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BI-DIRECTIONAL PSEUDO-DYNAMIC TEST OF CIRCULAR SECTIONAL CFST BRIDGE PIERS

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ABSTRACT

Bi-directional loading test are carried out to examine response behavior of circular sectional CFST bridge piers under the prescribed ground accelerations in the Design Specification of Road Bridge in Japan. Both unilateral and bi-lateral excitations are imposed to the 2.25m high pier models with the cross sectional diameter of 480mm. It is found from the test results that the maximum restoring force of test specimens obtained in bi-directional loading tests was almost the same as that obtained in single-directional loading tests. However, deformation capacity of CFST bridge piers deteriorated considerably when subjected to bi-directional dynamic loadings.

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Bi-directional loading test are carried out to examine response behavior of circular sectional CFST bridge piers under the prescribed ground accelerations in the Design Specification of Road Bridge in Japan. Both unilateral and bi-lateral excitations are imposed to the 2.25m high pier models with the cross sectional diameter of 480mm. It is found from the test results that the maximum restoring force of test specimens obtained in bi-directional loading tests was almost the same as that obtained in single-directional loading tests. However, deformation capacity of CFST bridge piers deteriorated considerably when subjected to bi-directional dynamic loadings.

Introduction

The elevated highway in the urban area is recognized as one of the most important structures for its survival during massive earthquakes plays an important role in post-earthquake rescue [1]. For highway bridge piers, the present seismic design specifications suggest performing static analysis, dynamic analysis, and response verification in longitudinal and transverse directions independently and superimposing the responses in two lateral directions [2]. However, the actual seismic waves consist of three-directional components in orthogonal directions, and the seismic response of the structure is accordingly influenced by more than one-directional seismic excitation. It is difficult to accurately evaluate the seismic performance of actual structures subjected to bi-directional horizontal seismic motions through merely single-directional loading tests.

In recent years, many research efforts focused on investigating basic characteristics of the seismic response of bridge piers through bi-directional cyclic loading tests or pseudo-dynamic loading tests [3-6]. However, for partially concrete-filled steel tube (PCFST) bridge piers, which have been used in earthquake-prone regions in Japan because of their excellent structural performance and properties [7-10], the test data under coupled ground motions in two horizontal directions are insufficient. Therefore, in this study a series of static cyclic tests and single- and bi-directional hybrid loading tests on twelve circular-sectional specimens were conducted. Test results due to bi-directional earthquake excitations were compared with those obtained during single-directional loading tests.

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Test Program

Test Specimen

All PCFST test specimens used in the study are cantilever-type with fixed conditions at the footing and free at the top, similar to common bridge piers. The effective height from the top horizontal loading point to bottom is 2250 mm. All test specimens are made of 6-mm-thick SS400 steel, of which the nominal yield strength is 235 N/mm^2, and the outside diameter of the cross section is 480 mm. A schematic illustration of test specimens is shown in Fig. 1. The radius-thickness parameter R_t = 0.073 and slenderness parameter λ = 0.286 are designed for the test specimen. The values of R_t and λ are both compliant with the seismic design specifications. In this study, the concrete fill height is 0.50 h, which is determined by the recommending formula introduced in the specifications. The uniaxial compressive strength of concrete is 22.0 MPa. The axial load ratio P/P_y= 0.15 is used in the tests, where P_y is the nominal squash load of the steel pier without considering the filled-in concrete.

Test Setup

A three-directional (3D) loading system is adopted in this study, as shown in Fig. 2. Three 1000 kN actuators and a loading support apparatus are used to apply tri-directional loads on top of test specimens. The loading support apparatus included two loading arms and a 3D movable roller. Outer ends of loading arms are rigidly connected to two horizontal direction actuators. Inner ends could move along the roller surface with negligible friction to keep the axes of loading arms always pointing toward the center of the roller. The measuring system consisted of three groups of displacement transducers and three load cells located at the end of the loading axis of each actuator. A complex displacement measuring system is required because displacement of the loading center point cannot be measured directly. The related details of this experimental system can be referred in the literature [6]. Due to the limitation of length, no more tautology will be stated here.

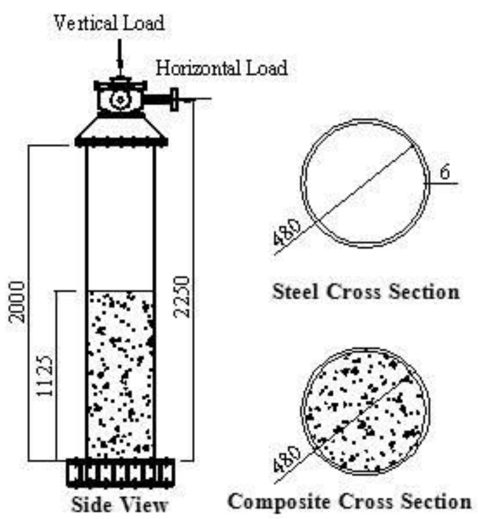

Figure 1. PCFST specimen used in the test (unit: mm).

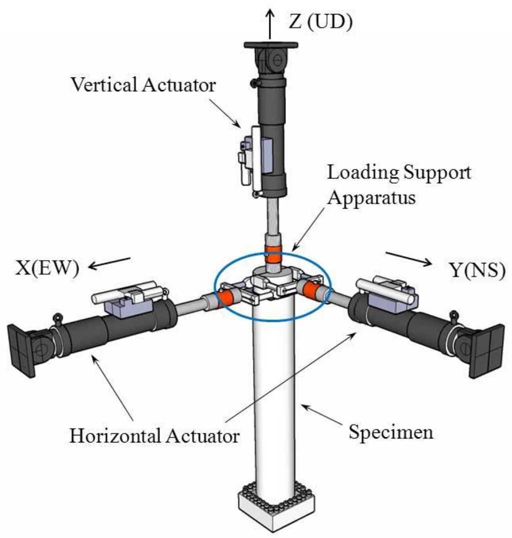

Figure 2. 3D loading system.

Test Results and Considerations

Quasi-Static Cyclic Loading Test

Before the hybrid loading test, the static cyclic loading test in a single horizontal direction was performed to obtain common fundamental properties of specimen S-50 partially filled with concrete. 'S' indicates static cyclic loading, and the following number denotes the height ratio of the concrete fill. Cyclic loading patterns consist of a sequence of complete cyclic displacements such as $0.5\delta_0$, $1.0\delta_0$ (three cycles), $1.5\delta_0$, and $2.0\delta_0$ (three cycles) until collapse. The displacement increment δ_0 (=8.46 mm) is the yield displacement of the S-00 steel pier without concrete fill. The corresponding load is defined as the yield load H_0 (=85.6 kN).

Hysteresis curves of cyclic loading test are shown in Fig. 3, in which horizontal displacement and load are non-dimensionalized by the yield values δ_0 and H_0, respectively. It can be observed from the figure that in comparison with specimen S-00 without concrete, the maximum load increased by 25% in specimens S-50 with concrete fill height of 0.50*h*. The displacement at the 95% of the maximum load on the post-peak curve increased more than that of the specimen S-00 by approximately 44%. The above comparisons show that the seismic behavior of PCFST bridge piers under single-directional loading can be effectively improved if the concrete fill height is significantly increased.

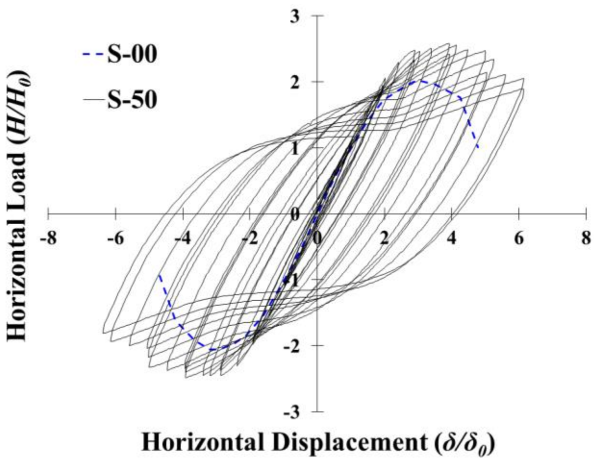

Figure 3. Hysteresis curves for static cyclic loading tests.

Pseudo-Dynamic Loading Test

Input Parameters in Pseudo-Dynamic Loading Test

In the pseudo-dynamic loading test, the structural displacements caused by the earthquake are calculated by computers using a stepwise integration procedure and applied quasi-statically to the test specimen. The resulting restoring forces of test specimen are measured and fed back to the analysis model as part of the input for the next calculation step. The test specimens were scaled according to actual bridge piers with a length scale factor S of 4. The properties of the actual bridge piers, such as mass m = 514 t, the initial rigidity k_0 = 61.3 kN/mm, the damping coefficient c = 0.562 kN·s/mm and the natural frequency T = 0.576 s are determined based on the static cyclic loading test. Two types of design ground motions from the 1995 Kobe earthquake were used, which are JRT for Ground Type 2 (GT2) and PKB for Ground Type 3 (GT3), respectively, as shown in Fig. 4.

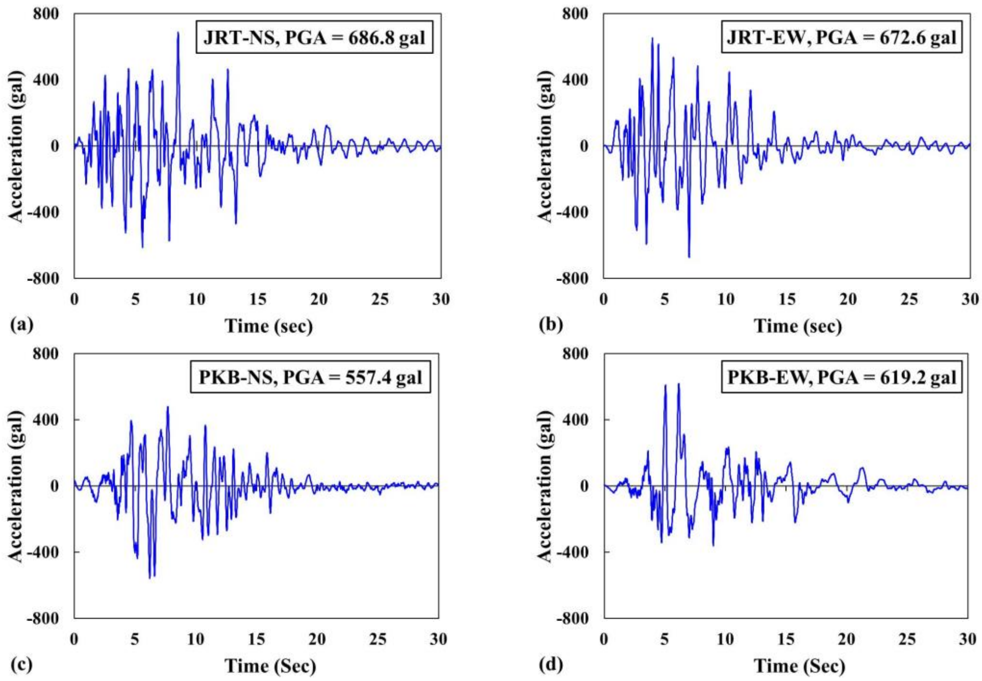

Figure 4. Input earthquake components used for hybrid loading test.

Time History of Displacement Response

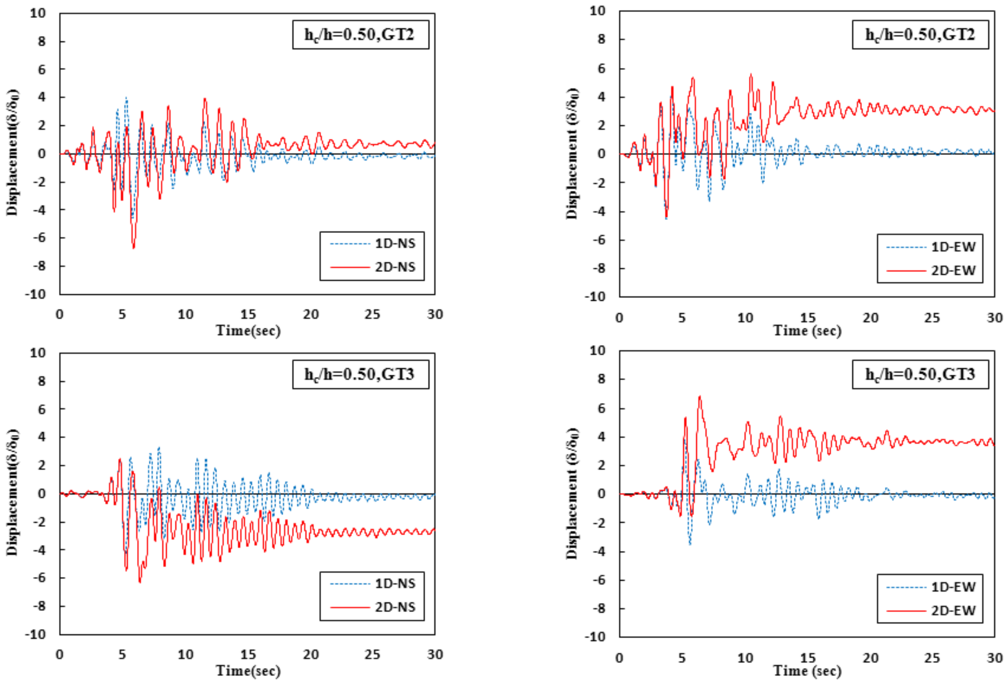

Figure 5. Displacement response of test specimens.

The time history diagrams of displacement response obtained from the pseudo-dynamic loading test are illustrated in Fig. 5, in which NS and EW directional displacement components obtained from the bi-directional loading test are indicated by red solid lines and the results due to the single directional loading are depicted by blue broken lines.

It can be clearly observed in Fig. 5 that maximum and residual displacements due to bi-directional loading are generally greater than those due to single-directional loading. For the GT2 case, the maximum displacement in NS and EW directions obtained from bi-directional loading are 1.47 and 1.22 times of the maximum displacement values from single-directional loading, respectively. For GT3, the corresponding maximum displacement increasing ratios of bi-directional loading to single-directional loading are 1.45 and 1.80, respectively. It can also be found in Fig. 5 that the residual displacements after single-directional loading are small. However, the specimens subjected to bi-directional loading present much greater residual displacement values than the limit value in the seismic design code.

Hysteresis Curves

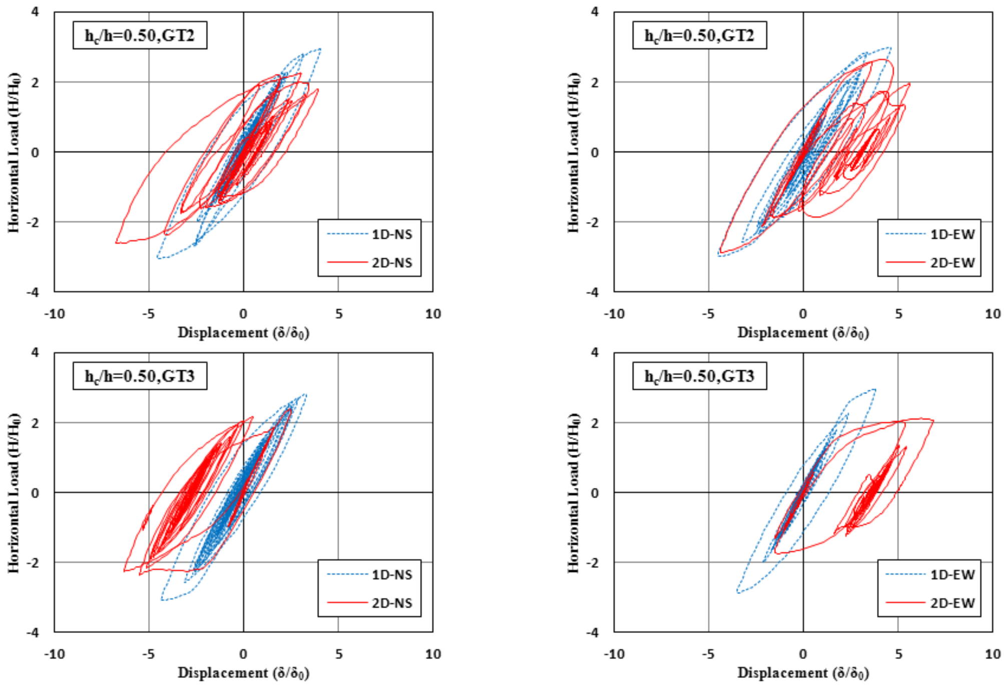

Figure 6. Hysteresis curves of test specimens.

Hysteresis curves for single-directional and bidirectional loading tests are shown as broken and solid lines in Fig. 6, respectively, in which plots in rows 1 and 2 correspond to test results for piers in GT2 and GT3, respectively. As deduced from Fig. 6, in comparison with results of single-directional loading tests, the specimens of bi-directional loading tests present a considerable degree of degradation in load resistance, accompanied with an increase in displacement. Average attenuation values were approximately 9% and 26% for GT2 and GT3, respectively. Degradation of restoring force may be due to local buckling deformation and accelerated by bi-directional loading. Once local buckling occurred, plates did not completely straighten back during reversed loading, and buckling deformation progressively increased. Then, the lateral resistance of the specimen gradually decreased.

Cumulative Energy Absorption

Cumulative energy absorptions of test specimens for GT2 and GT3 due to single-directional and bi-directional pseudo-dynamic loadings are shown in Fig. 7. It can be observed that the largest difference is obtained among the ground motion types and the cumulative energy absorption due to bi-directional loading tests is generally larger than those due to single-directional loading tests. It can be found in Fig. 7 that, in the case of EW directional component of GT2, the specimen absorbed 50% of all the energy from 3.0 to 4.2 second and reached its peak around 12 second, while in the NS direction the specimen finished its 70% energy 2.5 seconds later than that of EW direction. Then slowly absorbed energy and the peak appeared until 15 second. For the cases of GT3, the specimen finished its 90% energy absorption value of EW directional component from 5.0 to 6.3 second, while in the NS direction it takes much more time to reach the peak.

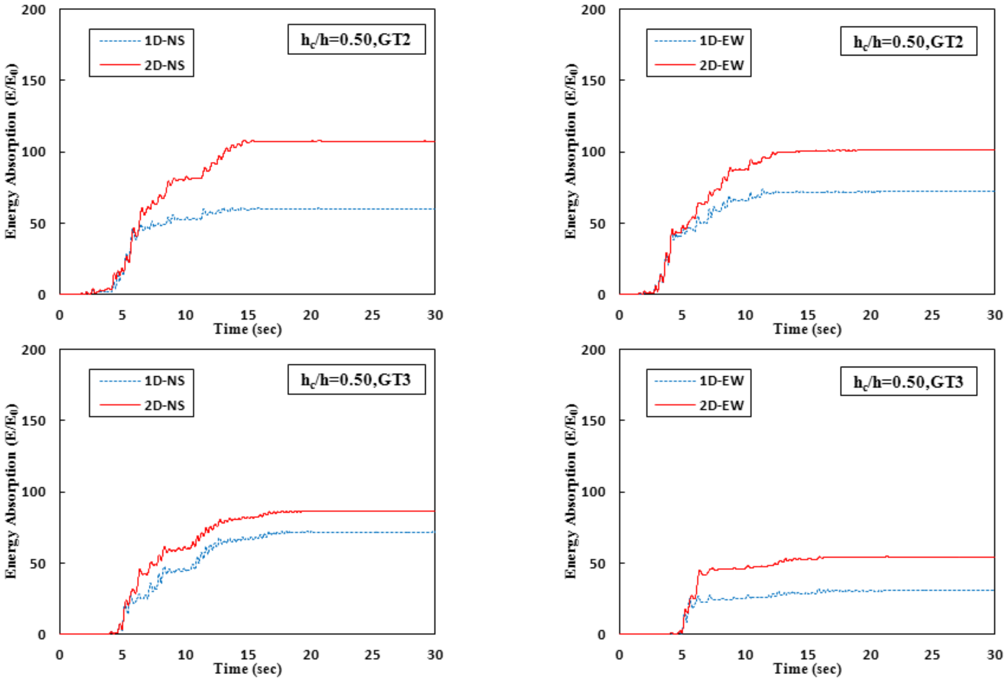

Figure 6. Hysteresis curves of test specimens.

Conclusions

In this study, the pseudo-dynamic loading tests were conducted using the circular section PCFST bridge pier models under the single directional loading in the NS and EW direction independently and bi-directional loading. The acceleration data of two different ground levels specified in the Design Specification of Road Bridge in Japan were used in the tests.

The maximum horizontal load components caused by bi-directional loading were approximately 9%~26% lower on an average than those of the single-directional loading tests. Differences in displacement response between single- and bi-directional loading tests were clearly observed. Maximum displacement due to bi-directional loading for GT2 and GT3 was much larger than that due to single-directional loading. The residual displacement of tested piers showed similarities in maximum displacement. However, the difference between single-directional and bi-directional loadings was significantly increased.

For the cumulative energy absorption, the largest difference appeared among the three ground types, and the cumulative energy absorption caused by the bi-directional loading is generally larger than that due to single- directional loading.

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