EXPERIMENTAL EVALUATION OF CONFINEMENT AND GROUND MOTION CHARACTERISTICS EFFECTS ON RC BRIDGE PIERS

Xiao GE¹, Nicholas A. ALEXANDER², Mohammad M. KASHANI³

ABSTRACT

This study reports a set of benchmark shaking table tests of four large-scale RC columns. Three of columns have identical design dimensions and details. They are subjected to three difference ground motions: (i) a near-field without pulse record, (ii) a near-field pulse-like record and (iii) a far-field record. All three records are spectrally matched to a common elastic spectrum. These particular benchmark column tests are designed to explore the influence of non-ergodic properties of the ground motion time-series on the seismic performance of RC bridge piers. The fourth column is identical in geometry and main-reinforcement detailing, however, it is lightly confined with larger horizontal ties spacing. The same far-field ground motion is used to test this column to examine the confinement effects on RC bridge piers during an earthquake.

Keywords: Reinforced concrete; Bridge pier; Ground motion; Inelastic buckling; Shaking table test

1. INTRODUCTION

Reinforced concrete (RC) bridge piers are regarded as the most vulnerable part of RC bridges. Therefore, the research on the nonlinear dynamic behaviour of piers subjected to seismic loading is required. When bridges are subjected to seismic loading, plastic hinges form in their piers, while the deck remains elastic. In current seismic design codes (BSI 2010; Caltrans 2013), the plastic hinge has been treated as an important indicator of seismic performance. The formation of the plastic hinge is influenced by sufficient concrete confinement and mechanical properties of reinforcing bars. The external load is another important factor affecting the seismic behaviour of RC components. Ground motions varied in non-stationary properties (e.g. duration, frequency content and velocity pulse) can result in different response of RC columns in lateral displacement, stiffness degradation and energy dissipation.

Over past the few years, many researchers have investigated the nonlinear static and dynamic behaviour of RC columns numerically and experimentally. Paultre and Légeron (2008) proposed novel equations to predict RC column ductility by evaluating confinement reinforcement. It suggests that effective confinement makes most contribution to the ductile performance of RC columns. Kashani et al. (2015; 2016; 2017a; 2017b; 2017c) and Kashani (2017) experimentally and numerically evaluated the seismic performance of RC columns considering the influence of different ground motion types, reinforcement buckling and cyclic degradation. They suggest that pulse effect can amplify the peak response of RC columns, near-field ground motions with velocity pulse usually cause more damage to structures with low natural frequency, and inelastic buckling and degradation have more influence on shorter RC columns. Phan et al. (2007), Brown and Saiidi (2011), Mohammed (2016) investigated ground motion characteristics effects on RC column by shaking table tests. Their work illustrates that near-field ground motion records usually cause more violent response of RC columns compared to far-field ground motion records. Near-field ground motion records containing a large amplitude velocity pulse could lead to asymmetric displacement response. A long duration ground motion could cause more displacement

¹Ph.D. Candidate, Dept. of Civil Engineering, Univ. of Bristol, Bristol, United Kingdom, xiao.ge@bristol.ac.uk
²Senior Lecturer, Dept. of Civil Engineering, Univ. of Bristol, Bristol, United Kingdom
³Associate Professor, Faculty of Engineering and the Environment, Univ. of Southampton, Southampton, United Kingdom
capacity loss of RC columns. This study investigates how structural detailing and ground motion characteristics impact on the seismic behaviour of RC columns using shaking table experiments. Ground motion records of Northridge, Imperial Valley and Manjil are selected from FEMA P695 (2009) to represent (i) near-field without pulse (NFWP), (ii) near-field pulse-like (NFPL), and (iii) far-field (FF) ground motions. To keep non-stationary properties of ground motions, all records are spectrally matched to FF record by a mathematical algorithm developed by Alexander et al. (2014). Four medium scale RC columns with same dimensions are cast for this test. Three of them with same structural details are tested under the excitation of NFWP, NFPL and FF ground motions respectively to explore the significance of non-stationary ground motion characteristics. The fourth column has the same geometry, but with less confinement is tested under FF ground motion to evaluate the horizontal reinforcement effects on the seismic behaviour of RC columns. Each column is tested under the different intensity of ground motions (25%, 300% and 500%) to study the performance of RC column in different damage levels. Aftershock test is conducted for each column to evaluate the residual seismic capacity of damaged columns. In this paper, hysteresis behaviour, natural frequency variant, time-effective stiffness analysis and time-frequency analysis of all specimens are presented.

2. EXPERIMENTAL PROGRAMME

2.1 Specimen Fraction

Four medium scale cantilever RC columns are cast. The structural details and dimensions are shown in Figure 1. The specimens are 2300mm high and cast in a concrete foundation of 700mm in height and 1500mm in width. The dimension of specimen cross-section is 250mm × 250mm. The specimens are vertically reinforced by 8 steel bars with a diameter of 16mm. Three of the specimens are designated as well-confined columns, where shear links with a diameter of 8mm are employed at 80 mm spacing as horizontal reinforcement. The other one, designated as the lightly-confined column, is horizontally reinforced by same shear links at 200mm spacing. Compressive tests are conducted to characterise the mechanical properties of the concrete. The results show the average strength of concrete is 40 MPa. The names and details of four columns are summarised in Table 1.
Figure 1. Structural details of two types of specimens.

Table 1. Specimen naming.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ground Motion</th>
<th>Test Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well confined column</td>
<td>Near-field without pulse</td>
<td>NFWP</td>
</tr>
<tr>
<td></td>
<td>Near-field pulse-like</td>
<td>NFPL</td>
</tr>
<tr>
<td></td>
<td>Far-field</td>
<td>FF-WC</td>
</tr>
<tr>
<td>Lightly confined column</td>
<td>Far-field</td>
<td>FF-LC</td>
</tr>
</tbody>
</table>

2.2 Test Setup

This test is conducted on a 3m × 3m, 6 degrees of freedom shaking table at the University of Bristol. A steel support frame is bolted on the table to prevent the column from complete collapse. The column is fixed on the centre of the table by four pieces of steel to prevent any horizontal movement during the test. These channel sections are fixed by 20 bolts to guarantee the rigidity of specimen fixation. Four mass blocks (1 tonne each) are allocated on each corner of the table to lower the centre of gravity. In this way, unexpected rocking movement is prevented. Three mass blocks (3 tonnes in total) are fixed on the top of the specimen to simulate the superstructure of the bridge and provide the axial load. The layout of the setup is shown in Figure 2. The coordination system is introduced in this work. In this system, x, y and z are the plane of shaking direction, out of the plane of shaking direction and vertical direction, respectively.

Figure 3 shows the layout of instrumentations. An accelerometer is placed on the top of the foundation to record the input acceleration. An accelerometer is positioned on the top of the column to monitor the acceleration response during the test. In order to estimate the initial force, two accelerometers are placed on the middle mass block on the top of the column to record acceleration in x and y directions. Four cable extension position transducers (Celescos) are connected from the specimen to the steel safety frame to record the displacement response. Eight Linear Voltage Displacement Transducers (LVDTs) are placed on the bottom of the column to monitor the small vertical displacement. The data can be used to estimate the flexure of the column.

2.3 Ground-Motion Modification

As mentioned previously, ground motion records of Northridge, Imperial Valley, and Manjil earthquakes are chosen as NFWP, NFPL and FF ground motions from FEMA P695 (2009). The acceleration time-histories of the three records are shown in Figure 4. Given that our interest is on the influence of non-stationary content of ground motions (e.g. general envelope, duration, velocity-pulse), the influence of peak ground motion acceleration (PGA) and peak ground motion velocity (PGV), should be excluded.

Alexander et al. (2014) proposed an algorithm named Reweighted Volterra Series Algorithm (RVSA) to modify the acceleration time-history with a target spectrum. In this process, the time-history will be decomposed into discrete Volterra series. The frequency content of each Volterra series kernel is determined by employing the stationary wavelet transform. By reweighting each kernel, the original record can be matched to a target spectrum. In this work, NFWP and NFPL ground motions are matched by the spectrum of FF ground motion through RVSA.

In order to investigate the seismic performance of RC column in different damage levels. Scale factors of 25%, 300% and 500% are employed in the test to represent slight, extensive and complete damage. To evaluate the seismic-resistant capacity of RC columns after being completely damaged in an earthquake, another round of test with an intensity of 300% is conducted for each column.
Figure 2. The layout of shaking table.

Figure 3. Instrumentations of the test.

Figure 4. Time-histories of spectrally matched (a) NFWP, (b) NFPL and (c) FF.
White-noise tests are employed prior to the first round and after each round of test. In white-noise tests, a low-amplitude input ground motion with equal intensity in different frequency is applied. The response spectrum of the column can be used to detect natural frequency and damping.

3. TEST RESULT AND DISCUSSION

3.1 Force-displacement Relation

Figure 5 shows the hysteresis loop of the well-confined column under FF ground motion (FF-WC) in each damage level test. In this work, the base force is normalised by the axial load (30KN), the lateral displacement is normalised to column height (2.3m); i.e. drift ratio. As expected, the column shows linear response in slight damage level test. In extensive damage level test (300%), both force and displacement responses are larger. The slope of the hysteresis loop decreases significantly, which indicates the stiffness reduction of the column. In the complete damage level test (500%), larger displacement response can be observed, but the force response has barely changed. This illustrates the classical degradation due to ductile behaviour. In both extensive and complete damage level tests, the column tilts into the positive x-axis during the test. As shown in Figure 6, concrete cover spalling is significant in the positive x-axis. The asymmetry of concrete cover damage leads to permanent top displacement of the column after the end of the ground motion excitation. In aftershock test (300%), the specimen shows similar peak force response but smaller peak displacement compared with extensive damage level test. The cyclic degradation is smaller than extensive damage level test, which means energy dissipation capacity of the column reduces after reinforcement bar yielding in complete damage level test.

![Figure 5](image)

Figure 5. Displacement-force relation of FFWC in (a) slight, (b) extensive, (c) complete damage level tests and (d) aftershock test
The behaviour of four specimens in aftershock tests has been compared. The corresponding hysteresis loops are shown in Figure 7. NFWP exhibits largest displacement response and most cyclic degradation among three columns. The NFPL ground motion has the shortest duration and least cyclic degradation. Therefore, duration of ground motion may have a direct effect on the cyclic degradation. FF-LC has larger peak lateral displacement response than FF-WC but smaller peak force response. It illustrates that residual stiffness of FF-LC is lower than FF-WC in aftershock test. It can be observed that FF-LC exhibits more cyclic degradation than FF-WC. Therefore, the contribution of confinement to the residual seismic-resistant capacity of RC structures can be confirmed.
3.2 Stiffness and Natural Frequency Analysis

Stiffness change is an indicator of structural integrity. During large seismic events that induce inelasticity, changes in stiffness and frequency should be observable. Concrete cracking, reinforced bar yielding and cyclic fatigue can result in stiffness deterioration (Ni Choine et al. 2016, Kashani et al. 2017). Tracking stiffness degradation can help researchers and engineers understand the nonlinear softening (frequency drop) behaviour of structures. Therefore, monitoring stiffness variant during an earthquake is a key part of Structural Health Monitoring (SHM). In this work, stiffness variation corresponds with frequency response. Hence, stiffness and frequency response are evaluated through following methods: (i) white-noise test, (ii) stiffness derived by hysteresis force-deflection loops, and (iii) time-frequency analysis.

3.2.1 Low amplitude white-noise test result

A set of low amplitude white-noise tests are conducted to the pristine columns and after each round (25%, 300%, 500% and aftershock) of testing. Both input and output acceleration time histories can be transferred into frequency domain content by an algorithm proposed by Welch (1967) to estimate the power spectral density (PSD). In this work, the transfer functions input and output spectral densities are estimated by a toolbox based on Welch’s algorithm (Vold et al. 1984). NFWP is taken as an example and shown in Figure 8. In this figure, the frequency of the peak can be regarded as the natural frequency. Two modes can be clearly observed in white-noise tests. Higher modes are neglected due to the noise in high-frequency part of the spectrum. The natural frequency variant is normalised by the natural frequency of each pristine column respectively (as shown in Figure 9).

Figure 9 shows that the average frequency of mode 1 drops to about 45% of the pristine column value; while the average frequency of the mode 2 drops to about 65% of the pristine column value. The main natural frequency dropping occurs in extensive damage level tests (300%) in both modes. It applies on all specimens. As shown in Figure 6, concrete cover cracking and spalling initiate in extensive damage level tests, which is regarded as the main reason for natural frequency degradation. In complete damage level tests (500%), reinforcement bar yielding occurs. However, there is no significant natural frequency reduction can be detected in this round of tests according to white-noise test results. Therefore, longitudinal reinforcement bar yielding may not account for the significant drops in natural frequencies. In the aftershock tests, the NFPL record (with velocity pulses) causes significant further damage to an already damaged column. Similar the FF-LC record (a low confinement column) also causes significant further damage to an already damaged column. This suggests that large aftershocks with a pulse-like characteristic exciting older low-confinement RC bridge piers may induce significant further damage. Further work is required to quantify this qualitative assertion.
3.2.2 Time-stiffness analysis during earthquake shaking

The system natural frequencies derived in white-noise tests are obtained by frequency domain analysis. The white-noise excitation has a very small amplitude, hence it is assumed that the system behaves linearly during this white noise test. This does not allow us to determine the variation of stiffness (and frequency) in time during earthquake tests. Calculating them in time domain is possible to track the stiffness/frequency degradation during the earthquake. Given that stiffness represents the relation between force and displacement and both force and displacement time histories are recorded during the test, stiffness can be derived by least square linear fit of force/displacement over a moving time window. The slope of this least square line can be regarded as the instant stiffness of the column. By this method, the stiffness time history can be obtained. Subsequently, it can be transferred into natural frequency time-history assuming that the system mass is invariant with time. The natural frequency time history of NFPL in extensive damage level test is shown in Figure 10.
3.2.3 Time-frequency analysis during earthquake shaking

Time-frequency analysis is another method of determining response frequency variation of RC columns during an earthquake. The Wigner-Ville Distribution (WVD) is one of the time-frequency analysis methods. In WVD, only acceleration (inertial force/mass) response time-history is used to generate the time-frequency distribution. In practice, it is far easier to measure acceleration of structure than deformation. As shown in Figure 11, the WVD of each specimen in extensive damage level test (300%) is generated by a toolbox developed by Auger et al. (1996). The corresponding response frequency time history derived by fitting hysteresis loop is also presented in Figure 11 as the comparison.
Frequency estimates derived by two methods are in good agreement in large amplitude part of the response. It confirms that response frequency WVD is a good estimate of instantaneous system frequency, especially in large amplitudes part of a ground motion time-history. After the violent response, WVD method shows lower natural frequency. Prior to high-amplitude response part, observable frequency reduction can be detected in all specimens. This is attributed to the opening of the cracks generated in slight damage level tests (25%). When the oscillation reaches a certain critical level, the cracks open again. The natural frequency decreases sharply. This is why the frequency degradation before large-amplitude response part shows a brittle step-like trend.

4. CONCLUSIONS

This paper reports a set of shaking table tests of RC bridge columns with different structural details under different ground motion excitation. Based on the analysis of test results, the conclusions can be drawn as follows:

1. It has been proved that efficient confinement can make a significant contribution to seismic-resistant ability. It can reduce the natural frequency and stiffness drop of RC columns. Compared with the columns lacking confinement, RC columns with efficient confinement exhibit less cyclic degradation and smaller peak drift during an earthquake.

2. Based on the response of all specimens, it can be concluded that main stiffness degradation happens before complete damage. Concrete cover cracking and spalling count for this phenomenon. The stiffness of three well-confined columns shows a little reduction after complete damage level tests. It illustrates that longitudinal rebar buckling has limited influence on rigidity decreasing of well-confined RC columns.

3. Monitoring natural frequency variation by the Wigner-Ville Distribution (WVD) during an earthquake has been shown to be very useful. The WVD only requires acceleration response of the structure to determine damage identification.

5. ACKNOWLEDGMENTS

The study presented in this paper was supported by the Geotechnical and Earthquake Engineering Research Group at the University of Bristol, and the University of Southampton. The authors wish to express their gratitude to Mr David Ward and Dr Jibin Chen for their help in experimental preparation.
REFERENCES


