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The effect of displacement paths on biaxial pseudodynamic test of a rocking column

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ABSTRACT: Currently there is still a lack of multi-directional earthquake loading simulations due to the high cost and setup complexity. However many structural failures are caused by the combined effect of multi-directional loading. In addition, there is no definitive guidance on the effects of different displacement tracking objectives on the results of multi-directional physical earthquake simulations. This study tested a post-tensioned rectangular rocking concrete column with externally mounted energy dissipators pseudodynamically subjected to simultaneous biaxial loading, emulating bidirectional earthquake ground motion. The experiments used different displacement tracking strategies and found that particular tracking strategies gave rise to additional plastic deformations of the specimen and consequently resulted in appreciable differences in the time history predictions both in amplitude and phase lag. The experiments also revealed a design deficiency of the externally mounted energy dissipators. The dissipators failed prematurely under buckling during bidirectional loading, a phenomenon that has been missed in previous earthquake simulations.

1 INTRODUCTION

To date, most experimental seismic simulations only consider uniaxial load action along the principal axes of a specimen. However earthquake loading is multi-directional in nature and most often occur at an oblique angle to a structure's principal axes. Even when considering unidirectional earthquake excitation only, torsional responses should be expected since most structures are irregular. The importance of including multi-axial effect is further highlighted by the Canterbury Earthquakes experience where many structural failures were attributed to the combined effect of multi-directional loading. Therefore, additional research effort considering multi-axial earthquake load is needed to understand the complex coupled structural responses particularly during inelastic excursions, where stiffness degradation in one axis can significantly affect the same parameter in the other.

1.1 Test specimen and setup

This study conducted biaxial pseudodynamic (PSD) tests on a rocking column. The test specimen was a free-standing concrete column with unbonded post-tensioning (PT) bars and replaceable, externally mounted dissipators (EMD) made from mild steel bars. The PT bars enabled controlled rocking behaviour and the replaceable mild steel bars provided dependable energy dissipations capability during rocking. The structural system was inspired by the PRecast Seismic Structural System (PRESSS) technology which ensured protection against significant structural damage even after a major earthquake event (Priestley, Sritharan et al. 1999). The Alan MacDiarmid building in Victoria University of Wellington, shown in Figure 1 is the first building in New Zealand to adopt such system (BBR Contech 2011).

The low-damage behaviour of an unbonded PT column enables the specimen to be reused for multiple tests. It is worth mentioning that the test specimen in this series of experiments was similar to the specimens in a previous study by Marriott (2009). The column had a rectangular cross-section (490 × 250 mm) and a cantilever height of 1600 mm. The column had 12 – D10 as longitudinal reinforcements and D10 transverse reinforcements spaced at 120 mm centers. All reinforcing bars were Grade 300 deformed bars. The column sat atop a concrete foundation block, and the EMD were bolted to the base of the column through a steel brackets. These dissipators were designed to provide energy dissipation as they cycled between tension and compression when the column displaced. The load to the column were applied through actuators in displacement-control mode, connected at right angles at the top of the column by means of steel plates and four M25 threaded steel rods. A schematic drawing of the test setup is shown in

Figure 2 and photographs of the actual test setup are shown in Figure 3.

Figure 1 The Alan MacDiarmid building, Victoria University of Wellington (left), and close up of the EMD (right) (BBR Contech 2011)

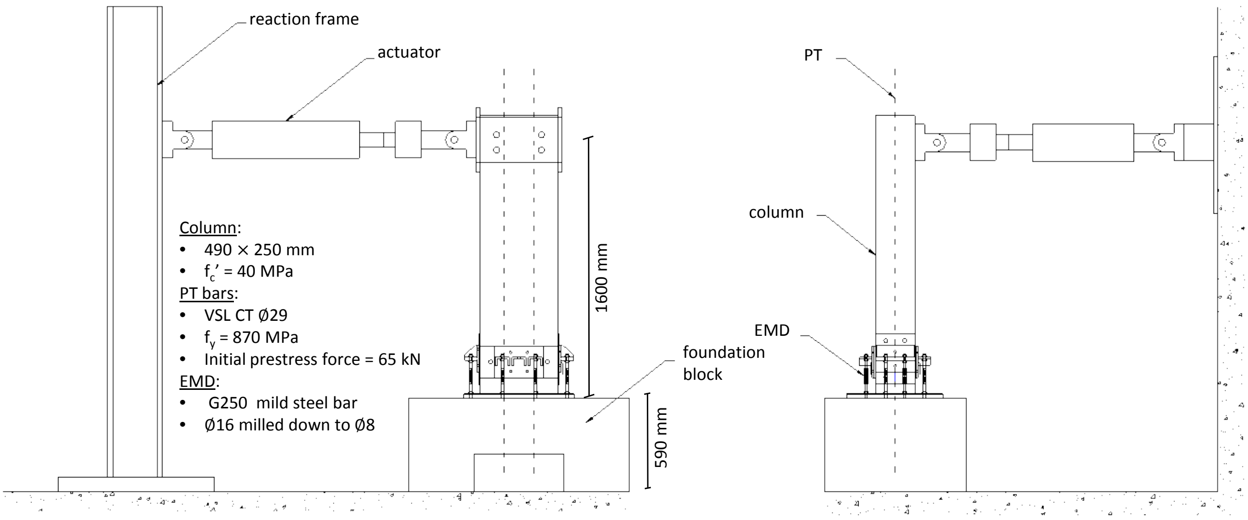
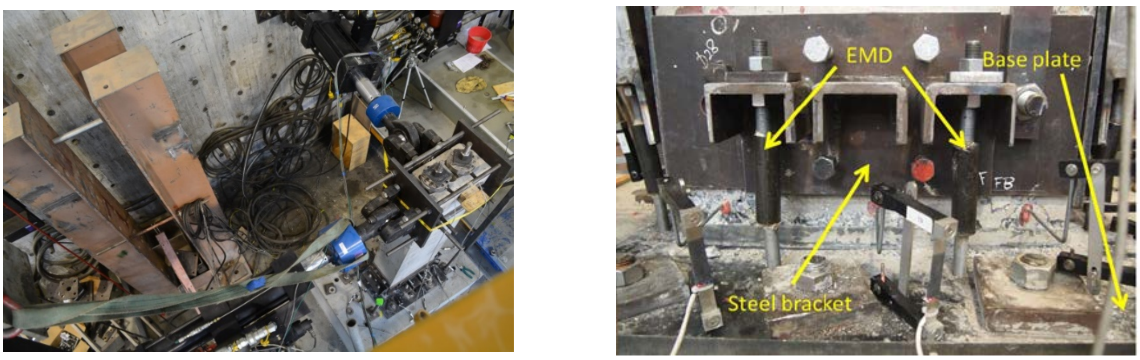


Figure 2 Elevation view of test setup, stronger axis face (left) and weaker axis face (right)



a) b)

Figure 3 Actual experiment setup, a) view from above and b) column base detailing

1.2 The pseudodynamic method

The pseudodynamic (PSD) method subjects a specimen to a displacement history that is determined interactively, according to a numerical model of the system and the measured specimen response during the course of the test. This testing technique is particularly advantageous for seismic simulations as it allows dynamic and inertial effects to be replicated in the numerical model, hence allowing otherwise very large dynamic forces on the physical specimens to be applied at a slower rate or pseudostatically. A description of the basic algorithm is available in Shing and Mahin (1984).

In a 2D application, the column displaces in two transverse directions at the top. The principal axes of the cross section are no longer aligned with the actuator axes due to finite actuator lengths (Figure 4). Therefore an iterative procedure had been developed to account for this geometric error during control signals generation as well as feedback signals processing.

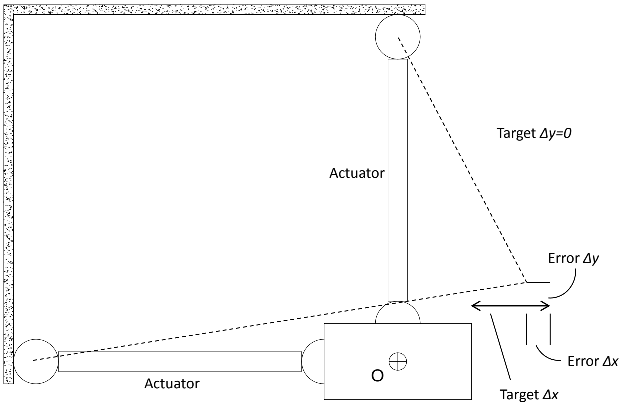


Figure 4 Geometric error in displaced column

1.3 Displacement tracking strategies

To date, the effect of different displacement tracking strategies on the results of multi-directional physical earthquake simulations is yet to be assessed. Previous studies have shown that different load paths lead to different inelastic load-deformation behaviour of structures (Bousias, Verzeletti et al. 1995), and consequently different energy dissipation capability which may not always be proportionally related to the ultimate strength capacity for a given displacement path (Watanabe, Sugiura et al. 2000, Qiu, Li et al. 2002).

In the current research, the rocking column was subjected to three patterns of displacement paths in *x*- and *y*- directions during each time step according to the numerical model in the computer. Referring to Figure **5**, the experiments adopted a “staggering” pattern among infinite possible paths to move the column from Point 1 to Point 2. In the first pattern (denoted I in Figure **5**), the column was displaced along the stronger axis (henceforth called the *X*-axis) while it was held steady in the weaker axis (henceforth called the *Y*-axis). Afterwards, the column was displaced along the *Y*-axis until Point 2 was reached while the *X*-axis position was held steady. The second pattern (denoted II) was similar to Pattern I except with the order of loading reversed. The third pattern (denoted III) is the conventional path where the column was displaced along both axes simultaneously. Using different displacement tracking for the same earthquake record in a PSD test is analogous to subjecting the structure to a different load path; since the displacement amplitudes the structure is reaching are expected to be the same, the path the structure takes to reach these amplitudes determine how much energy is dissipated.

1.4 Experiment regime

The experiment adopted earthquake records that were selected and scaled based on the NZS1170.5:2005 (Standards New Zealand 2004) guidelines for time-history analyses. These records represented the seismicity of the greater Wellington region (Oyarzo-Vera, McVerry et al. 2012).

Figure 6 shows the site-specific target spectra of the assumed region, as well as the pseudo-spectral acceleration (*PSA*) of the scaled earthquake records. The dashed lines indicate the range of periods whose *PSA*s were scaled according to the procedure in NZS1170.5:2005.

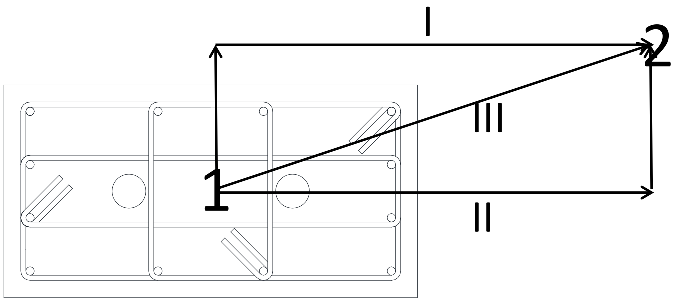


Figure 5 Different displacement paths to a target displacement

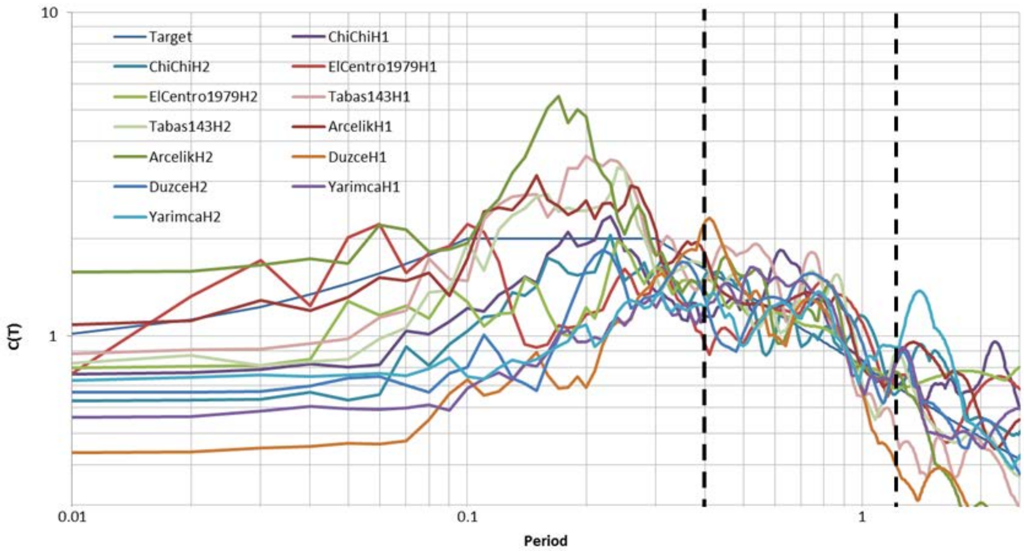


Figure 6 *PSA* of the family of earthquake records used in the testing regime

a) b)

Figure 7 Buckled EMD, a) during experiment and b) after experiment

2 RESULTS AND DISCUSSIONS

2.1 EMD failure

There are two factors that presumably contributed to the failure of the EMD. The first is the the biaxial loading at the column led to large bending actions on the EMDs. As the EMD motions were no longer predominantly axial, on compression cycles following tension cycles, concentrated rotation developed at the junctions where the anti-buckling grouted sleeve terminated. This resulted in significant eccentricity for the axial force and premature failure of the EMD. Figure **7** shows a buckled EMD, highlighting that concentrated rotation occurred around the end of the milled-down portion. Although it has been shown through component testing and uniaxial cyclic assemblage test that the EMD yielded dependably in tension and compression (Marriott 2009), full performance under bidirectional earthquake attack was evidently nulled. Preliminary analyses of the experiment results indicated that the EMD failed at about 50% of the intended capacity. It further highlights the importance of considering the effect of multi-axial load on such system.

2.2 PSD test results

This section presents the PSD test result from four earthquake records simulations. The PSD tests adopted a timescale factor of 50 such that a 30-second earthquake record would have taken 25 minutes. Accordingly, the time axes in the following time history plots have been adjusted to reflect the timescale of the actual earthquake. Figure 8 shows the displacement time history and force displacement response of the column from the 1999 Duzce earthquake simulation. Figure 8a) and c) highlights noticeable differences in amplitude and phase of the column displacements in both axes due to different displacement tracking strategies. It should be noted that a classical flag-shaped hysteretic curves did not develop as seen in Figure 8b) and d), along with appreciable residual drifts. This was in part caused by a large crack at one corner of the column and therefore sliding, opening and closing of this crack dominated the hysteretic behaviour. The figure also highlights the poor performance of the EMD due to buckling and slippage. Due to space limitation, other time histories and force-displacement results are not shown but similar trends are also observed.

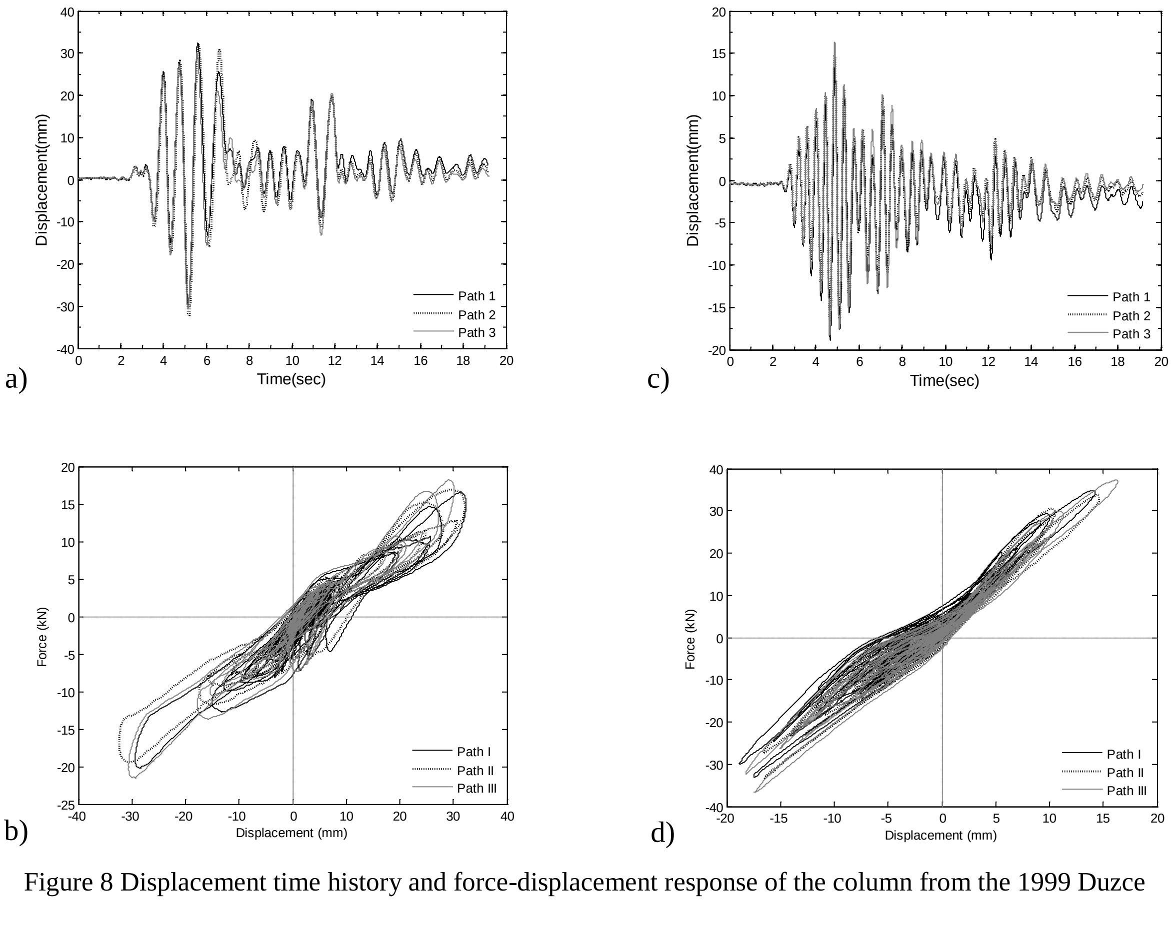


Figure 8 Displacement time history and force-displacement response of the column from the 1999 Duzce

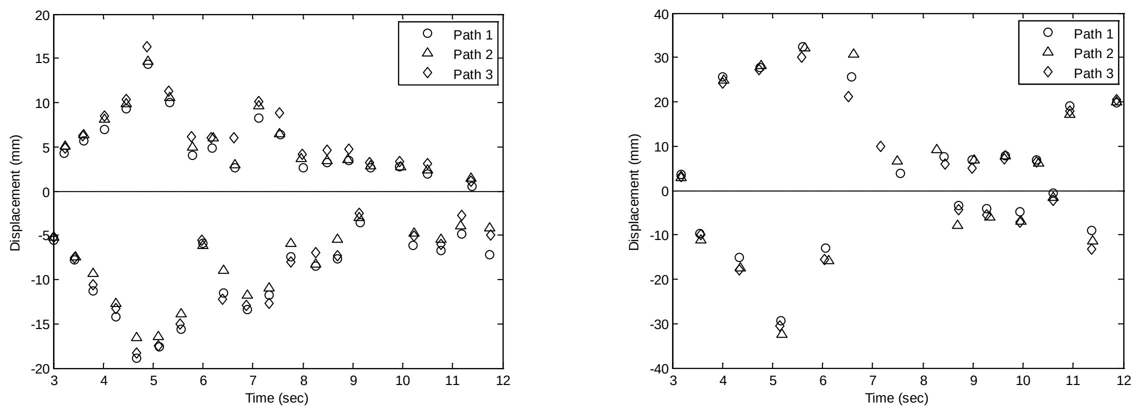
earthquake simulation for the weak (a and b) and strong (c and d) axes

The tracking strategy Path III can be thought as the ideal solution in the absence of true reference result from full dynamic tests (e.g. shake-table test), or idealised numerical simulation, considering the column will take the shortest deflection path in real earthquake event. For each tracking strategy, the positive and negative amplitudes attained at every half-cycle in the displacement time history can be identified, such as shown in Figure **9**, from the result of 1999 Duzce earthquake simulation. The amplitudes attained by tracking strategies Path I and Path II can then be quantified in term of their differences, relative to Path III. Mathematically, these amplitude differences can be represented in a normalised form ε defined as,

$$\varepsilon_i = \frac{A^i - A^{III}}{A^{III}} \tag{1}$$

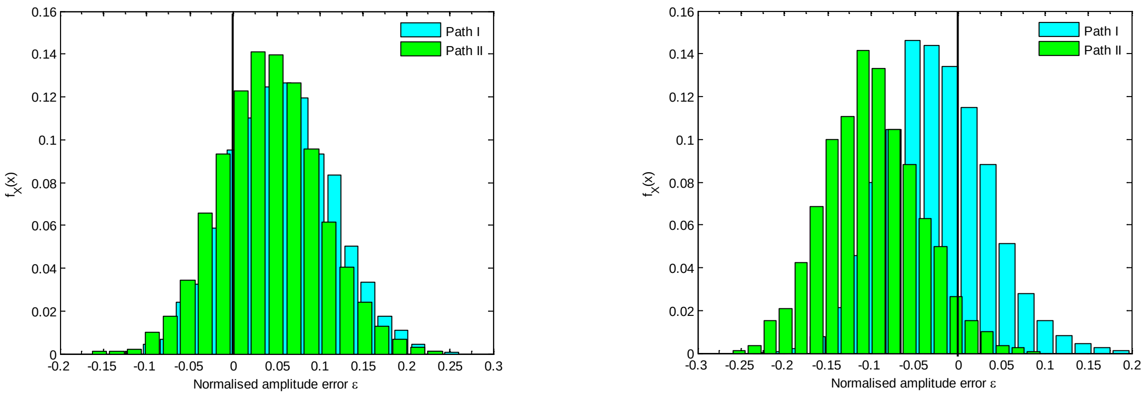
In Equation 1, A = amplitude and i = I or II e.g. A^i indicates amplitudes attained during Path i test. Consequently any negative values ε indicate that the attained amplitudes in Path I or II are smaller than the reference value Path III, while positive values indicate the opposite. Note that although Figure **9**a) and b) only show part of the displacement amplitudes of the complete time history for clarity purpose, Equation 1 takes into account all displacement amplitudes throughout the response histories.

Collating the normalised amplitude errors from each cycle in the earthquake time history, Figure 10-13 plot the distributions of these differences as a density function, $f_X(x)$. In each plot, a solid black line parallel with the vertical axis is drawn at zero ε. The peak (median) of the density function will coincide with this line if different displacement paths produced the same displacement amplitudes on average. It is interesting to note that the median values of ε across all results are mostly positive, i.e. the amplitudes at peaks of each cycle attained via Path I and II are generally larger than Path III. Note that during Path I or Path II tests, the column displaced a greater distance compared to Path III, providing greater opportunity for accumulated plastic deformation in the column. Therefore it is likely that the column developed a lower restoring force which in turn led to larger displacement amplitudes in the PSD algorithm.



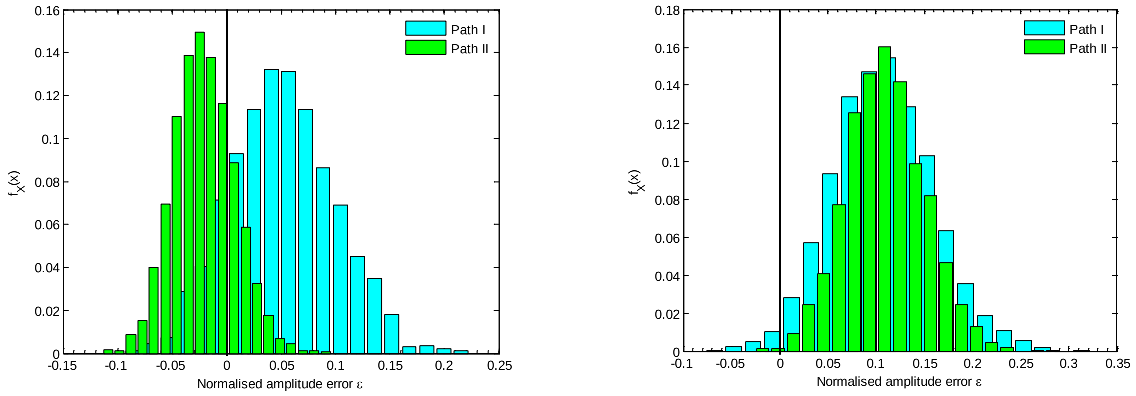
a) b)

Figure 9 Displacement amplitudes attained during the 1999 Duzce earthquake (Duzce,Turkey) simulation, a) *X*-axis and b) *Y*-axis



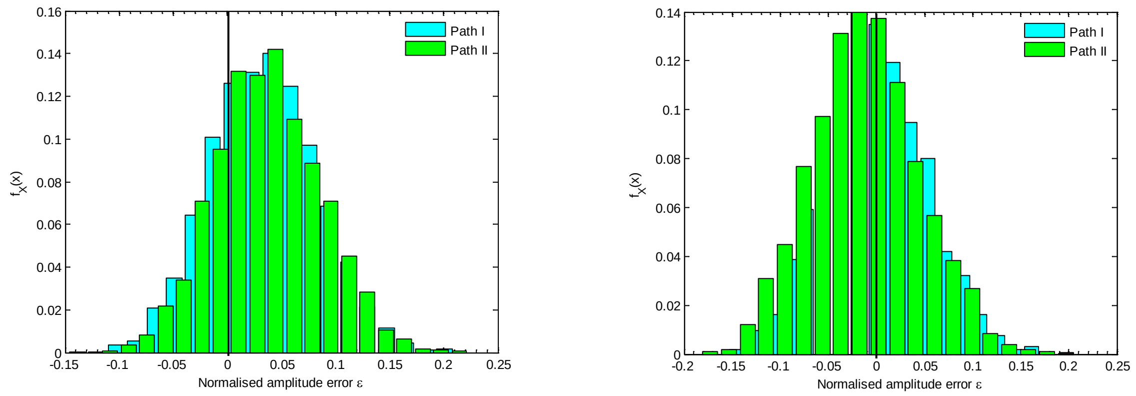
a) b)

Figure 10 Distribution of normalised amplitude errors from 1979 Imperial Valley earthquake simulation, a) *X*-axis and b) *Y*-axis



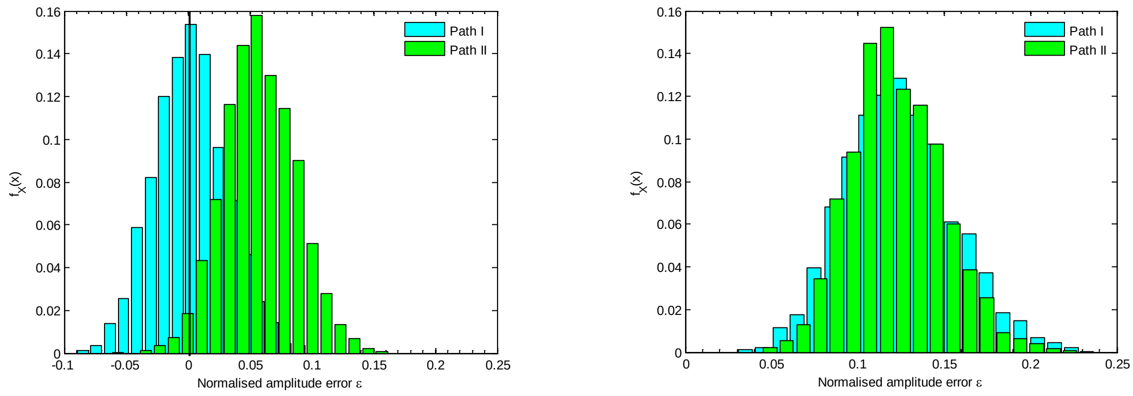
a) b)

Figure 11 Distribution of normalised amplitude errors from 1999 Duzce earthquake (Duzce,Turkey) simulation, a) *X*-axis and b) *Y*-axis



a) b)

Figure 12 Distribution of normalised amplitudes errors from 1978 Tabas earthquake (Tabas, Iran) simulation, a) *X*-axis and b) *Y*-axis



a) b)

Figure 13 Distribution of normalised amplitudes errors from 1999 Yarimca earthquake (Kocaeli, Turkey) simulation, a) *X*-axis and b) *Y*-axis

3 CONCLUSION

This study on a rocking column has shown that different displacement paths in bidirectional earthquake simulations led to different inelastic response as expected. This phenomenon occurs in quasi-static tests as well as PSD simulations. Three displacement tracking strategies were employed and the resulting error distributions suggest that different displacement tracking strategies led to noticeable differences in the displacement amplitudes attained by the specimen. The experiments also exposed deficient performance of the externally mounted energy dissipators. While it has been missed during previous study, the experiments showed that the dissipators failed prematurely due to buckling under bidirectional loading. This phenomenon deserves further investigation through more bi-axial experiments.

4 ACKNOWLEDGEMENT

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