INTERNATIONAL DISTRIBUTED HYBRID SIMULATION OF 2-SPAN CONTINUOUS BRIDGE

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ABSTRACT :

To evaluate a seismic response of bridge systems, it is important to adopt the most appropriate model for each component. In this study, the seismic response of a bridge with a C-bent and a single RC pier and a steel pier is evaluated. Whereas the single RC pier is modeled by the fiber model, the C-bent RC and the steel pier are modeled by the hybrid experimental models because any numerical models cannot take into account their strong nonlinear behavior. OpenSees and OpenFresco are used to conduct the international hybrid simulation. As the results of the international hybrid simulation between Kyoto Univ. and UC Berkeley, the nonlinear seismic response of the bridge system can be obtained and the distributed hybrid simulation is found to be a powerful tool for the evaluation of structural systems.

KEYWORDS: Hybrid simulation, Bridge system, C-bent RC column, Strong nonlinear response

1. INTRODUCTION

C-bent columns are usually constructed in an urban expressway because available space is very limited in urban area. Not only eccentric vertical load but also the coupling of flexural, shear and torsion deformation applies C-bent columns. Therefore the residual deformation tends to accumulate in the eccentric side (Kawashima et al. 2003). Since a bridge consists of multiple piers, girders and bearings, the behavior of one component has an interaction to others and it is important to evaluate the seismic performance of the bridge as the system, including multiple piers. For the simulation, it is important to adopt the most appropriate model for each component. Hybrid simulation was developed to take into account the seismic behavior of a structure, including components that are difficult to model numerically. Recently a distributed hybrid simulation method has been very actively developed, and this hybrid simulation is now one realistic option to evaluate the whole structural systems.

2. PROTOTYPE BRIDGE SYSTEM AND NUMERICAL SIMULATION

2.1. Bridge Structure

The bridge system in this study is a two-span continuous bridge (Figure 1). It consists of a RC single pier (P1), RC C-bent pier (P2) and steel single pier (P3). The height of these piers is 10 m. The girder of 60 m is supported by elastomeric bearings.

2.2. Numerical Model

The objective of this study is to evaluate the seismic behavior of the bridge system in the longitudinal direction. Although the input earthquake motion is inputted in the longitudinal direction, a 3-dimensional model has to be used because P2 is the C-bent type. In this study, the piers and the girder are modeled by line-type models and the bearings are modeled by springs (Figure 2). The beam of the C-bent pier is modeled by a rigid beam. When the girder responds due to the earthquake, P1 and P3 deforms flexural in the longitudinal direction. Therefore P1 can be modeled by a fiber model, and P3 can be modeled by a spring model with steel material model. P2 deforms not only but also torsional, but since there is no appropriate numerical model for the coupling of flexural and torsional behavior of RC columns, the fiber model is used for the flexural deformation and the 3D beam model with a linear torsional rigidity is used for the torsional deformation independently.

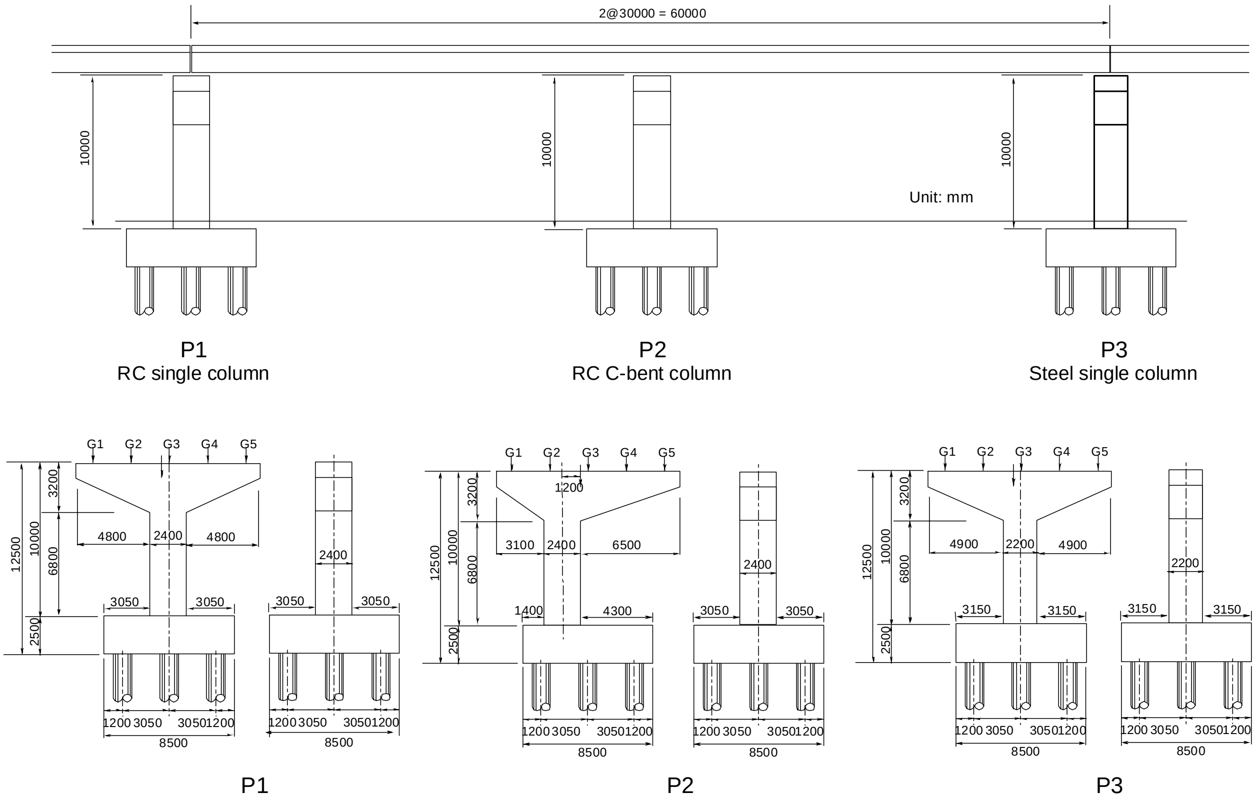


Figure 1 Bridge system

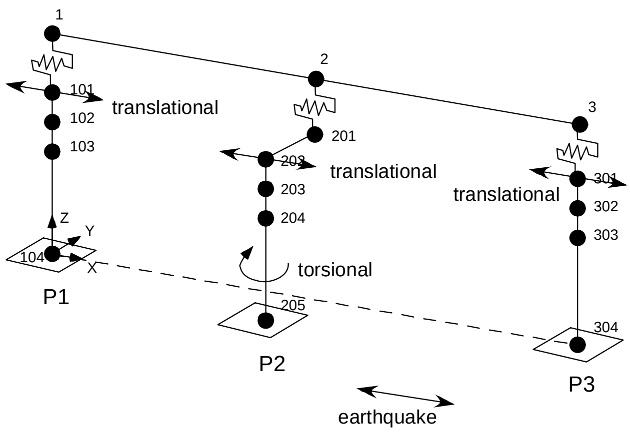
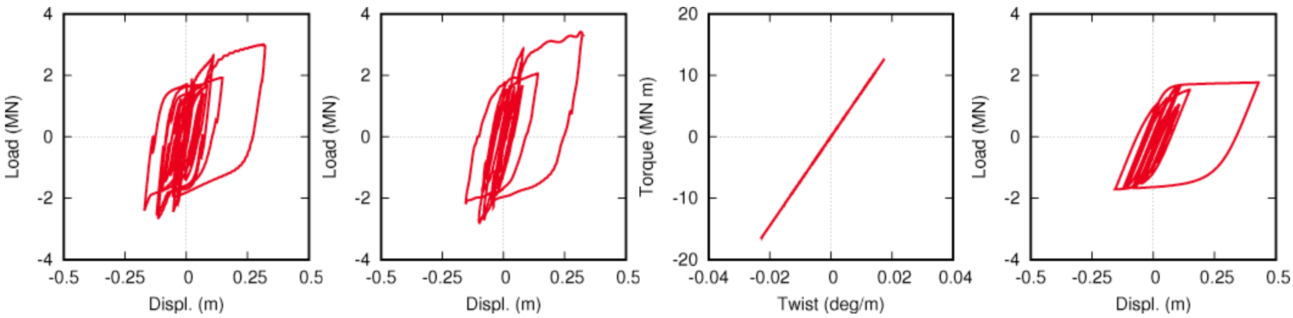
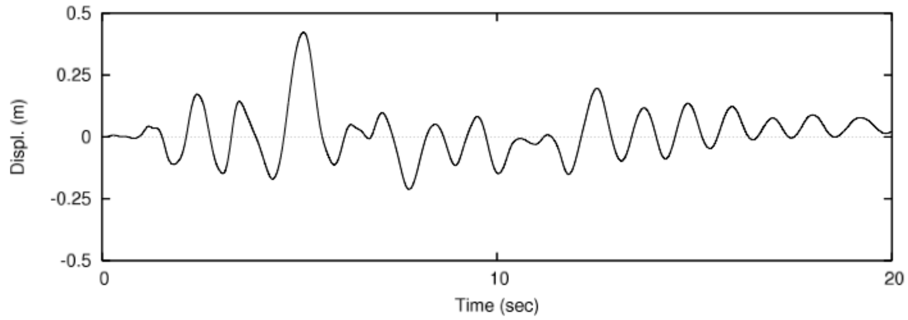


Figure 2 Analytical model

A seismic response analysis of Figure 2 was carried out. 80% JR Takatori records (NS), Kobe Earthquake 1995, are inputted in the longitudinal direction of the bridge systems. Rayleigh damping of 5% is used and the equation of motion is solved by the alpha-OS method. In this analysis, OpenSees (Open System for Earthquake Engineering Simulation) is used. The hysteresis loops of the piers and the displacement response of the girder are shown in Figure 3. The hysteresis of P2 shows the Since the flexural and torsional behavior of P2 is uncoupled, much more appropriate model for P2 is needed to evaluate the bridge system.



(a) P1 (b-1) P2 (flexural) (b-3) P2 (torsional) (c) P3



(d) Displacement response of the girder

Figure 3 Results of numerical simulation

3. CYCLIC LOADING TEST OF C-BENT RC COLUMN

3.1.Test unit and loading system

To evaluate how strongly coupled between the flexural and the torsional behavior of the C-bent RC column of the prototype bridge, a cyclic loading test are conducted.

A test unit is 1/7.5 scaled model and has a square cross-section of 320mm and a height of 1255mm. Figure 4 shows the bar arrangement. Deformed longitudinal bars with a 10 mm diameter (D10) are provided int double at the eccentric tension side in the column. In this test, the eccentric compression and tension sides are called as N and S sides (Figure 5). The spacing of the stirrup is 40 mm. The maximum size of the aggregate of concrete is 15 mm.

The loading system is shown in Figure 5. The steel cap is attached at the top of the column and the vertical load and the horizontal deformation are applied at 400 mm and 750 mm from the center of section, respectively. The vertical load is 90 kN. These actuators are controlled by Shimadzu digital controllers.

3.2. Test Results

Test results are shown in Figure 5. In this section, the value of the result is expressed by the prototype scale considering the similitude. Figure 5(a) is the load-displacement hysteresis loop from the horizontal actuator. Since the displacement transducers are attached to measure the rotation of the section, the hysteresis loop can be divided into the flexural and torsional modes (Figure 5(b) and 5(c), respectively). Whereas the flexural mode shows a large hysteretic damping, the torsional model shows a inversed S shape and a small damping. Furthermore the strong coupling between the flexural and torsional behaviors of this pier can be recognized. According to the crack pattern of the column, torsional cracks are distributed along the height but the angle of the cracks change into horizontal at the bottom. It means that the flexural and the torsional behaviors are strongly coupled especially at the bottom.

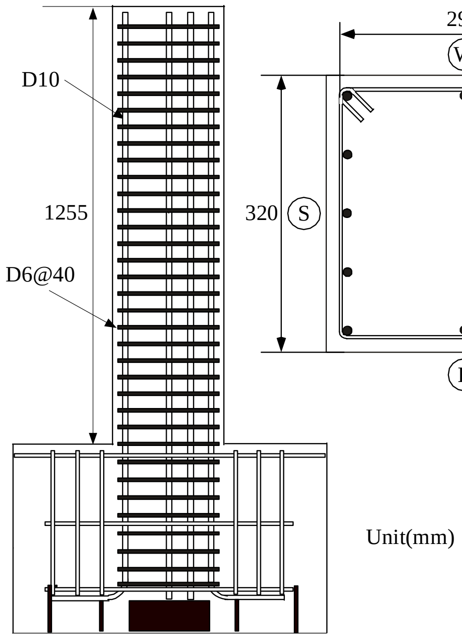


Figure 4 Test unit

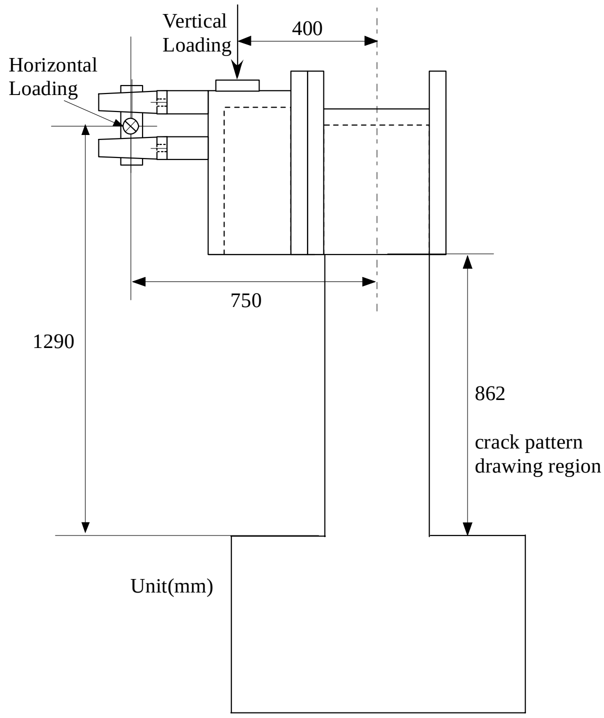
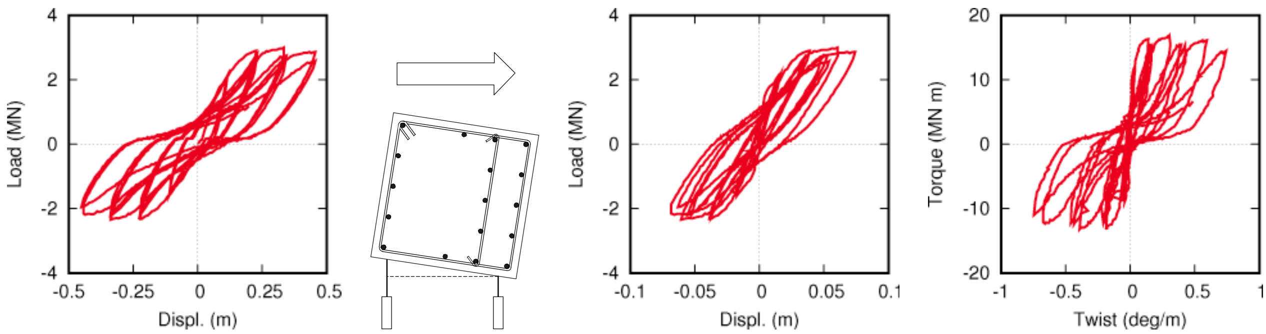


Figure 5 Loading system (view from E side)



(a) Actuator response (b) Flexural mode (c) torsional mode

Figure 6 Hysteresis loops of test unit

4. FRAMEWORK FOR DISTRIBUTED HYBRID SIMULATION

4.1. Distributed Hybrid Simulation System

Hybrid simulation provides a versatile, realistic and cost-effective method for simulating the seismic response of structural systems experimentally. A hybrid simulation is a combination of physical simulation of a specimen in a laboratory, using standard servo-controlled actuators, with computational simulation of the system to provide information about performance due to earthquake ground motion. The hybrid simulation is very powerful system but since it need to control experimental equipments, very simple analytical models were used in the previous studies. The conventional hybrid systems cannot collaborate the existing powerful numerical analysis and cannot control multiple experimental equipments. The more flexible software for the hybrid simulation had been requested.

4.2. OpenFresco

The Open Framework for Experimental Setup and Control (OpenFresco) is a software system for hybrid simulation of structural systems. For the earthquake engineering user, OpenFresco is a practical and easy to use software package that allows a wide variety of hybrid simulation algorithms, laboratory and control systems, experimental setups, and computational simulation models to be combined for a specific hybrid simulation. For the researcher or developer interested in new hybrid simulation methods, the architecture of OpenFresco provides a great deal of flexibility, extensibility, and re-usability through an object-oriented software framework. The design, implementation, and proof-of-concept of OpenFresco was described in Takahashi and Fenves 2006. Schellenberg and Mahin 2006 provided a complete summary of the progress using OpenFresco for a range of hybrid simulation applications.

An important aspect of OpenFresco is that the finite element software uses a general form of an element, termed the Generic-Client Element. The user does not have to create an experimental element in the finite element software when the Generic-Client Element is used. The Generic-Client Element can be easily implemented into any finite element software that allows user-defined elements. This feature allows OpenFresco to be used with a wide variety of computational software packages, such as LS-DYNA® or ABAQUS®. For developers and advanced users, experimental elements can be created for more sophisticated applications, but for most users interested in hybrid simulation, the Generic-Client Element should be sufficient.

OpenFresco v 2.5 can be downloaded from OpenFresco web site at NEESit repository (OpenFresco2008)

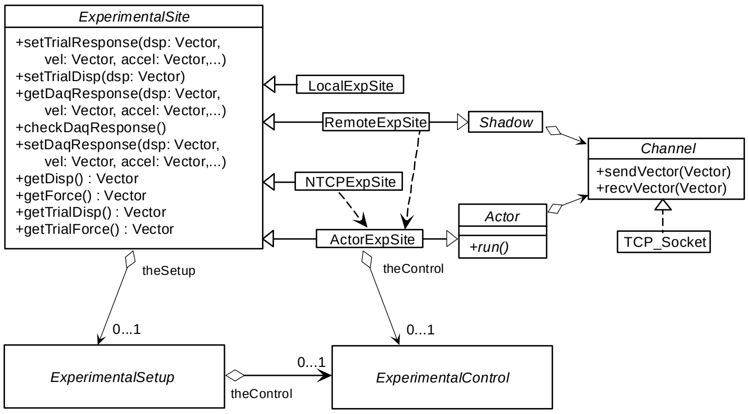


Figure 7 Class diagram of OpenFresco

5. DISTRIBUTED HYBRID SIMULATION OF BRIDGE SYSTEM

5.1. Hybrid Modeling

Since P1 is expected to be flexural during earthquake, the fiber model with stress-strain relationships of concrete and steel bar is adopted. Since P2 is expected to behave complicatedly, the hybrid experimental model is adopted. The coupling of flexural and torsional deformation automatically satisfies the deformation of the experimental C-bent RC column test unit. P3 can be modeled by the spring model, but it is also modeled by the hybrid experimental model to take into account the bucking and/or breakage of the steel pier. The C-bent RC test unit of P2 was tested at Kyoto University, Japan, and the steel single test unit was tested at nees@berkeley, USA. The other components are modeled as linear system.

80% and 100% JR Takatori records (NS), Kobe Earthquake 1995, are inputted in the longitudinal direction of the bridge systems. The analytical time interval is set to 0.01 sec and the equation of motion is solved by the alpha-OS method.

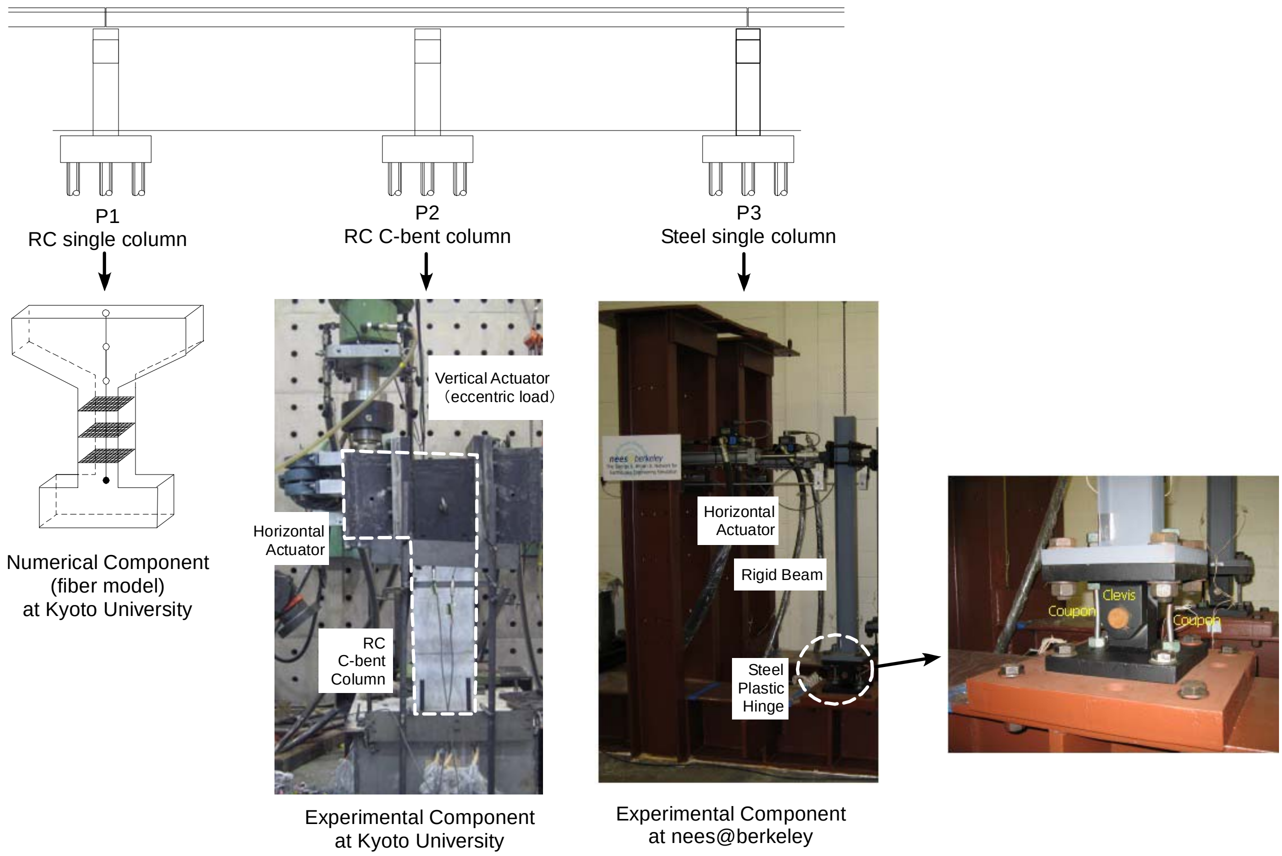


Figure 8 Hybrid model of the prototype bridge

5.2. Simulation System

5.2.1 Test units

A C-bent RC column at Kyoto University is the same in Section 3. A steel column at nees@berkeley consists of a replaceable nonlinear steel plastic hinge with a rigid column.

5.2.2 Hardware

Since the same loading system can be used in a pseudodynamic test, almost components in the loading system at Kyoto University are the same in Section 3. The experimental server is added to the loading system for the communication between a computational client and generate analog signal to the control system. One actuator is used at nees@berkeley for loading of the deformation and controlled by digital signal from xPC target system.

5.2.3 Software

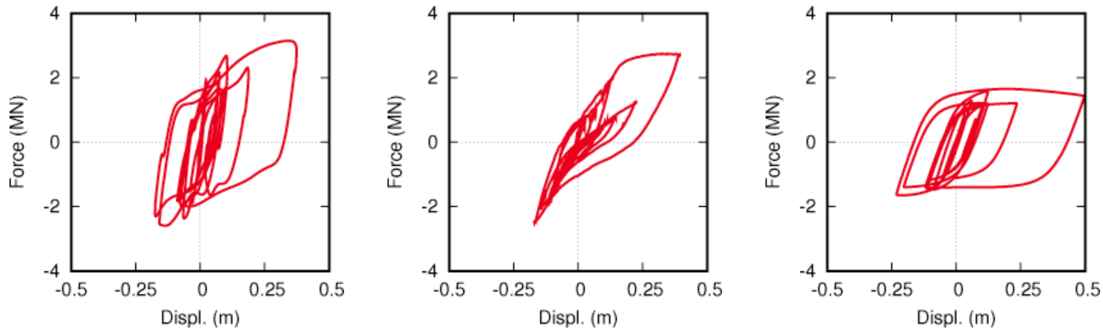
OpenFresco is used for managing the distributed hybrid simulation. TCP/IP network is used for communication between Kyoto University and nees@berkeley. Open System for Earthquake Engineering System (OpenSees) is adopted as the numerical program. OpenSees is an object-oriented framework for numerical seismic analysis (Fenves et al. 2004) and developed at the Pacific Earthquake Engineering Research Center, USA. OpenSees is adopted as the numerical program of NEES (Network for Earthquake Engineering Simulation), USA and now widely used worldwide.

5.3. Results of Hybrid Simulation

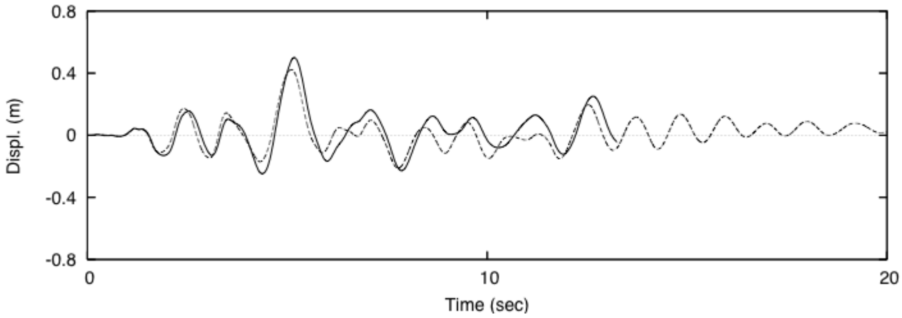
The load-deformation hysteresis loops of piers and the displacement response of the girder in case of 80% input are shown in Figure 9. The analytical condition is the same as the numerical simulation in Section 2. Torsional cracks were observed in the RC test unit and the hysteresis loop of P2 show narrow inverted-S shape because of the coupling of flexural and torsional deformation. Although P3 shows relatively large nonlinearity, it behave stable. The dotted line in the Figure 9(d) is the response by the numerical analysis shown in Figure 3(d). Since the energy dissipation by P2 in the hybrid simulation is smaller than that in the numerical simulation, the maximum displacement of the girder in the hybrid simulation becomes larger.

Following 80% input test, 100% input test was conducted (Figure 10). Since P2 had been already damaged by 80% input test, the hysteresis loop shows much narrower than before. And also the plastic hinge of P3 broke and the hysteresis loop changed into the small loop. Even in such a strong nonlinear case, the distributed hybrid test can be conducted stable.

In these tests, the time for solving the equation, communication between USA and Japan, controlling the test setups and measuring data during the analytical time step 0.01 sec. could be completed within 1.0 sec. As the results, the 20-second simulation could be 30-minute hybrid simulation. This test speed is almost the same as the conventional hybrid test at local test facility.



(a) P1 (b) P2 (c) P3



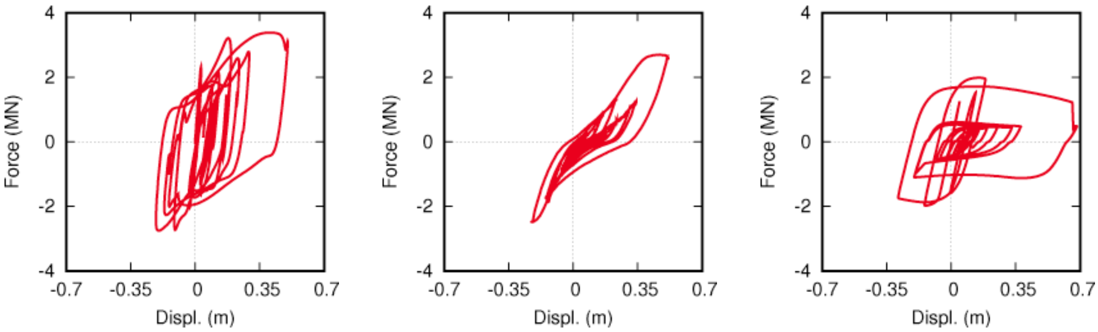
(d) Displacement of the girder

Figure 9 Results of hybrid simulation (80% JR Takatori record)

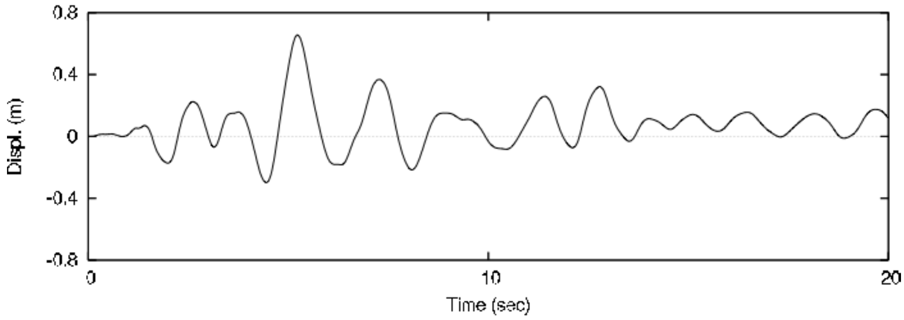
6. CONCLUSIONS

In this study, the seismic response of two span continuous bridge with C-bent column are examined by distributed hybrid simulation. It can be concluded as follows:

1 The hybrid simulation with OpenFresco and OpenSees can simulate the complicated structural system with the most appropriate model. In this study, the RC single column was modeled by the fiber model and the RC C-bent and the steel single column are modeled by the hybrid experimental models. As the results, the coupling of flexural and torsional behavior of the C-bent pier and the breakage of the Steel columns can be evaluated.



(a) P1 (b) P2 (c) P3



(d) Displacement of the girder

Figure 10 Results of hybrid simulation (100% JR Takatori record)

2 Since this framework is very stable even in these strong nonlinear cases, the distributed hybrid simulation is found to be a powerful tool for the evaluation of structural systems.

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