Bridge Seismic Response Experiment Program using E-Defense

by

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ABSTRACT

This paper introduces a large scale shake table experimental program on bridge structures using E-Defense. The bridge program was formulated by Japan and US researchers as one of the US-Japan cooperative research program based on NEES and E-Defense collaboration. Component model (C1 model) and system model (C2 model) are included in the program. Objectives of C1 model is to clarify the failure mechanism of reinforced concrete bridge piers using as large models as possible to eliminate barriers of scale and loading rate effect. C2 model is to study the complex system behavior of bridges to failure. Background, objectives, proposed models and tests cases are briefly introduced.

KEYWORDS: Seismic design, Seismic retrofit, Bridges, US-Japan cooperative research, E-Defense, NEES

1. INTRODUCTION

E-Defense is the world largest shake table of National Research Institute for Earth Science and Disaster Prevention (NIED), Japan [1]. The table is 20 m long and 15 wide with the maximum payload of 1,200 tf. Peak acceleration, velocity and displacement which can be excited by E-Defense under full load are 0.9 g, 2 m/s, +/- 1 m, respectively, in the two lateral directions, and 1.5 g, 0.7 m/s and +/- 0.5 m in the vertical direction.

It was built to advance the scientific knowledge in earthquake engineering as a consequence of the extensive damage of urban infrastructures in the 1995 Kobe, Japan earthquake. “why did structures suffer such extensive damage during the Kobe earthquake?,” “what were the mechanism of failure?,” and “what extend do structures fail under near-field ground motions?” are the basic motivations of constriction of E-Defense.

A large scale shake table test on bridge structures was identified as one of the high priority research areas using E-Defense. A large scale bridge experimental program as well as two other programs (steel buildings and information technology) was initiated in 2005 as one of the US-Japan cooperative research programs based on NEES and E-Defense collaboration. The project is coordinated by US-Japan Joint Technical Coordinating Committee.

Since E-Defense was built for clarifying the extensive damage of structures during the 1995 Kobe earthquake, breakthrough experiments which are significantly important as a benchmark test for clarifying the failure mechanism and/or enhancing the seismic performance of structures are expected.

2. FORMULATION OF EXPERIMENTAL PROGRAM

Program on large-scale shake table test on bridge structures was formulated based on discussions among Japan and US researchers. It was extremely valuable to formulate the program from conceptual stage of the project based on discussion. Outline of the past discussion is briefly presented in the following.

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The 1st planning meeting was held in April 2004 in Shin-Kobe with participation of nearly 50 researchers from Japan and US. Through discussion on research needs in earthquake engineering, it was agreed that high priority of mutual interest to Japan and US researchers included bridge structures, steel buildings and information technology [1, 3]. Both bridges and buildings were seriously damaged during the Loma Prieta, Northridge and Kobe earthquakes, and considerable research based on component testing was conducted following these earthquakes to develop new design recommendations. It was thought highly profitable for both Japan and US to assess system level behavior of structures designed using these new recommendations, and to explore the seismic performance of similar structural systems that were not yet researched [3].

Research needs of bridge structures included progressive failure, soil foundation structure interaction, liquefaction-induced lateral displacement and forces, retrofit strategies and measures, protective systems and responses to spatially varying ground motions.

The 2nd and 3rd planning meetings were held in Arlington in July 2004 and Miki in January 2005, respectively. Besides discussion on the general framework of the NEES and E-Defense collaboration and budget, research needs for bridge structures were discussed.

An extremely important occasion to research community on bridges was two day US-Japan Workshop on Large-scale Testing on the Seismic Performance of Bridges in February, 2005 in San Francisco. Twelve Japanese and seventeen US researchers attended the workshop as shown in Fig. 1. Discussion was directed to research plan and scheduling of the large-size shake table experiments using E-defense and NEES as well as the research needs and current research activities related to bridge earthquake engineering. Among a number of research items discussed were clarification of the failure mechanism, evaluation and development of effective seismic retrofit measures, performance evaluation of current bridges under extreme ground motions, and further enhancement of the seismic performance of bridges. High priority research targets for large-scale shake table experiments using E-Defense supported with NEES facilities were identified to include;

- performance evaluation and retrofit & repair of reinforced concrete columns under combinations of loading,
- progressive collapse of bridge system,
- new technologies, and
- seismic response modifications.

Fig. 1 US-Japan Workshop on Large-scale Testing on the Seismic Performance of Bridges, February, 2005, San Francisco, USA

In the WS, group discussion was conducted for 1) RC columns, and 2) progressive collapse and isolation. Following are the outline of proposed programs.

RC columns:

Because failure of RC columns was one of the most major mechanisms of the damage of 1998 Loma Prieta, 1994 Northridge and 1995 Kobe earthquakes, study on RC columns is a high priority research area. The points of discussion were as follows;

- Integrated experimental strategy and program on reinforced concrete columns should be

established so that large-scale experiments using E-Defense and medium-size experiments in both the US and Japan are complementary.
- Large-scale experiments on reinforced concrete columns should be conducted using as large models as possible to clarify and solve the problems inherent to small & medium-size experiments.
- Experimental and analytical research on failure mechanisms, seismic retrofit, performance evaluation under extreme ground motions and further enhancement of the seismic performance of columns should be conducted.
- Japan-side plan is to start experiment on the failure mechanisms of RC columns with insufficient development at cut-off, followed by experiments on seismic retrofit and the performance evaluation of columns designed based on current seismic design codes. Scheduling of experiments will be confirmed among Japan and US researchers after preliminary design of models and catch system in Japan and research funding allocation in the US.
- Pre-NEES research programs which were funded in US in 2004 should be incorporated in this research collaboration. Possible involvement of Japanese researchers in the pre-NEES program was discussed.
- Catch and setup system should be as flexible as possible to enable wider range of experiments including but not limited to single columns, bents or multiple span models.

Progressive failure and isolation:

Due to limitation of table size and loading capacity, realistic shake table test on bridge system response consisting of various structural members could not be conducted in the past. This is one of the breakthrough experiments which are required to advance the current knowledge on bridge performance under destructive near-field ground motions. Possible programs discussed on progressive failure are as follows;

- Progressive collapse testing should involve seismic response of a whole bridge system (piers, bearings, superstructure, spans, abutments, unseating devices, etc.) with sequential or progressive failure modes of structural components
- Industry (agencies, corporations, designers, owners/operators, etc.) has a strong interest and high need for better knowledge on system behavior related to progressive collapse, and for analysis tools to accurately and reliably capture this system response
- US-Japan collaboration can be highly successful and integrated because there is a strong shared interest in all of the various aspects of progressive collapse
- Because of the high complexity and costs of system-level tests, the E-Defense and NEES tests should be planned to be modular and to allow the greatest possible flexibility
- Areas of collaboration include
    - ✓ Innovative and advanced structural control technologies (for bearings, energy dissipation systems, 3D response and pounding, interaction of various systems, etc.)
    - ✓ New testing procedures to simulate broader system behavior (e.g. hybrid testing with substructuring, distributed tests, etc.)
    - ✓ Development of new type sensors for progressive collapse that can measure information needed (for testing, and eventually health monitoring purposes)
    - ✓ Development of analysis and design tools to achieve the above purposes

On the occasion of 4th planning meeting in August 2005 in Miki, Japan and US researchers agreed to conduct shake table test using E-Defense on two type models; 1) component models and 2) system models. They are called C1 test (C1 models) and C2 test (C2 models), respectively.

C1. Component experiments (single columns)

Component experiments on single RC column models with as large sections as possible was proposed as shown in Fig. 2 to provide test data so that they could be used as a bench mark test for clarifying the scale effect and 2D/3D excitation effect. It was agreed among Japan and US researchers that both Japan and US contributed to C2 test.

The objectives of the C1 test is to

- clarify the failure mechanism of RC columns which failed during 1995 Kobe earthquake,
- clarify effectiveness of the standard seismic retrofit measures for existing RC columns ,
- clarify the seismic performance of RC columns designed based on the current design requirements under the current design ground motions,
- clarify the seismic performance of RC columns designed based on the current design requirements under stronger than the current design ground motions, and
- clarify the effect of damper technology.

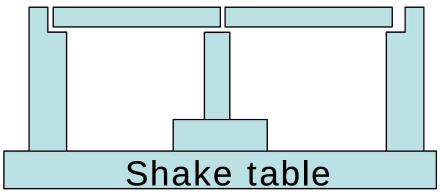


Fig. 2 Component Model (C1 Model)

Clarification on failure mechanism of premature shear failure at cut-off due to insufficient development is important for Japan because it was one of the most extensive failures during 1995 Kobe earthquake [2]. It is also interesting to study the effect of composite materials jacket for seismic retrofit because it is well implemented to columns as well as steel jacket.

C2. System experiments (progressive collapse)

System experiment is proposed to clarify system failure mechanism of a bridge consisting of a deck, columns, abutments, bearings, expansion joints, and unseating prevention devices as shown in Fig. 3 under various loading conditions. The objectives of C2 test are;

- clarify progressive failure modes of a bridge system due to combination of poundings and rupture of expansion joints, bearings, restrainers and columns
  - ✓ Effect lock of failed bearings & expansion joints
  - ✓ Interaction of failed structural components
- Advanced and critical columns
  - ✓ High ductility columns
  - ✓ Re-centering columns
  - ✓ Rocking seismic isolation
  - ✓ C-bent columns
  - ✓ Interlocking spiral columns
  - ✓ Square columns with cross bars
  - ✓ Columns subjected to combined flexure, axial force and torsion
- Advanced dampers and energy dissipating units
- Advanced unseating prevention devices

To achieve the objectives, proposed are modular models in which a part of structural components can be replaced to enable repeated experiments under various conditions. Thus, experiments are expected for straight, skewed and curved bridges which are supported by various type columns and foundations (single cantilever columns, multi-column bents, re-centering columns, interlocking spiral columns, inverted L (C-bent) columns, moment-resisting frame piers, lightly reinforced wall piers, high performance columns, circular and rectangular, solid and hollow, rocking isolation, columns with different heights, etc.). Tests for C2 model accommodated with advanced dampers, energy dissipators and unseating prevention devices are also proposed.

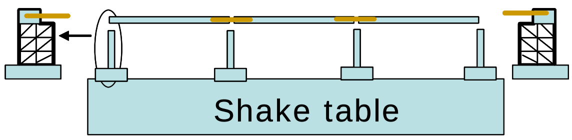


Fig. 3 System Model (C2 Model)

Table 1 Test Program on Component Models (C1) and System Models (C2)

Fiscal Year	Test Programs
2005	Preliminary tests & analyses; ● Pushover, cyclic and hybrid loading tests on premature shear failure ● 3D shake table tests ● Progressive failure
2006	Preliminary tests & analyses; ● Pushover, cyclic and hybrid loading tests on flexure and premature shear failure ● Shake table and cyclic loading tests using NEES facility ● Shake table test using scaled models ● Progressive failure
2007	Large-scale tests on component models (C1 models) using E-Defense; ● Test on flexural failure using a column build in 1970-1980s ● Test on premature shear failure using a column built in 1970-1980s
2008	Large-scale tests on component models (C1 models) using E-Defense; ● Test on steel jacket retrofit using a column build in 1970-1980s ● Test on carbon fiber sheet retrofit using a column build in 1970-1980s ● Test on a column designed based on the current code
2009	Large-scale tests on system models (C2 models) using E-Defense; ● Tests on progressive failure ● Tests on advanced technologies

A bridge program meeting was held to accelerate planning of the bridge program in December 2005 in San Francisco. The test program proposed at the US-Japan workshop on large-scale testing on the seismic performance of bridges, February 2005, San Francisco and 4th Planning Meeting, August 2005, Miki were reviewed and reaffirmed. Research needs were reviewed and agreed as follows:

- clarification of the failure mechanism,
- evaluation and development of effective seismic retrofit measures,
- performance evaluation of bridge columns designed based on current design codes under extreme ground motions, and
- further enhancement of the seismic performance of bridges.

3. PROPOSED MODELS AND TEST CASES

Based on discussions prevented in the previous chapter, an experimental program consisting of C1 and C2 models was formulated as shown in Table 1. Preliminary experiments and analysis as well as design of C1 and C2 models are conducted in 2005 and 2006. Tests using E-Defense are scheduled in 2007-2009.

Five tests are planned for C1 models at this stage. Two C1 model tests are scheduled in 2007; one is a column which fails in flexure, and the other is a column which fails in premature shear failure. They are typical columns built in 1970-1980s and collapsed during 1995 Kobe earthquake.

Verification of seismic retrofit for shear using steel jacket and carbon fiber jacket is scheduled in 2008. Two C1 models designed so as to fail in premature shear failure are retrofitted. Experiments on two C1 models designed based on the current seismic design criteria are also scheduled in 2008 to clarify the seismic performance under the design ground motions and further redundancy under stronger than the design ground motions. Several tests are planned using module C2 model in 2009. However, the test program

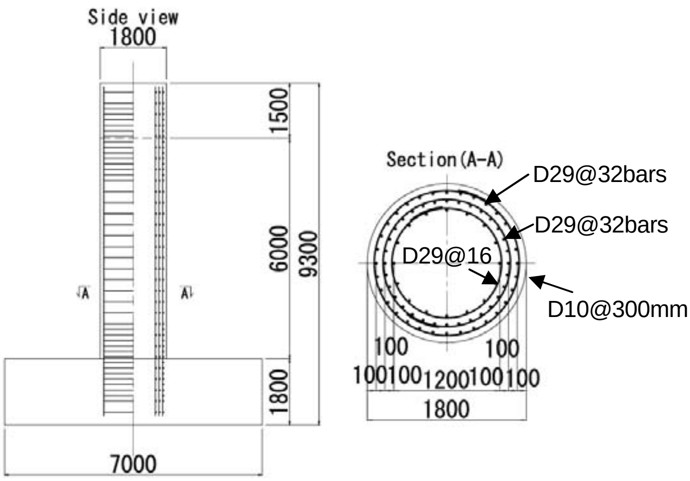
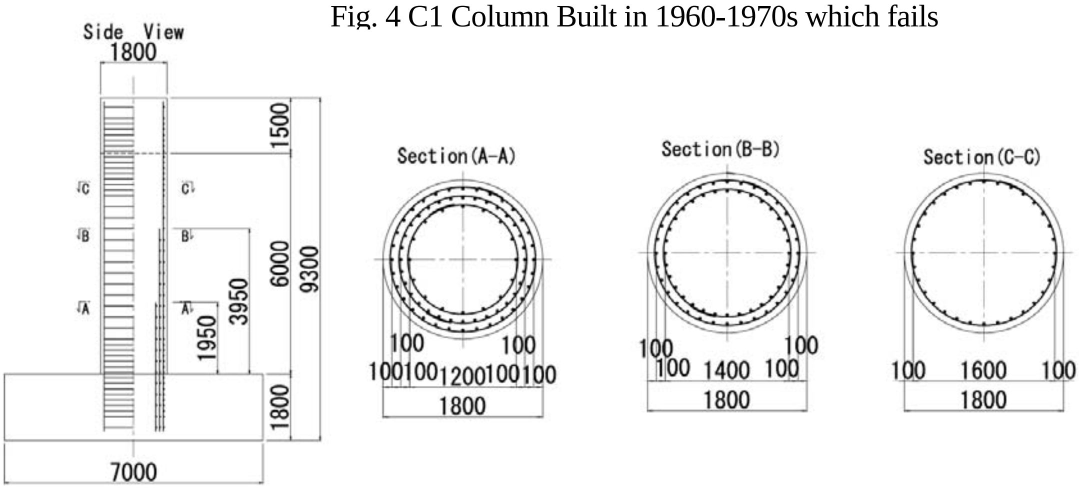


Fig. 4 C1 Column Built in 1960-1970s which fails



Unit: mm

Fig. 5 C1 Column Built in 1960-1970s which fails

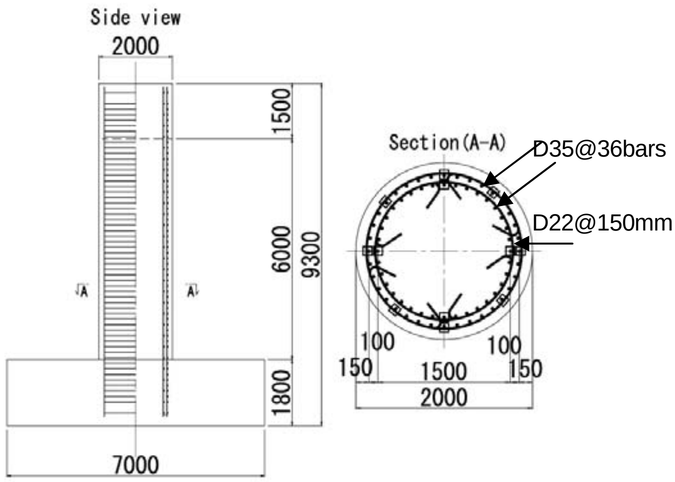
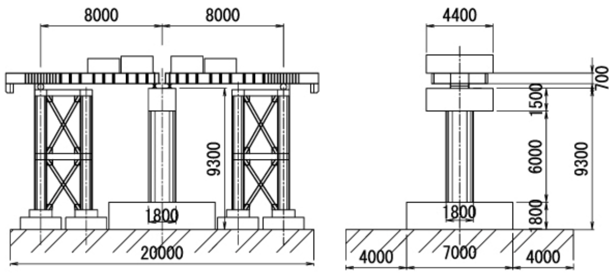
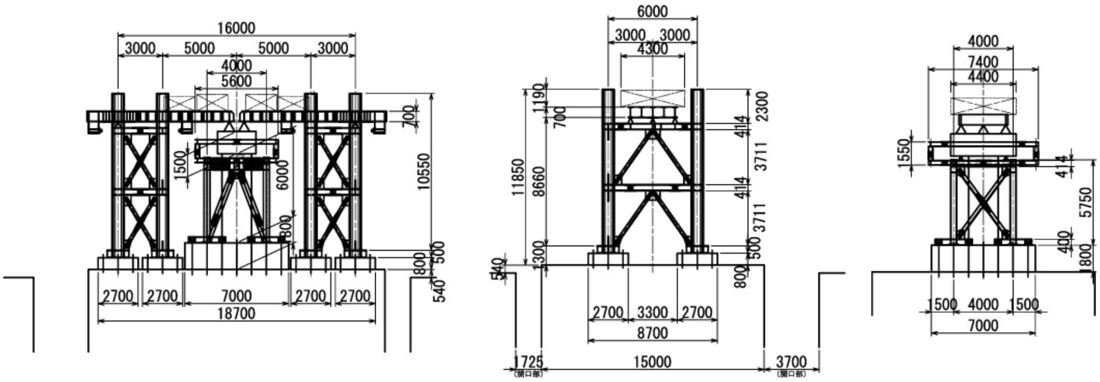


Fig. 6 C1 Column Built based on the Current



(a) Support System



(b) Support and Catch Systems

Fig. 7 Support and catch Systems

will be subjected to modification based on experiments in 2007 and preliminary experiments and analyses.

Figs. 4 and 5 are show C1 model columns built in 1960-1970s which fails in flexure and shear, respectively and Fig. 6 shows C1 model column built based on the current design codes. They are 7.5 m tall circular columns with 1.8m and 2m diameter, supported by 1.8 m thick footing. Two simple decks with steel masses are pin connected to a C1 model. Total weight of a deck with mass is 21t+147t=168t. The decks are not for representing real decks but for supporting 2@147t masses. The decks are supported by steel columns with high stiffness and strength at both ends using movable bearings. Inertia force of two decks and masses are imposed to model column in the longitudinal direction. A certain friction force develops at the movable bearings, but it is limited. However because end columns contribute to support

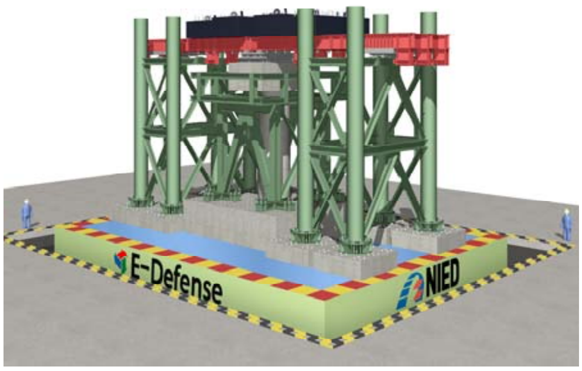


Fig. 8 Component Model (C1 Model)

the inertia force of two decks and masses through the movable bearings (movable in the longitudinal direction, but pin connected in the transverse direction) in the transverse excitation, the masses on decks are set as close to model column as possible.

Because mass of the column with footing and the two decks with steel masses is 310.5 t and 336 t, respectively, total mass of a model is 646.5 t. Thus total weight including catch system as shown in Fig. 7 is 900.5 t. However 50% mass is further added on decks for clarifying redundancy of C1 model designed based on current code, the maximum mass of C1 model is 1,068.5 t including catch system. Fig. 8 shows anticipated model and catch system for C1 models.

4. PRELIMINARY TESTS AND ANALYSES

Following four preliminary tests and analyses were conducted for clarifying testing procedure and proving comparative data, based on request of NIED in 2005 and 2006.

Shake table test on three circular columns with 600 mm diameter was conducted at the Public Works Research Institute in 2005 and 2006 as shown in Fig. 9. Two columns tested in 2006 were 1/3 scaled model of C1 columns scheduled to be excited in 2007. One was column which failed in flexure and the other was column which failed in shear. Loading setup and catch system which were closed to the real systems for E-Defense experiment were used. Experimental

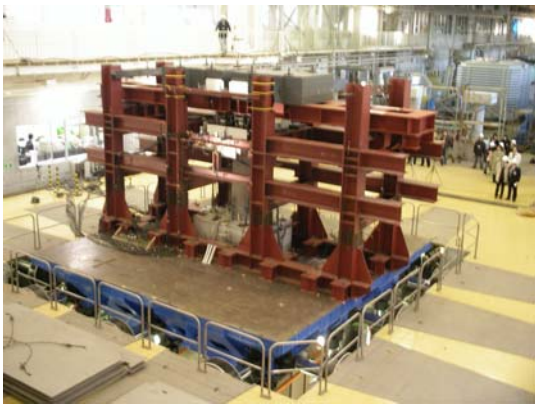
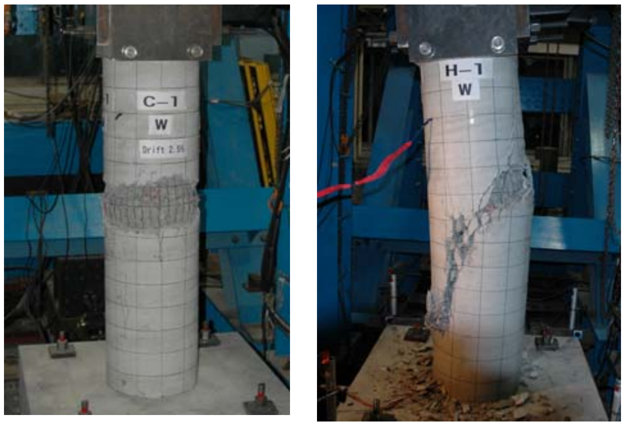


Fig. 9 Shake Table Test on 1/3 Scaled C2 Columns at Public Works Research Institute

results can be directly compared to E-Defense experiment on C1 models [4, 5].

A series of pushover, cyclic, and hybrid loading was conducted on 8 circular columns with 400 mm diameter at Tokyo Institute of Technology in 2005 and 2006 as shown in Fig. 10. They had two cut-offs with insufficient development so they failed in premature shear. They were 2/9 scaled model of C1 model scheduled to be tested in 2007. Flexure and shear failure mechanism was clarified by varying shear and flexural strength ratios. Loading protocol dependence of failure modes was also studied [6, 7].



(a) (b)

Fig. 10 Loading test on 2/9 Scaled C2 Models under (a) Cyclic Loading and (b) Hybrid Loading using Near-Field Ground Motion at Tokyo Institute of Technology

Shake table experiment was conducted as shown in Fig. 11 on two interlocking spiral columns and two rectangular columns jointly by Pacific Earthquake Engineering Research Center, University of California, Berkeley and Tokyo Institute of Technology in 2006. Interlocking spiral columns had two interlocking spirals and had a section of 400x280 mm and 440x280 mm. Rectangular columns had two cross bars and had the same sections with the interlocking spiral columns. They were excited by yield and design level table accelerations several times to failure. Comparative evaluation on the seismic performance of interlocking spiral columns and rectangular columns was conducted.

Fig. 11 Shake Table Experiment on Interlocking Spiral and Rectangular Columns (University of California, Berkeley)

An international hybrid simulation with two experimental components at Kyoto University and University of California, Berkeley was conducted in 2006 to evaluate seismic response of a bridge with a C-bent and a single RC and a steel piers. Fig. 12 shows testing set-up. Numerical analysis was also conducted [8, 9, 10].

(a) (b)

Fig. 12 Experimental Set-up at (a) Kyoto University and (b) University of California, Berkeley

5. COCLUDING REMARKS

Extensive effort has been devoted to reveal deficiency of design practice and to develop seismic design technologies of structures whenever significant damage occurred in past earthquakes. However it was difficult in the past to accumulate real data on structural failure and to verify adequacy of seismic design technologies of structures because of long recurrent time of significant earthquakes. Small scale experiments were insufficient to provide realistic seismic performance data of bridge components and systems inherent to problems of small scaled experiments.

E-Defense enables researchers to conduct large scale experiments on bridge structures so that limitations inherent to small scaled experiment can be eliminated for breaking through disputed problems. US-Japan cooperative research can be highly successful by integrating the efforts in both sides to experimental strategy and programs on bridge structures using E-Defense and NEES in a complementary manner. The authors wish to contribute for enhancing seismic design technology of bride structures in this program by dissolving critical problems which cannot be studied based on small scale experiment.

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