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Full-scale implementation of active structural control

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ABSTRACT: An active bracing system has been designed, fabricated and installed in a full-scale dedicated test structure for structural response control under seismic loads. Addressed in this paper are design, fabrication and performance issues related to the development of the active bracing system. The performance of the system and lessons learned during the first year of operation are discussed. These discussions provide a realistic assessment of the potential benefit which can be derived from an active system on the one hand, and system design capability requirements on the other.

1 INTRODUCTION

The possible use of active control systems as a means of structural protection against seismic loads has received considerable attention in recent years. It has now reached the stage where active systems have been installed in full-scale structures (Soong 1990). The focus of this paper is on the development of an active bracing system for implementation to a full-scale dedicated test structure and on its performance through evaluation of some initial test results.

Active control using structural braces and tendons has been one of the most studied control mechanisms. Systems of this type generally consist of a set of prestressed tendons of braces connected to a structure, their tensions being controlled by electrohydraulic servomechanisms. One of the reasons for favoring such a control mechanism has to do with the fact that tendons and braces are already existing members of many structures. Thus, active bracing control can make use of existing structural members and thus minimize extensive additions or modifications of an as-built structure. This is attractive, for example, in the case of retrofitting or strengthening an existing structure.

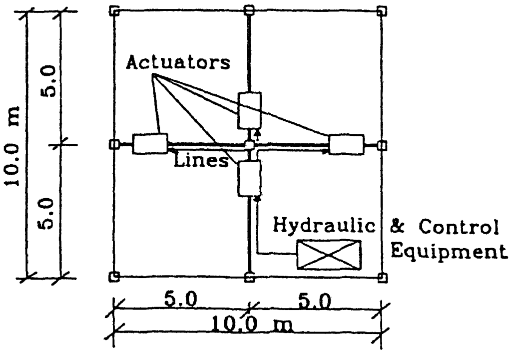
Recently, a comprehensive experimental study was designed and carried out in order to study the feasibility of active bracing control using carefully calibrated structural models. In the first two stages, a 1:4 scale three-story model structure (3m tons, 2.5m high), modeling a shear frame building, was controlled using diagonal prestressed tendons activated by a servocontrolled hydraulic actuator. These experiments permitted a realistic comparison between analytical simulations and experimental results which were easily extrapolated to full-scale prototypes. Furthermore, important practical considerations such as time delay, robustness of control algorithms, modeling errors and structural control system interaction could be identified and evaluated. In the third stage, a substantially larger and heavier six-story model structure (20m tons, 7.5m high) was controlled experimentally using multiple sets of diagonal active tendons producing substantial response reduction under various simulated earthquakes.

This paper focuses on full-scale implementation of an active bracing system in an experimental six-story frame structure (600m tons, 15m high) constructed in a seismic prone area of Japan. The system was designed using extrapolated results from previous experimental studies and analytical simulations. The control system was assembled in the experimental structure, calibrated and tested by microtremors, by free vibrations of the structure and by forced vibrations supplied from the movement of an active mass damper used as an active exciter. The paper presents the highlights of the design and some initial test results. The issues of long-term operation and reliability are also addressed.

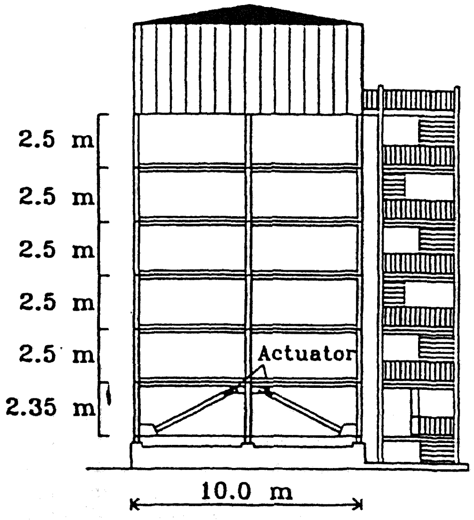
2 TEST STRUCTURE AND ACTIVE BRACING SYSTEM

2.1 *Test structure*

A dedicated full-scale structure was erected for performance verification of two active structural control systems, i.e., an active mass damper and an active bracing system. Located in Tokyo, Japan, the structure is a symmetric two-bay six-story building as shown in Figure 1. It was constructed of rigidly connected steel frames of box columns and W-shape beams with reinforced concrete slabs at each of the floors. Weighing 600 metric tons, the structure was designed as a relatively flexible structure with a fundamental period of 1.0 sec in the strong direction and 1.5 sec in the weak direction in order to simulate a typical high-rise building. It is assumed that the floor slabs are rigid in their planes and the structure does not twist; accordingly, the space structure was modeled as a fixed-base plane frame with three degrees of freedom (horizontal, vertical and rotation) at each joint in the eigenvalue analysis The stiffness of the concrete slabs was taken into account by considering rigid zones at ends of the members in analytical modeling. The spectral properties of the structure are given in Table 1.



(a) Top View



(b) Front View

Figure 1. Test Structure and Active Bracing System

Table 1. Modal frequencies of test structure

Mode	X-direction (Hz)	Y-direction (Hz)
1	0.900	0.650
2	2.700	1.800
3	4.650	2.975
4	6.850	4.125
5	9.400	5.425
6	12.75	7.250

2.2 *Active bracing system (ABS)*

As shown in Figure 1, the biaxial active bracing system consists of a pair of hydraulic actuators in each of the principal directions with the diagonal braces connected to the first floor. The actuators, monitored by two hydraulic servovalve controllers with auxiliary hydraulic actuators, are capable of generating 685 kN of control force in each direction.

Velocity sensors are attached to the base, the first, the third and the sixth floors and an accelerometer is placed at the base. Measurements derived from these sensing devices serve as the feedback state variables in either of the two proposed control algorithms. The PC-Limited 286 microcomputer facilitated with A/D and D/A boards is used for on-line computation. The control logic is implemented on an 80286-24 MHz processor and an 80287-10 MHz co-processor.

2.3 *Design earthquakes*

For design purposes, the peak velocity of the design earthquakes was taken to be 10 cm/sec based on local seismic records of the past seven years (maximum = 9.5 cm/sec). Accordingly, the scaled (32%) El Centro earthquake with 98 cm/sec^2 (0.1 g) peak acceleration was determined as the design earthquake which corresponds to the criterion of 10 cm/sec maximum velocity. Response analyses were also carried out using a series of recorded earthquake time histories to verify the adequacy of the design specifications.

2.4 *Control algorithms*

The real-time computations in the microcomputer were based on a reduced order model (ROM) active control algorithm. Two basic algorithms based on the classical closed-loop linear optimal control law (Reinhorn, et al. 1989) were designed for this investigation: (a) three-velocity feedback which uses only velocities measured at three critical floors in the structure (Soong, et al. 1991) and (b) velocity feedback with observer which accounts for full dimensional state feedback with aid of a state estimator (Soong et al. 1991).

Both algorithms were modified to include the compensation of delays in the force application with respect to the measured signal. The time delays are a result of phase shifts in instruments, conditioners, time required for on-line computation and time required for the actuator to respond. A phase type compensation was employed in connection with compensation of a parallel time delay in computations and actuators. All compensations are based on field measured performances of the control components (Reinhorn, et al. 1989).

2.5 *Simulated results*

Simulations using several design earthquakes produced satisfactory results. The maximum power required during an earthquake reaches 20 kw for most earthquakes. The total energy consumption during an earthquake of one minute will be of the order of 0.3 kwh to 0.9 kwh which can be delivered from passive electrical power sources.

A typical structural response of the full-scale system is shown in Figure 2. The performance is shown for the top floor of the structure where both displacements and accelerations are reduced. As a result, the base shear is also substantially reduced. The required resources to produce such performance are shown in Figure 3 (for the strong direction of the structure with both actuators operating in this direction). The large forces are required for short periods of time associated with several power peaks and a rapid initial energy demand.

3 DESIGN OF ACTIVE BRACING SYSTEM (ABS)

The primary parameters upon which the detail system design is based are the control force, the actuator displacement and the actuator velocity, which are related to the determination of the actuator capacity, the cylinder stroke, and the flow rate requirement of the hydraulic servovalve. In addition, the total flow of the hydraulic fluid required during a seismic event is the basis for sizing the hydraulic supply system. During the operating period of the active system, the hydraulic servo-controller supplies a constant flow of oil regardless of the actual requirement. When the demand of oil is more than what is supplied, the accumulator will pressure a subsidiary flow to the actuator cylinder; inversely, when supply is more than demand, excess oil will be discharged into the accumulator, thus no additional pumping is necessary during the short period of earthquake excitation. For economic reasons, the pumping rate of the controller is determined to be the average flow rate estimated over the time history of the cumulative flow such that the accumulator volume is minimized. These design parameters were established in accordance with the simulated results of resource demands required for a desired structural performance under the design earthquake as discussed below.

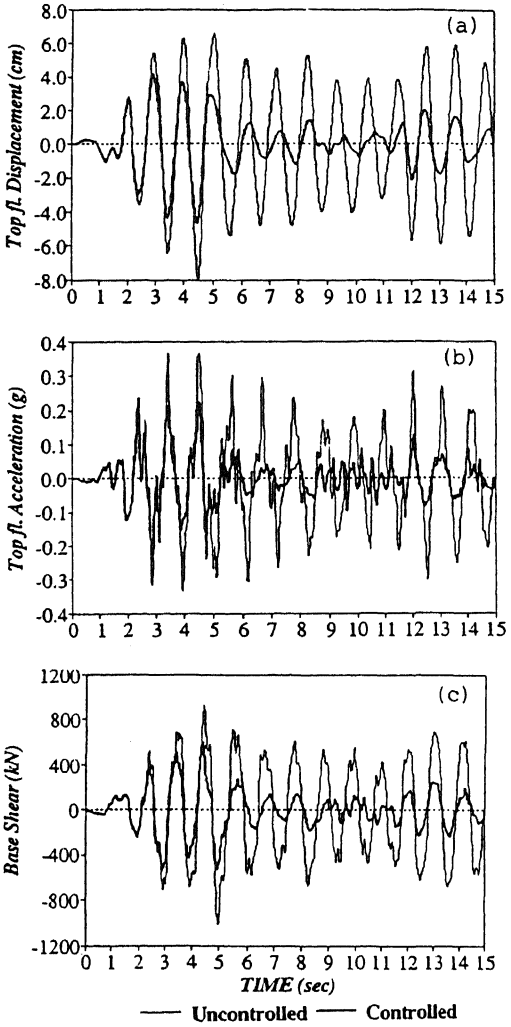


Figure 2. Structural Response under 32% El Centro Earthquake

3.1 *Hydraulic actuators*

The maximum control force and the specification of the hydraulic actuators were determined based upon the experimental study of a 1:4 scaled model. The expected maximum control force for the full-scale model weighing 600 metric tons was estimated to be about 712 kN under 32% El Centro earthquake. Based on this estimate and the available manufactured units, two 35-ton hydraulic actuators were chosen in each direction. In other words, the active system can provide 685 kN maximum control force uniaxially.

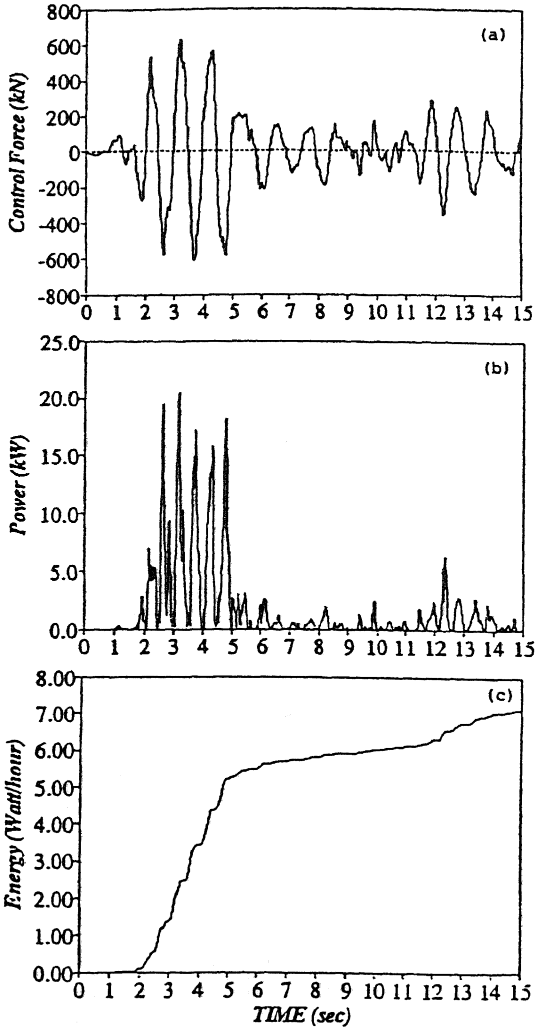


Figure 3. Control Requirements under 32% El Centro Earthquake

Having determined the specification of the hydraulic actuators, further analysis of the control system can be performed based on the associated parameters. A stiffness of the diagonal brace (including the actuator) of 61.3 kN/mm was assumed in the simulation in order to estimate the actuator displacement and velocity. Changes in the structural eigenproperties due to implementation of additional braces are insignificant, therefore the influence of bracing on the structural dynamics was neglected in the analysis. The flow rate requirement of the actuator or the hydraulic servovalve was in turn calculated from the piston area of the cylinder and the actuator velocity based on a first-order approximation. Analytical simulations were performed only in the strong direction for design purposes and the same design specifications were used in the other direction.

3.2 *Passive power resource*

The required flow rate of the hydraulic cylinders can be determined approximately in terms of the piston area and the actuator velocity. Figure 4 illustrates the cumulative flow accumulated during an earthquake, which is obtained by integrating the time history of the flow rate. The slope of this curve represents the instantaneous flow rate required to achieve the control goal. It is observed from interpreting the slope of the curve that system demand is the highest between 2 and 5 seconds and less so over the rest of the time history, a property apparently resulted from the nonstationary nature of the earthquake motion and the control effect contributed in the previous time period. The linear curve represents the cumulative volume of a constant flow which is obtained by minimizing the difference between the demand and supply of oil using the least-square criterion. The largest difference between the cumulative flow and the average flow indicates the minimum volume of the hydraulic accumulator to be considered in design.

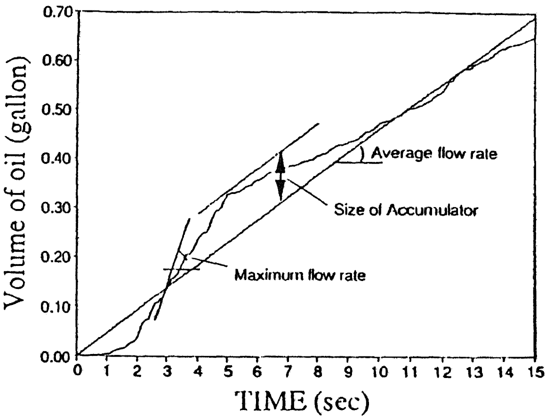


Figure 4. Cumulative Oil Flow during 32% El Centro Earthquake

3.3 *Automatic control operation*

The hydraulic power for the active bracing system needs to be continuously available, yet it is not practical to have the hydraulic system operating constantly. For this reason, the system was designed in such a way that the hydraulic system remains in a ready, but dormant, state, with the control software capable of bringing the system to full operation. To accomplish this, the control software must be able to monitor the status of the control hardware, and adjust the state as necessary. In addition, the hydraulic system must be capable of almost instantly supplying full power to the active braces.

These requirements led to special modifications of the standard control hardware, as well as the addition to the control program of subroutines with the logic for starting, stopping, and monitoring the status of the system. The hydraulic power required for rapid starts is stored in the accumulators, which can supply enough power to allow the hydraulic pump to reach full pressure operation. The accumulators can also drive the actuators for approximately one minute, longer than most major earthquakes, in the event of a power failure. The ability of the computer to regulate the system is provided through a series of digital connections between the computer and the analog controller. The digital communications allow the computer to control the hydraulic system, and to monitor the status of the system hardware.

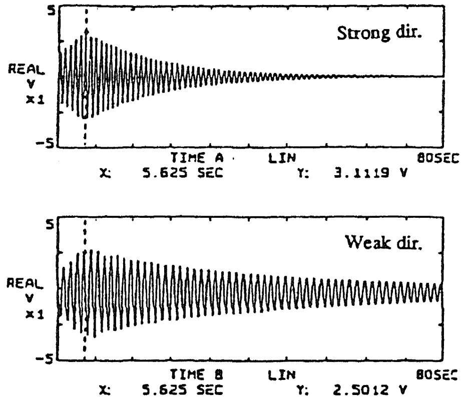
3.4 *System Reliability and Maintenance*

In order to properly protect the system and the structure from damage in the event of a full or partial failure of the control system, a number of fail-safes were added to both the hardware and the software. The hardware fail-safes which were installed will stop the system in a variety of potentially dangerous situations. The control software uses a series of checks and fail-safes to continuously verify its own integrity and the status of most of the system hardware. In addition, the control software contains test routines which can be manually activated in order to verify the efficiency and performance of the entire control system.

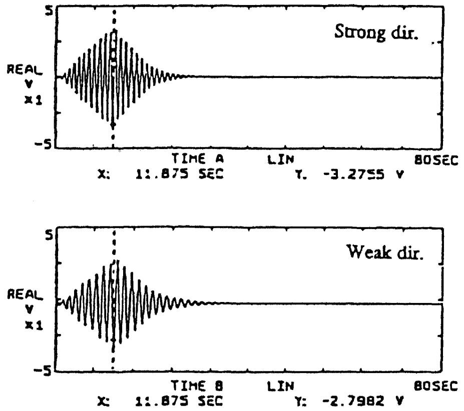
Long term maintenance of the system is needed. If strict tolerances are not met, the continuous wear can lead to degradation in the system performance, and even to failure. During the first year of operation of the ABS, some parts of the bracing connections loosened slightly, resulting in instabilities in the control system at low levels of excitation. Tightening of the loosened connections returned the system to the original level of performance. The standard maintenance must include manual inspection and verification of the system components on a regular basis.

4 EXPERIMENTAL PERFORMANCE OF CONTROL SYSTEMS

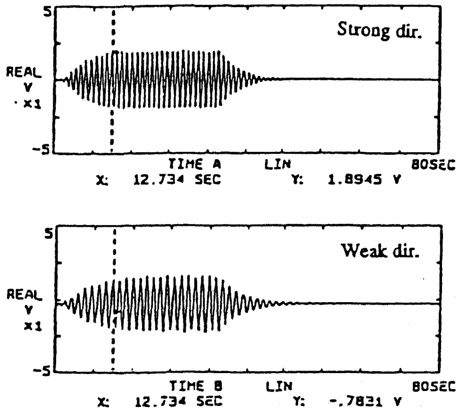
Initial tests were performed on the site when construction was completed. The tests included three stages: (a) control of microtremor excitation due to traffic and wind; (b) control of free vibration of the structure after excitation produced by the use of the active mass damper as a force exciter; and (c) control of forced vibration using the active mass damper exciter. Typical results are presented herein as an illustration of the system performance.



(a) Uncontrolled free vibration



(b) Controlled free vibration



(c) Controlled forced vibration

Figure 5. Preliminary Test Results of Full-scale Structure

Figure 5(a) shows the uncontrolled structural response in both directions. The decayed rate of the uncontrolled response is very slow because the system is only slightly damped (1% in the strong direction and 0.5% in the weak direction). Figure 5(b) shows the build-up of the structural vibration and then the influence of control applied at the peak of excitation. The increase in damping is evident, showing, for example, an increase from 0.5% to 3.5% in the weak direction. The influence of control during forced vibration is shown in Figure 5(c). The response builds up in the transient stage and reaches its steady state, which is evidently smaller than the previous tendency as shown in Figure 5(b).

5 CONCLUSIONS

Presented in this paper are design, simulation and performance of a full-scale active bracing system which was recently installed in a full-scale test structure. All components of the system were selected from currently available hardware and the power and energy resources required for this structural application were found to be within limits of current technology.

Analytical simulation and initial structural tests indicate that the system can produce significant structural response reduction. While more widespread applications of active structural control systems must await more extensive analytical and experimental verification, results obtained to date have been very encouraging and more full-scale demonstrations are expected to confirm these findings.

ACKNOWLEDGEMENT

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