Shaking Table Tests to Simulate Earthquake Responses of Passive Control Structures

Michio Yamaguchi
Graduate Student, Tokyo Institute of Technology, Yokohama, Japan

Satoshi YAMADA
Associate Professer, Tokyo Institute of Technology, Yokohama, Japan

Masayoshi Nakashima
Kyoto University, Kyoto, Japan

Akira WADA
Professer, Tokyo Institute of Technology, Yokohama, Japan

ABSTRACT: In this paper, an experimental method of shaking table test on partial moment resisting steel frames is discussed. This experiment system, shown in Fig.1, consists of a Mass, a Spring, a Loading Beam, a Specimen and a Shaking Table. By this composition, the natural period of this experiment system is about 0.7-0.8 second which value is nearly the same as middle rise steel buildings. Features of this experiment system are as follows.

1. This experiment method can estimate the response of partial frame against Real Time Speed Earthquake.
2. This method approximately reproduces an earthquake resisting behavior of the partial frame.
3. It is possible to effectively utilize the performance of small and medium size shaking table.

1 INTRUDUCTION

After two big earthquakes, Northridge and Hyogoken-Nanbu occurred in 1994 and 1995, it became popular to require much seismic performance for structures. Moreover, in recent years steel materials for structures varied form low yield strength steel to high yield strength steel and these materials have been adapted to strengthen structures as well as viscosity and viscoelastic materials.

With this background, A. Wada is suggested the concept of Damage tolerant structures (A. Wada 1991). This structure consists of main frames and seismic members. Main frame only support the vertical load and remains elastic during earthquakes. While input earthquake energy is concentrated and absorbed by seismic members. This kind of structure has a lot of advantages such as: better seismic performance, more economic, large life span, environmentally friendly and so on.Recently, many studies for various damping devices have been taken (such as Y.MAEDA 1998 and E.SAEKI 1996 A.WADA 1997). However, member tests by means of fixing within the frame is not so many (E.SAEKI 1996 and K.KASAI 1997). A behavior of an actual building during earthquake that is most important to grasp is normally done by means of analytic tools. Though real behavior of frames and damping devices with elastoplastic ranges are very complicated. Therefore, it needs to understand the behavior of frames under shaking table test to simulate real earthquake.

2 METHOD OF EXPERIMENT

In common cases, shaking table tests are carried with specimens of partial frame model, input wave is modified a lot on time history domain. It is compressed on time history in order to fit in frequency spectrum for that natural period shortened. In this case, with such method, strain rate is different from that of real behavior in structures. Especially in the case with damping device that depends on velocity, the response behavior is a completely different matter.

In order to solve these problems, the experiment system using shaking table tests is proposed in this paper. The concept of this system is show in Fig 2-1. And outline of this system is shown in Fig.2-2 and Photo.2-3. This experiment system corresponds to actual buildings. This system consists of a weight, a spring, a loading beam, a specimen and a shaking table. The weight simulates the weight of the upper part of the model building. A spring is connected to the weight and the loading beam by series methods. And a spring simulates the stiffness of upper part of the building. By these compositions, the natural period of this experiment system is about 0.7-0.8 seconds, which is nearly the same as the natural period of a medium rise steel building. Such a system decreases a scale down effect of a partial frame specimen by setting a natural period. Visualized earthquake resistant behavior makes easy to understand the superiority of damage tolerant structures because of real time speed.

The major part of weight is a row slab whose weight is

about 10 tonf. In addition, balance weights and safety devices are included. Total weight of the system is about 16.0 tonf. The weight is hanging like a pendulum with wire ropes. This hanging technique makes shaking table release from a restriction under a gravity load, especially for small and medium size shaking tables. The weight produces inertia force while the shaking table test.
As for the spring, This spring consists of two isolators that arranged in parallel. Shear deformations are indicated in Fig.2-4. The stiffness of elastic spring is 10.0kN/mm. Deformation limit is 25.0cm.

The specimens are1/2 span and half size scale model, which is picked up from a building. The beam (literal member) end is supported on a pin condition and near beam-to-column connection is supported on a pin-roller condition. A connection between a specimen and loading beam, which is wide flange beam, is used split-T that connected with bolts. (Fig. 2-5) The split-T is connected to web member of loading beam. The rotation stiffness is much smaller than that of other part of experiment system. Therefore, this connection is dealt with as a pin support. Another end of the loading beam is in connected too.

In this test, shaking table is used as single degree of freedom system. There are some devices to prevent out-plate displacements in the experiment system. These are shown in follows.
1.Two pins are arranged in parallel at the end of a specimen. This technique is a role to enhance stiffness against another degree of freedom.
2.Middle part of the column, steel plate with a teflon sheet is welded. If it occurs out-plate displacement, it plays a role to restrict extra deformations.
3.The loading beam is restricted by an equal technique.
4.The weight is supported with four rollers, which are very tough and restricts extra deformations.
Attention to a safety of this shaking table tests, it is constructed a safety devices. Its outline is indicated in Fig.2-6. The mechanism is that O-section bars absorb energy of the system to be deformed by a wide flange beam connected to be the weight, if it occurred extra deformations.

3 SPECIMENS (shapes and performance)

Tests were taken with two types of specimens, Moment Resistant Frame 1 (M.R.F.1),show in Fig.3-1, using ordinary so far and Moment Resistant Frame 2 with Hysteretic Damper (M.R.F.1 with damper),show in Fig.3-2.

Table.3-3 sections of the elements

	M.R.F.1	M.R.F.2(with damper)
Beam	BH-340x200x 6x 9	BH-240x170x 6x 9
Column	BH-280x280x12x22	BH-220x220x12x19
Yielding Steel Core	-	25x16

Specimens are partial frame models that are divided from a vertical steel building. Considering symmetry of buildings, 1/2 span half-size scale model is used. The length of beam member (literal member, Lb) is 2000mm; the length of column (vertical member, Lc) is 2500mm. Both members have H-section (shown in Table.3-3)
The connection panel is reinforced with double plates. In order to prevent local buckling, three pieces of stiffeners are arranged with equal distance in beam-to-column connection.

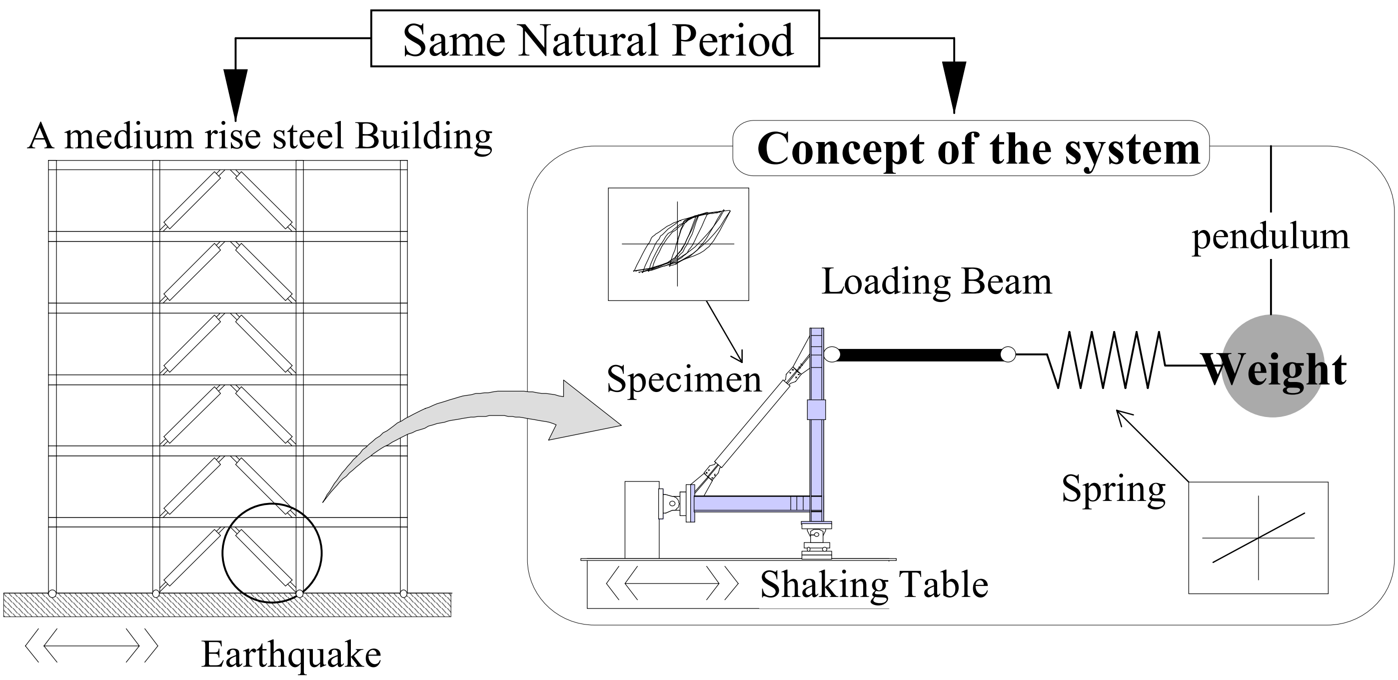

Fig.2-1 Concept of the experiment system

Non-scallap detail is applied for beam-to-column connections. Because it is paid no attention to great earthquakes that it occurs fractures at beam-to-column connections. A damper is a Hysteretic and brace type damper. It is called “unbonded brace”. The mechanism of unbonded brace is shown in Fig.3-3. The unbonded brace

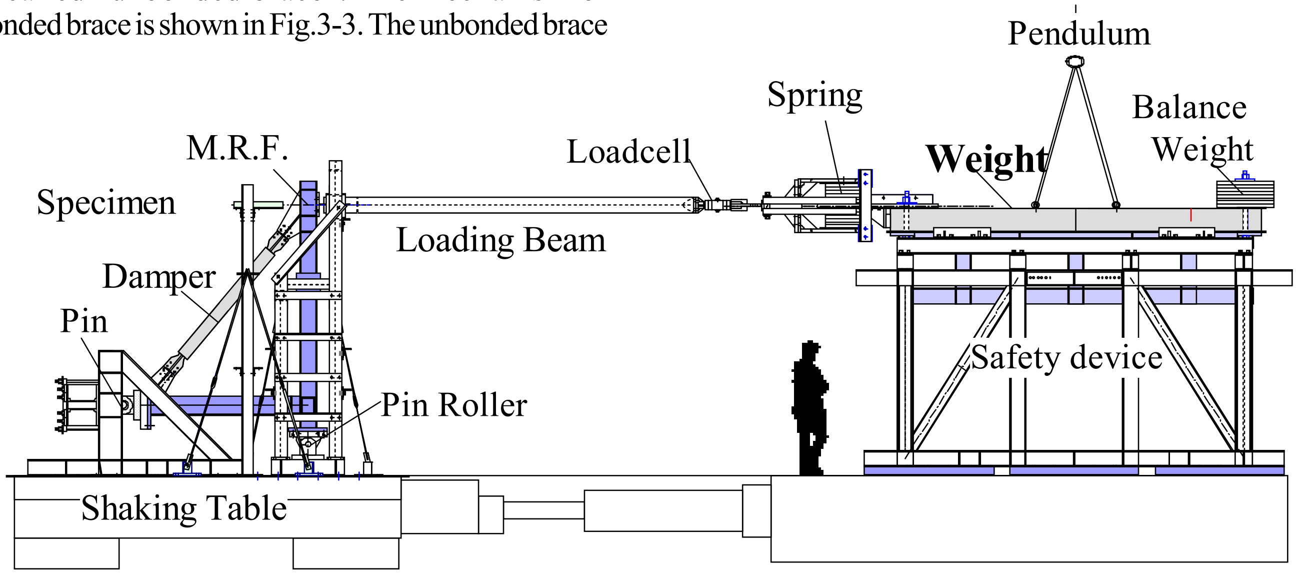

Fig.2-2 Outline of the experiment system

Photo.2-3 Experiment system

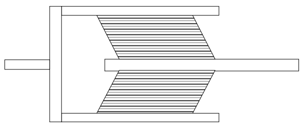

Fig.2-4 Spring

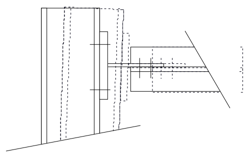

Fig.2-5 Pin joint

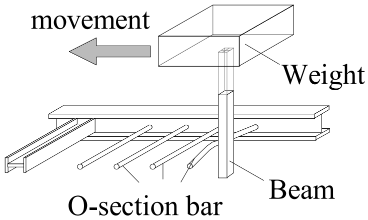

Fig.2-6 Outline of a safety device

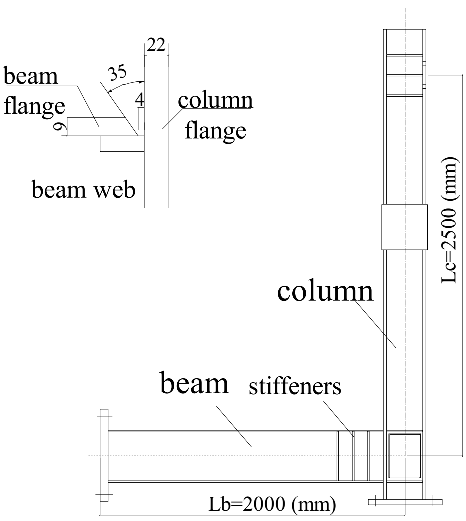

Fig.3-1 Specimen of M.R.F.1

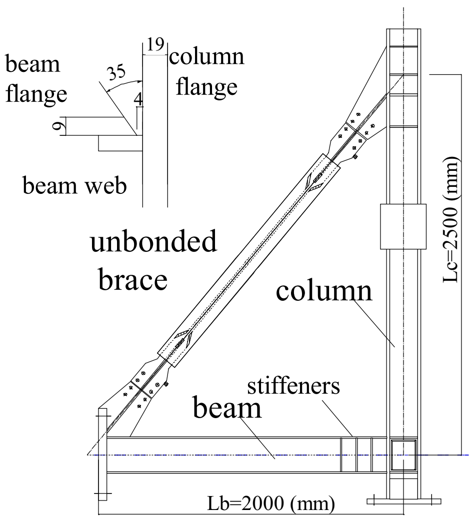

Fig.3-2 Specimen of M.R.F.2 with damper

used in this experiment is shown in Fig.3-4. This is to prevent Euler buckling of central steel core by encasing it over its length in a steel filled concrete or mortar. Therefore unbonded brace provides a stable behavior in both sides of tension and compression.

Table.3-5 shows the mechanical properties of material of specimens obtained from tension tests.
In this test, upper limit of resisting force is as 15 ton for performance of shaking table.For a yielding steel core of the unbonded brace, it is selected low yield steel (BT-LYP100) which is able to expect an energy absorption in ranges of small amplitudes, so its yield strain is very small.

Fig.3-6 shows resisting force-displacement relation of both specimens. The curves are obtained from analysis.

Design points of specimens to which we pay attention in the case designed cross section are shown as follows.

1.Shear forces at yield point of both specimens are designed equally (about 90 kN).

2.Shear ratio with horizontal resisting force between M.R.F.2 and damper is about 1:1.

3.M.R.F.2 is designed to have large elastic ranges, compared with M.R.F.1, therefore its section depth beam and column are slender.

4 ABOUT IMPUT

4-1 Shaking Table

The Shaking table, used in this test, is medium size and belongs to the Disaster Prevention Research Institute, Kyoto University. This table has six degree of freedoms. In this test, however, it is used as single degree of freedom system by means of fixing other 5 degrees of freedom. Fig.4-1 and Fig.4-2. show the performance curve of this shaking table concerned with Acceleration-Period relation and with Velocity-Period relation.

At first, we assume the weight of a Mass to be15 tonf. In attention to ranges 0.7-0.8sec (in Fig.4-1. gray zone) which is natural period of this system considering an expansion of period by plasticity. We recognize that this shaking table has sufficient capacity to shake table so far as 1.0 G. In order to inflict much damage to specimens, it is required to have capacity to shake with sufficient velocity. Fig.4-2. shows that the shaking table has enough capacity to shake table as fast as 100 kine.

4-2 Types of input waves

Considering the variety of real ground motions, we choose three earthquake records shown in Table 4-3.

Table4-3.input waves

Year	Earthquake	Record	component	description
1940	Imperial Valley	El_Centro	NS	El_Centro
1968	Tokachi	Hachinohe	EW	Hachinohe
1995	Hyogoken-nanbu	Kobe JMA	NS	Kobe

Shaking time is determined at 30.0 sec, since amount of Energy input with elastoplastic analysis during first 15.0 sec is more than 90 percents of total input energy, and very little over 30.0 sec with these input waves. It is an acceleration record to control shaking table. However, those input waves are little reversed. Because integration of original acceleration records of earthquake gives phenomena such as remaining velocity of shaking table or divergence of displacement. Compensation approaches of input waves are shown in the follows.

1. Removal of long period components more than 10.0 sec.
2. Base line compensation.

Through these compensations, numerical integration was taken again. Input waves were generalized with Maximum-velocity of ground motion (shaking table), after being confirmed maximum displacement.

4-3 Input levels

Generally, in the case of designs of real buildings,the input level was established at first as a design criteria. On this experiment, the process order is reversed, decided with considering relative evaluation between performance of specimens, experiment system and intensity of input wave. Design criteria and maximum-velocity of ground motion are shown in table 4-4.

Table.4-4 Input Level

Input Level	Design Criteria	Maximum-velocity
Level_1	Protection of Faculty	25.0kine
Level_2	Protection of Property	50.0kine

In ordinary input level is depend on the structural designer's requirment. According to "the theory of Damage Tolerant Structure", the purpose of structure demanded, if it occur equivalent Level 1 earthquakes, is "Protection of Faculty". And in Level 2 is "Protection of Property". These are an outline of required seismic performance by the structures.

Deciding an approach of concrete input level is as follows: It was determined by means of elastoplastic analysis of SDOF model that is this experiment system. Fig.4-5 shows correspendence relation between input level and force-displacement relation, which is derivered from pre-analysis of specimen. Input levels are shown with maximum response displacement which is the results of elastoplastic analysis using El Centro earthquake.

Assumptions of behavior in both input levels are as follows: On Level 1 shaking, frames of both specimens are remained within elastic ranges, although the steel core of the damper is already yields and absorbs energy. On Level 2 shaking ,M.R.F.1 is yielding a lot, although the frame of M.R.F.2 with damper remained within elastic ranges.

4-4.TEST PROCEDURES

The procedure is planed and shown as follows: concerned with section 4-4-1~4-4-3, these are defined as tests to compare the seismic performance of both specimens, M.R.F.1 and M.R.F.2 with damper.

4-4-1.Pulse-wave test

Shaking table test using pulse wave with small amplitude is taken in order measure the damping ratio and natural period of this system.

4-4-2. Level 1 tests

Maximum-velocity of input wave is 25.0 kine. Using this Input level, seismic performance of M.R.F.2 with damper is compared with M.R.F.1. Behaviors of both specimens are maintained within elastic ranges. Procedures of input waves are El Centro, Hachinohe and Kobe.

4-4-3. Level 2 tests

Maximum-velocity of Input wave is 50.0 kine. Using this Input level, seismic performance of M.R.F.2 with damper is compared with M.R.F.1. on elastoplastic ranges. Only M.R.F.1 received a lot of damage.

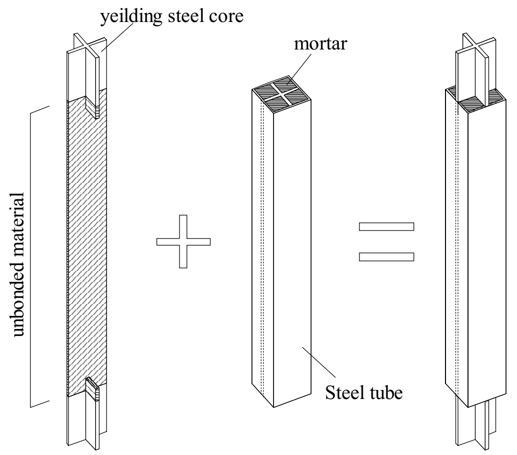

Fig.3-3. mechanism of unbonded braces

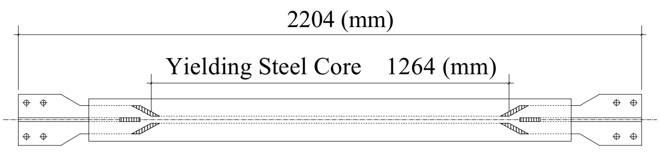

Fig.3-4. unbonded braces

Table3-5. Mechanical properties•@

Steel	Yield stress Mpa	Tensile strength Mpa	Yield strain %	Elingation %	Yield ratio
SN400A(web)	311	435	0.148	31.7	0.71
SN400A(flange)	292	451	0.142	30.8	0.65
LYP100(damper)	96	258	0.240	59.6	0.37

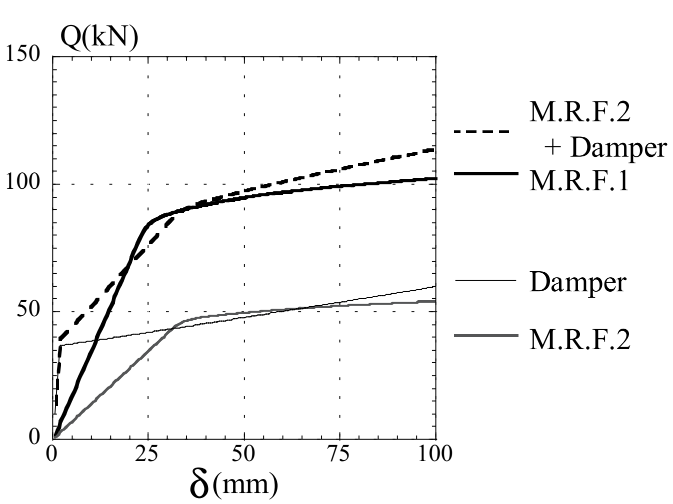

Fig.3-6. force-displacement relation of specimens

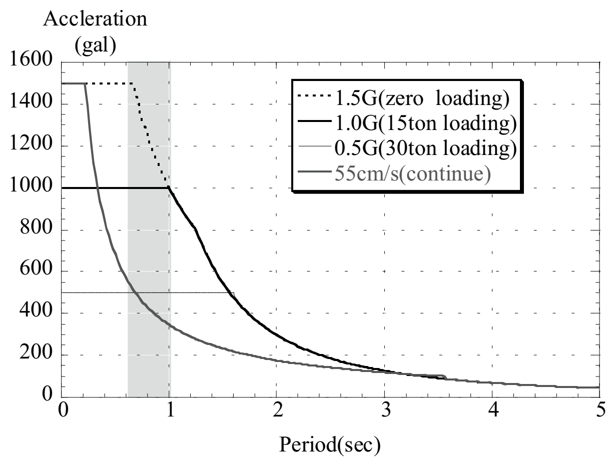

Fig.4-1. Performance curve of the shakig table
(acceleration-period ralation)

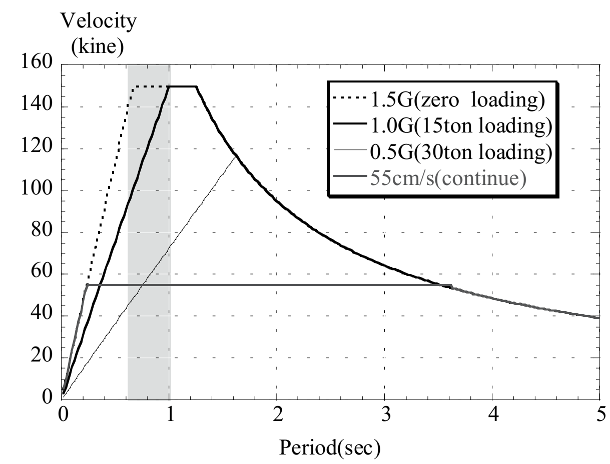

Fig.4-2. Performance curve of the shakig table
(volocity-period ralation)

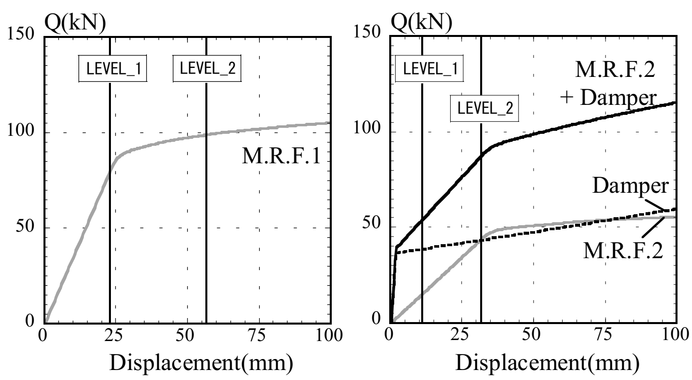

Fig.4-5. relationship between specimens and input levels

6 RESULTS

Fig.6-1 shows results of impulse wave tests. And equation of natural period of this experiment system is shown in Eq.6-2.

Table.6-1 results of pulse wave tests

	Period	damping ratio
	(sec)	(%)
M.R.F.1	0.82	1.70
M.R.F.2 with damper	0.70	2.30

$$T = 2\pi \sqrt{\frac{M_{mass}}{K_{system}}} \quad (6\text{-}1) \qquad K_{system} = \frac{K_s \cdot K_{spe}}{K_s + K_{spe}} \quad (6\text{-}2)$$

T: natural period of the system, M_{mass}: mass of the weight
K_{system}: stiffness of the system, K_s: stiffness of the spring
K_{spe}: stiffness of the specimen

Natural period of this experiment system with both specimens are nearly the same as that of a middle rise steel building (about 0.7-0.8 seconds). About equations, it is recognized that natural period of this system depends on Ks (stiffness of spring). A difference in natural period is about 10%. Therefore, it is anticipated that amount of input energy to the system is nearly equal order for both specimens. Damping ratios in both tests were 1.7%(M.R.F1) and 2.3% respectively. These values are nearly same as the damping ratio of actual structures. Therefore it was judged that we constructed the experiment system, which is appropriate on natural period and damping ratio.

As typical test results, relative deformations (weight and specimen) are shown in fig.6-3. In this case, type of specimen is M.R.F.1. And input wave and level are El Centro level 2.The correspondence (concept) of experimental system and the actual structure is shown in figures of 6-4. I t is proven that both specimens and weight keep the vibration along a natural period. And, the deformation of the weight shows 24.9cm in largest deformation (8.8cm) of the specimen, and the weight has approximately expressed the movement of center of gravity of the structure, as it is shown in fig. 6-4.

6 CONCLUSIONS

Features of experimental system proposed in this paper are shown in the following.

1. This experiment method can estimate the response of partial frame against Real Time Speed Earthquake.
2. This method approximately reproduces an earthquake resisting behavior of the partial frame.
3. It is possible to effectively utilize the performance of small and medium size shaking table.

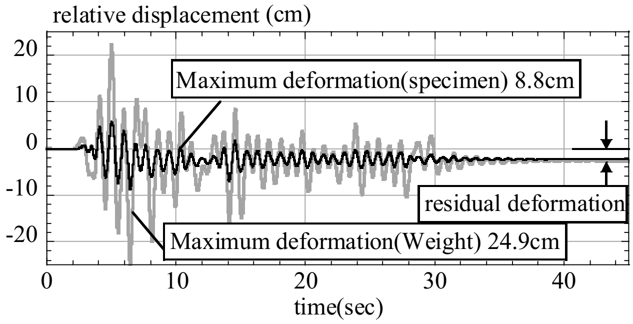

Fig.6-3 Relative deformations time history

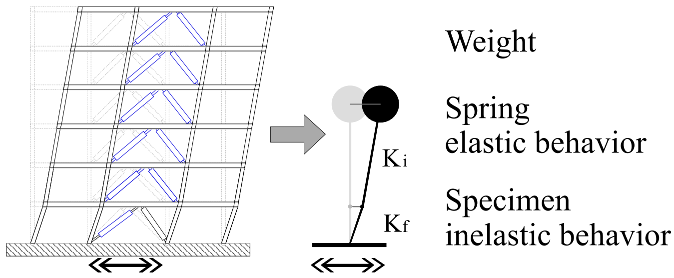

Fig.6-4 The behavior of experiment system(concept)

Actual shaking table tests were carried out, and a following knowledge was obtained.

1. The experimental system , which simulates an actual structure was constructed.
2. It was confirmed that in which the movement of the weight is similar to the movement of center of gravity position of an actual structure.

PREFERENCE

Akira WADA; Damage Tolerrant Structure, Proseeding of Fifth U.S.Japan Workshop on The Inprovement of Structural Design and Construction Practices, Applied Technology Council, 27-39, 1991

Yasushi MAEDA et al; Fatigue properties of axial-yield type hysteresis dampers, J. Struct. Constr. Eng., AIJ, No.503,109-,Jan., 1998

Eiichiro SAEKI et al; Analytical study on the unbonded brace fixed in a frame, J. Struct. Constr. Eng., AIJ, No.489,95-,Nov., 1996

Eiichiro SAEKI et al; A study on htsteresis and hysteresis energy characteristics of low yield strength steel, J. Struct. Constr. Eng., AIJ, No.473,159-,Jul., 1995

Eiichiro SAEKI et al; Experimental study od practical-scale unbonded braces, J. Struct. Constr. Eng., AIJ, No.476,149-,Oct., 1995

Hiroshi AKIYAMA et al; Experimental method of the full scale shaking table using inertial loading equipment, J. Struct. Constr. Eng., AIJ, No.505,139-,Mar., 1998