ROLES OF LARGE STRUCTURAL TESTING FOR THE ADAVANCEMENT OF EARTHQUAKE ENGINEERING

Masayoshi Nakashima

Professor, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan;
Director, E-Defense, National Research Institute for Earth Science and Disaster Prevention (NIED), Tsukuba, Japan
Email: nakashima@archi.kyoto-u.ac.jp

ABSTRACT :

The paper touched upon three issues in earthquake engineering. First, the earthquake threat of Japan is briefly introduced, followed by a discussion on the critical needs of collapse characterization and performance verification. Second, benefits of large-scale structural tests are discussed in terms of the size effect, rate-of-loading effect, redundancy effect, and effectiveness of numerical analyses. These benefits draw a statement such that it is sensible to test structures in the full-scale instead of miniatures, as systems instead of members, loaded dynamically instead of quasi-statically, until collapse instead of mild inelasticity. Third, the development of E-Defense, a very large shaking table facility, is presented, and previous and ongoing research projects using large-scale test specimens are introduced.

KEYWORDS: Experiment, Large-Scale Testing, Shaking Table, Numerical Simulation

1. INTRODUCTION

1.1 Seismic Vulnerability of Japan

The 1995 Hyogoken-Nanbu (Kobe) earthquake caused devastating damage to buildings and infrastructures in Kobe and its vicinities (Architectural 1995; Kinki 1995; Nakashima et al 1998a; Nakashima 2001). Lessons learned from the earthquake were extended into numerous aspects, including structural, economical, societal, cultural, and human ones. Since that time, much research and development has been implemented throughout Japan for the mitigation of earthquake disasters. The 1995 Kobe earthquake, however, is not the sole motivation for such action, because Japan is destined to suffer from large earthquakes on a periodical basis. Figure 1 shows a map of Japan, and an ocean ridge called the Nankai trough is running deep along the Pacific Coast of Japan. The trough is divided into three regions, Tokai, Tonankai, and Nankai, named from the east. Slips and ruptures occurred periodically in these regions.

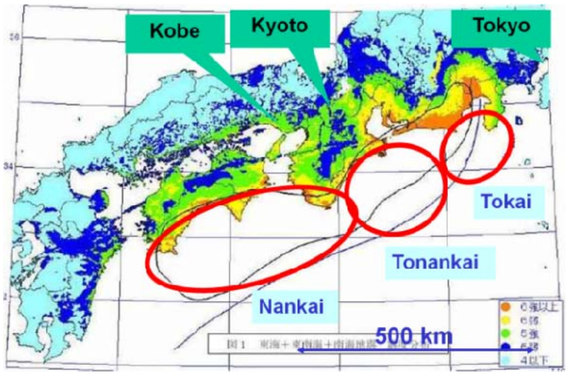


Figure 1 Ocean-ridge earthquake anticipated in Japan

For many centuries, slips and ruptures of the three regions had been occurring with an interval of one hundred to one hundred and fifty years. Observing the pattern of the previous earthquakes, Japan is most likely to be hit by a next large earthquake by the middle of this century. In 2005, the Council of National Disaster Mitigation chaired by the Prime Minister of Japan disclosed a damage estimate that Japan would sustain if the Nankai trough were ruptured again (Council 2004). According to the estimate, shall the three regions rupture all together, about forty million people, equivalent to one-third of the entire population of Japan, would be affected; about one million houses and buildings would collapse; about twenty-five thousand folks might lose their lives, and the economic loss would amass to close to one trillion US dollars (direct loss only). These estimated values area at least ten times greater than those observed in the 1995 Kobe earthquake. Another very serious piece of data was disclosed recently. Twenty-two percent of large companies whose stocks are open to the Tokyo stock market have their headquarter functions in high-rise buildings in downtown Tokyo, while their sales are accumulated to about 30% of the total Japanese sales. Shall our metropolitan region be hit by a large shaking, the Japanese economy would be affected very seriously. As these statistics clearly indicate, the earthquake disaster was, is, and will remain the most critical national problem in Japan.

Referring to the 1995 Kobe earthquake, many Japanese were convinced that the following two lessons are most notable in the structural aspect. One is: cities and towns throughout Japan have large stocks of old buildings and infrastructural systems whose seismic capacity is insufficient. To prepare for future large earthquakes, it is crucial to accurately evaluate their existing seismic capacities and then to retrofit and rehabilitate accordingly. Another is: much larger shaking than that contemplated in current seismic design is known to be possible. Evaluation of the reserve seismic capacity of existing buildings and infrastructural systems, development of design and construction technologies to enhance the seismic capacity, and implementation of these technologies for real design and construction are critical.

These lessons are relevant to the characterization of collapse margin, defined as the reserved capacity that the structure would possess beyond the level of damage considered in seismic design to the ultimate collapse. Quantification of this margin is a key for the decision of retrofit and rehabilitation. For the past fifteen years, much research has been conducted in the name of “performance-based seismic design” on the development of innovative systems by which to enhance functionality, operability, and safety of structures. Typical of these are structural systems with base-isolation and passive damping systems. Whatever devices and elements and systems are invented, they shall be checked for their actual performance before being transferred with confidence to real design and construction practices.

1.2 Needs for Realistic Date on Structural Performance

Both of these critical needs, i.e., the characterization of complete collapse and the verification of actual performance, are very relevant to structural testing, because we need *real data* for the characterization and verification, which can only be supplied by realistic tests. However, realistic data on complete collapse, complete failure, and actual performance are yet limited. We have two means of obtaining real data. One is to equip actual structures with sensors throughout and wait for a large shaking, and the other is to make mock structures in the laboratory and load the structures artificially. The first option is no doubt very effective in obtaining most realistic data, but the probability to acquire useful data seems to be low. Suppose we take the second option, here are problems to debate. First, are we fully aware that complete failure is very different from mild inelasticity and small to medium damage? Second, is the size very important, in other words, can miniature models reproduce the actual behavior? Third, is the rate-of-loading serious, in other words, can behavior in dynamic condition be duplicated reasonably by quasi-static loading test? Fourth, what about the effect of redundancy? Are member tests sufficient to predict the system behavior, or are the system tests needed? Finally, what about strong and formidable numerical simulation? Can the virtual simulation replace time consuming, expensive, and clumsy-looking physical tests? In the discussion to follow, the writer would like to present his view about these issues in light of the collapse characterization and verification of actual performance.

2. RELIABILITY OF DATA OBTAINED FROM STRUCTURAL TESTING

2.1 Scale Effects in Size and Rate-of-Loading

Here is a very fundamental question, i.e., is a "full-scale test" indeed necessariy, and what is wrong about a test with a miniature? Figures 2 shows a building frame as a whole. Columns and beams are represented by lines, and connections are represented by points in which no volume is present. In reality, a column is never a line, or a connection is never a point. For example, in reinforced concrete, a column is reinforced with many bars, etc. In steel, bolts and plates are installed everywhere in the connection. We all know that these so-called "details" often become a trigger of damage and according failure. For the question whether or not these details can be duplicated in reduced-scale models, the answer is most likely "NO." Two steel beams were loaded cyclically, one in the full-scale and the other in a one-tenth reduced-scale (Nakashima 1998b; Liu 2003). In the full-scale case, the cyclic behavior in terms of the beam-end moment versus rotation relationship (Figure 3(a)) is very ductile, but the specimen failed by fracture from the weld at the beam-to-column connection at a rotation of 4 %. In the reduced-scale case, the corresponding cyclic behavior (Figure 3(b)) exhibits very stable loops until a rotation of more than 20%. This significant difference was attributed to the treatment of the beam-to-column connection in the reduced-scale specimen. Because of the thinness of the beam flanges and web of the reduced-scale specimen, welding was not possible to connect them to the column; hence mechanical joints were adopted for the connection. Deletion of the most important source of damage, i.e., welding, was fatal to duplicate the failure behavior.

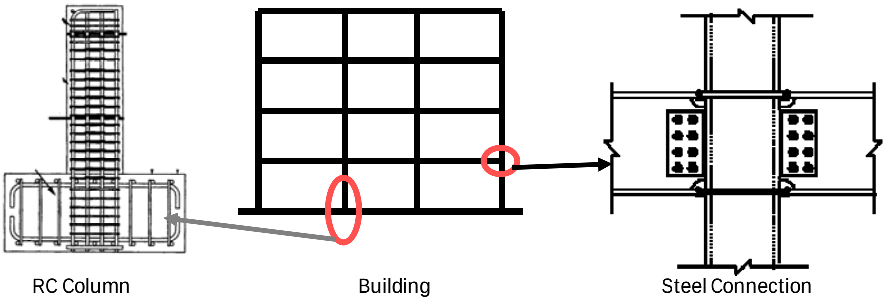
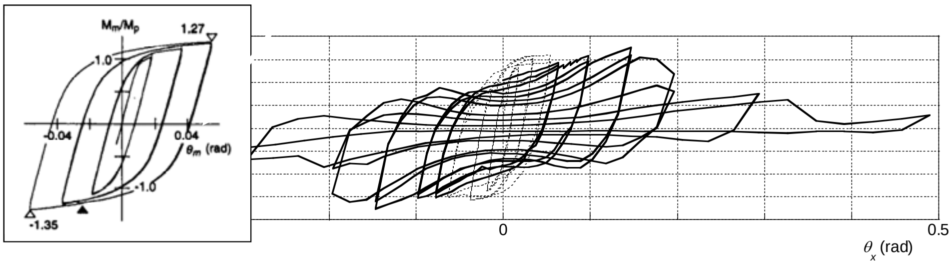


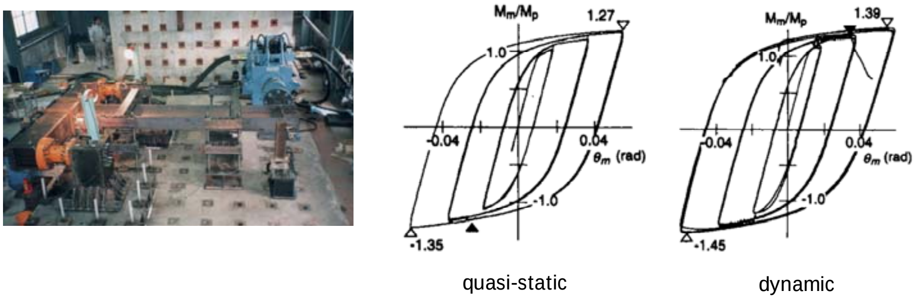
Figure 2 Scaling of structures



(a) (b)

Figure 3 Beam-end moment versus rotation relationship: (a) full-scale test; (b) reduced-scale test

Previous studies on material tests with various strain rates indicate that a larger rate-of-loading tends to increase the strength but reduced the toughness and ductility. To examine the effect of rate-of-loading, shown in Figure 4(a) is a setup for a test of welded steel beam-column connection subjected to cyclic loading (Nakashima 1998b, Suita 1998). A T-shape subassemblage was loaded at the tip of the beam by a dynamic actuator. Two identical specimens were loaded with different speeds, one quasi-statically and the other dynamically with a velocity commensurate with the velocity that would be induced in strong earthquake conditions. Figure 4(b) and (c) show the end-moment versus rotation curves obtained from the two tests. They were rather similar; in fact the dynamically loaded specimen exhibited more ductile behavior before the fracture in the beam flange. In the statically loaded specimen, the fracture surface was brittle, while it was ductile in the dynamically loaded specimen. This occurred because of the transfer of the dissipated energy to the thermal energy, which resulted in a constant rise of temperature in the plastified steel during the dynamic loading test. After many cycles of large inelastic deformations, the temperature increased nearly by seventy degrees, and the increased temperature made the material more ductile. As this example implies, the rate-of-loading effect is much more complex in steel members and systems than in materials loaded monotonically.

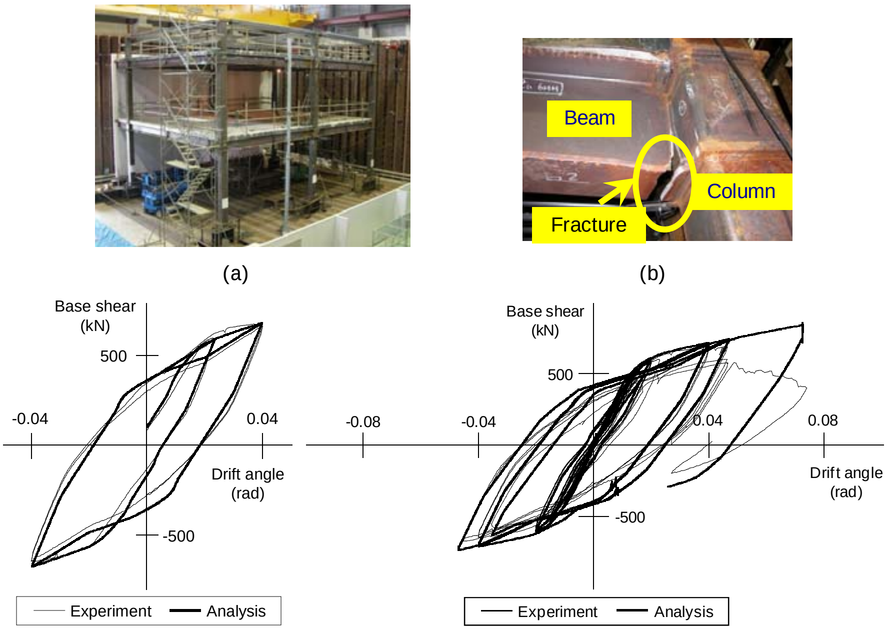


(a) (b) (c)

Figure 4 Cyclic loading test to steel beam-to-column connection:
(a) test setup; (b) quasi-static loading test; (c) dynamic loading test

2.2 Member Behavior versus System Behavior

A test on a full-scale model of a three-story steel moment frame shown in Figure 5(a) was conducted (Nakashima et al 2006; Nakashima et al 2007; Okazaki 2007 et al). The objectives of the test were to acquire real information about the damage and serious strength deterioration of a steel moment frame, to study the interaction between the structural frame and nonstructural elements, and to examine the capacity of numerical analyses commonly used in seismic design to trace the real cyclic behavior. During the loading with a 4% drift angle, fracture occurred at a beam-end, having caused a drop of resistance by about 15% (Figures 5(b)). Upon the fracture, however, the forces were distributed immediately, the resistance recovered accordingly, and stable behavior was achieved for further loading. This was a clear indication of the benefit of redundancy.



(a) (b)

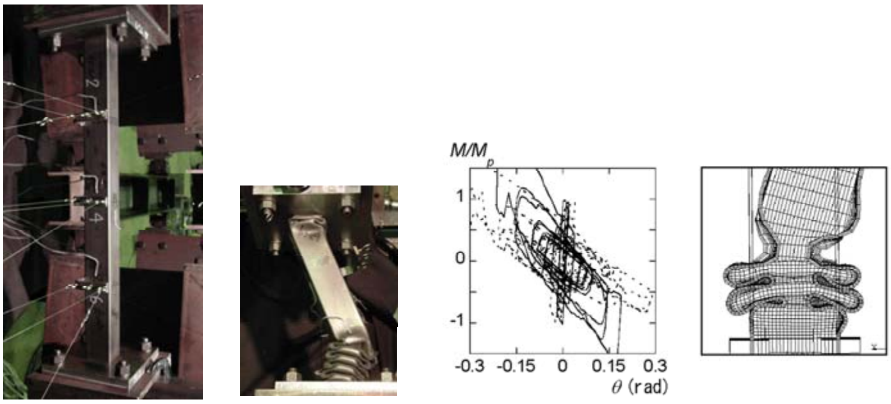
(c) (d)

Figure 5 Test on a three-story steel moment frame: (a) test specimen; (b) beam fracture; (c) comparison with numerical analysis up to medium drift angle; (d) comparison with numerical analysis up to large drift angle

Figure 5(c) shows a comparison between the experimental hysteresis and hysteresis obtained numerically for the cyclic loading up to a drift angle of 4%. The analysis adopted a typical frame analysis with member-by-member representation with concentric plastic hinges. Panel zone behavior was also considered. A very good correlation between the test and analysis is notable, demonstrating the effectiveness of commonly used numerical analyses for the prediction of inelastic behavior of steel moment frames. For larger deformation greater than 5% in the drift angle, the test structure started deteriorating significantly because of the damage to column bases (anchor bolt fracture) and first story columns (local buckling). When the test was terminated at the overall drift angle of 8% (which corresponded to 13% in the first story drift angle), the corresponding resistance was dropped to about 60% of the maximum strength. Figure 5(d) shows a comparison between the test and analysis in large deformation range. Discrepancy is notable toward a very large drift. It occurred, because the analysis did not allow for serious strength deterioration in the column bases and columns.

2.3 Strength of Numerical Simulation

The next example is a test on instability and complete failure of steel columns (Nakashima et al 2005). The tested column sustained a constant vertical compressive force and repeated horizontal shear. Figure 6(a) and (b) show the test specimen before and after the test. The test was continued until the test column could not sustain the gravity, so the specimen at the end was shortened very significantly, involving many rounds of elephant foot buckling. Numerical analyses using finite element codes were carried out to examine the effectiveness and limitations of such numerical analyses. When thick-shell elements were used for the analysis, the correlation with the tests was very reasonable up to a chord angle of about 5%, and the experimental and analytical buckling shapes were in reasonable agreement. When the buckling progressed and contact began between buckles, the analyses with thick-shell elements stopped because of inability of convergence. When solid elements were used instead of thick-shell elements and a contact option was adopted, the analyses were able to trace the contact behavior to a certain extent (up to the formation of two buckles) (Figure 6(c)). The correlation between the test and analysis, however, was significantly different, and the analysis eventually stopped due to the inability of convergence. It is evident from this example as well as the other example on the three-story steel moment frame that numerical analyses are powerful for the simulation of inelastic behavior of structures but still insufficient to guarantee the reliable data on structural collapse and failure that involve serious instability and change in topology.



(a) (b) (c)

Figure 6 Steel column test: (a) before test; (b) after test; (c) comparison with FEM analysis

Considering the issues addressed in this section, i.e., the size effect, rate-of-loading effect, redundancy effect, and effectiveness of numerical analyses, the writer wishes to contend the following: Recalling the critical needs of collapse characterization and performance verification, it is sensible to test structures in the full-scale instead of miniatures, as systems instead of members, loaded dynamically instead of quasi-statically, until collapse instead of mild inelasticity.

3. DEVELOPMENT AND ACTIVITIES OF E-DEFENSE

3.1 Establishment of E-Defense

Stimulated by the 1995 Kobe earthquake, the Government of Japan decided to establish a large experimental facility for the advancement of earthquake engineering. Along this effort, the National Research Institute for Earth Science and Disaster prevention (NIED) administered the construction of a shaking table facility, known as E-Defense (Hyogo 2005). E-Defense was completed in March 2005, and its operation started in April 2005. E-Defense is considered as a facility to test a structure as a whole, in the full-scale, dynamically, and to collapse. The E-Defense table is attached with five actuators in each horizontal direction and supported by fourteen actuators installed vertically underneath the table (Figure 7). The table is 20 m by 15 m in the plan dimension and can accommodate a specimen up to a weight of 12 MN (1,200 metric ton). The unique feature of the table is that this can produce shaking of a velocity of 2 m/s and a displacement of 1 m in the two horizontal directions simultaneously.

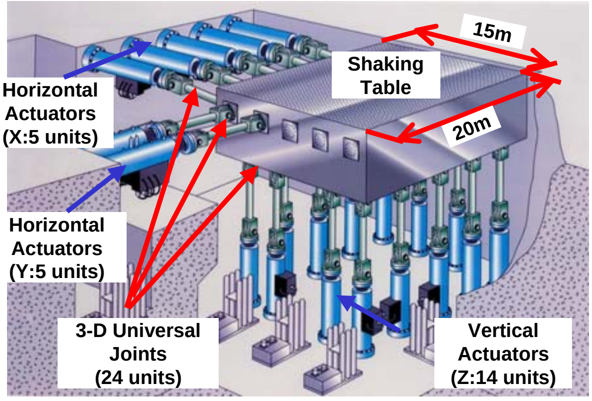


Figure 7 Shaking table in E-Defense

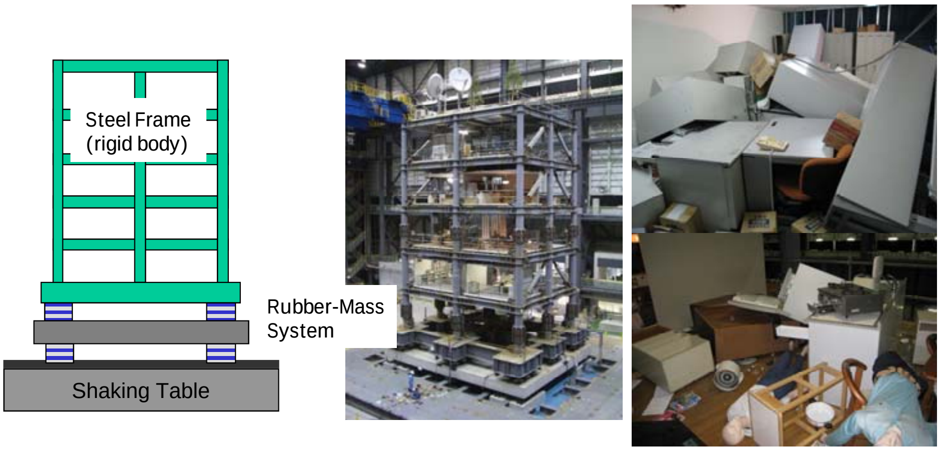
Between 2002 and 2006, E-Defense participated in a comprehensive research project named “Special Project for Mitigation of Earthquake Disaster in Urban Areas” sponsored by the Japanese Ministry of Education, Culture, Sports, Science, and Technology, nicknamed MEXT. In the project, E-Defense conducted a series of shaking table tests for three types of structures. One is wood houses, another is reinforced concrete buildings, and the last is soils and foundations. Notable examples are shown below. A pair of then thirty years old houses, built and used by a private owner living, were tested (Figure 8(a)). The houses were transported from the built-site to E-Defense, and put on the table side by side. One of them was retrofitted following the Japanese retrofit guideline, while the other remained untouched. The JR Takatori motion, the one with 1.2 m/s of the maximum ground velocity and the largest recorded in the 1995 Kobe earthquake, was inputted to the table in all three directions. The retrofitted house was able to endure and escape from collage, while the untouched house lost the fist story completely. This test became a perfect public appeal for the importance of seismic retrofit. A full-scale six-story reinforced concrete building that weighed 10,000 kN (1,000 metric ton) was tested (Figure 8(b)). The specimen were three bays and two bays in the plan, and a shear wall arranged in the mid-bay extended from the bottom to the top. The specimen was designed using the design practice of early 1970s. The unreduced JMA Kobe motion, another large motion recorded in the 1995 Kobe, was inputted in all three-dimensions. The structure sustained serious damage (shear failure) to the first story shear wall and columns. The correlation between the expected damage and observed damage was very reasonable, which demonstrated the effectiveness of our prediction methods. Liquefaction and lateral spreading of a soil-pile-structure system was tested using a huge rigid box (Figure 8(c)). In the test, the unreduced JMA Kobe motion was inputted, and serious failure of the system was reproduced. It was notable that detailed measurements of the pressure distribution along the piles were made possible thanks to the realistic sizes adopted for the piles.

(a) (b) (c)

Figure 8 Large-scale tests conducted after inauguration of E-Defense:
(a) wood house test; (b) RC building test; (c) soil-pile-structure test using rigid box

3.2 Ongoing Research Projects

As stated in the beginning of this paper, large ocean-ridge earthquakes are likely to occur by the middle of this century. One serious concern about such quakes is long-period, long-duration shaking that would hit large cities including the Tokyo metropolitan area, in which several hundred high-rise buildings do exist. Such shaking may produce very large floor responses, characterized by large velocities and displacements, to the structure, which in turn would cause serious damage to nonstructural elements, furniture, and other building contents particularly in upper floors. To reproduce such large floor responses, a special test setup shown in Figure 9(a) and (b) was developed. The test structure was treated as a rigid frame. A two-layer mass-spring system consisting of concrete slab and rubber bearings were inserted between the rigid frame and shaking table. This system served as an amplifier of the table motion to the level of floor responses expected in upper floors of high-rise buildings. Here, the input motion to the table had to be carefully adjusted so that the motion would reproduce the desired floor response on the rigid frame placed on the table. The test was conducted with various types of furniture placed on the specimen's floors; the maximum floor responses of 1.3 m in the displacement and 2.4 m/s in the velocity were achieved; and serious damage to the contents (Figure 9(c)) was investigated. A critical need of clamping the furniture against sliding and overturning became very evident from the test.



(a) (b) (c)

Figure 9 Test for reproduction of floor responses in high-rise building:
(a) amplification system; (b) test frame; (c) damage to furniture

Another special setup shown in Figure 10 was developed to reproduce earthquake responses of steel high-rise buildings subjected to ocean-ridge earthquakes, this time for the investigation of structural performance and damage. Under severe cyclic loading, structural components in such buildings, particularly beam-to-column connections, may be damaged seriously as a result of low-cycle fatigue. In the setup, a multiple-layer mass-spring-damper system was placed on the top of the physical test frame that represented the lower portion of the prototype structure. The addition of the mass-spring-damper system made it possible to match the vibration characteristics such as the natural periods between the prototype and test structure. Synthesized ocean-ridge motions were inputted to the test structure, and responses of 2.2 m/s and 1.0 m in the maximum velocity and displacement were achieved. The test provided us a set of unprecedented data on the seismic performance of high-rise steel buildings.

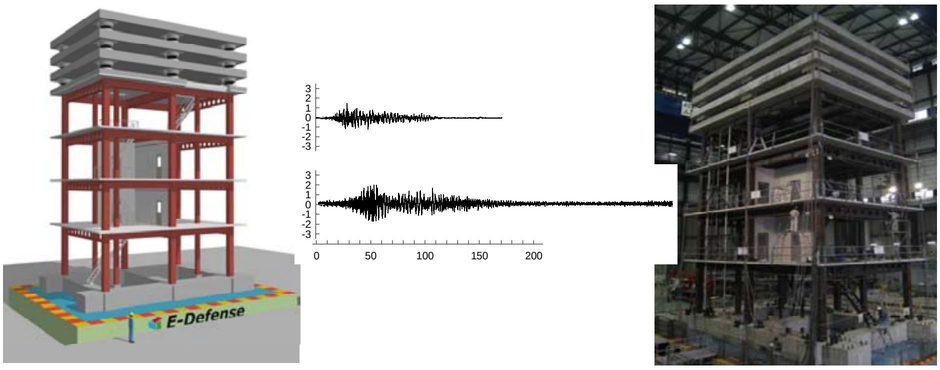


Figure 10 Test for structural performance of high-rise building

3.3 International Collaboration

In the USA, the idea of developing a national network of research laboratories grew in the early 1990s, and those efforts culminated in the development of the George E. Brown Network for Earthquake Engineering Simulation (NEES) in 1999 (George 2005). In the initial phase of this development, fifteen large experimental facilities were chosen at various sites, and their installation was completed in 2004. Earthquake disaster and its mitigation is a very critical problem in both countries; both NEES and E-Defense facilities have similar missions and functions in research of mitigation of earthquake disasters, and the two countries have a very long history of collaboration on earthquake engineering research and practices. In consideration of these, a very natural conclusion was the research collaboration through complementary usage of the two facilities. Since 2004, the research communities in the USA and Japan discussed extensively on visible and close research collaboration and reached an agreement that steel buildings and bridges would be the immediate targets of collaboration. On the Japanese side, NIED established a five-year project focused on the collaboration, and in compliance with the agreement, two theme projects were formed in 2005: E-Defense Steel: Advancement of Steel Building Structures and Innovative Systems, and E-Defense Bridge: Performance Evaluation and Upgrading of RC Bridge Structures.

E-Defense Steel has set up three types of tests. One is a collapse test of a four-story steel moment frame. Second is a series of tests using a five-story model frame equipped with various types of dampers. The third is another series of tests applied to innovated systems using a newly developed TestBed, which provides inertial forces to the test structure in a versatile manner. Among the planned tests, the collapse test was completed successfully in the fall of 2007 (Figure 11(a)), and accuracies of numerical analyses to trace the behavior of the structure involving severe nonlinearities, damage, and collapse were examined. E-Defense Bridge has set up two types of tests. One is a series of tests on single RC bridge piers designed with obsolete design practice. The other is a bridge model supported by multiple RC piers, also designed using old practice. In both tests, existing performance will be checked, and the effectiveness of retrofit will be evaluated. The very first single pier test was completed successfully in the winter of 2007 (Figure 11(b)), and the failure that was similar to that observed in the 1995 Kobe was reproduced.

E-Defense has completed a total of twenty-six experimental projects featured with large-scale test specimens during the past three years from the inauguration of E-Defense (April 2005) to March 2008. Regarding the international collaboration, a seven-story wood house test conducted in 2007 with an Italian research team is also notable.

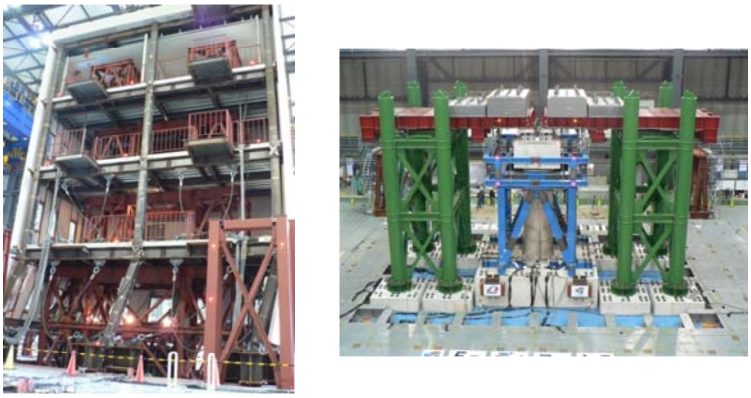

(a) (b)

Figure 11 NEES/E-Defense collaboration:
(a) collapse test on a four-story steel moment frame; (b) RC bridge pier test

4. CONCLUDING REMARKS

The paper touched upon three issues in earthquake engineering. First, the earthquake threat of Japan is briefly introduced, followed by a discussion on the critical needs of collapse characterization and performance verification. Second, benefits of large-scale structural tests are discussed in terms of the size effect, rate-of-loading effect, redundancy effect, and effectiveness of numerical analyses. The writer believes that it is sensible to test structures in the full-scale instead of miniatures, as systems instead of members, loaded dynamically instead of quasi-statically, until collapse instead of mild inelasticity. Third, the development of E-Defense is presented, and previous and ongoing research projects using large-scale test specimens are introduced. Many of the results obtained from those projects are to be presented in the Fourteenth World Conference on Earthquake Engineering (14WCEE).

E-Defense is a very large shaking table, probably the largest in the world as of today, but we are in no manner boasting about the size of E-defense. Our organization (NIED) fully understands that “large” is not synonymous with “good.” After all, good and useful research is achieved only through intellect and enthusiasm of the participants in the test. To this end, NIED tries its best to recruit as many experts available in Japan and overseas as possible for research projects conducted at E-Defense, and wishes to implement community-based research that involves all layers of researchers and professionals engaged in earthquake engineering. NIED also sets up a goal of collaboration within the international community of earthquake engineering by the timely discloser and sharing of the data obtained from the tests in E-Defense, thereby trying to contribute the advancement of earthquake engineering and the mitigation of earthquake disasters in all regions that are prone to earthquake disasters.

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