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A COMPARATIVE EXPERIMENTAL STUDY ON THE PERFORMANCE EVALUATION OF INFILLED RC FRAMES USING QUASI-STATIC AND PSEUDO-DYNAMIC TESTING METHODS

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ABSTRACT

An experimental investigation on three identical 1/3-scaled reinforced concrete (RC) infilled frame specimens was conducted. The specimens were one-bay and one-story type and loaded laterally from top of column location. The first specimen was tested with quasi-static (QS) test method using a drift-based reversed cyclic loading pattern. The pseudo-dynamic testing (PsD) method was carried out with simulated low and high inertial masses representing bottom and top story levels of typical mid-rise RC buildings. A selected ground motion acceleration record was used representing the current Turkish Earthquake Code (TEC, 2007) acceleration spectra which consist of service, design and ultimate PGA levels of 0.20g, 0.40g and 0.60g, respectively. The sectional and global response parameters such as strength, stiffness, energy dissipation capability and damage observations were compared between these two test methods. The observed damage levels resulting from PsD testing methodology could be interpreted using various PGA intensities. However, in QS testing, these intensity variations cannot be readily obtained from the test results since no direct relation exists between drift-based and intensity-based loadings. When comparing the two different test methodologies, although the strength and the stiffness degradations corresponding to each level of PGA intensity were consistent with each other, the energy dissipation of the specimens that was obtained from the PsD testing became more than the one tested with QS test for the same level of story drifts.

Introduction

Past earthquakes showed that infilled walls used in RC frames had many advantages in the event of seismic actions in terms of improvements in global stiffness, lateral strength, energy

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dissipation capacity and overall dynamic behavior characteristics of structures (Mosalam, 1997). Shake table tests on infilled RC frames conducted by Hashemi and Mosalam (2006) resulted nearly 4 times higher structural stiffness, shortened natural period by nearly 50%, increased damping coefficient from about 4% to 12%, and also increased energy dissipation capacity in the system. It was concluded that the infill walls have significant role in the strength and ductility of the structure and should be considered in both analysis and design. Mosalam et al. (1998) applied PsD technique for testing a two-bay, two-storey gravity load designed steel frame infilled with unreinforced concrete block masonry walls. It was concluded that the imparted and hysteretic energies correlated well with the observed damage state. Accordingly, the PGA intensity may be considered as a global measure to quantify the damage state of the structure.

In this study, three 1/3-scaled infilled RC frames were investigated. Two of them were tested under the effect of acceleration records with simulated inertia, while the remaining one was tested by QS test method.

The objective of this study is to determine the seismic performance of infilled frames through investigating the differences between QS and PsD testing methodologies on the response of infilled RC frames in terms of strength, stiffness, energy dissipation capability and observed damage levels.

Specimen Details

The dimensions of test specimens and reinforcing detailing are given in Fig. 1.

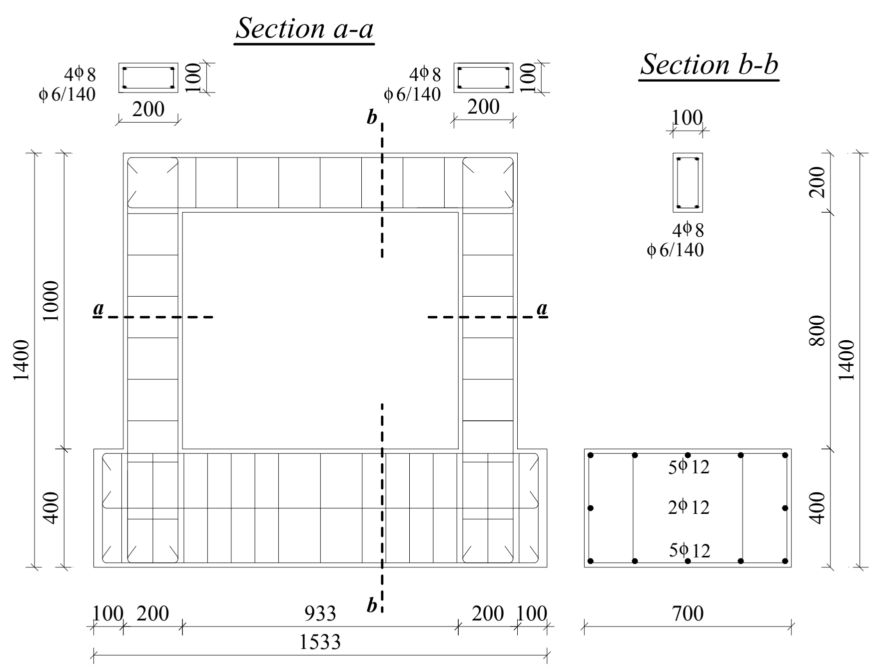


Figure 1. Schematic view and reinforcing details of test specimens.

Longitudinal reinforcement ratios in columns and beams were taken as 1%, while transverse reinforcement ratio was taken as 0.4%. The bricks of infill walls were produced specifically for this experimental study in order to account the 1/3 geometric scale. In order account for workability and the geometric scaling factor, a specially-designed concrete mixture with small-diameter aggregate of 10 mm and super plasticizer was used. All test specimens were cast at the same time in two stages, first the foundations then followed by the frame elements.

Test Set-Up and Instrumentation

The specimens were subjected to cycles of lateral displacements. The lateral loading system consisted of a servo-controlled 280 kN-capacity hydraulic ram, positioned at the top of the specimen aligned with the central axis of the beam. The footing of the specimen was fixed to the rigid steel beam of the test frame which was connected to the laboratory's strong floor via post-tensioned rods. Fig. 2 illustrates the test set-up including testing frame, hydraulic actuator, reaction wall and strong floor.

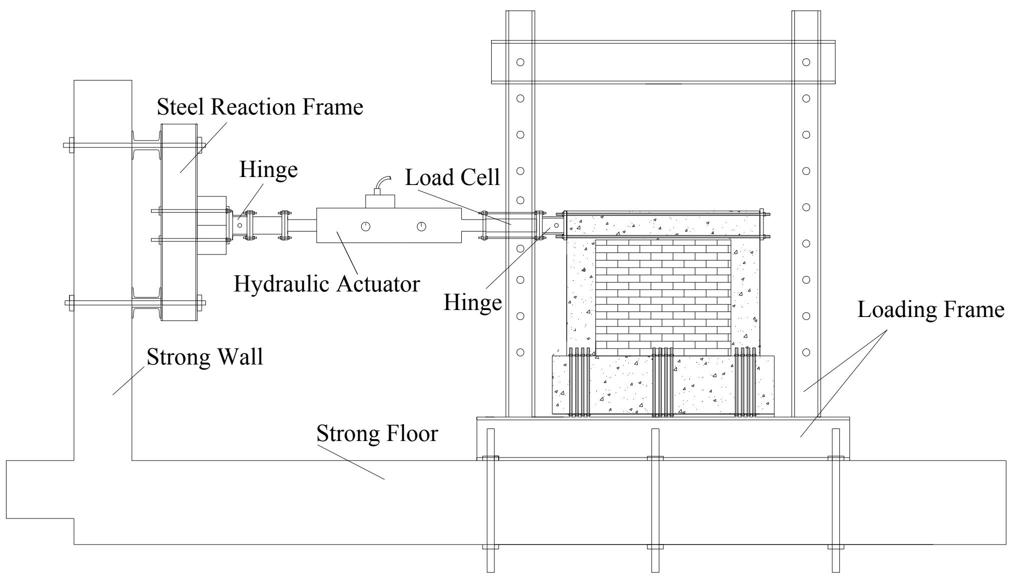


Figure 2. Schematic view of the test set-up.

Restoring forces were measured with a load cell attached to the actuator. Also, various strain gauges and displacement transducers were placed on re-bars and the specimen, respectively. In addition, an optical displacement transducer with a high degree of resolution capacity was positioned in the middle and on one side of the beam to measure lateral displacement which is used as input to PsD test.

Loading Types

Two types of lateral loadings were applied to the specimens. In QS type of loading, the increments of storey drifts were applied as shown in Fig. 3. The gradual incremental displacements were selected in order to be consistent with typical loading pattern used in the literature.

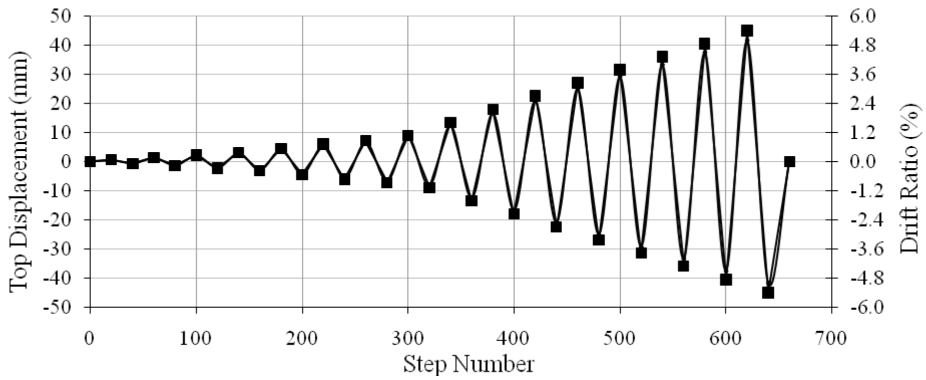


Figure 3. The displacement-based loading protocol used in QS tests.

In the PsD test, the ground acceleration data was used while evaluating the equation of motion of the i^{th} step, which is given in Eq 1.

$$[m]\{\ddot{x}_i\}+[c]\{\dot{x}_i\}+\{\bar{f}_i\}=-[m]\{1\}\ddot{x}_{gi} \tag{1}$$

where m is the mass (M_1=0.0085kNs^2/mm and M_2=0.0221 kNs^2/mm are two alternative mass conditions), $\ddot{x}$ is relative acceleration, c is damping, $\dot{x}$ is relative velocity, $\bar{f}$ is restoring force measured from the specimen and $\ddot{x}_g$ is the ground acceleration. Eq. 1 is solved numerically by using central difference method. The velocity and acceleration terms could be written in terms of displacements in Eqs. 2 and 3 where Δt indicates time increments.

$$\{\dot{x}_i\}=\frac{\{x_{i+1}\}-\{\dot{x}_{i-1}\}}{2\Delta t} \tag{2}$$

and

$$\{\ddot{x}_i\}=\frac{\{x_{i+1}\}-2\{x_i\}+\{x_{i-1}\}}{(\Delta t)^2} \tag{3}$$

Substituting Eqs. 2 and 3 into Eq. 1, the $i+1^{th}$ step displacement could be evaluated from the following equation.

$$\{x_{i+1}\}=\frac{2[m]\{x_i\}+\left(\frac{\Delta t}{2}[c]-[m]\right)\{x_{i-1}\}-(\Delta t)^2\left(\{f_i\}+[m]\{1\}\ddot{x}_{gi}\right)}{[m]+\frac{\Delta t}{2}[c]} \tag{4}$$

A portion of the Duzce/Bol090 component of the acceleration record with high peak region was used in this study, (PEER Strong Motion Data Base). Fig. 4 illustrates the acceleration record and its elastic response spectrum compared with the code-specified response spectrum.

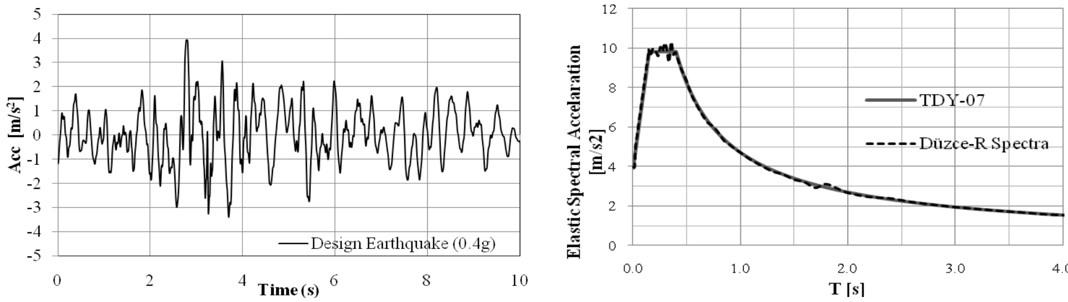


Figure 4. A portion of Duzce/Bolu090 acceleration record and its elastic response spectrum.

There different PsD loading levels of service, design and ultimate states with magnification factors of 0.5, 1.0 and 1.5, respectively, as per TEC2007 were applied to the specimens. Also, the corresponding PGAs for are given as 0.20g, 0.40g and 0.60g, respectively.

Test Results

QS Test Results

QS test results corresponding to various drift levels are given in Table 1.

Table 1. QS Test Results.

% Drift	Restoring Force (kN)	Observations
0.15	49.0	First flexural cracks were observed on the columns.
0.25	65.0	Infill wall separated from RC frame.
0.69	88.0	First diagonal crack occurred on the infill wall.
2.00	80.0	The width of the wall separation reached 6 mm. Concrete spalled off at the bottom level of the column.
4.00	65.0	Corner crushing at the bottom ends of columns was observed. Spalling of cover concrete and buckling of rebars occurred.
5.00	58.0	The infill wall experienced excessive damage and its effect to the frame was completely lost. Consequently, the lateral load capacity decreased to the level of the RC bare frame.

The test specimen failed when excessive spalling of the concrete at the bottom level of the column occurred. Also, various diagonal cracks and separation of the infill wall from the frame were observed.

Fig. 5 shows force-displacement relationship and strain variation in the longitudinal reinforcement at bottom of column section, and illustrates typical observed crack pattern and damage states on backbone curve.

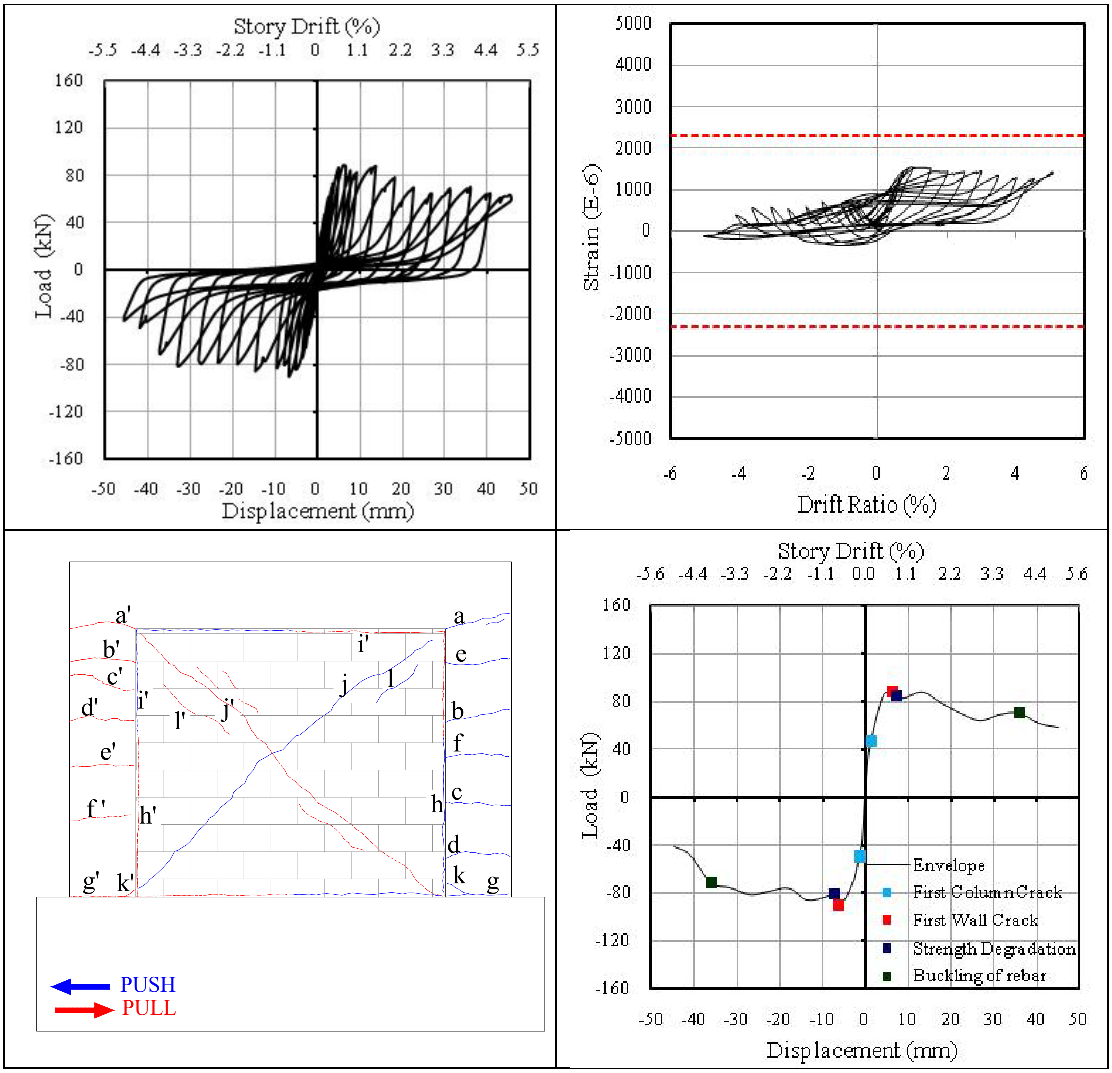


Figure 5. Force-displacement relationship, bottom of column strains and damages occurred in QS test.

PsD Test Results

PsD test results with low inertia mass (M_1) corresponding to various PGA levels are given in Table 2.

Table 2. PsD Test Results Corresponding to Low Inertia Mass (M_1).

PGA	Observations
0.2g	Maximum restoring force and displacements were 28 kN and 1.3 mm (0.14%), respectively. The width of flexural cracks were in the range of 0.1 mm.
0.4g	Maximum restoring force and displacements were 60 kN and 2.4 mm (0.27%), respectively. The width of distributed flexural cracks was measured to be 0.2 mm. First separation of infill wall occurred at this stage of loading.
0.6g	Maximum restoring force and displacements were 90 kN and 3.6 mm (0.4%), respectively. At this PGA level, the widths and the amount of cracks increased considerably.

PsD test results with high inertia mass (M_2) corresponding to various PGA levels are given in Table 3.

Table 3. PsD Test Results Corresponding to High Inertia Mass (M_2).

PGA	Observations
0.2g	Maximum restoring force and displacements were 92 kN and 4.42 mm (0.49%), respectively. The observed maximum flexural crack widths throughout the columns were about 0.8 mm. There was no damage in the infill wall at this stage.
0.4g	Maximum restoring force and displacements were 118 kN and 22 mm (2.45%), respectively. Strength degradation started at 22 mm (2.45% drift) of top displacement. Maximum crack widths occurred throughout the column elements were about 3.5 mm. Diagonal cracks and corner crushing occurred at this stage. Most of the longitudinal reinforcements at the bottom section of the columns yielded after the peak acceleration value.
0.6g	Test could not be achieved due to excessive damage of the specimen.

Fig. 6 illustrates the restoring force versus top frame displacement relationships for each PGA levels for both mass conditions.

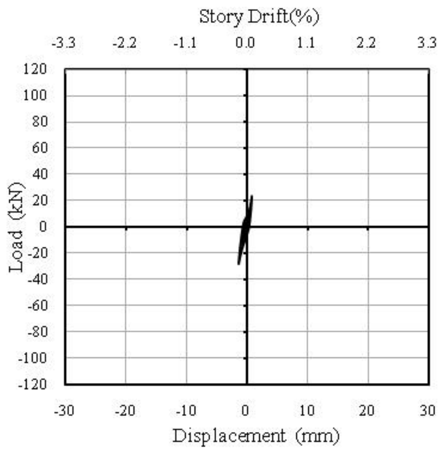
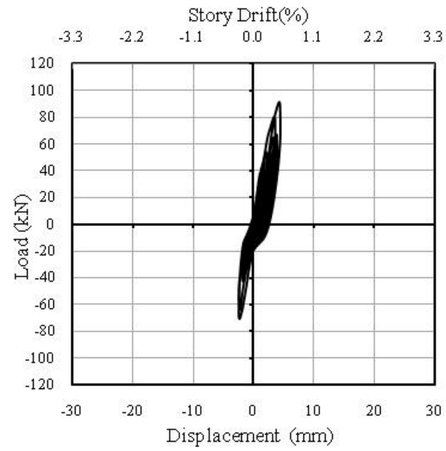
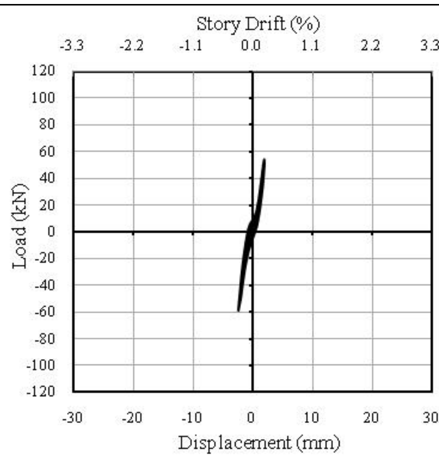
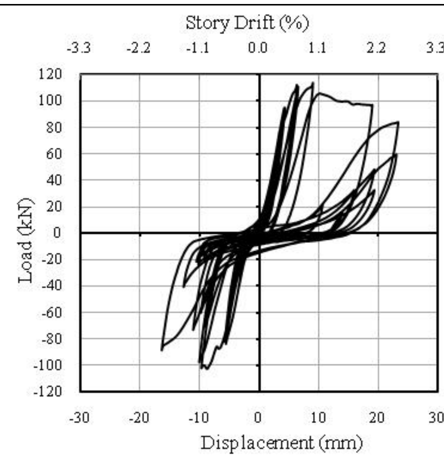
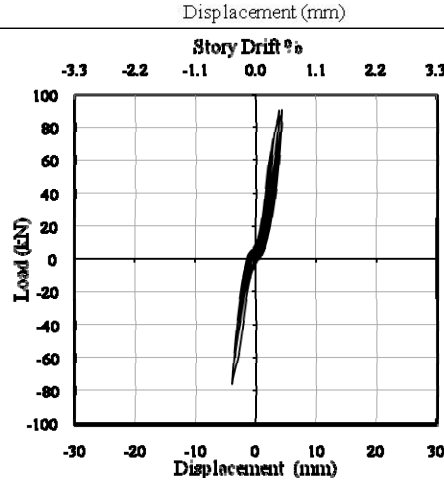
PGA	Low Inertia Mass (M_1)	High Inertia Mass (M_2)
0.2g		
0.4g		
0.6g		

Figure 6. Restoring force versus top frame displacement relationships for M_1 and M_2.

Figs. 7 and 8, for M_1 and M_2 mass conditions, respectively, illustrate cumulative crack pattern and rebar strains that were measured from bottom of column locations where maximum stresses have occurred.

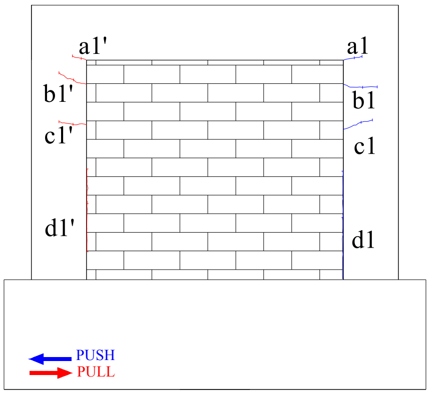
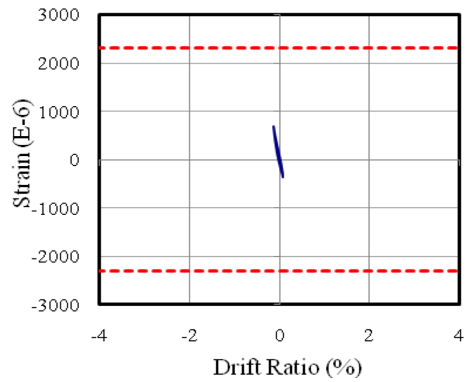
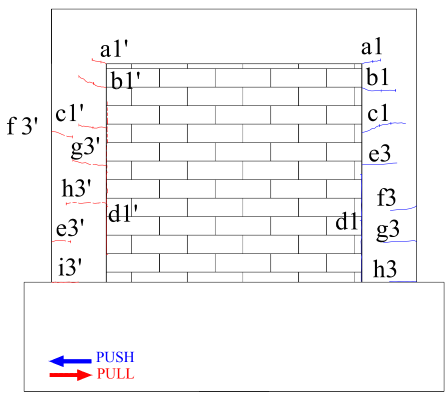
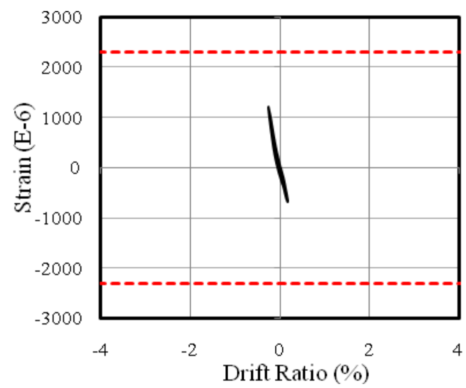
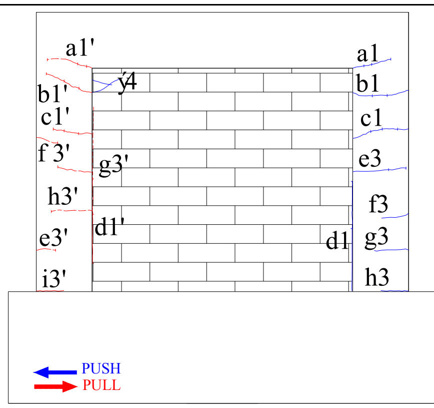
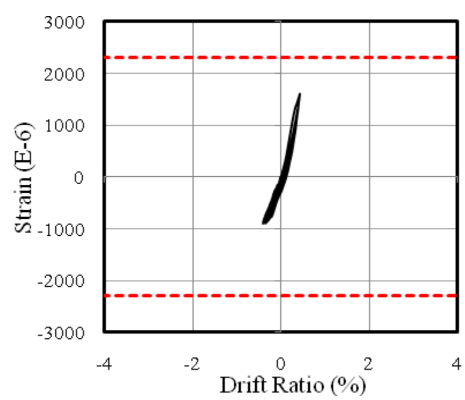
PGA	Cumulative Damage Pattern	Strain at Bottom Column Section
0.2g		
0.4g		
0.6g		

Figure 7. Cumulative Damage Pattern and strains at Bottom Column section for M_1 mass condition.

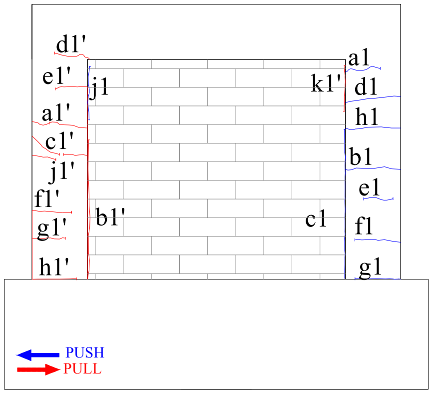
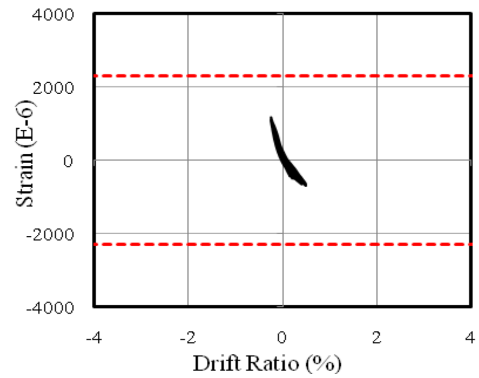
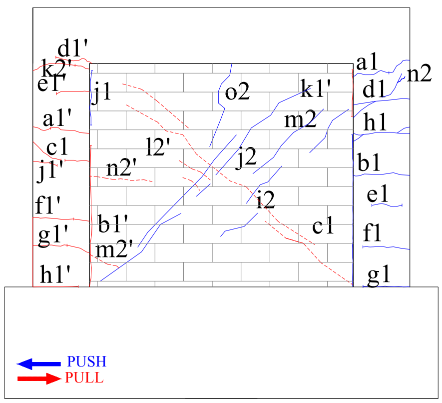
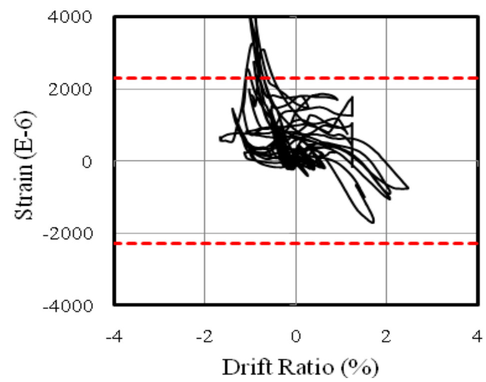
<table>
<tr><th>PGA</th><th>Cumulative Damage Pattern</th><th>Strain at Bottom Column Section</th></tr>
<tr><td>0.2g</td><td>
</td><td>
</td></tr>
<tr><td>0.4g</td><td>
</td><td>
</td></tr>
</table>

Figure 8. Cumulative Damage Pattern and strains at Bottom Column section for M_2 mass condition.

Analysis of Test Results

The maximum restoring forces and corresponding lateral top displacements for various PGA levels obtained from PsD tests are plotted on the force-displacement envelope of QS test. Similarly, the cumulative dissipated energies and corresponding lateral drifts for various PGA levels obtained from PsD tests are plotted on the cumulative dissipated energy curve of QS test. Here, the energy magnitudes were calculated cumulatively using the areas enclosed the hysteresis loops. These comparative analyses are shown in Fig. 9.

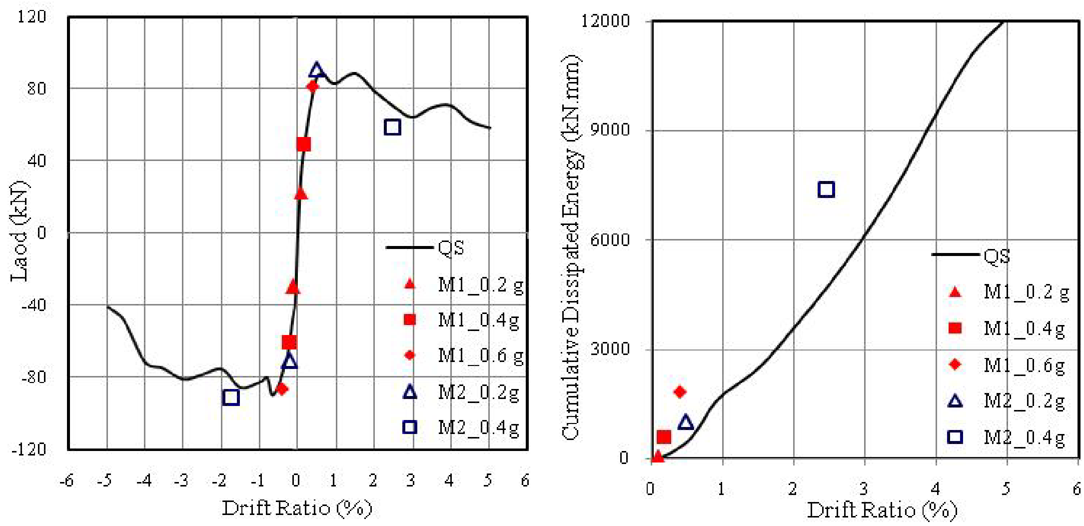


Figure 9. Comparative load-deformation and energy dissipation relationships for QS and PsD tests.

Conclusions

The following conclusions could be reached as follows:

1. The restoring forces corresponding to the maximum drifts that were obtained from the PsD tests showed a close behavior pattern, regardless of the level of inertial masses compared with QS tests, up to the 1% story drift.
2. Although general behavior of any specimen could be obtained in QS test using a common drift-based loading protocol, it is not possible to predict the restoring force levels corresponding to PGA levels. However, in PsD tests, the maximum strengths for low (M_1) and high (M_2) inertial masses were observed at PGA=0.6g and 0.4g, respectively.
3. Only the flexural cracks for M_1 case on columns at the end of the PGA=0.6g PsD test were observed, while for M_2 case, in addition to flexural cracks, separation of wall from the frame as well as diagonal cracks on the wall were observed at the end of the PGA=0.4g PsD test. This shows the effect of inertial masses on the damage magnitude. Even tough similar damages were observed during the QS tests, it is not possible to determine which level of PGA’s created these damages.
4. For M_2 mass condition more damage were observed during PsD tests compared with QS tests.
5. The cumulative energy dissipation is found to be comparatively less in QS tests for the varying drift ratios due to the greater number of reverse cycles used in PsD tests.

Acknowledgments

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PEER Strong Motion Data Base http://peer.berkeley.edu/smcat/search.html.

TEC, 2007. *Turkish Earthquake Resistant Design Code.*

Revisions of Paper #514

1. page 3: typo - "In order account" should be "In order to account".

This concrete mistake have been corrected.

2. The equations are of poor quality and almost not readable.

The equations have been re-written in better quality.

3. The sentence after eq. 1 is very misleading and confusing. It says that M1 and M2 are the masses of top and bottom storey of typical mid-rise RC buildings. Did the authors consider the test structure a multiple storey mid-rise building? The subsequent discussion seems to indicate that only single storey frames were tested. Further, the sentence implies that M1 and M2 are masses at two different stories while subsequent discussion says that they are masses assumed for two different single storey test specimens.

The experimental study has been conducted on single bay and single storey RC frames. Two of the specimens were tested under the effect of acceleration records. M_1 and M_2 which are low and high mass conditions are used in the pseudo-dynamic tests. Depending on the critics the sentence has been modified as follows: *'where m is the mass (M_1=0.0085kNs^2/mm and M_2=0.0221 kNs^2/mm are two alternative mass conditions)'*.

4. page 4: it is said that unconditionally stable finite difference method was used for PsD tests. Nevertheless, the equations that follow represent the central difference method was used (if the reviewer read them correctly considering readability). This method is conditionally stable rather than unconditionally stable.

The sentence has been revised as *'Eq. 1 is solved numerically by using central difference method'*.

5. The authors should clarify whether the PGA values indicated correspond to the 1/3-scale model or full-scale structure.

The test specimens were constructed respecting to the similitute rules, (Noor, 1992). According to the rules, the scaling factors used in this study for the dimensions, masses and acceleration are

3, 9 and 1.0, respectively.

6. Figures 6 and 9 are inconsistent. Figure 6 shows that the maximum force developed for M2 is about 110 kN while Figure 9 shows that it is below 100 kN.

Fig. 6 corresponds to the base-shear versus top displacement relationships obtained from the PsD tests. However, Fig.9 shows the observed maximum top displacements and their corresponding base shears obtained from the PsD tests. This is the reason why you get different base shears from the two diagrams.

7. Conclusion No. 1 is not appropriate. First, PsD test with M2 shows much higher strength than QS test. Second, PsD with M2 was hardly beyond the elastic limit and therefore cannot be compared to the other two tests.

Conclusion 1 has been revised is as follows: *'The restoring forces corresponding to the maximum drifts that were obtained from the PsD tests showed a close behavior pattern, regardless of the level of inertial masses, compared with QS tests up to the 1% story drift'.*

8. Conclusion No. 4: It is not clear form the hysteresis curves that the PsD tests had more loading cycles than the QS test. This is definitely not true for the PsD test with M1. The authors must substantiate this statement for the case with M2.

The acceleration record used in the PsD tests has more loading cycles than the displacement pattern used in the QS tests. The authors are agree with the reviewer at the point that M1 case is not comparable with QS. Therefore, the conclusion 4 has been revised as follows: *' For M2 mass condition more damage were observed during PsD tests compared with QS tests'.*