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Experimental Study of a Controlled Rocking Bridge Pier

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Summary

Controlled rocking of steel braced frames has been proposed for the seismic retrofit of structures. The controlled rocking approach allows a frame to uplift from its support at the base-of-column to foundation interface while displacement-based steel yielding devices are implemented at the base location to control the response. Past studies have focused on analytical investigations of the response of such a system along with design applications for controlled rocking bridge piers. This paper discusses shake table testing of a 4-legged, steel braced pier representative of a 1/5 length scale highway bridge pier. The model is subjected to a series of seismic excitations about one of its primary orthogonal axes, using horizontal and vertical base motions, and rotated 45deg. to investigate pier behavior that would be expected from bi-directional horizontal base inputs. Ground motions from the 1940 El Centro and 1994 Northridge earthquakes are used along with a synthetically generated motion. The steel yielding devices used during testing are triangular plates that yield in flexure as the pier uplifts and rocks at its base. Results of testing focus on overall behavior of the controlled rocking pier including global hysteretic response, uplifting displacements, and pier forces.

Introduction

The developments of seismic protective systems that provide nonlinear elastic behaviour and prevent damage to a structure's primary members have recently received increased interest. This is in part due to a growing appreciation for the ability of such systems to efficiently withstand seismic demands elastically (without damage) or directing damage to easily replaceable structural "fuses". These types of systems can often also be designed to provide a self-centering ability. This behaviour has been achieved through post-tensioning of structural members (Mander and Cheng 1997; Christopoulos et al., 2002; Garlock et al., 2005). However it may also be achieved by simply allowing structures to uplift from their foundation while preventing sliding, creating a rocking response. The seismic behaviour of conventional structural systems, such as special moment-resisting frames, concentrically braced frames, and eccentrically braced frames (AISC 2005), can be satisfactory from a life safety point of view (FEMA 2003), however damage to members can leave the structure unusable until costly repairs can be made.

In order to complement the system otherwise free to uplift, Pollino and Bruneau (2007) have proposed a controlled rocking approach for seismic resistance in which passive energy dissipation devices are added at the uplifting location to control the rocking response of steel braced frames. The devices considered were displacement-based steel yielding elements that could be calibrated to achieve a desired level of response. The cyclic hysteretic behavior including P-Δ effects and a capacity-based design method were developed. The design method used a number of design constraints including limiting maximum displacements, impact velocity, and maximum dynamic forces such that the structure could remain elastic and self-center following excitation. Simplified methods of analysis were used to predict system response. Parametric studies, that used nonlinear time history analyses, were performed to evaluate the design and simplified analysis methods.

In order to further investigate the dynamic rocking response of controlled rocking steel braced frames, an experimental study was conducted using a 5 degree-of-freedom (5DOF) shake table in the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo (UB). A 1/5 length scale specimen, representative of a 4-legged steel braced highway bridge pier was used during testing. The model was subjected to a series of seismic excitations about one of it's primary axes (θ=0deg.), using horizontal and vertical base motions, and rotated 45deg. (θ=45deg.) to investigate behavior that would be expected from bi-directional horizontal base inputs. Triangular steel plates that yield in flexure were used as the passive energy dissipation devices during testing.

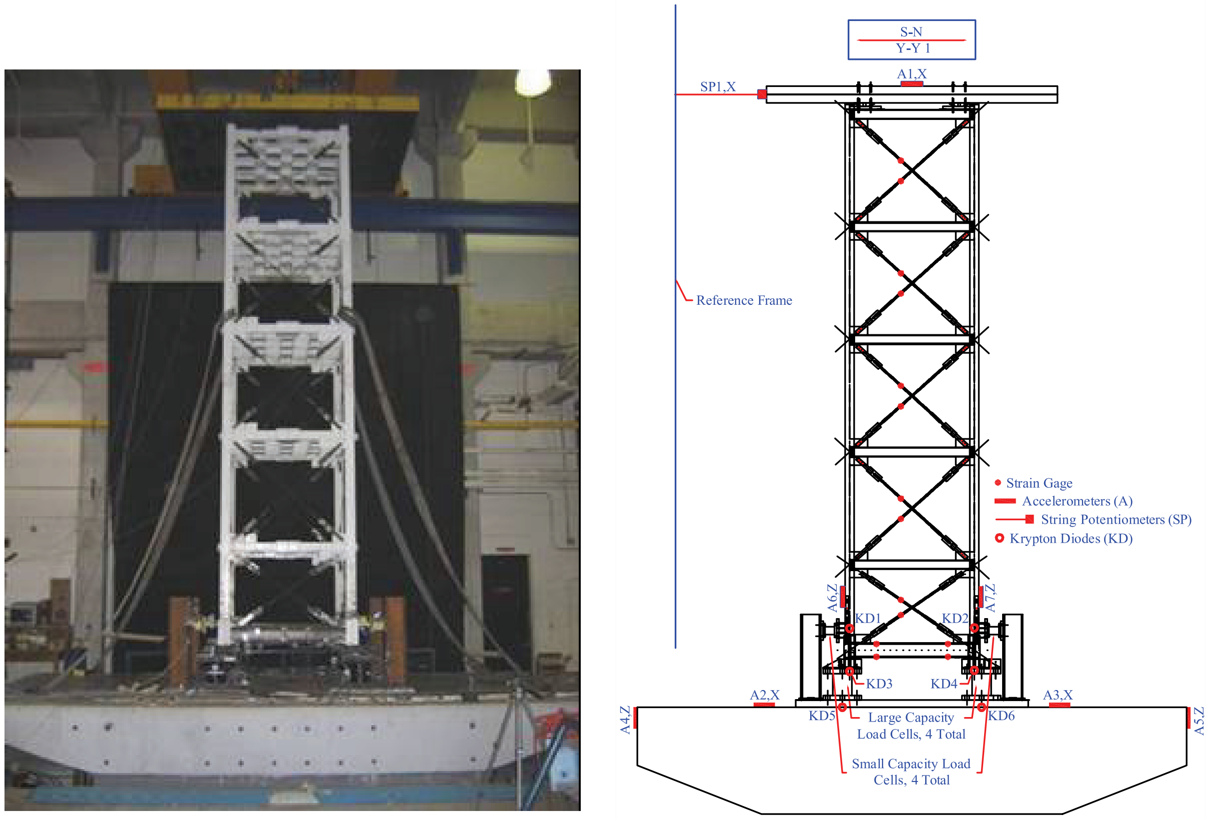
Specimen Properties

It was desired to have the largest scaled model reasonably possible given the available resources in the laboratory (table size, capacity; vertical clearance). Prototype properties are based on a brief review of drawings of existing bridges supported on steel truss piers (Pollino and Bruneau 2004). Model scale was ultimately controlled by the vertical distance from the shake table to a workable crane clearance height (Figure 1). This led to a length scale factor of approximately 5 based on the prototype height of 30.3m. Other scale factors were determined following an artificial mass simulation scaling law.

The primary similitude requirements targeted were the "fixed-base" lateral and vertical periods of vibration of the model (T_{om} and T_{Lm}), the shearing mode period of vibration (T_{vm}), and the applied and restoring forces of the model which are controlled primarily by the added mass. Although an added mass of 69.4kN/g is required by similitude, steel plates totaling 75.2kN/g were used since they were readily available in the laboratory. Connection of the mass to the pier was made through 16-9.5mm fully-tensioned, high-strength threaded rods through the 2-90mm thick steel mass plates, a double concave hardened steel bearing, mild-steel connection plate, and 2-19.1mm plate washers. The connection was designed to transfer shear force in the horizontal plane and vertical forces and moments between the mass and pier.

Modifications were made at the base of the specimen to create the boundary conditions to allow the rocking response. Angles surrounded the base plate of each pier leg that were designed to transfer the horizontal shear forces in bearing however no resistance to vertical uplift was provided through this connection except for friction that may occur along an angle's leg as the pier leg uplifts. The angles were bolted to the top of large load cells that were attached to the shake table.

Steel yielding devices with bi-linear hysteretic behavior were designed with connections to only provide a vertical force to the base of the pier legs. The important design quantities for the devices are the plastic device force (V_p), elastic stiffness (k_e), and maximum allowable vertical displacement. Different steel yielding devices were considered for experimental testing including buckling-restrained braces (AISC 2005) and shear panel devices (Zahrai and Bruneau 1999). However, scaling



(a) **(b)**

Figure 1. Experimental Pier Specimen (a) Picture of Specimen on Shake Table and (b) Instrumentation Layout

both the braces and shear panels resulted in devices that were not easily and reliably manufactured or fabricated. The number of design parameters for TADAS devices (Tsai et al., 1993) resulted in dimensions of a device that could be fabricated at this scale. Devices were designed with local strength ratios (η_L) of 1.0, 0.67, and 0.33 and to undergo a rotation ($\Delta = \Delta_{up}/L_{TADAS}$) of 0.15rad. during testing. The local strength ratio, η_L, is defined as:

$$\eta_L = \frac{V_p}{w/4} \qquad (1)$$

Experimental Facilities and Instrumentation

The experimental testing was performed on the 5-DOF shake table in the SEES Laboratory at UB. The table has a nominal capacity of 20-tons with an acceleration of 1.15g and 2.30 g in the horizontal and vertical directions respectively. The table is driven by 2 horizontal and 4 vertical hydraulic actuators that are programmable with feedback control to simultaneously control displacement, velocity, and acceleration.

The instrumentation used included accelerometers, string potentiometers, 8 strain gauge based load cells, and strain gauges that were attached onto the specimen. A Krypton K600 high performance dynamic mobile coordinate measurement machine that uses 3 cameras and LEDs is used to measure displacements near the base of the structure. The instrumentation layout for the experiments is shown in Figure 1b.

Table Input

The input excitation to the shake table included banded white noise excitation and three seismic ground motion histories. The banded white noise tests were performed to identify elastic dynamic characteristics of the model. The white noise excitation had frequency content in the range of 0-50Hz and had a PGA of approximately 0.05g. The seismic input included ground motions from the 1940 El Centro earthquake (Array #9), 1994 Northridge earthquake (Newhall), and a synthetically generated record. The pseudo-acceleration response spectrums from these three motions, in model scale are shown in Figure 2.

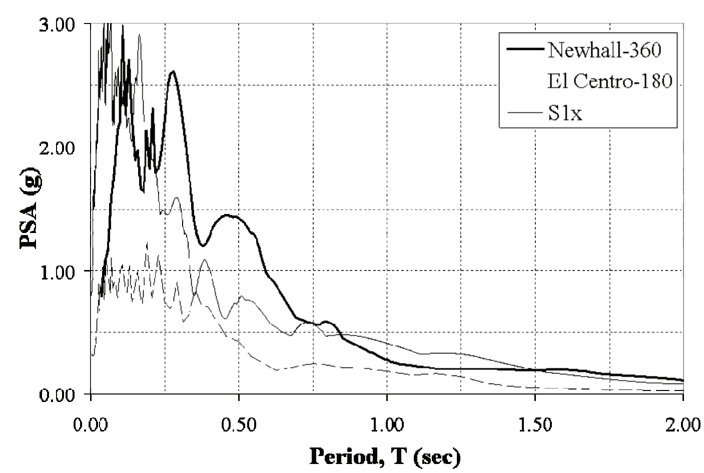


Figure 2. Target Pseudo-Spectral Acceleration Spectra for 3 Seismic Inputs

Experimental Testing Results

A sample set of results are presented in Figure 3 for the case with η_L=0.67, θ=0deg. and subjected to the synthetic record amplitude scaled by 1.5. The pier relative displacement was calculated using the string potentiometers at the top of the pier (total displacement) and the Krypton diodes on the table (table displacement and rotation). The maximum relative displacement was observed to be approximately 100mm however no residual displacement was present at the end of the test. The global hysteretic response of the pier shows the “flag-shaped” behavior and significant fluctuation in the base shear due to the excitation of the vertical “shearing” mode of vibration. Pier leg axial force histories, recorded from large capacity load cells, are shown for the two legs on the South and North end of the specimen. The TADAS hysteretic behavior was recorded from small capacity load cells and relative vertical displacements between Krypton diodes. The device rotation is calculated as the relative vertical deformation across the device divided by the device length. No damage was visually observed within the pier specimen following testing (only inelastic behavior in the ductile "fuses"). Also, white noise testing revealed no change in the specimen's dynamic properties from test to test.

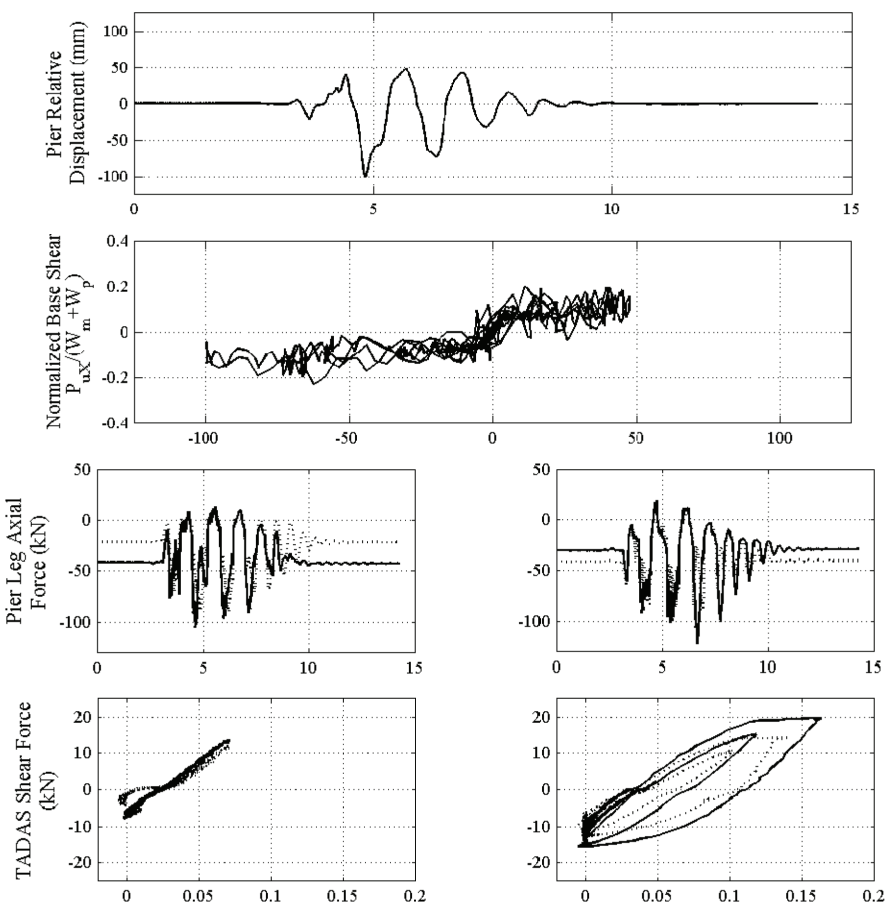


Figure 3. Experimental Testing Results (θ=0deg., η_L=0.67, Syn-150%)

Conclusions

An innovative approach for the seismic resistance of steel braced frame structures that allows uplift and rocking of braced frame structures at the foundation support has been investigated here through dynamic shake table testing. A 1/5 length scale model of a steel braced highway bridge pier was constructed and tested under strong seismic shaking. Experimental results of the controlled rocking model bridge pier demonstrated stable, elastic behavior of the pier while all damage was forced into the easily replaceable ductile structural "fuses". The simplified methods of analysis used for design were shown to provide conservative estimates of response with reasonable accuracy.

Future Research

A second phase of experimental testing is planned for early spring 2007 on one of the 6-DOF shake tables in SEESL. This phase of testing will include bi-directional horizontal input along with vertical excitation and also investigate the use of nonlinear viscous dampers along with steel yielding devices as the passive energy dissipating devices. Further analytical studies are planned to investigate system response of bridges supported on braced steel bride piers that allow controlled rocking of the more slender piers to seismically protect the bridge. Also, finite element analysis will be used to study the issue of dynamic, pulse buckling near the base of pier legs.

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