Bi-directional Loading Hybrid Test of Square Section Steel Piers

Tetsuhiko Aoki and Ji Dang
Aichi Institute of Technology, Japan

ABSTRACT:
Bi-directional loading test are carried out to examine response behavior of square section steel bridge piers under the prescribed ground accelerations in the Design Specification of Road Bridge in Japan. Each of these ground seismic motions has two horizontal components. Both uni-lateral and bi-lateral excitations are imposed to the 2.4m high pier models with the section of 450mm x 450mm. It is found from the test results that the bi-lateral excitation deteriorates the lateral bearing force of the piers compared to the uni-lateral loading.

Keywords: Bi-directional, hybrid test, response behavior, steel bridge piers, square section

1. INTRODUCTION

The elevated highway in the urban area is recognized as one of the most important structures, because it plays a significant roll especially after earthquakes had attacked and urgent rescue becomes to be required. After the Kobe Earthquake, the seismic design specification (Japan Road Association, 2002) in Japan have revised but the present design procedure is such that the one horizontal directional loading is applied in the bridge axis and the perpendicular to it, independently, because it is considered that the possibility of occurring their maximum values at the same time is low. It accounts another reason that there still few test results on the horizontal two directional loading for the bridge piers. However it should be consider such effect on the structures during strong seismic excitation, because actual seismic excitation operates to structures in the horizontal arbitral direction.

The bi-directional loading test for square steel columns is performed by Watanabe et al. (2000) in which the test specimens are relatively small cross section made of the electronic welded and cold formed rectangular steel tube. Nagata et al. (2004) conducted single and bi-directional hybrid test using the same test specimens above mentioned under the Kobe Earthquake acceleration data, JMA, and demonstrated the difference between two loading test results. Though these tests are leading studies but the size of tested specimens is relatively small and the section is rolled without residual stress, differ from the welded section with stiffened plates in the practical structures. Moreover the test conducted under only single sort of seismic acceleration data.

In this study, horizontal bi-directional loading hybrid test is performed using the welded square section steel piers with stiffened plates and the test results are compared with those of the one directional loading test.

2. TEST PROGRAM AND TEST PROCEDURE

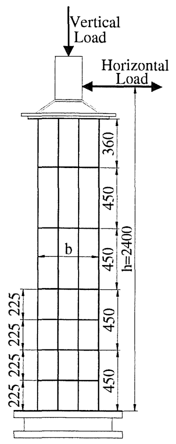
2.1. Test Program

Test pier models are formed from square cross section composed of four stiffened steel plates with two vertical stiffeners. The width of the cross section is 400mm x 400mm and plate thickness is 6mm. The cross section of vertical stiffeners is 6mm x 55mm. The steel grade of the plates is SM490, which nominal yield strength is 325 N/mm^2. The test pier arranges diaphragms at each 450mm along the height h=2.4m, but four diaphragms near the base at each 225mm. The side view and cross section of the test pier is depicted in Fig.1 (a), (b). The width-thickness parameters R_R=0.517 and R_F=0.169 and slenderness parameter λ=0.344 are used for the test specimen.

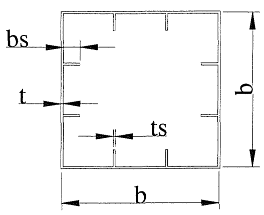
2.2. Experiment System

As the loading system, three 1000kN actuators are set in the horizontal NS and EW directions and in the vertical direction aiming to the loading point O, as shown in Fig. 2, which coincides with Cartesian coordinate X, Y and Z, respectively with the origin O. The special loading support apparatus which can rotate in the three directions at every end of three loading axes is designed as illustrated in Fig. 3.

The measuring system constitutes three load cells located at the end of each of actuators on the same loading axes, and three groups of displacement transducers (DTs). First group DTs are used to measure the horizontal displacement of the loading point O. These DTs are string pull type and arranged in the plane (measure plane) including the loading point O at the pier top, as indicated D1 and D2 in the Fig. 4(a). The end of the string connects to the center of side of square measure plane at point A and B in the Fig. 4(a). The end of string of other DTs named C9 and C10 are connected to the corner of the measure plane to know the rotation angle of the measure plane about the vertical axis Z. Second group of DTs are prepared along with sliding rods set up vertically at four corners of the pier base to measure the angle of the measure plane at the top of the pier, which are illustrated as C5 to C8 in Fig 4(b) as well as third group of DTs named C1 to C4, which determine the rotational angle of the pier base and the named C11 and C12 are used for horizontal shifts.



(a) Side View of Specimen



(b) Cross Section of Specimen

Figure 1. Test specimen

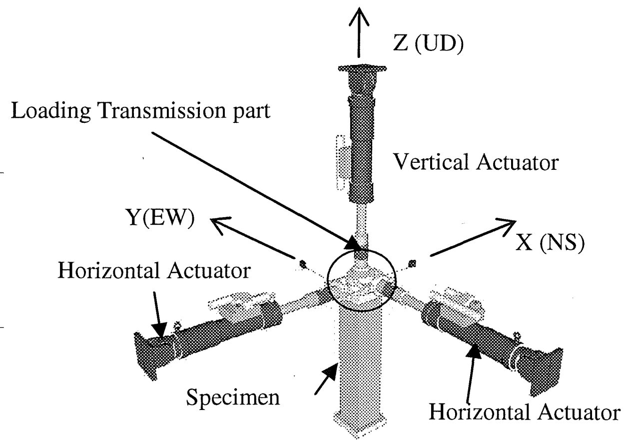


Figure 2. Loading System

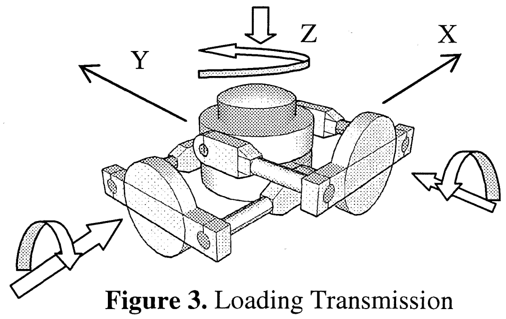
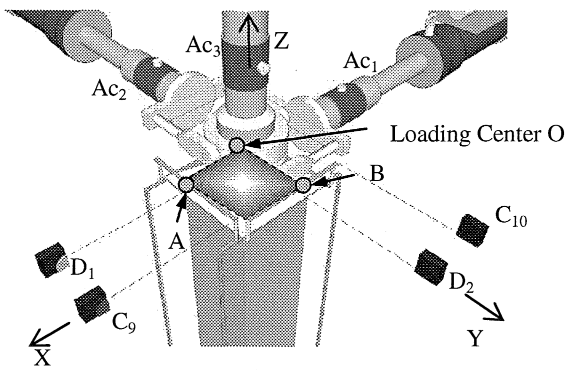


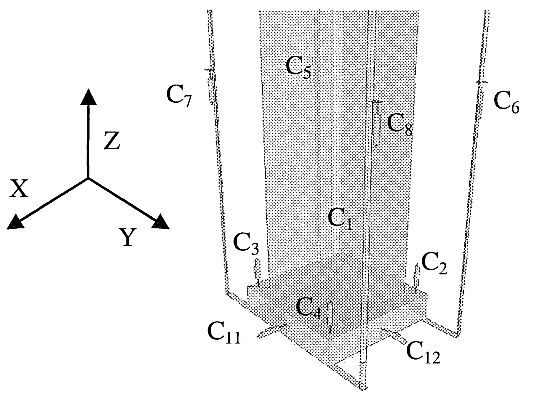
Figure 3. Loading Transmission

2.3. Static Cyclic Loading Test in the Horizontal Single Direction

Prior to the hybrid loading test, the static cyclic loading test in the horizontal single direction was performed using two pier specimens named S1 and S2 to obtain the fundamental properties. For the simple comparison, the constant vertical load of $P/P_y = 0.15$ (P=648kN) is applied to all test piers, where P_y=4322kN is calculated from the nominal cross sectional area (A= 133.0cm^2) of the pier and the nominal yield point of the steel plate (σ_y =325Mpa). The yield displacement δ_0 of the test pier is defined at the time when the measured strain at the bottom of the pier reaches the yield strain obtained from the tensile coupon test. The corresponding load is defined as the yield load H_0.



(a) Top



(b) Base

Figure 4. Settings of Meters

2.4. Hybrid Test in Single and Bi-Directional Loading

The hybrid tests in horizontal single and bi-directional loading are conducted using three earthquake acceleration data corresponding to three different ground levels of one, two and three, which are composed of N-S and E-W components, respectively. The hybrid test system is modeled to the single- and two- degree-of-freedom for the single and for bi-directional loading, respectively, both with single mass at the top of the pier.

2.5.1 Test program

In the hybrid test, dynamic analysis is conducted by computer using the physical properties of actual bridge piers under the actual seismic acceleration data together with the laboratory loading test applying the basic scale factor S is 4. Three seismic data are correspond to the ground hardness level 1(hard), JMA(Japan Meteorological Agency), level 2(medium) , JRT(Japan Railway at Takatori) and level 3 (soft), PKB(Port-island Kobe Bridge), which are prescribed in the Road Bridge Design Specification in Japan. The properties of the actual bridge pier, such as mass m, the initial rigidity k_0, the damping coefficient c and the natural frequency T are determined based on the single directional cyclic loading test as m=1058(t), k_0= 64(kN/mm), T= 0.807(sec) and c=0.823 that calculated from $c = 2h\sqrt{k_0 m}$.

2.4.2 Protocol of the displacement control

The equation for the dynamic analysis of the bi-directional hybrid test is represented as follows.

$$[M]\{a\}_{n+1} + [C]\{v\}_{n+1} + \{R\}_{n+1} = [M]\{a_g\}_{n+1} \tag{2.1}$$

where

$$[M] = \begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix},\ [C] = \begin{bmatrix} c & 0 \\ 0 & c \end{bmatrix},\ \{R\}_{n+1} = \begin{Bmatrix} R_x \\ R_y \end{Bmatrix}_{n+1},\ \{a\}_{n+1} = \begin{Bmatrix} a_x \\ a_y \end{Bmatrix}_{n+1},\ \{v\}_{n+1} = \begin{Bmatrix} v_x \\ v_y \end{Bmatrix}_{n+1},\ \{a_g\}_{n+1} = \begin{Bmatrix} a_{g,x} \\ a_{g,y} \end{Bmatrix}_{n+1}.$$

$\{a\}$ and $\{v\}$ are acceleration and velocity at the gravity center of the mass of the model, respectively and $\{a_g\}$ is seismic acceleration vector. The suffix x and y indicates variable relating to the N-S and E-W direction, respectively. The suffix n and n+1 denotes the value at the time $n \times \Delta t$ and $(n+1) \times \Delta t$, respectively. The time interval Δt =0.01 sec is chosen in this study.

The response displacement, velocity and acceleration are calculated using following well-known Newmark's β method (β=1/6).

$$\{\delta\}_{n+1} = \{\delta\}_n + \{v\}_n \Delta t + \frac{1}{2}\{a\}_n \Delta t^2 + \beta(\{a\}_{n+1} - \{a\}_n)\Delta t^2 \tag{2. 2.a}$$

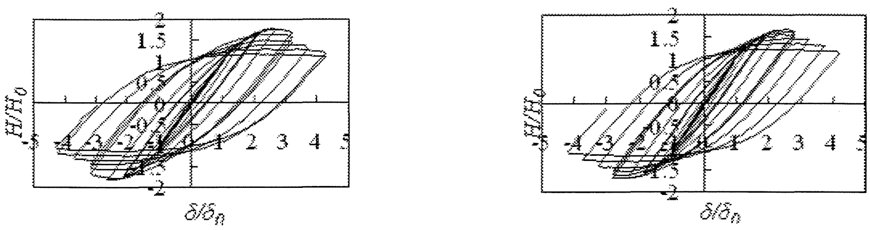
$$\{v\}_{n+1} = \{v\}_n + \frac{1}{2}\{a\}_n \Delta t + \frac{1}{2}\{a\}_{n+1} \Delta t \tag{2.2.b}$$

The bi-directional horizontal forces $\{R\}$ of the pier are obtained by measuring value of loading to the specimen. Introducing $\{R\}$ into Eqn. 2.1, the response displacement, velocity and acceleration at the point O in the time $(n+1)\times\Delta t$ are found using Eqn. 2.2.

3. TEST RESULTS AND CONSIDERATIONS

3.1. Results of the Single Directional Quasi-Static Cyclic Loading Test

The relationship between horizontal load and displacement of the single directional quasi-static cyclic loading test due to the specimen S1 and S2 are represented in Fig. 5(a), (b). The yield load H_0(=233 kN) and the yield displacement δ_0(=15mm) are defined as the average of the test results and are used to non-dimentionalize the load H and displacement δ obtained here and for the hybrid test hereinafter.



(a) Test S1 (b) Test S2

Figure 5. Horizontal Force-Displacement Relationship of Quasi-static Tests

3.2. Hybrid Test Results

3.2.1 Time history of response displacement

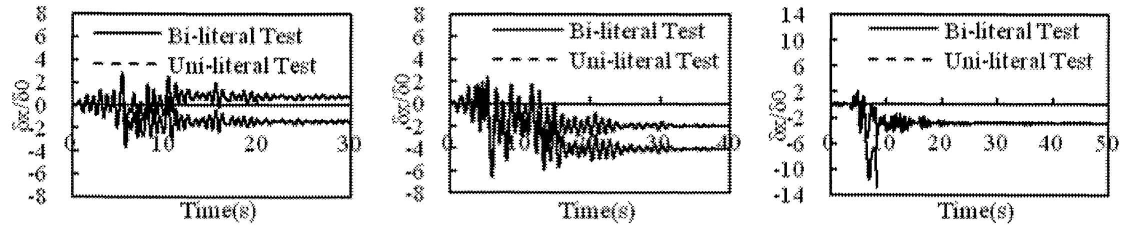
The time history diagrams of response displacement obtained from the hybrid test are illustrated in Fig.6, in which NS and EW direction displacement components calculated from the bi-directional loading test are indicated by solid lines and the results due to the single directional loading are depicted by broken lines. The examinations for each of the classified ground seismic accelerations are demonstrated as follows.

For the case of the acceleration of ground level 1, JMA, it can be seen from Fig. 6(a) for NS direction loading, that the maximum displacement appears in the positive (north) direction for the single and bi-directional loading at first 5.4 second. Soon, the opposite side maximum displacement emerged at 5.7 second. The displacement history between two loading process diverged from around 5.7 sec as shown in the figure. The residual displacement was -1.45 δ_0 for the single directional loading and 0.70 δ_0 for the bi-lateral loading. As seen in Fig. 6(b) for the EW direction loading, almost same behavior were observed at the same time but those magnitude were smaller than that of NS direction. The residual displacement is also small and no difference is recognized between two loading procedures.

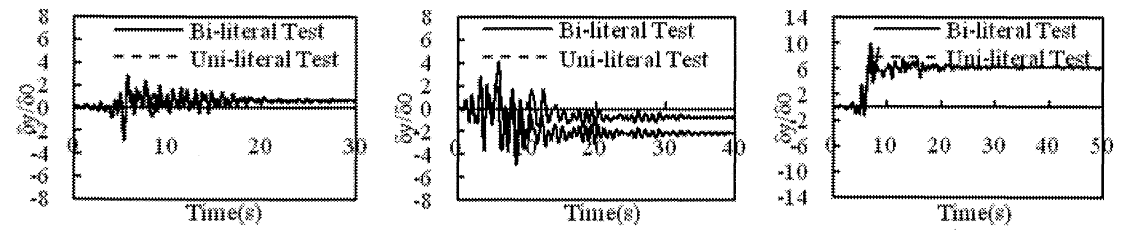
For the case of the ground level 2 acceleration of JRT, as seen in Fig.6(c), the maximum displacement amplitude and the maximum load in the NS direction loading appear at 5.3 to 6.0 seconds for the bi-directional loading test. Then, after 13 seconds, the center of displacement amplitude becomes twice that of the single directional loading, and leads to the residual displacement with -4.1 δ_0. On the other hand, it is observed from the EW component time history as shown in Fig. 6(d), that the single directional loading exhibits the maximum displacement of -4.8 δ_0 at 8.4 second and left the residual displacement of -2.1 δ_0, which is twice that due to the bi-directional loading.

For the case of the ground level 3 acceleration, PKB, Fig. 6(e) shows the displacement history in the NS direction. Whereas the result of the single directional loading indicates the maximum displacement of -5.2 δ_0 at 6.1 seconds and converged with the residual displacement of 3 δ_0, the displacement of the bi-directional loading keeps growing with the short return back on the way and finally leads to collapse. The almost same behavior is observed in the EW direction record.

It can be said from above mentioned considerations that the specific characteristics are not noticeable associated with the maximum displacement and the residual displacement also, between the bi-directional and the single directional loading except for the case of ground level 3 acceleration.



(a) JMA-NS (c) JRT-NS (e) PKB-NS



(b) JMA-EW (d) JRT-EW (f) PKB-EW

Figure 6. Time History of Response Displacement

3.2.2 The horizontal force and displacement hysteretic curve

The horizontal force and displacement hysteretic curves are illustrated in Fig.7, where solid lines indicate the NS and EW components obtained from the bi-directional loading and broken lines indicate the single directional loading. The maximum loads acquired from each loading test are listed in Table 2 to compare between the single and bi-directional loadings. The following is the considerations for the results each ground level acceleration.

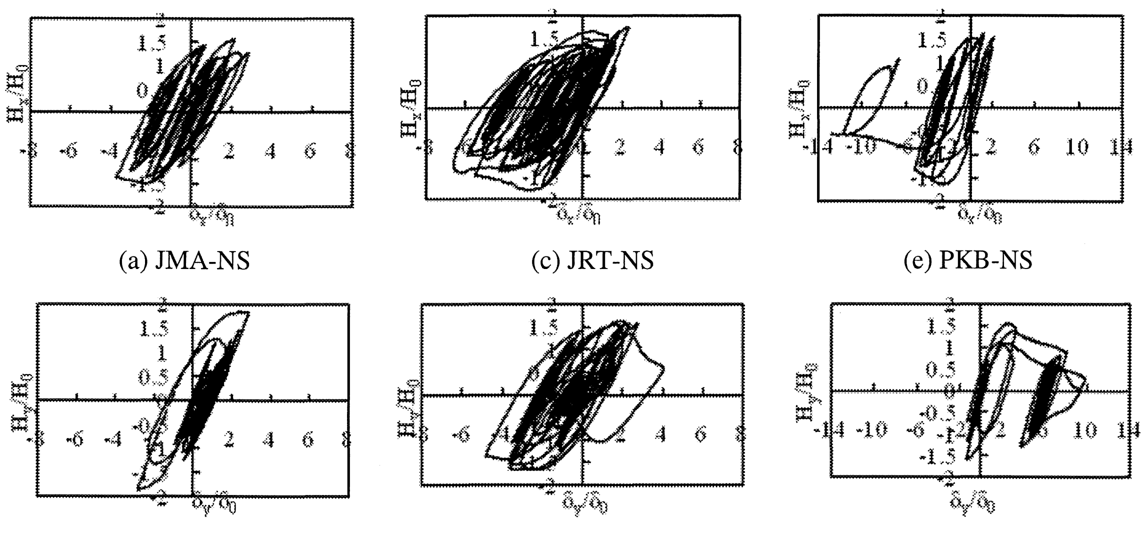
Table 2. The Maximum Load in the Hysteretic Loops of each Loading Test

Ground Level	NS direction (H_{max}/H_0)				EW direction(H_{max}/H_0)			
	Uni-direct	Mu	Bi-direct	Mb (ΔM)	Uni-direct	Mu	Bi-direct	Mb (ΔM)
1	1.56 -1.52	1.54	1.28 -1.42	1.35(-12%)	1.86 -1.85	1.86	1.31 -1.31	1.31(-30%)
2	1.75 -1.80	1.78	1.40 -1.50	1.45(-16%)	1.64 -1.65	1.65	1.56 -1.65	1.61(- 2%)
3	1.60 -1.64	1.62	1.45 -1.27	1.36(-16%)	1.54 -1.58	1.56	1.11 -0.97	1.04(-33%)

Mu, Mb= mean of the maximum load by Uni- and Bi-direction, respectively, ΔM= (Mu-Mb)/Mu

Fig.7 (a), (b) draw the results for the ground level 1 acceleration in NS and EW direction, respectively. The maximum load due to the bi-directional loading deteriorates 12% and 30% lower than that of the single directional loading in the NS and EW directions, respectively. This is considered obviously to be affected by the bi-directional simultaneous loading. It appears in Fig.7 (a) for NS direction loading that relatively large displacement caused just after the peak load on the curve due to the single loading and the center of vibration shifted to the minus direction, whereas the bi-directional loading keeps it near the original position. The positions of maximum loading nearly correspond with the positions of maximum displacement in all hysteretic curves.

Fig.7(c), (d) shows the results for the ground level 2 acceleration, JRT. The maximum loads due to the bi-directional loading fall down 18% and 12% in the NS and EW direction, respectively, than that of the single directional loading. The EW direction load component of bi-directional loading indicates great deterioration after 2 δ/δ_0 as seen in Fig. 7(d), while the load hysteretic curve due to the single loading does not.



(a) JMA-NS (c) JRT-NS (e) PKB-NS

(b) JMA-EW (d) JRT-EW (f) PKB-EW

Figure 7. Hysteretic Relationship

The test results for the ground level 3 acceleration, PKB is illustrated in Fig.7 (e), (f). In the case of bi-directional loading, the E-W direction load reaches the maximum value near at $2\delta/\delta_0$, followed increasing of displacement and then pier had collapsed. However, the response displacement due to the single directional loading remains without fall down. The instantaneous maximum load composed of the NS and EW direction loads of the bi-directional loading represents almost same value as the average of the NS and EW direction loads due to the single directional loading for all ground levels.

The different response behaviors are recognized between the single and bi-directional loading especially in the ground level 3.Two reasons can be explained. One is the difference of characteristics of seismic acceleration among three grounds. Second is that the vibration of ground and the pier come to resonate approaching two major frequencies of the input seismic acceleration and the responding pier that suffers damage and changes its oscillating frequency during excitation.

4. CONCLUSIONS

In this study, the hybrid loading tests are conducted using the square section steel bridge pier models under the single directional loading in the NS and EW direction independently and bi-directional loading. The acceleration data are of three different ground levels specified in the Design Specification of Road Bridge in Japan.

The maximum load due to the bi-directional loading decreases than those of the single directional loading. The instantaneous maximum resultant load composed of the NS and EW direction loads of the bi-directional loading represents almost same value as the average of the NS and EW direction loads due to the single directional loading for all ground levels. The regular tendency is not noticed for the maximum response displacement between two loading procedures for the grand level 1 and 2. However, for ground level 3 which is soft ground among three, the pier under the bi-directional loading resulted in collapse though the tested pier subjected the single directional loading keeps stand until seismic excitation finished.

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