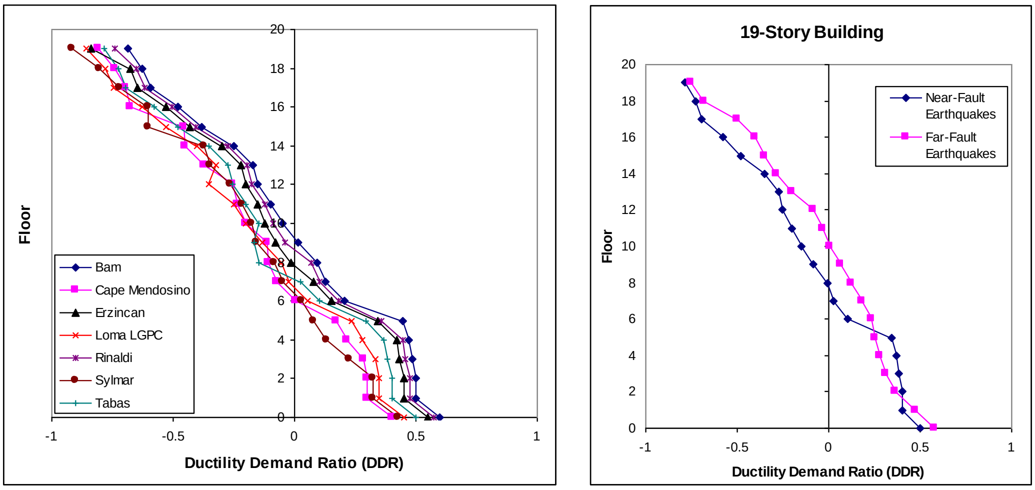
Figure 4. Ductility demand ratios for 13-story buildings (a) near-fault records; (b) mean values



(a) (b)

Figure 5. Ductility demand ratios for 16-story buildings (a) near-fault records; (b) mean values

The buildings with flanged shear walls subjected to near-fault records performs much better. Possibly because, in near-fault earthquakes, most of the seismic energy from the rupture arrives in a single large pulse of motion that occurs at the beginning of the record. The arrival of the velocity pulse in a near-fault record causes the structure to dissipate considerable input energy in relatively few plastic cycles and flanged shear walls can appropriately dissipate this considerable input energy.



(a) (b)

Figure 6. Ductility demand ratios for 19-story buildings (a) near-fault records; (b) mean values

7. CONCLUSIONS

This paper presents the results of a comprehensive analytical study on the seismic behaviour of flanged shear wall buildings subjected to near-fault earthquakes having Forward Directivity. 126 time-history analyses have been performed in order to evaluate the seismic behaviour, and the results were presented. The following conclusions can be drawn based on the results.

(1) medium- and high-rise buildings subjected to far-fault earthquakes will suffer slightly more damage than buildings subjected to near-fault earthquakes.

(2) Near-Fault ground motions that impose large ductility demands on the buildings cause less structural damage to buildings with fanged shear walls.

(3) Drift is a major issue in medium and high-rise buildings subjected to near-fault earthquakes. Since buildings with shear walls tend to be stiff, drift-sensitive elements are not significantly damaged in buildings with flanged shear walls.

(4) The buildings with flanged shear walls subjected to near-fault records perform much better. Possibly because, in near-fault earthquakes, most of the seismic energy from the rupture arrives in a single large pulse of motion that occurs at the beginning of the record. The arrival of the velocity pulse in a near-fault record causes the structure to dissipate considerable input energy in relatively few plastic cycles and flanged shear walls can appropriately dissipate this considerable input energy.

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