Journal of Japan Association for Earthquake Engineering, Vol.4, No.3 (Special Issue), 2004

A RESEARCH PROJECT BY SPECIAL COORDINATION FUNDS FOR PROMOTING SCIENCE AND TECHNOLOGY —ENHANCEMENT OF EARTHQUAKE PERFORMANCE OF INFRASTRUCTURE BASED ON INVESTIGATION INTO FRACTURING PROCESS—

Masanori HAMADA

[1]Professor, Department of Civil and Environmental Eng., Waseda University,
Tokyo, Japan, hamada@waseda.jp

ABSTRACT: This paper introduces the outline of a research project on enhancement of earthquake performance of infrastructures based on investigation into fracturing process of structures. This project was sponsored by MEXT and managed by three institutions, JSCE, NIED and BRI. It was started in April 1999 and ended in March 2003.

Key Words: Performance-based design, Research project, Fracturing process, Liquefaction

INTRODUCTION

The Ministry of Science and Education, Culture, Sports and Science (MEXT) sponsored a research project for five years from 1999 to 2003 by using The Special Coordination Funds for Promoting Science and Technology. The title of the research project is Enhancement of Earthquake Performance of Infrastructures Based on Investigation into Fracturing Process. This research project was proposed and managed by three institutions, Japan Society of Civil Engineers (JSCE), Nation Research Institute for Earth Science and Disaster Prevention (NIED) and Building Research Institute (BRI).

The project consisted of the following three major themes;

1) Research on fracturing process of structures, foundations and ground
2) Development of technologies for diagnosis and retrofitting of existing structures
3) Development of experimental technologies for future researches by utilizing a big shaking table under construction (E-Defense)

The first theme which was raised from the lessons of the 1995 Kobe earthquake covered concrete and steel buildings, bridges, grounds and foundations. The aim of the second theme was the development of effective and economical methods for retrofitting and diagnosis of the existing structures with low earthquake resistance, which still remained though a large number of bridge piers of highway and railway, and concrete columns of subways had been reinforced after the Kobe earthquake. The goal of the thirds theme was to develop experimental technologies for the Three-Dimensional Shaking Table for Full-Size Fracturing Test (E-Defense), which is now under construction, and will be completely built up by the end of 2004. This theme covered the control technologies during rupture tests, data measurement and processing, and preparation of large-scale ground and foundation models for E-Defense.

BACKGROUND OF THE RESEARCH PROJECT

The Kobe earthquake destroyed a large number of highway bridges, railway structures, quay walls and subways. A huge number of collapses of buildings and houses became the direct cause of the loss of more than six thousands lives. Many technical as well as social and political lessons have been learned from this earthquake disaster. Among them, the most important lesson should be the enhancement of earthquake resistance of structures for prevention of total collapses against future earthquakes in order to save human lives.

To achieve this goal, JSCE proposed two principles for earthquake resistant design and retrofitting of infrastructures. The first principle is to examine earthquake resistance of structures against two levels of earthquake ground motions, and the second one is promotion of the performance-based design. These two JSCE-proposed principles were adopted into the National Master Plan of Earthquake Disaster Prevention after the Kobe earthquake. The JSCE's recommendation on two levels of earthquake ground motion describes that Level 1 is the ground motion which has been used for the conventional earthquake resistant design in Japan. The probability of the occurrence of Level I ground motion is estimated to be once or twice during the whole life of structure. Level II ground motion is caused in the vicinity of intra-plate faults with a magnitude as great as 7. It may be also caused by the earthquakes with a magnitude around 8 at the plate boundaries in the Pacific Ocean. After the Kobe earthquake, most of earthquake resistant design codes for highway bridges, railway structures, port and harbor facilities, and lifeline facilities were revised based on the two principles proposed by JSCE and The National Master Plan for Disaster Prevention. In these codes, two levels of ground motion were adopted and the procedures of performance-based design were regulated.

However, even after the revision of the design codes, performance-based design against two levels of earthquake ground motion is still insufficiently realized. For an example, the relationship between the earthquake force and the deformation of an elevated railway bridge, which were severely damaged by the Kobe earthquake, is schematically shown in Fig. 1.

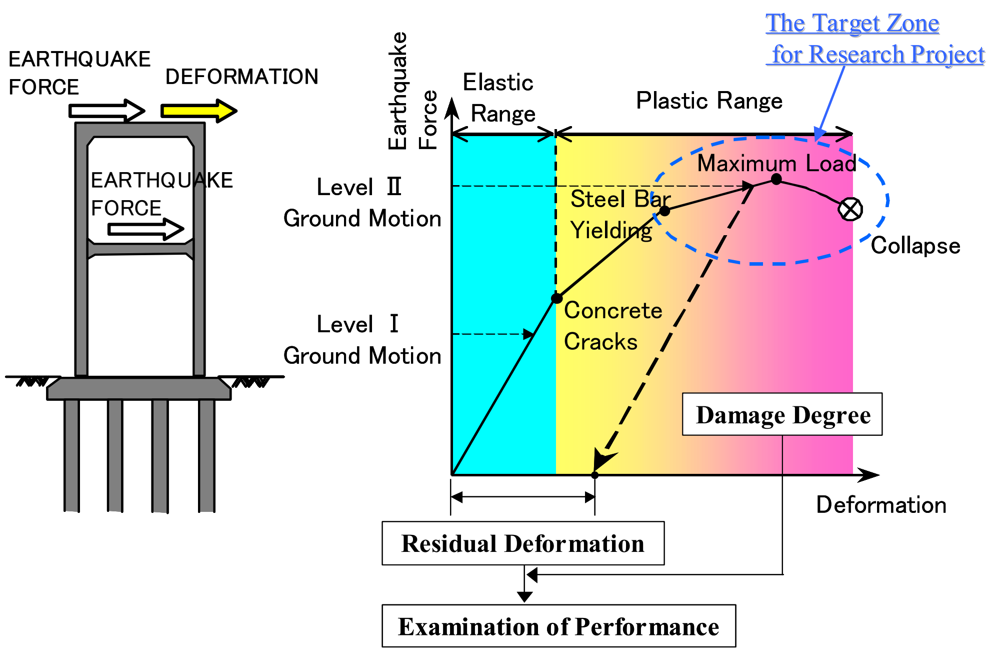

Fig. 1 Examination of performance of an elevated bridge subject to earthquake force

The stiffness of the structure decreases along the process of the occurrences of concrete cracks and steel bar yielding. And the structure will collapse after a maximum load. The performance of the structure against the level II ground motion is examined by the damage degree of the structural members, and the residual deformation, which are governed by the behavior of the structure in large plastic deformation zone. But it is recognized that the knowledge and information regarding this zone particularly including the path from the maximum load to the collapse have been insufficiently accumulated until now. This aspect leads the main target of this research project to the investigation of the behavior of structures in this zone in order to establish and realize a rational performance-based design against the level II ground motion.

MEXT organized a research promotion committee and two sub-research groups to promote the research project. The first group is responsible for the development of experimental technologies for E-Defense, which is led by Prof. Shimizu of Iwaki-Meisei Univ. The second group has a responsibility for the research on the failure process of structures by utilizing the existing experimental facilities in Japan, led by Prof. Iemura of Kyoto University. 7 universities, 8 public research institutes and 2 private sectors joined this research project.

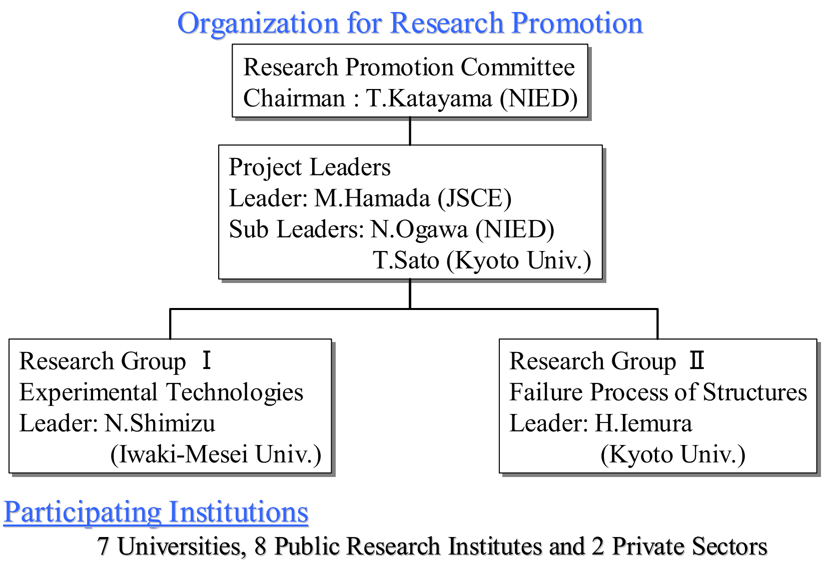

Fig. 2 Organization of research project

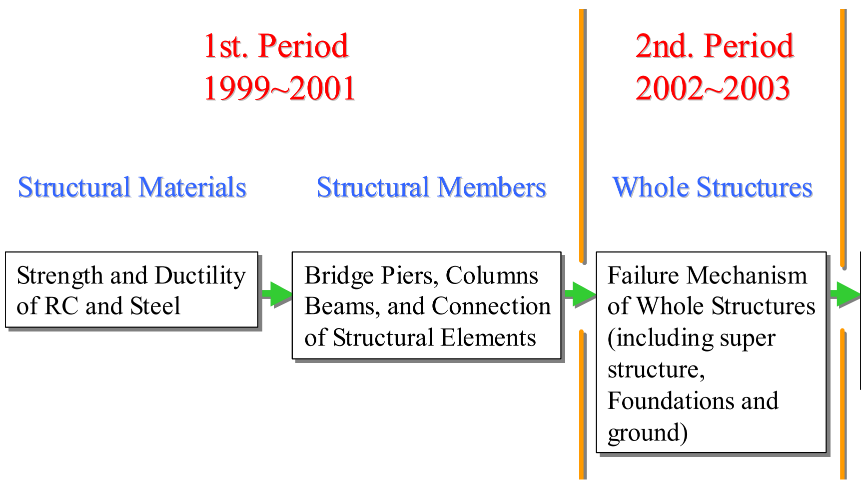

Fig. 3 Research flow of failure mechanism of structures

One of the characteristic aspects of the promotion of this research project on the failure mechanism of structures is that the first period of three years was spent mainly for the research on rupture process of materials and structural members, and that the second period of two years has been spent mainly for the research on the failure mechanism of the total structures, including superstructures, foundations and ground. In future, this research will be taken over by the researches utilizing E-Defense

INTRODUCTION OF RESEARCH RESULTS

Concrete buildings

The failure process of concrete buildings was investigated according to the method as shown in Fig. 4. The strength and the ductility of concrete columns were first investigated against two-dimensional bending under high axial loading. And at the second stage the method of the reinforcing of the connection between beams and columns was investigated. Finally, the failure process of the total structure was investigated by shaking table test of a large scale model. Based on this series of experiments, a numerical model was developed to predict the behavior of concrete buildings from large deformation to the collapse(Kusunoki et al. 2002).

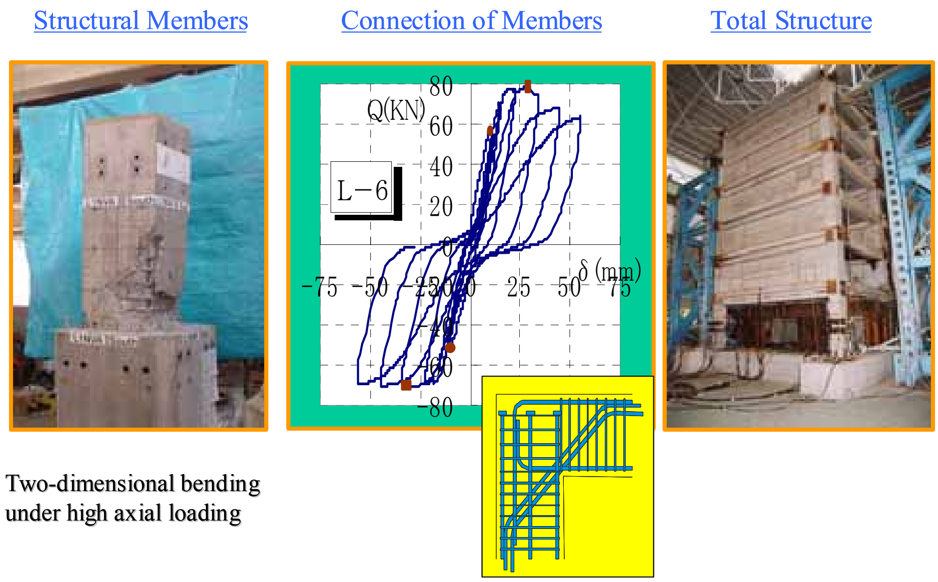

Fig. 4 Research on failure process of concrete buildings
(after Kusunoki et al. 2002)

Steel structures

A similar procedure was adopted for the research on the failure process of steel structures. Firstly, the material properties, strength and ductility against high strain rate were examined and the large deformation behavior of steel columns by two-dimensional bending and torsion under high axial force were studied. Then the large deformation behavior of the joint between steel column and beam was investigated by using full-scale model as shown in Fig. 5(Matsumoto et al. 2000, Yamada et al. 2001). After these tests on materials and the structural members, the experiments on three-dimensional steel frame have been carried out. Finally, based on the experimental results, a numerical model was developed to predict large deformation behavior and failure process.

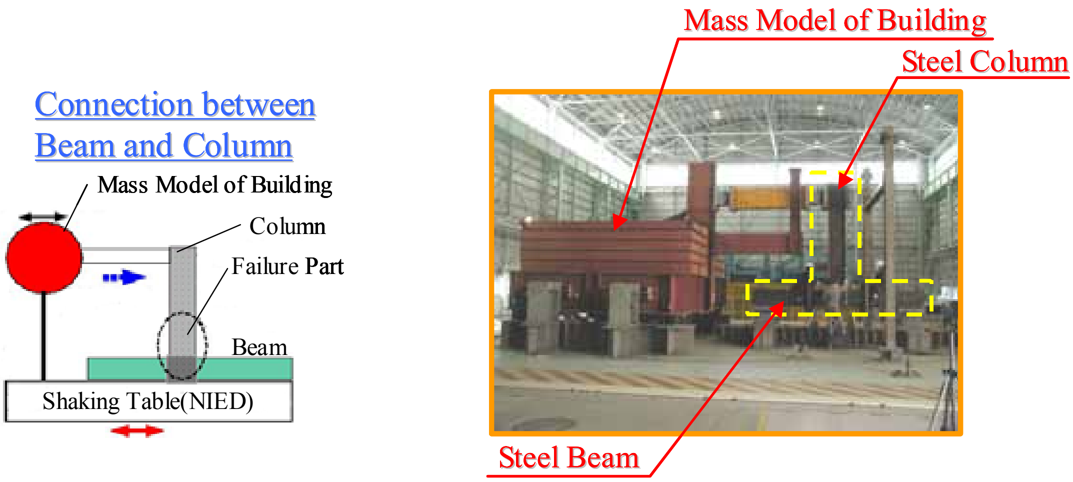

Fig. 5 Test on failure process of connection between steel beam and column
(after Matsumoto et al. 2000, Yamada et al. 2001)

Development of high-performance structure

In this research project, high performance structures for bridge piers have been also developed against the level II ground motion. Fig. 6 shows a reinforced concrete pier with unbounded steel core bar, which was developed by H. Iemura et al(Iemura et al. 2004). Unbounded high-strength core bars are installed into a concrete pier and connection part with a footing. Both ends of the bars are anchored. Unbounded high strength core bars increase the second stiffness in the force-displacement relationship and decrease the residual displacement after earthquakes.

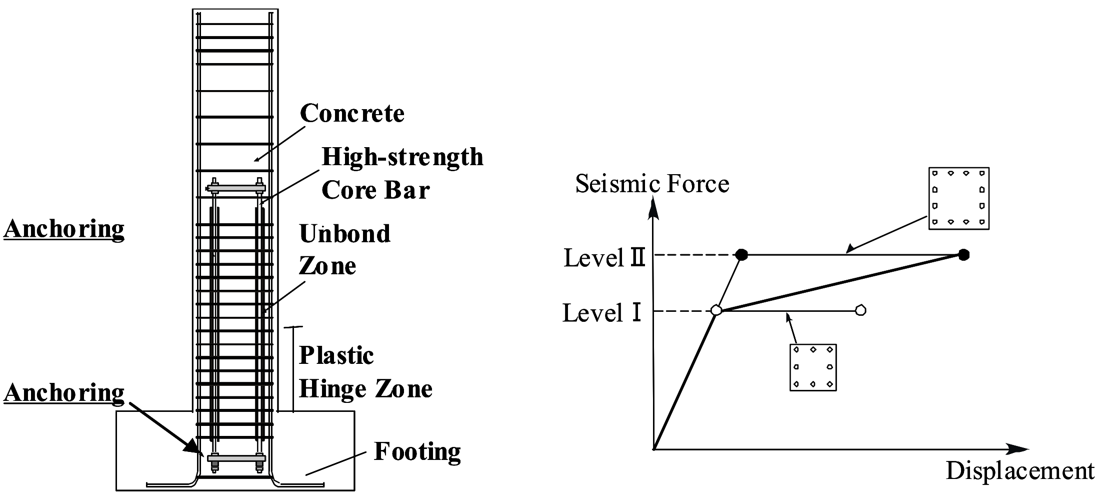

Fig. 6 RC column with unbounded high strength steel bars
(after Iemura et al. 2004)

Fig.7 also shows a new idea for concrete filled steel column proposed by N. Horichi et al(Horichi et al. 2003). The column consists of an outer and inner tubes, and all part of the space is filled by concrete. The outer tube has a thin slit. This structure is expected to increase the ductility and to decrease the residual deformation.

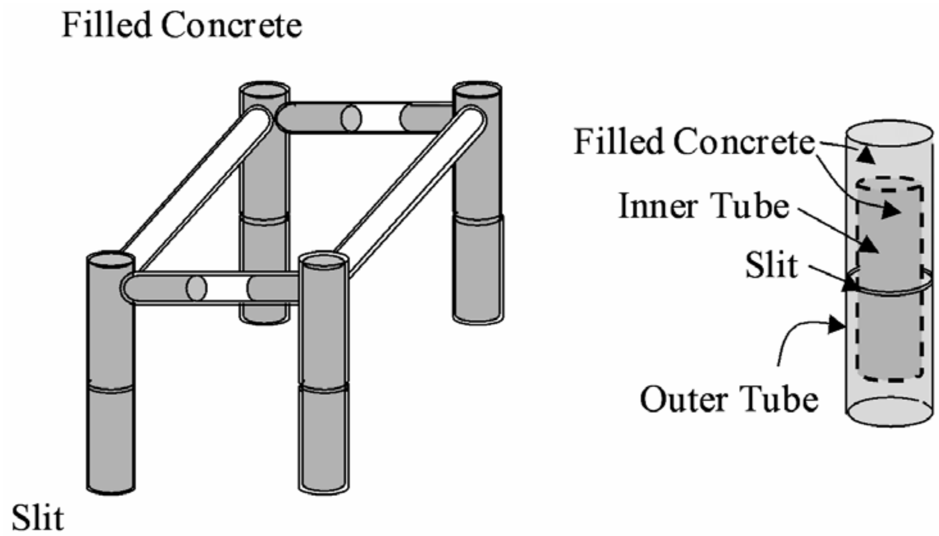

Fig. 7 Concrete filled steel column and bean
(after Horichi et al. 2003)

REAEARCH ON LIQUEFACTION-INDUCED GROUND DISPLACEMENT

Studies on performance of foundations against liquefaction-induced large ground deformation are one of most important theme of this research projects, because the large ground deformation caused severe damage to foundation piles and buried pipes of lifeline systems during past earthquakes such as the 1864 Niigata earthquake and the 1995 Kobe earthquake.

There are two main themes for the liquefaction-induced ground displacements. One is to develop a method for the prediction of the magnitude of the ground displacements in both of the horizontal and the vertical directions. The second theme is to establish a rational procedure of earthquake resistant design of foundations and buried structures against large ground deformations.

In order to develop a prediction method of the magnitude of the ground displacements, the fluid properties of liquefied sand during its flow were studied by three kinds of tests, flow tests of liquefied sands under 1 g and centrifuge conditions, and shear tests of perfectly liquefied sands as shown in Fig. 8(Hamada and Takahashi 2004). It was reported from these tests that the coefficient of viscosity of flowing liquefied sand decreases with an increase of shear strain rate. This means that liquefied sand behaved as non-Newtonian flow such as pseudo-plastic flow or Bingham flow. Based on these experimental results and the case studies on ground flow during past earthquakes, a method was proposed to predict the ground displacements due to liquefaction.

As for the characteristics of the external forces on foundations from flowing liquefied soil, several experiments under 1-g and centrifuge conditions were carried out(Jang and Hamada 2004). It was reported that the fluid force proportional with the flow velocity of the liquefied sand was applied on the foundations when the sand layers were perfectly liquefied. On the other hand, when the sand layers were partially liquefied, the force proportional with the ground displacements was dominant on foundations. These findings from the tests on liquefaction-induced ground displacement can provide useful information and knowledge for the establishment of a rational procedure of earthquake resistant design of foundations and buried structures against liquefaction and its induced ground displacements.

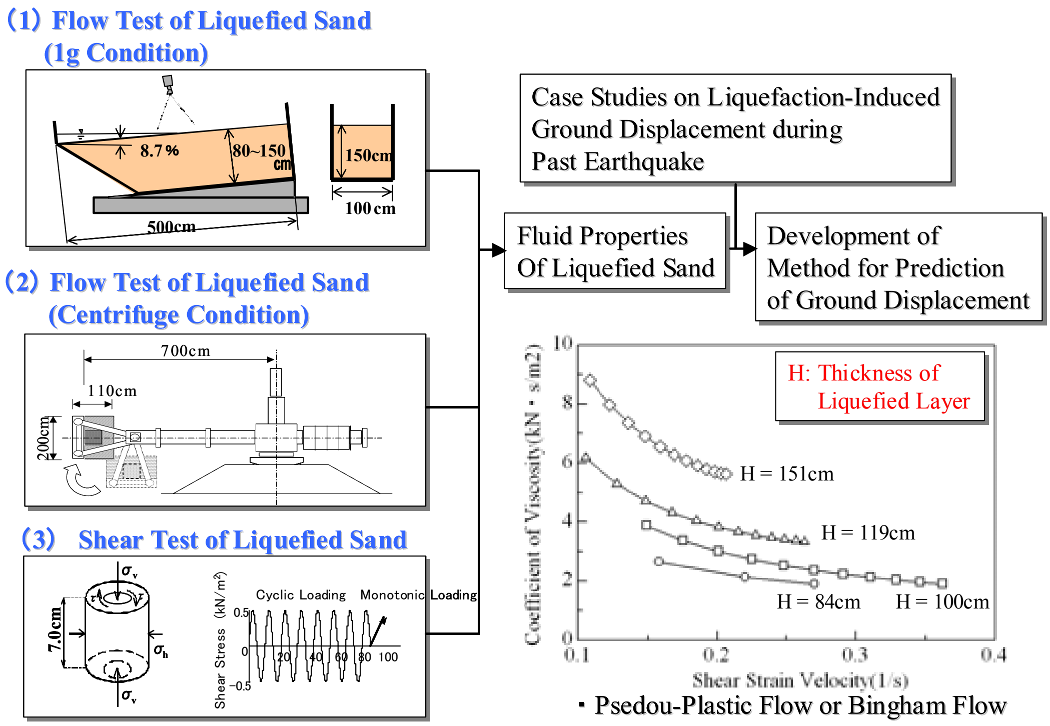

Fig. 8 Development of method for prediction of ground displacements

CONCLUSIONS

This research project supported by the Special Coordination Funds for Promoting Science and begun in 1999 fiscal year and has just ended in March of 2004. The main targets of the research project are as follows; 1) to investigate into the failure process of ground and structures by utilizing the experimental facilities in Japan, 2) to prepare the experimental technologies for employing the three-dimensional big shaking table (E-Defense), which is currently being constructed in Miki city, Hyogo Prefecture, Japan.

With regard to the first research target, the research activity was evolved and the important findings for the seismic performance based design were accumulated according to the great effort of the research groups. Especially an expected result was achieved as concerned with the investigation on the collapse process in the pilot building and the large deformation of pile foundations due to the lateral flow of liquefied sand.

Moreover, high-performance new structures were developed for bridge piers. One is a concrete bridge pier which has high strength steel core bars at the connection with the footing. The other is a concrete-filled pier with double steel tubes.

Regarding the second research target, an expected result on the development of the control method of the shaking table and the measurement during large scale fracturing test and the preparation of large scale saturated sand test sample has been obtained. The author also considers the E-Defense to become a powerful facility in the investigation of the large deformation behavior and the destruction process, although the experiments by E-Defense require a huge amount of research funds. However, the discussions shall be focused not only on utilization of E-Defense, but also on how to establish a comprehensive plan of the research for earthquake disaster prevention. The details of the research results can be referred through the following homepage;

http://faculty.web.waseda.ac.jp/hamada/index.htm

ACKNOWLEDGMENT

The author wishes to extend and dedicate his sincere gratitude to Mr. Yuji Takahashi (Kajima Corporation) and others, who have steadily assisted the author as a secretariat. The acknowledgement particularly notifies that this project could not be accomplished without the dedicated effort of Mr. Takahashi. The research activity of all the participants shall be promoted and contributed for the enhancement of earthquake performance of infrastructures increasingly.

REFERENCES

Hamada, M. and Takahashi, Y. (2004). "An experimental study on the fluid properties of liquefied sand during its flow." *Proc., 13th World Conference of Earthquake Engineering*, Paper No. 641.

Horichi, N., Yoda, T., Katsuo, S. and Hosaka, T. (2003). "Capacity to carry static load at the corner joints of a rigid frame with concrete-filled circular steel pipes." *Proc., 10th International Symposium on Tubular Structures, Spain.*

Iemura, H. Takahashi, Y. and Sogabe, N. (2004). "Development of unbonded bar reinforced concrete structure." *Proc., 13th World Conference of Earthquake Engineering*, Paper No. 1537.

Jang, J. and Hamada, M. (2004). "An experimental study on the loads on foundation piles from flowing liquefied soil." *Proc., 13th World Conference of Earthquake Engineering*, Paper No. 3112.

Kusunoki, K., Kato, H., Fukuta, T. and Kumazawa, F. (2002). "Experimental study on dynamic response characteristics of frame structures with eccentricity." *Proc., 3rd US-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*.

Matsumoto, Y., Yamada, S. and Akiyama, H. (2000). "Fracture of beam-to-column connection simulated by means of the shaking table test using the inertial loading equipment." *Proc., STESSA 2000, Montreal*, 215-222.

Organization for Promotion of Civil Engineering Technology, JSCE, *EEPI News Letter* No.1~No.15

Yamada, S., Matsumoto, Y. and Akiyama, H. (2001). "Full-scale shaking table test of structural elements using the inertial loading equipment." *Proc., International Seminar & Workshop on New Direction for the Enhancement of Structural Performance, Seoul*, 163-171.

(Submitted: May 17, 2004)
(Accepted: July 2, 2004)