WISE DYNAMIC TESTING FOR KNOWING STRUCTURES MORE

Akira Wada[1], Mineo Takayama[2] and Satoshi Yamada[1]

ABSTRACT

In this decade, large shaking tables were installed at the UC San Diego in USA and the E-Defense in Japan. The bed of the E-defense can support 1200 metric tons and 20m tall structures. This is very large comparing to the past facility and is very strong machine, but actual buildings are bigger and taller than the one that could be on the table. Total weight of a tall building will be heavier over 100,000 metric tons and height of a tall building is higher than 300m in Japan and 800m in the world.

Researchers can test only 5 story buildings at the E-defense and test 10-story buildings but very small floor area at the UCSD. We cannot test actual buildings. Then, we need new wise ideas for understanding and knowing the behaviors of actual large structures due to large earthquakes. We will discuss the history of Japanese researches and introduce 4 wise and innovative dynamic tests.

EARTHQUAKE ENGINEERING GROWING BY PAST SEVERE DISASTERS

Before Galileo Galilee had written “Two New Sciences”, the first textbook of structural mechanics about 370 years ago, we have not any equation for knowing strength of a beam or a column, but humankind is wise and has some intuition. Old carpenters or old contractors could built very beautiful buildings and architectures such as Pyramids in Egypt, Parthenon in Greece, Pantheon in Rome or 5 story pagodas in Japan and so on more than 1000 or 2000 years ago. These buildings have very good performance for a long time, but many buildings were also collapsed by many reasons. In some cases, engineers in the ancient time learned better construction technology by observing collapses and failures. In the 20th century, we have had many severe earthquake disasters and we have learned much from these events and understood the structure behavior better under earthquakes.

a. Building structures have to have adequate lateral strength.
b. Structural members and total structures have to have some deformability.
c. A structure has to have enough integrity.
d. Supporting own gravity weight after an earthquake is fundamental importance.
e. Location of construction, soil condition, and foundation are also fundamental importance.
f. Soil-structure interaction has significance influence to a response of a structure. In some cases, beneficial effect would be, but other case, adverse effect would be to the responses of the structure.
g. A pattern of maximum response of story shear forces could be defined for an earthquake event, but it also changes due to characteristics of earthquakes such as frequency content. The enemy cannot be defined in our science.
h. Strong columns and weak beams structure is preferable.
i. Strong shear-walls or steel braces are very effective to increase seismic capacity.
j. Negative slope of stiffness makes a structure instable.

---

[1] *Structural Engineering Research Center, Tokyo Institute of Technology; Yokohama, Japan*
[2] *Department of Architecture and Building Engineering, Fukuoka University; Fukuoka, Japan*

k. Not only horizontal movements but also rotation along Z-axis has strong effect to collapse behavior of a structure.
l. Joints of beam to column or joints of brace to beam-column are very important. Details are very important.
m. Supplemental damping devices increase a seismic capacity. Passive controlled structure is one of good seismic structure examples.
n. Seismic isolation is also one of good seismic structure examples
o. Three important roles of seismic design are 1) Preventing collapse of building to save human life, 2) Reparable structure after an earthquake to keep a building property, 3) Keeping a function of building to reduce business interruption due to an earthquake. If possible, we, structural engineers, want to make a building that can cover these three roles.
p. Expectation of public for a good earthquake performance is growing up year by year.
q. Resilience of life, city and country is next important words for structural engineers.

ENGINEERS MUST KNOW WHAT WILL HAPPEN BEFORE IT HAPPENS

Structural engineers want to know how a building behaves when an earthquake hits it in future. They have to know what will happen in the building that they are designing and building. We can test beams, columns and joints of these members taking a part from actual building structures. When we have enough research money, we can test two-story to several story of whole building structure. Regretfully, we cannot test more than ten story-building structures, since we have not large enough testing laboratory in the world.

We have an analytical approach using high-speed computers to be able to know the structural behavior under earthquake loadings. When we can grasp the mechanical properties of structural members and structural frames through the results of individual component tests, we can make a mathematical nonlinear model in the computer. Calculation itself has not any problem now, because that we can use high-speed and large-capacity computers. Then we can get a lot of information from the calculated results.

The structural test is the induction process, but the numerical analysis is the deduction process. The structural design is also deduction process and synthetic approach. This is very important. We are using many engineering products such as mobile phones, automobile cars, airplanes and so on, these products are made by mass-production and these functions are checked right after when consumers start to use. On the contrary to these products, building structures are made individually. Since a severe earthquake may be occurred rarely, actual performance can be revealed only when the earthquake happens.

Humankind has built many buildings and many big cities. But not all we have done are based on our experiences. Then we have to know what will happen in the actual building structures in future earthquake event by any possible ways before any troubles happen. The static tests and the dynamic tests should give us a lot of important information and important knowledge.

AIMS OF STRUCTURAL TESTS AND NEEDS OF REALISTIC TESTS

As discussed above, the structural tests give us important knowledge and many ideas. We do not need to explain more why we do structural tests. Structural materials such as concrete, steel and other materials can be changed to increase strength. Structural engineering is a field of design works and, the innovative engineers will make new structures or new structural systems beyond those we had past. Then we have to test the structures or new structural systems.

a. Understanding and knowing the structures better.

b. Making safer structures, more economical structures and higher performance structures.
c. Finding weak point of our structures before an actual earthquake hits them.
d. Avoiding failures and increasing the reliability of the structures.
e. Getting the government permission of new ideas.
f. Making a design guideline, a design standard and a design code.
g. Increasing sympathetic friends of engineers and researchers understanding about new ideas and new deign.
h. Persuading the building owners about our design and persuading general public about new ideas.
i. Increasing understanding of the structural behavior for young students and young engineers. The experimental test is good experience for young people.

For these aims, realistic dynamic tests are most effective method and they have strong visual persuasive power. In this paper, we would like to introduce some examples of our researches in last 30 years.

TINY SEISMIC ISOLATED STRUCTURES WITH HORIZONTAL HEAVY INERTIA MASSES

Professors Hideyuki Tada and Mineo Takayama have tested tiny seismic isolated structures using also small shaking table in October 1982. 4 rubber bearings were supporting one floor and the diameter of the rubber is only 30mm. Fundamental natural period is too short because that the floor is light and stiffness of rubber is little high. In many cases, small specimens have short natural period. At that time, they could not capture the typical behavior of seismic isolated structures. They needed heavy horizontal inertia weight. Then, 5 metric-tons iron weight hanged from crane was connected to the side of the specimen. Fundamental natural period of the total system become long enough to show the dynamic behavior of seismic isolated structure as shown in Photo-1 and Photo-2. Next step, the same research group has done 5-story seismic isolated structure using same idea as shown in Fig-1. This system has 5-separated horizontal inertia masses hanged from the high tower in the laboratory.

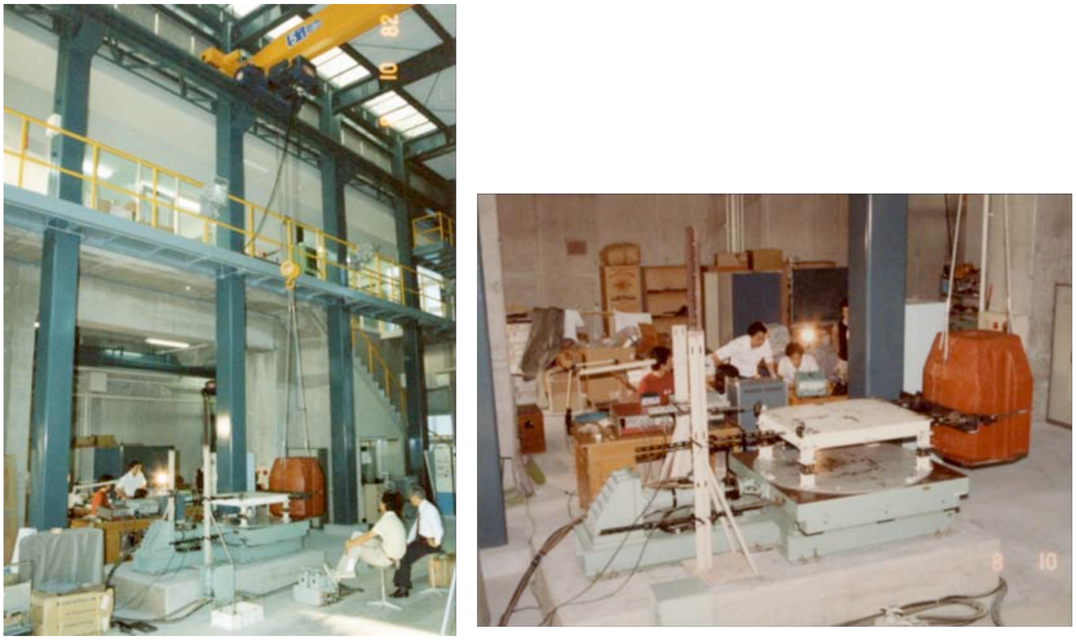

Photo 1. and Photo 2. Tiny seismic isolated structure with heavy iron weight

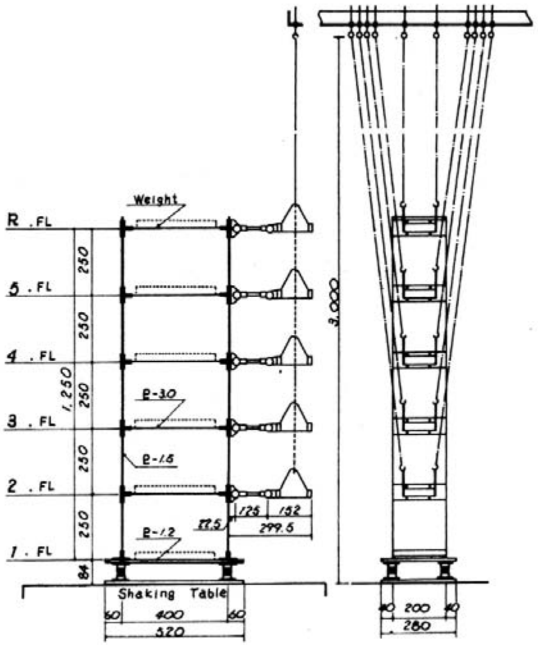

Fig. 1. 5-story seismic isolated structure and 5-horizontal inertia masses

SEISMIC RETROFITTED REINFORCED CONCRETE FRAMES ADDED SUPPLEMENTAL DAMPERS

The research team of Dr. Masanori Iiba and Professors Satsuya Soda, Eiichi Inai, Hiroshi Kuramoto and Akira Wada has done reinforced concrete frames having supplemental dampers with horizontal inertia mass set on 4 flexible rubber bearings at the large-scale earthquake simulator of the National Research Institute for Earth Science and Disaster Prevention in 1998. The reinforced concrete frames we tested were designed by old Japanese building code and seismic capacities were not adequate. But we could get many useful data and BBC took a film of our tests and broadcasted to the world through the program called “Tomorrow’s World”.

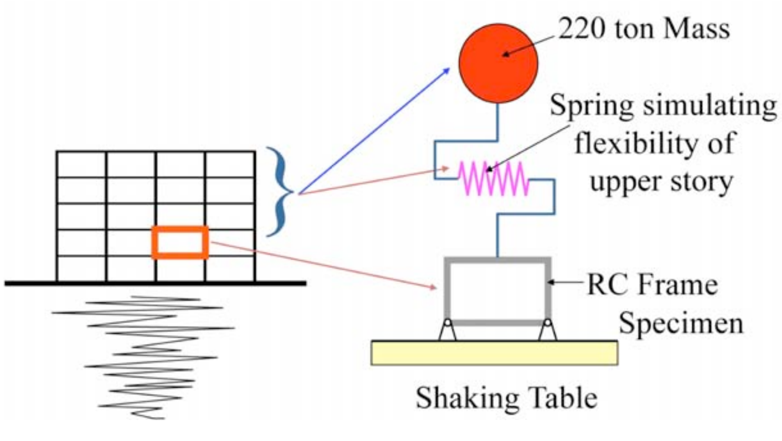

Fig.2. Additional mass and flexibility

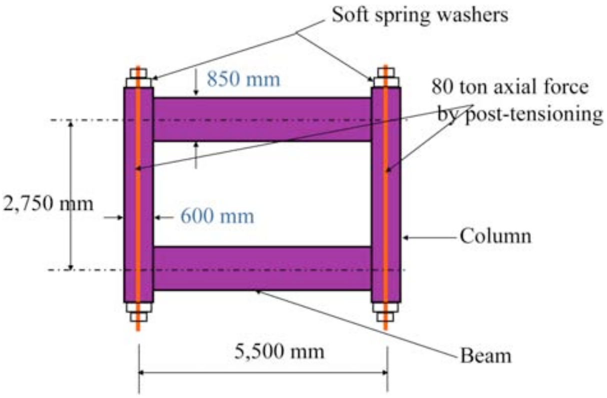

Fig.3. Introduction of column axial forces

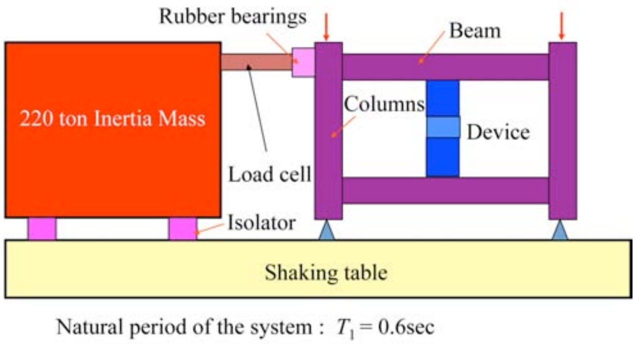

Fig.4. Elevation view during test

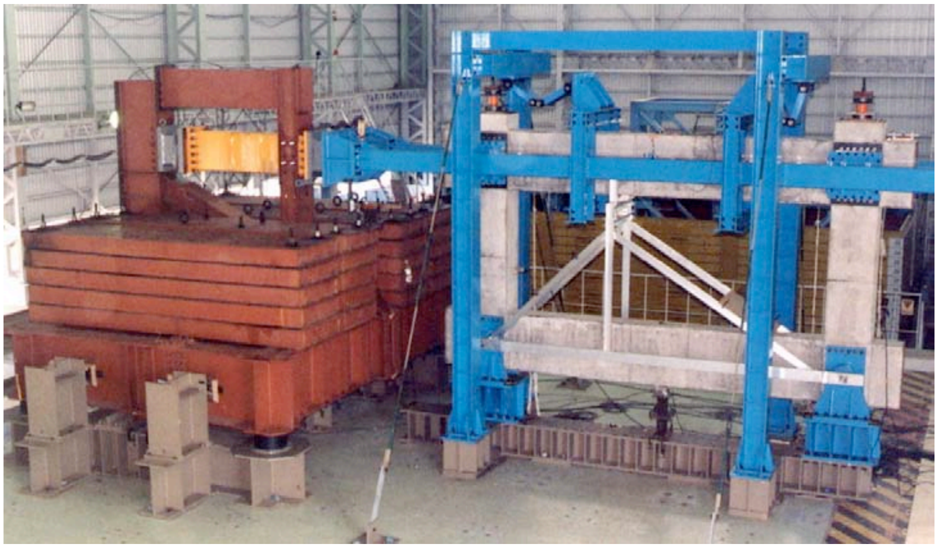

Photo 3. Very heavy steel inertia weight and reinforced concrete frame

PASSIVE CONTROLLED STEEL FRAMES WITH HORIZONTAL INERTIA MASS

The research team of Professors Satoshi Yamada, Masayoshi Nakashima, Toru Takeuchi and Akira Wada has done steel frames having supplemental dampers with horizontal inertia mass hanged from the crane beam at the shaking table of the Disaster Prevention Research Institute, Kyoto University in 1999. We tested only one story frame taken from a several story steel frame. Horizontal weight simulates other part of story of the original building. Soft spring made of rubber bearings simulates flexibility of other part of the original frame. Total system composed of the specimen frame, soft spring and horizontal mass has 0.6 natural period. We could test many frames using this system with not much research money.

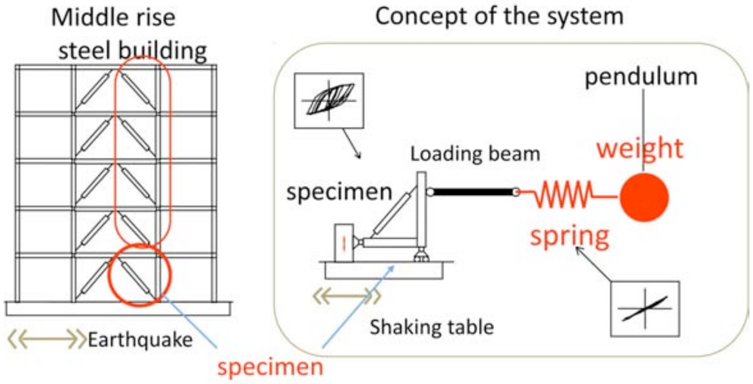

Fig.5. Model steel frame and a specimen with inertia weight and spring

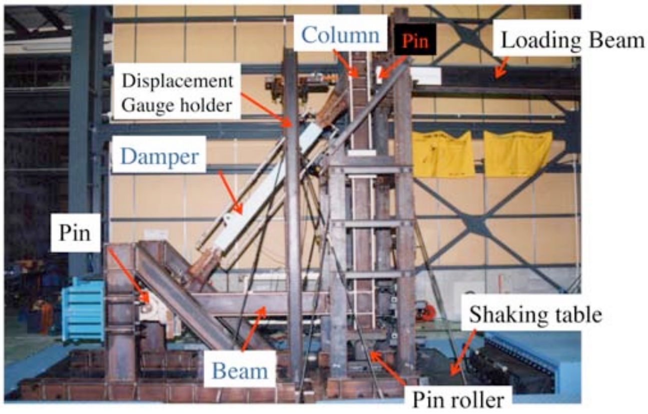

Photo 4. Beam, column and buckling restrained brace on the shaking table

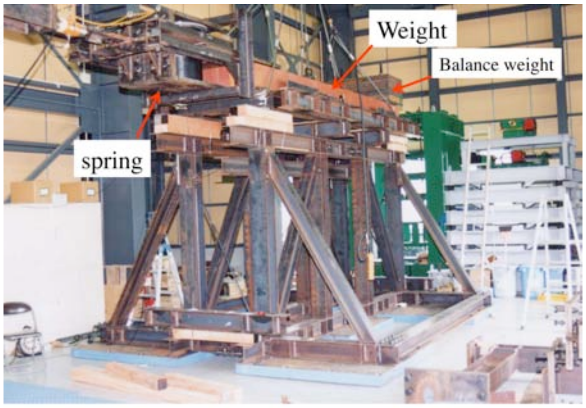

Photo 5. Inertia iron weight and spring of 2 rubber bearings

COLLAPSE TESTS OF VERY SMALL STEEL FRAMES IN HIGH GRAVITY CIRCUMSTANCE OF CENTRIFUGE MACHINE

The centrifuge machines have been used for the static or dynamic stability tests in the research field of soil mechanics and foundation engineering. When the specimen size is 1/10 of the actual scale of a structure, total weight of the structure become 1/1000, but sectional area of the member is only 1/100. Then, stress level become 1/10 of actual stress in the structure. Nonlinear effect of the structural member cannot be treated correctly in the 1/10 specimen. P-delta effect becomes also very small when the specimen's weight is too light. The research group of Dr. Hideo Katsumata, Professors Satoshi Yamada and Akira Wada have done the collapse tests of very small steel frames in the very high gravity circumstance of centrifuge machine at the Technical Research Institute of Obayashi Corporation. 3, 12 and 30 story steel frames have tested here. The centrifuge could produce 100G gravity and the testing container could have a 2m high specimen. We could test 200m tall buildings using this strong machine theoretically. Since the scale of a specimen is 1/100, it was very difficult to make the specimen precisely.

Photo 6. Big centrifuge and container at the Obayashi Technical Research Institute

3-Story week columns and strong beams steel frame

The first try was a test of a 3-story steel frame shown in Fig.6 and Photo 7. The frame had 4 columns in every floor, sectional shape of all columns was 1mm thickness and 20mm diameter tube. Beams were very strong. Then, the shear capacity of each floor was equal. We took the test under 30G and shake the container horizontally. Finally, the columns at ground floor were broken, just after that, second and third floor collapsed. Most dangerous collapse mode was happened. We took several valuable video movies.

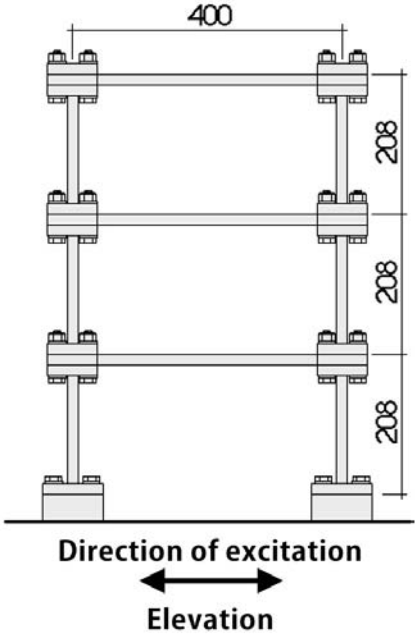

Fig.6. 3-story steel frame composed of 4 tube columns and 4 rigid beams

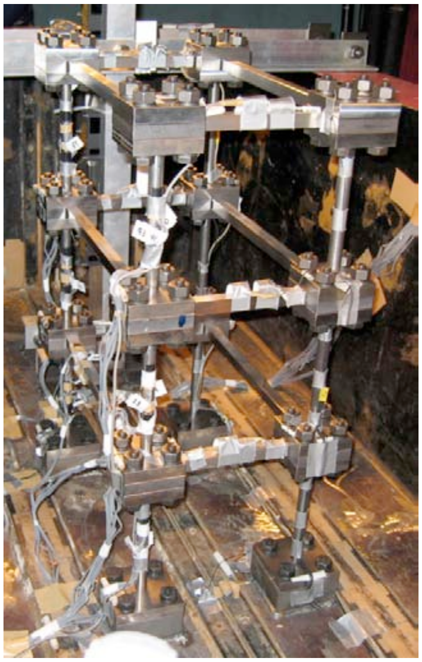

Photo 7. 3-story steel frame in the container of the centrifuge machine

12-Story strong columns and week beams steel frame

The second try was 12-story frame. The frame was made as weak beams and strong columns structure. We took the test under 60G and shake the container horizontally. It had perfect vibrations under medium horizontal acceleration. Next, we applied large horizontal acceleration to the container, then the frame become unstable as shown in Photo 9. Finally, the whole frame was perfectly collapsed as shown in Photo 10.

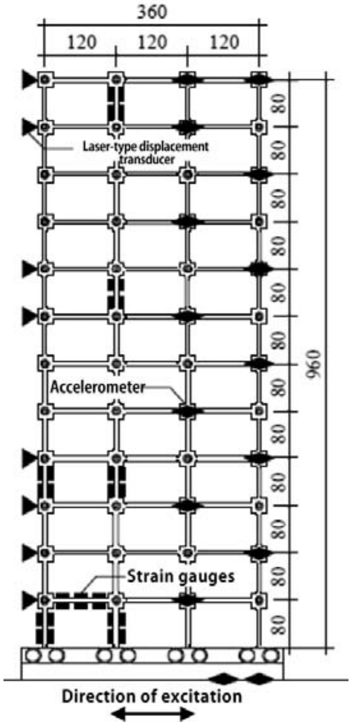

Fig.7. 12-story steel frame

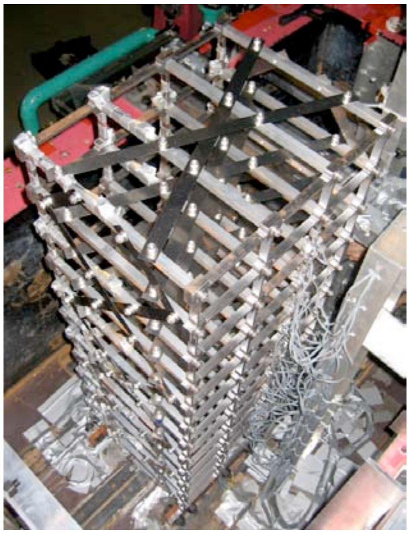

Photo 8. 12-story frame in the container

Photo 9. Loss the stability of frame just before collapse

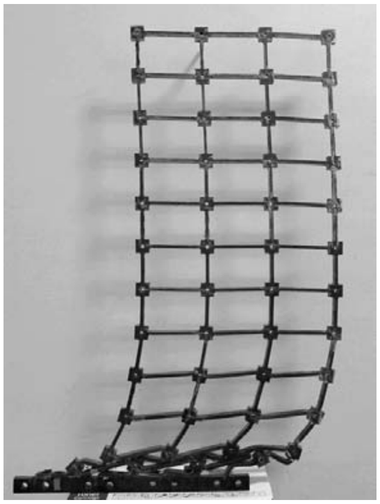

Photo 10. Final collapse of 12 story frame

30-Story steel frame having center wall and strong outrigger beam

The third try was 30story frame having a center wall and a strong outrigger at middle hight. We took the test under 60G and shake the container. The relationships of story shear and story deformation getting from the test were very beautifull, almost all stories yielded and ductility factors were around 2 to 3. The center wall and the outrigger were very effective to control the vibration mode. These members should increase the seismic capacity of the building structures.

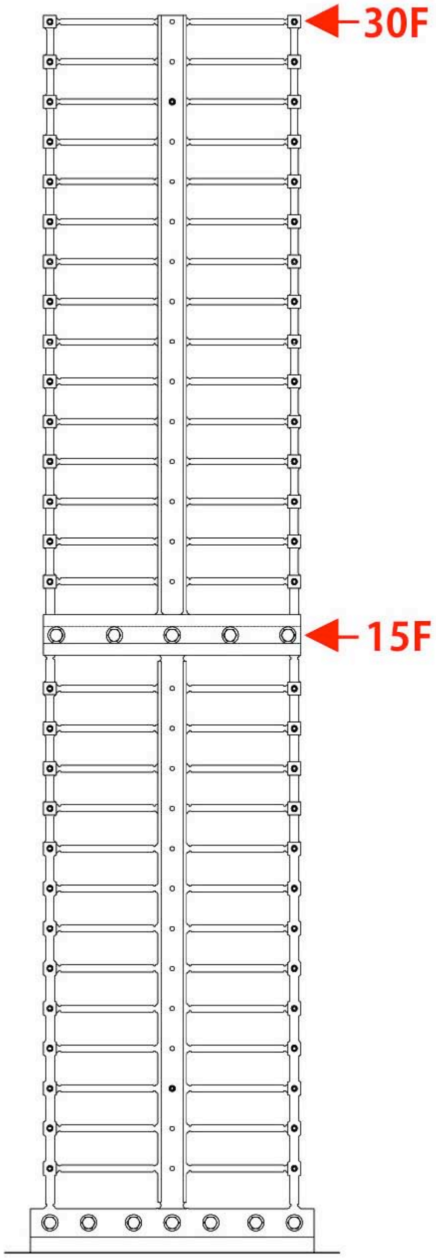

Fig.8. 30-story steel frame

Photo11. 30-story frame

CONCLUSIONS

Actual buildings become bigger and larger every year, and many cities in the world are growing larger every year. Structural engineers must engineer safer buildings and safer cities for people. We have to know how the structures behave under strong earthquakes. We need to do not only the static structural test but also dynamic test. But often, the test facilities have some limitation. Researchers and engineers have to use these facilities under the combination with deep thinking and innovative ideas.

After the Loma Prieta Earthquake in 1989, many professors and engineers discussed about the performance based earthquake engineering. Japan experiences 20% of strong earthquakes in the world, but only 1% to 2% buildings are constructed by using seismic isolation or passive controlled devices. We need to promote these new technologies and increase the number of practical applications in not only Japan but also in all countries exposed to the earthquake risk.

REFERENCES

Iiba, M., Inai, E., and Kuramoto, H. 2002. Full-scale shaking table tests on dynamic failure of reinforced concrete building using old seismic regulation. *Journal of Structure Construction Engineering.* Architectural Institute of Japan. Tokyo, Japan. (in Japanese)

Iiba, M., Inai, E., Kuramoto, H., and Wada, A. 2005. Shaking table tests on partial full-scale reinforced concrete frames with shear failure in colimns using inertial loading equipment. *Proceedings, The First International Conference on Advances in Experimental Structural Engineering.* Nagoya, Japan.

Kuramoto, H., Iiba, M., and Wada, A. 2002. A seismic evaluation method for existing reinforced concrete buildings retrofitted by response controlling techniques. *Journal of Structure Construction Engineering.* Architectural Institute of Japan. Tokyo, Japan.

Tada, H., and Takayama, M., et al. 1983. Small model tests of seismic isolated structures. *Summaries of Technical Papers of Kyushu Chapter Architectural Research Meeting,* Architectural Institute of Japan, Fukuoka, Japan. (in Japanese)

Yamaguchi, M., Yamada, S., Ogihara, M., Ogihara, M., Narikawa, M., Takeuchi, T., Maeda, Y., and Wada, A. 2000. Earthquake resistant performance of moment resistant steel frames with damper. *Proceedings, Behavior of steel structures in seismic areas.* STESSA2000. Montreal, Canada.

Yamaguchi, M., Yamada, S., Maeda, Y., Ogihara, M., Takeuchi, T., Narikawa, M., Nakashima, M., and Wada, A. 2001. A shaking table test procedure simulating earthquake responses of actual structures -Seismic performance of moment resisting steel frame with damper part 1-. *Journal of Structure Construction Engineering.* Architectural Institute of Japan. Tokyo, Japan. (in Japanese)

Yamaguchi, M., Yamada, S., Maeda, Y., Ogihara, M., Takeuchi, T., Narikawa, M., Nakashima, M., and Wada, A. 2001. Evaluation of seismic performance of partial frames using the shaking table test -Seismic performance of moment resisting steel frame with damper part 2-. *Journal of Structure Construction Engineering.* Architectural Institute of Japan. Tokyo, Japan. (in Japanese)

Wada, A., Yamada, S., Takazawa, M., Seki, M., Katsumata, H., Higuchi, S., and Okuda, H. 2006. Earthquake collapse tests of miniature steel frame model using large centrifuge machine. *Proceedings, 8th U.S. National Conference on Earthquake Engineering, 100 Anniversary Earthquake Conference.* San Francisco, California.