# Performance verification of actual seismic response controlled structure with AVS system

S. Hiehata & K. Ogasawara
*Kajima Technical Research Institute. Japan*

M. Takahashi, T. Nasu & N. Niwa
*Kobori Research Complex. Kajima Corporation. Japan*

T. Kobori
*Kyoto University and Kajima Corporation, Japan*

ABSTRACT: The AVS (Active Variable Stiffness) system is an active seismic response control system which can suppress a building's response to seismic vibrations by actively controlling its structural stiffness with the use of small amounts of electrical energy, establishing a non-resonance state against large earthquakes. To amass various data which are neccessary to develop the system for practical use, the system was applied to an actual building as a trial. This paper describes a forced vibration test conducted to determine the basic characteristics of the system applied to this building and earthquake observation records obtained during the system's operation. Also, simulation analyses were conducted, resulting in good agreement with the test results and observation records. The earthquake observation results showed that the response of the building in the controlled condition was significantly less than in the uncontrolled condition, which was obtained from the simulation analysis.

## 1 INTRODUCTION

Although valuable knowledge has been accumulated from seismic research, and a lot of progress has been made in building technology in an endeavor to minimize earthquake disasters, it is still not possible to escape from them. With the aim of minimizing the effets of such occurrences, the authors have proposed the active seismic response controlled structure (Kobori et al. 1986-1). In 1989, an AMD (Active Mass Driver) system was pioneered and successfully installed in the newly built Kyobashi Seiwa Building in midtown Tokyo, as the first of its kind in the world, and its initial efficiency has been verified by means of succeeding seismic observations (Kobori et al. 1990-1, 1991-1).

Active seismic response control systems, i.e., the systems that suppress vibrations by applying a control force to the building, or the so-called seismic force control type as represented by the AMD system, have been the object of a lot of research (Aizawa et al. 1990, Samari et al. 1985, Soong et al. 1991 etc.) However, such systems are limited in their operation due to a lack of sufficient power. Therefore, their aim has been mainly to reduce building vibrations of moderate earthquaes and strong winds (e.g. typhoon). In contrast, to fulfill the mission of controlling major earthquakes, the ultimate objective of the active seismic response control, the authors have proposed the variable stiffness seismic response control system (Active Variable Stiffness - AVS) (Kobori et al. 1986-2). With this system a building can protect itself against the large destructive forces of large earthquakes by controlling its own structural characteristics (stiffness) by creating a non-stationary and non-resonant state against earthquake motions that change from moment to moment.

Up to now, analytical and experimental research (Kobori et al. 1990-2,3, 1991-2) have been conducted on this AVS system and its development for practical application (Kobori et al. 1991-3,4) has been promoted. This paper describes the first practical application of the AVS system to an actual building and the results of verification tests conducted to determine its basic characteristics . It also presents the earthquake records obtained from observations since the system was placed in operation, to confirm its effectiveness based on the simulation analysis.

## 2 COMPOSITION OF AVS SYSTEM

### 2.1 Outline of subject building

The building to which the AVS system is applied is an integral part of the shaking table experimental facility shown in Photo 1 and Fig.1. It is a 3-story structural steel building, called the Control Building, and is placed on the same foundation as the adjacent reinforced concrete shaking table building. However, from above ground this building (total weight of approx. 400tf) is structurally independent. The structural outline of the control building is shown in Fig.2. Braces have been placed in the transverse direction (gable side) of the building, and the variable stiffness devices (VSD) have been installed between the respective brace-top and the lateral beam. These devices function to alter the building's stiffness in the transverse direction (controlled direction). In other words, the variable stiffness device can work in two ways, i.e., to lock (engage: brace becomes effective) the connection between the brace and the beam, or to unlock (release: brace becomes ineffective). The building has been designed for earthquake resistance as a frame structure that does not require braces, in accordance with the current Japanese Building Law.

## 2.2 AVS system

1. Control aim: The objective of the AVS system is to actively control the structural response due to earthquakes from small/moderate to severe intensities. However, the main purpose here is to collect earthquake observation data.

2. System composition: The AVS system as shown in Fig.3 consists of the following: 1) an earthquake accelerometer (on the 1st floor) to detect and measure the earthquake motions, 2) a seismic motion analyser, 3) a control computer for selecting the building's stiffness and to monitor the functional condition of the various devices, 4) variable stiffness devices, 5) an emergency electrical power source, and 6) building vibration measurement sensors installed on each floor.

3. Control method: The earthquake motions analysis type feedforward control scheme as shown in Fig.4 was adopted. When an earthquake occurs, the acceleration record measured on the 1st floor is input simultaneously into the seismic motion analyzer. The seismic motion analyzer consists of 3 types of band pass filter that possess passing characteristics, such as simulated by earthquake response features, of stiffness types that the building can select (3 types as shown in Table 1) for its control. The outputs from the band pass filter simulate the responses of stiffness types during the earthquake , and the control computer selects the stiffness type that gives the smallest output amplitude (less resonance) by comparing these outputs. Based on the selection results, the variable stiffness device alters the stiffness of the building and ceaselessly functions to produce non-resonance. The judgment by the control computer is conducted every 4 msec.

4. Variable stiffness device: The state of device installation is shown in Photo 2, and its specification is shown in Table 2. The device is a two ended rod type enclosed hydraulic cylinder with a piston inside. A valve is inserted into the tube that connects the two cylinder chambers, and its open/close function controls the oil movements therein. This results in locking or unlocking of the connection between the beam and the brace, thus producing two kinds of stiffness at each floor of the building. For the valve function, only 20 watts of electricity per device is needed. Therefore, active control up to large earthquakes can be achieved with a small amount of energy, and its emergency electrical power source can continue to operate the system for 30 minutes even after a black-out of the regular power supply. Also, as the device does not generate a force, there is no possibility of it producing building excitation.

## 3 CHARACTERISTICS VERIFICATION TEST

After the building was constructed, a forced vibration test was conducted to determine its vibration characteristics and the basic features of the AVS system.

## 3.1 Test method

The arrangement of the vibration generator and measurement instruments is shown in Fig.5. The generator (eccentric weight type, maximum vibration force 10tf) was placed on the middle of the roof, and forced excitation was applied in the transverse direction, which is the control direction. The building was subjected to stationary excitation with the variable stiffness device in all stories in both the locked and unlocked conditions, and the resonance curves of respective cases were obtained. A small earthquake was assumed for the excitation level and the exitation force kept constant (0.5tf in locked and 1.0tf in unlocked) within the frequency range of the vibration test, so that the roof level displacement during resonance was 1mm. Acceleration and displacement were measured simultaneously, and the measurement data were processed by the MIK system (Muto et al. 1973).

In addition, prior to the tests described herein, a preliminary forced vibration test was conducted before the variable stiffness device was installed in the steel frame. The resulting resonance frequency of the building is shown in Table 3.

## 3.2 Test results

The resonance curves measured on the west side of the building are shown in Fig.6 (a) and (b). Their amplitudes have been normalized for an excitation force of 1 tf. The first resonance frequency of the building with all floors in the unlocked condition is 1.71 Hz, and with all floors in the locked condition it is 2.43 Hz. The stiffness of the building is altered by the switching in the device, and it is plainly seen that the building vibration characteristics are changed.

Based on the resonance curves, the damping factor is calculated by the 1 $/\sqrt{2}$ method at approximately 13% and 3%, respectively, for conditions of unlock and lock of all stories. This result indicates that the damping factor is large compared to ordinary buildings, especially in the unlocked condition. This is because the damping resistance caused by the mechanism of the variable stiffness device tends to become large at a small vibration level.

The second resonance frequency for both cases may be seen in the vicinity of 7 to 8 Hz. However, a definite resonance peak cannot be recognized. This means that, for this building, the non-resonance control by stiffness alteration can be conducted taking account mainly of first natural frequency.

## 3.3 Simulation analysis

An analysis was conducted to simulate the test results, using a lumped mass vibration model as shown in Fig.7. The building stiffness elements consist of the structural steel frame, braces and structural secondary members (partitions, external wall, etc.). The stiffnesses of the structural steel frame and braces were evaluated based on the cross sections of the members, and the structural secondary members were identified by test results. Also, the variable stiffness device was modeled based on the performance test results of the unit device .

The results of the simulation analysis are compared with the test results as shown in Fig.8. The analytical results agreed well with the test results, thus verifying that the analytical model prepared here represents well the characteristics of the entire system including the building.

## 4 EARTHQUAKE OBSERVATION

After the building was completed, an earthquake occurred as shown in Table 4, thus offering the first opportunity to operate the system with actual control commands to make the stiffness change. The measurement instruments placed on each floor as shown in Fig.9 recorded the building's response during the earthquake.

Fig.10 shows the acceleration observation records of the 1st floor and the roof of the building in the longitudinal direction (uncontrolled direction) for the strongest 20-second vibration period near the beginning of the recorded earthquake. It can be seen that the response of the roof was significantly amplified compared to the 1st floor. The results of the simulation analysis are also shown in Fig.10. The analytical model of the building's response in the longitudinal direction is a lumped mass vibration model as shown in Fig.11. The building's stiffness elements consist of only a structural steel frame and a brace. As shown in Fig.10, this simple analytical model simulates well the observation record.

Fig.12 shows the acceleration and displacement observation records of the 1st floor and the roof in the transverse direction (controlled direction) by solid lines, obtained by averaging west and east side records of the building. The displacement in the figure shows the relative displacement of the 1st floor obtained by integrating of the measurement results of the velocity-sensor. It is recognized that the response amplification of the roof compared to the 1st floor is smaller than that in the longitudinal direction (uncontrolled direction).

When the AVS system detected the seismic motions, the normal locked condition of all floors was instantly switched over to the unlocked condition (2.41 second) , and when the earthquake ceased all floors returned to the locked condition (38.18 second) . This means that the earthquake possessed insignificant resonant frequency component relevant to the unlocked condition of all stories for the whole duration of the earthquake.

To determine the control effect, a simulation analysis was conducted to obtain the responses if the AVS system had not been installed ( uncontrolled case). The analytical model used for the uncontrolled case was provided by removing the variable stiffnes device from the model shown in Fig.7, i.e., the braces rigidly connected to the frame in each story. The analytical results are shown by dotted lines in Fig.12. It can be seen that the response under the controlled condition was significantly less than that under the uncontrolled condition. When the response decrease is compared based on the maximum values, the acceleration and displacement are reduced by 70% and 30%, respectively. This result verifies that the AVS system has operated effectively during an actual earthquake.

## 5 CONCLUSION

The AVS system has been developed and applied to an actual building, in which the structure itself alters its stiffness and achieves non-resonance against earthquake motions, and its active seismic response control performs effectively against large earthquakes. Characteristics verification tests and seismic observa-tions were conducted, producing information as follows:

1. Characteristics verification test: It was confirmed that the building stiffness could be altered and expected dynamic characteristics of the building could be obtained by the function of switching in the variable stiffness device. Moreover, the result of the simulation analysis reflected on the characteristics of the building and the variable stiffness device showed good agreement with the test results, proving the adequacy of the analytical model.

2. Earthquake observation: The AVS system executed the variable stiffness control during an actual earthquake as per requirement. The observation results showed that the response of the building were significantly less than in the uncontrolled condition, as obtained by simulation analysis.

As described above, it was verified that the AVS system can provide effective control during a real earthquake. This offers the favorable expectation that development of a practical application of the active seismic response control, including for earthquakes of severe intensities, has been greatly promoted .

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Photo 1 View of the Entire Building with AVS



Fig.1 Section of the Building



| Component | Member |
|---|---|
| Column | □-300 × 300 × 12 |
| Beam(Transverse) | H-390 × 300 × 10×16 |
| Beam(Longitudinal) | H-600 × 200 × 11×17 |
| Brace | ∅-165 × 4.5 |

(a)Plan (b)Transverse Section (c)Member List

Fig.2 Outline of the Building



Fig.3 Composition of the Control System



Fig.4 Feedforward Control Scheme
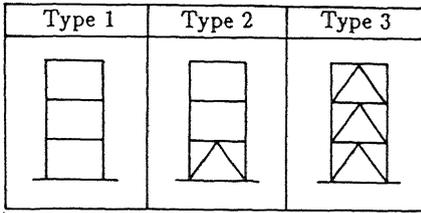
4180

## Table 1 Variation of Stiffness Type

| Type 1 | Type 2 | Type 3 |
|--------|--------|--------|

## Table 2 Specification of VSD

| Design Load | 35tonf |
|-------------|--------|
| Size | 730mm × ∅290mm |
| Weight | 250kg |
| Stroke | ± 50mm |
| Diam. of Piston | ∅180mm |
| Diam. of Rod | ∅100mm |

## Table 3 Resonant Frequencies(without AVS)

| Direction \ Order | 1st | 2nd |
|-------------------|-----|-----|
| Transverse | 1.69Hz | 5.85Hz |
| Longitudinal | 3.15Hz | 10.8Hz |
| Torsional | 2.83Hz | un-recognized |

Photo2 Installation of the VSD

Ø Transverse Displacement Pickup
Ø Transverse Accelerometer
⊖ Longitudinal Displacement Pickup
⊖ Longitudinal Accelerometer
Φ Vertical Accelerometer

Fig.5 Location of Vibration Generator and Measurement Instruments

1st Order Natural Frequency 1.71Hz

1st Order Natural Frequency 2.43Hz

(a)Type1(all 'unlocked')

(b)Type3(all 'locked')

Fig.6 Resonance and Phase Angle Curves of Transverse Direction with AVS (West Frame)

Co.     : Column
Br.     : Brace
S.S.M.: Structural Secondary Member
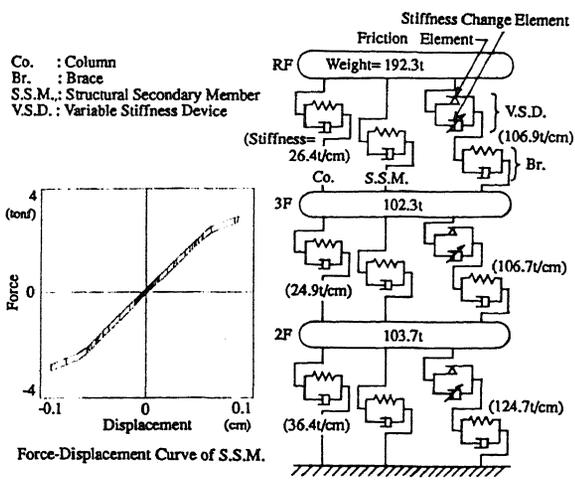V.S.D. : Variable Stiffness Device

Force-Displacement Curve of S.S.M.

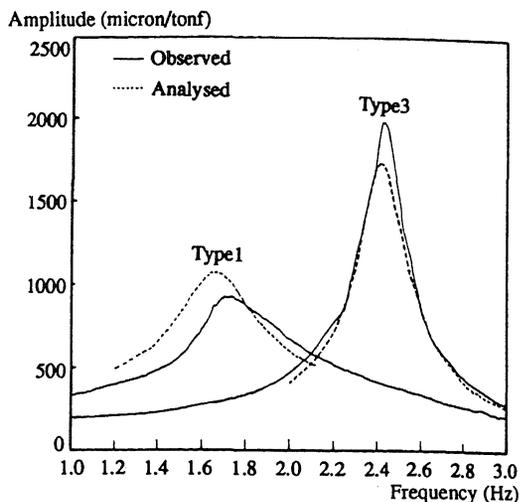Fig.7 Analytical Model (Transverse Direction)

Fig.8 Simulation of Resonance Curves (at RF)

Table 4 Earthquake Data

| Occurrence Date | Nov.19,1991 |
|---|---|
| Epicenter | The Tokyo Bay Chiba-City Coast |
| Magnitude | 4.9 |
| Focal Depth | 80km |
| Seismic Intensity | IV(Tokyo) |

Ø  Transverse Accelerometer
Ø  Transverse Velocimeter
■  VSD Sensors
⊖  Longitudinal Accelerometer

Fig.9 Location of Measurement Instruments
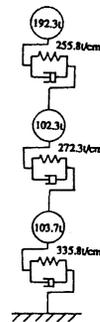for Earthquake Observation
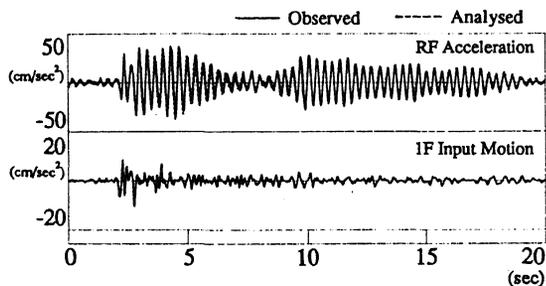
Fig.11 Analytical Model
(Longitudinal Direction)

Fig.10 Earthquake Observation Records and
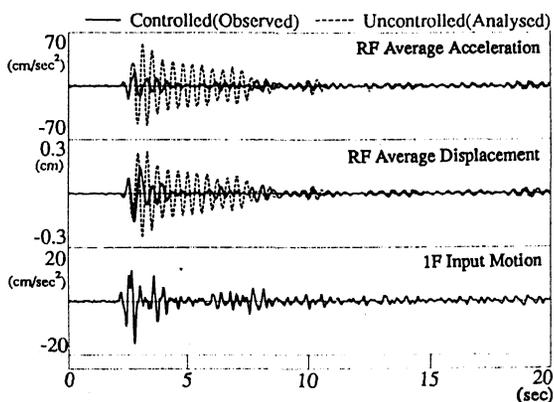Simulation Analysis for Longitudinal Direction
(Uncontrolled Direction)

Fig.12 Earthquake Observation Records and Control
Effect for Transverse Direction (Controlled Direction)