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An Overview of Active Structural Control under Seismic Loads

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The concept of active structural control as a means of structural protection against seismic loads, developed over the last 20 years, has received considerable attention in recent years. It has now reached the stage where active systems have been installed in full-scale structures. It is the purpose of this paper to provide an overview of this development with special emphasis placed on laboratory experiments using model structures and on full-scale implementation of some active control systems. Included in this paper is a report on the formation of a U.S. Panel on Structural Control Research and some discussion on possible future research directions in this exciting research area.

INTRODUCTION

In earthquake engineering, one of the constant challenges is to find new and better means of designing new structures or strengthening existing ones so that they, together with their occupants and contents, can be better protected from the damaging effects of destructive seismic forces. As a result, new and innovative concepts of structural protection have been advanced and are at various stages of development. In the passive area, they include base isolation and a variety of other mechanical energy dissipaters such as bracing systems, friction dampers, viscoelastic dampers and other mechanical devices.

Research and development of active structural control technology has a more recent origin. In structural engineering, active structural control is an area of research in which the motion of a structure is controlled or modified by means of the action of a control system through some external energy supply. In comparison with passive systems, a number of advantages associated with active systems can be cited; among them are (a) *enhanced effectiveness in motion control*. The degree of effectiveness is, by and large, only limited by the capacity of the control system; (b) *relative insensitivity to site conditions and ground motion*; (c) *applicability to multi-hazard mitigation situations*. An active system can be used, for example, for motion control against both strong wind and earthquakes; and (d) *selectivity of control objectives*. One may emphasize, for example, human comfort over other aspects of structural motion.

Thus motivated, considerable attention has been paid to active structural control research in recent years. It is now at the stage where actual systems have been designed, fabricated

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and installed in full-scale structures. A number of review articles [Miller et al., 1987; Kobori, 1988; Masri, 1988; Soong, 1988; Yang and Soong, 1988; Reinhorn and Manolis, 1989] and a book [Soong, 1990] have provided the reader with information and assessment on recent advances in this emerging area. In this paper, an update of this development is presented with special emphasis on experimental work that has been conducted in the laboratory and on full-scale implementation. This is followed by a discussion of possible future research directions and a report on the formation of a U.S. Panel on Structural Control Research with the aim of promoting research and development in this exciting emerging technological area.

BASIC PRINCIPLES

An active structural control system has the basic configuration as shown schematically in Fig. 1. It consists of (a) sensors located about the structure to measure either external excitations, or structural response variables, or both; (b) devices to process the measured information and to compute necessary control forces needed based on a given control algorithm; and (c) actuators, usually powered by external energy sources, to produce the required forces. When only the structural response variables are measured, the control configuration is referred to as *closed-loop control* since the structural response is continually monitored and this information is used to make continual corrections to the applied control forces. An *open-loop control* results when the control forces are regulated only by the measured excitations, which can be achieved, for earthquake inputs, by measuring accelerations at the structural base. In the case where the information on both the response quantities and excitation are utilized for control design, the term *open-closed loop control* is used.

To see the effect of applying such control forces to a structure under ideal conditions, consider a building structure modeled by an n-degree-of-freedom lumped mass-spring-dashpot system. The matrix equation of motion of the structural system can be written as

$$M\ddot{\mathbf{x}}(t) + C\dot{\mathbf{x}}(t) + K\mathbf{x}(t) = D\mathbf{u}(t) + E\mathbf{f}(t) \tag{1}$$

where M, C and K are the $n \times n$ mass, damping and stiffness matrices, respectively, $\mathbf{x}(t)$ is the n-dimensional displacement vector, the r-vector $\mathbf{f}(t)$ represents the applied load or external excitation, and the m-vector $\mathbf{u}$ is the applied control force vector. The $n \times m$ matrix D and the $n \times r$ matrix E define the locations of the control force vector and the excitation, respectively.

Suppose that the open-closed loop configuration is used in which the control force $\mathbf{u}(t)$ is designed to be a linear function of the measured displacement vector $\mathbf{x}(t)$, the velocity vector $\dot{\mathbf{x}}(t)$ and the excitation $\mathbf{f}(t)$. The control force vector takes the form

$$\mathbf{u}(t) = K_1\mathbf{x}(t) + C_1\dot{\mathbf{x}}(t) + E_1\mathbf{f}(t) \tag{2}$$

where K_1, C_1, and E_1 are respective control gains which can be time-dependent.

The substitution of equation (2) into equation (1) yields

$$M\ddot{\mathbf{x}}(t) + (C - DC_1)\dot{\mathbf{x}}(t) + (K - DK_1)\mathbf{x}(t) = (E + DE_1)\mathbf{f}(t) \tag{3}$$

Comparing equation (3) with equation (1) in the absence of control, it is seen that the effect of open-closed loop control is to modify the structural parameters (stiffness and damping) so that it can respond more favorably to the external excitation. The effect of the open-loop component is a modification (reduction or total elimination) of the excitation.

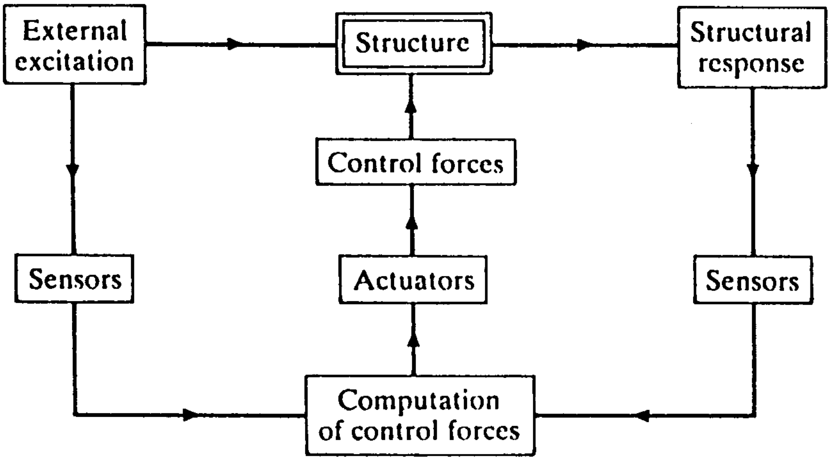


Figure 1 Block Diagram of Active Control

It is seen that the concept of active control is immediately appealing and exciting. On the one hand, it is capable of modifying properties of a structure in such a way as to react to external excitations in the most favorable manner. On the other hand, direct reduction of the level of excitation transmitted to the structure is also possible through active control.

The choice of the control gain matrices K_1, C_1 and E_1 in equation (2) depends on the control algorithm selected. A number of control strategies for structural applications have been developed, some of which are based on the classical optimal control theory and some are proposed for meeting specific structural performance requirements. The reader is referred to Soong (1990) for discussions of some commonly used structural control algorithms.

CONTROL SYSTEMS AND EXPERIMENTAL STUDIES

As in all other new technological innovations, experimental verification constitutes a crucial element in the maturing process as active structural control progresses from conceptualization to actual implementation. Experimental studies are particularly important in this area since hardware requirements for the fabrication of a feasible active control system for structural applications are in many ways unique. As an example, control of civil engineering structures requires the ability on the part of the control device to generate large control forces with high velocities and fast reaction times. Experimentation on various designs of possible control devices is thus necessary to assess the implementability of theoretical results in the laboratory and in the field.

In order to perform feasibility studies and to carry out control experiments, investigations on active control have focused on several control mechanisms as described below.

ACTIVE BRACING SYSTEM (ABS)

Active control using structural braces and tendons has been one of the most studied mechanisms. Systems of this type generally consist of a set of prestressed tendons or braces connected to a structure whose tensions are 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.

Active tendon control has been studied analytically in connection with control of slender structures, tall buildings, bridges and offshore structures. Early experiments involving the use of tendons were performed on a series of small-scale structural models [Roorda, 1980], which included a simple cantilever beam, a king-post truss and a free-standing column while control devices varied from tendon control with manual operation to tendon control with servovalve-controlled actuators.

More recently, a comprehensive experimental study was designed and carried out in order to study the feasibility of active bracing control using a series of carefully calibrated structural models. As Fig. 2 shows, the model structures increased in weight and complexity as the experiments progressed from Stage 1 to Stage 3 so that more control features could be incorporated into the experiments. Figure 3 shows a schematic diagram of the model structure studied during the first two stages. It is a three-story steel frame modeling a shear building by the method of mass simulation. At Stage 1, the top two floors were rigidly braced to simulate a single-degree-of-freedom system. The model was mounted on a shaking table which supplied the external load. The control force was transmitted to the structure through two sets of diagonal prestressed tendons mounted on the side frames as indicated in Fig. 3.

Results obtained from this series of experiments are reported in [Chung et al., 1988; Chung et al., 1989]. Several significant features of these experiments are noteworthy. First, they were carefully designed in order that a realistic structural control situation could be investigated. Efforts made towards this goal included making the model structure dynamically similar to a real structure, working with a carefully calibrated model, using realistic base excitation, and requiring more realistic control forces. Secondly, these experiments permitted a realistic comparison between analytical and experimental results, which made it possible to perform extrapolation to real structural behavior. Furthermore, important practical considerations such as time delay, robustness of control algorithms, modeling errors and structure-control system interactions could be identified and realistically assessed.

Experimental results show significant reduction of structural motion under the action of the simple tendon system. In the single-degree-of-freedom system case, for example, a reduction of over 50% of the first-floor maximum relative displacement could be achieved. This is due to the fact that the control system was able to induce damping in the system from a damping ratio of 1.24% in the uncontrolled case to 34.0% in the controlled case [Chung et al., 1988].

As a further step in this direction, a substantially larger and heavier six-story model structure was fabricated for Stage 3 of this experimental undertaking. As shown in Fig. 4, it is also a welded space frame utilizing artificial mass simulation. It weighs 42,000 lbs and stands 18 ft in height.

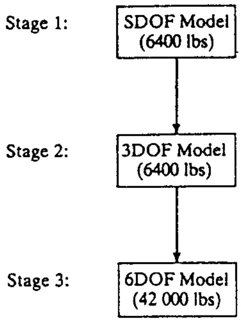


Figure 2 Laboratory Tests of Active Bracing Systems

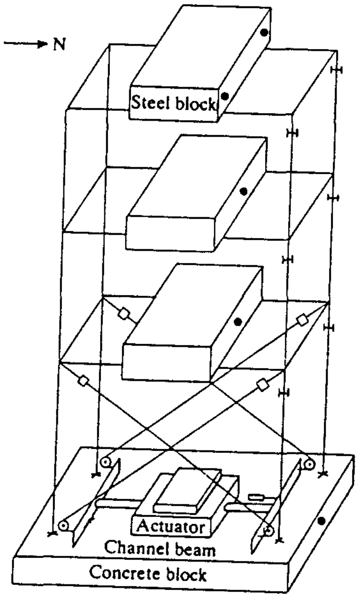


Figure 3 Schematic Diagram of Model Structure at Stages 1 and 2

Multiple tendon control was possible in this case and the following arrangements were included in this phase of the experiments:

(a) A single actuator is placed at the base with diagonal tendons connected to a single floor.

(b) A single actuator is placed at the base with tendons connected simultaneously to two floors, thus applying proportional control to the structure.

(c) Two actuators are placed at different locations of the structure with two sets of tendons acting independently.

Several typical actuator-tendon arrangements are shown in Fig. 5. Attachment details of the tendon system are similar to those shown in Fig. 3.

Another added feature at this stage was the testing of a second control system, an active mass damper, on the same model structure, thus allowing a performance comparison of these two systems. The active mass damper will be discussed in more detail in the next section.

For the active tendon systems, experimental as well as simulation results have been obtained based upon the tendon configurations stipulated above. Using the N-S component of the El-Centro acceleration record as input, but scaled to 25% of its actual intensity, control effectiveness was demonstrated. For example, in terms of reduction of maximum relative displacements, results under all actuator-tendon arrangements tended to cluster within a narrow range. At the top floor, a reduction of 45% could be achieved. Control force and power requirements were also found to be well within practical limits when extrapolated to the full-scale situation [Reinhorn et al., 1989].

In another small-scale structural model study, an active bracing system was studied whose main control objective is to steer the structural frequencies away from dominant (and damaging) frequencies associated with the seismic power spectra at each time instant [Kobori et al., 1988]. This can be accomplished using active bracings through length adjustment, sectional-area adjustment or position adjustment. A significant secondary control effect comes from phase modulation of the resonant force which is designed to cancel seismic loading imposed on the structure.

ACTIVE MASS DAMPER AND ACTIVE MASS DRIVER (AMD)

The study of this control mechanism was in part motivated by the fact that passive tuned mass dampers for motion control of tall buildings are already in existence. Tuned mass dampers are in general tuned to the first fundamental frequency of the structure, and thus are only effective for building control when the first mode is the dominant vibrational mode. This may not be the case; however, when the structure is subjected to seismic forces when vibrational energy is spread over a wider frequency band. It is thus natural to ask what additional benefits can be derived when they function according to active control principles. Indeed, a series of feasibility studies of active and semi-active mass dampers have been made along these lines and they show, as expected, enhanced effectiveness for tall buildings under either strong earthquakes or severe wind loads.

Recently, experimental studies of active mass damper systems have been carried out in the laboratory using scaled-down building models. In the work of Kuroiwa and Aizawa (1987), an AMD was placed on top of a four-story model frame. The moving mass was a variable, ranging from approximately 1% to 2% of the structural weight. The model structure, 1 m (width) x 1 m (depth) x 2 m (height) and weighing 970 kg, was placed on a shaking table which provided

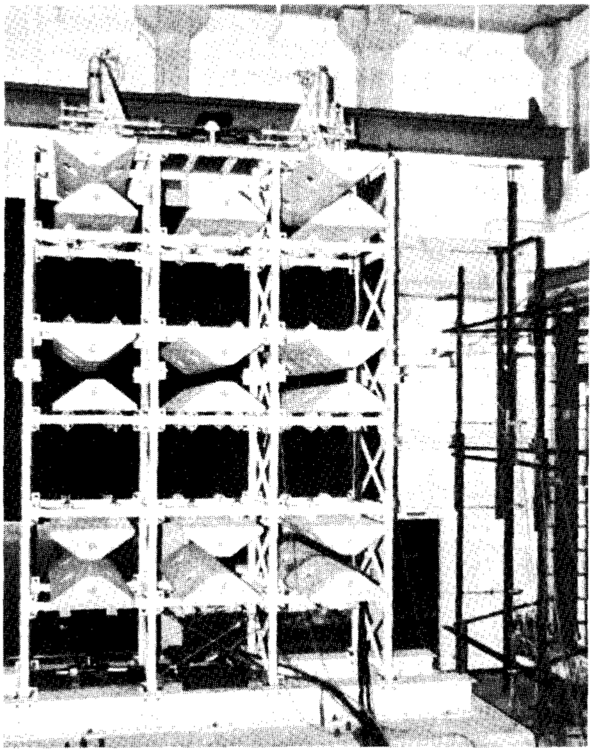


Figure 4 Model Structure at Stage 3

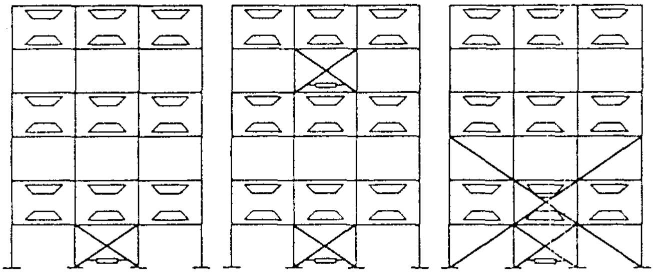


Figure 5 Examples of Actuator-Tendon Arrangements

simulated earthquake-type base motion. Following a closed-loop control algorithm and using three representative earthquake inputs, experimental results show that the maximum relative displacement reduction at the top floor could be as high as 50%.

In another experimental study, a moving mass termed an "active mass driver" was placed on a 0.5 m (width) × 3 m (height) three-story steel frame. The structure was mounted on a shaking table while an electro-magnetic force generator was adopted as the active controller. Experimental results indicate that a two-thirds reduction of the maximum acceleration and displacement could be achieved.

At a much larger scale, an active mass damper system was tested in conjunction with an active tendon system as described above. Using the same six-story 42,000-lb structure as shown in Fig. 4, the AMD system as shown in Fig. 6 was placed on top of the structure, which could be operated under different conditions by changing its added mass, it stiffness and the state of the regulator. A total of 12 cases were performed in the experiment.

One of the advantages of testing two different active systems using the same model structure is that their performance characteristics can be realistically compared. Extensive simulation and experimental results obtained based on the six-story, 42,000-lb model structure show that both AMD and ABS display similar control effectiveness in terms of reduction in maximum top-floor relative displacement, in maximum top-floor absolute acceleration, and its maximum base shear. They also have similar control requirements such as maximum control force and maximum power. Other information which may shed more light on their relative merits but is not considered here includes cost, space utilization, maintenance and other practical observations.

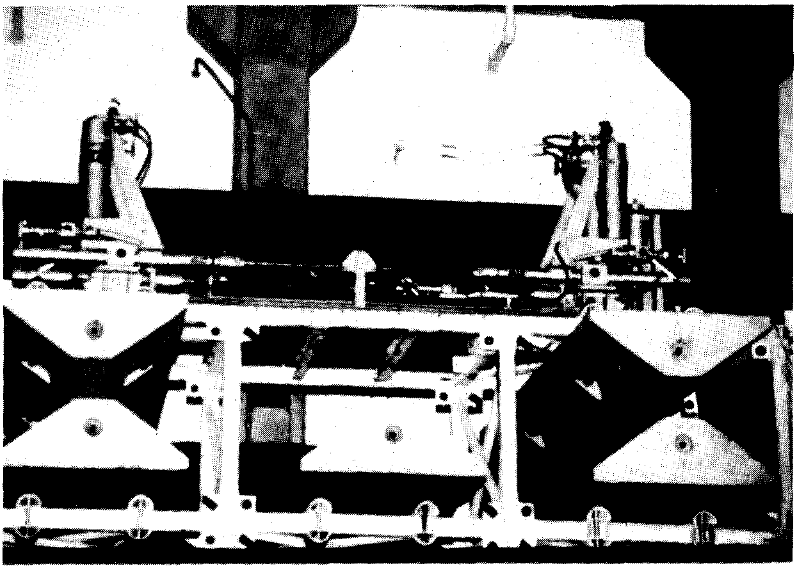


Figure 6 AMD on Top of Model Structure

VARIABLE STIFFNESS SYSTEMS

The main objective of a variable stiffness system is to use active systems in order to adjust the structural stiffness so that resonant modes of the structure can be steered away from dominant modes associated with the seismic input at each time instant. Small-scale experiments using this principle have been carried out [Kobori et al., 1990]. The experimental set-up consists of a three-story steel frame where active control actions are provided by bracing members with cylinder locking devices as schematically shown in Fig. 7. Each joint between a brace and the structural frame is engaged or disengaged by closing or opening a control valve in an active mode, thus altering structural stiffness.

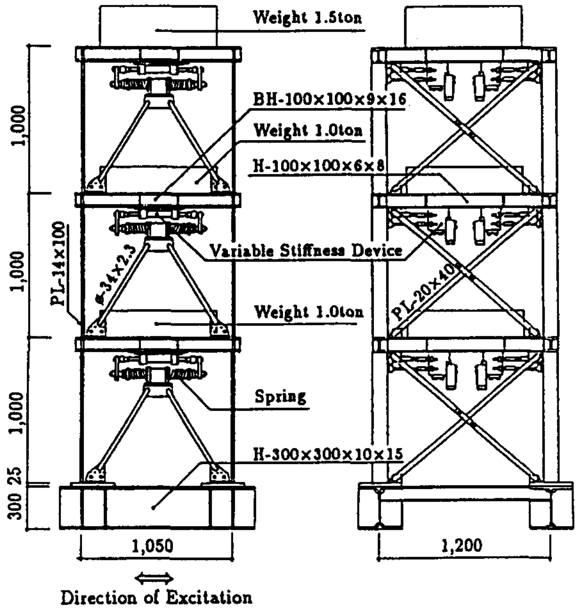


Figure 7 Variable Stiffness System [Kobori et al., 1990]

An attractive feature of this control scheme is that it does not require a large amount of external energy. In the experiment mentioned above, the only energy requirement was the 12 volts of electricity needed to operate the switch.

PULSE GENERATORS

Pulse control has also been a subject of experimental study in the laboratory. This control algorithm was tested using a six-story frame weighing approximately 159 kg and measuring six feet in height [Miller et al., 1987; Traina et al., 1988]. Figure 8 shows the model structure together with the test apparatus which includes vibration exciter, instrumentation, pneumatic power supply, and the microcomputer used for digital control. As shown in Fig. 9, the electrodynamic exciter, sensor, and pneumatic actuators were located at the top of the structure.

The actuators consisted of two solenoids which metered the flow of compressed air at 125 psi through eight nozzles, thus generating the required control pulses.

When the structure was subjected to a harmonic excitation at a frequency close to the fundamental frequency, it was shown that,, within ten periods of onset of control, the response was reduced to approximately 15% of its uncontrolled value.

Discussions on some of the recently developed cold-gas generators having potential structural control applications can be found in [Agababian Assoc., 1984a and 1984b]. In addition, pulse control experiments involving hydraulic and electromagnetic actuators have also been conducted in the laboratory [Traina et al., 1988].

ACTIVE PARAMETER CONTROL

Analytical and experimental studies have shown that a class of nonlinear auxiliary mass dampers, known as impact dampers, may be more efficient than the conventional (linear) dynamic vibration neutralizers in attenuating the response of oscillating structures subjected to nonstationary wide-band random excitation. The main factor for the effectiveness of properly designed impact dampers in limiting the vibrations of structures emanating from arbitrary dynamic environments is that the relatively small damping forces generated by the impacting (auxiliary) mass introduces chaos in the primary system response by disorganizing the orderly process of amplitude buildup, thus significantly reducing the structural response.

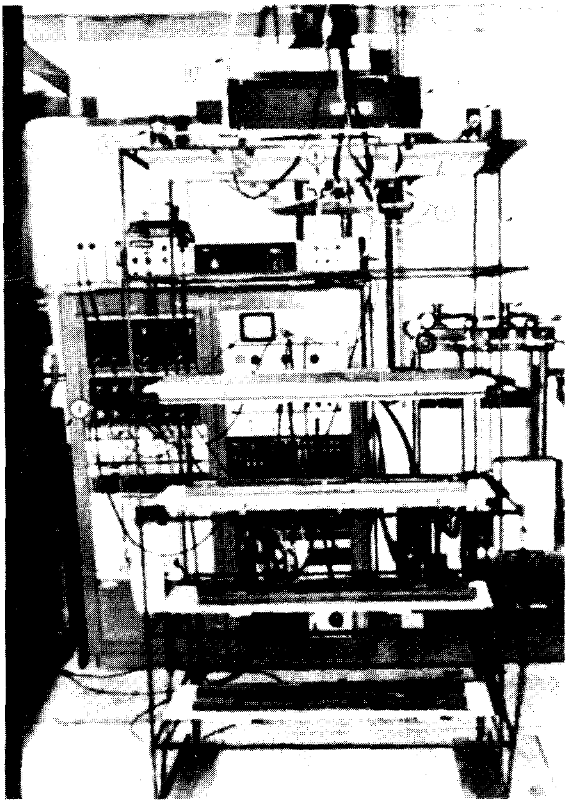
Motivated by the above discussion, Miller et al. (1987) developed and implemented two on-line active control algorithms that utilize pulse generators to emulate the action of optimally designed impact dampers, to suppress the vibrations of linear as well as nonlinear multidegree-of-freedom (MDOF) flexible structures responsing to arbitrary dynamic environments. These on-line control procedures have been shown to be quite effective in greatly reducing the rms response as well as the peak response of vibrating structures even when the excitation is nonstationary wide-band random. This significant improvement in efficiency is achieved because the active control algorithms under discussion are designated to maximize the influence of the control actuators either by (1) optimizing the relative magnitude of the control pulses or by (2) choosing the optimum time for applying the control forces. Both methods assume the availability of an external energy source to produce the control pulses on demand.

Since in many practical cases the amount of energy available for control purposes is limited, Masri et al. (1989) developed an alternate pulse-control strategy that economizes the use of control energy. This is accomplished by devising an on-line control procedure that attempts to optimize the *parameters* of incorporated impact vibration dampers attached to different locations within the vibrating flexible structure. Instead of using mass-ejection techniques (or equivalent methods) to directly furnish the needed control forces, an internal mechanism of momentum transfer between the primary structure and the auxiliary masses is employed. It is shown that the tradeoff between vibration damping efficiency and control energy economy does not lead to a major deterioration in the overall vibration reduction of the primary system as compared to what can be achieved with fully active pulse-control methods.

This semi-active on-line control algorithm has been shown to be suitable for situations in which detailed knowledge of the system structure is not available; only *local* measurements in the vicinity of each of the attached impact dampers are needed with this adaptive control method to determine the evolution of each impact damper clearance so as to optimize the vibration attenuation efficiency of the individual dampers. A stability analysis, simulation studies, and experimental tests with a mechanical laboratory model have demonstrated the feasibility, reliability, and robustness of this method.

AERODYNAMIC APPENDAGE

The use of aerodynamic appendages as active control devices to reduce wind-induced motion of tall buildings has several advantages, its main attractive feature being that the control designer is able to exploit the energy in the wind to control the structure, which is being excited by the same wind. Thus, it eliminates the need for an external energy supply to produce the necessary control force; the only power required is that needed to operate the appendage positioning mechanism. This type of control is clearly not suitable for seismic applications; however, it is included here for completeness.



LEGEND:

1 - Frame; 2- Exciter; 3 - RHS Thruster; 4 - LHS Thruster; 5 - Compressed Gas;
6 - Accelerometer; 7 - Displacement Follower; 8 - Microcomputer;
9 - Video Terminal; 10 - Pneumatic Supply Line; 11 - Nozzle

Figure 8 Six-Story Frame with Pulse Control Mechanism [Miller et al., 1987; Traina et al., 1988]

For this control scheme, a wind-tunnel experiment was conducted using an elastic model at a geometric scale of roughly 1:400 [Soong and Skinner, 1981]. This is schematically presented in Fig. 10. Its stiffness was provided by a steel plate fixed at the structure core as shown, and its length was adjusted so that under planned wind conditions in the wind tunnel used in the experiment, the first mode was dominant and was observed to be approximately 5 Hz.

The aerodynamic appendage consisted of a metal plate. It was controlled by means of a 24 VDC solenoid, activated by the sign of structural velocity as sensed by a linear differential transformer, followed by appropriate carrier and signal amplifications and a differentiator. The appendage area normal to the wind direction was roughly 2% of the structural frontal area when fully extended. A boundary layer wind tunnel was used to generate the necessary wind forces.

The active control experiment was performed under various wind conditions and a peak amplitude and velocity reduction of approximately 50% was observed.

OTHER CONTROL SYSTEMS

Discussed in the above are some of the most studied control mechanisms for structural applications. Many others have been proposed. Furthermore, the combined use of active-passive, or hybrid, systems have been suggested for some specific structural applications [Reinhorn et al., 1987; Kelly et al., 1987]. Hybrid control can alleviate some of the limitations which exist for either the passive system or the active system operating singly, thus leading to a very effective protective system. For example, in combination with a passive system, the force requirement of an active control system can be significantly reduced, which allows the active control device to operate at a much higher efficiency and effectiveness. At the same time, a purely passive system such as a simple elastomeric bearing is limited to low-rise structures because of the possibility of uplift of the isolator due to large horizontal accelerations. The addition of an active system is capable of minimizing this uplift effect.

The research on hybrid control systems has been focused on the following four problems:

(a) The use of active tendons operating at a level of the isolating medium, which is aimed at preventing excessive displacements of the foundation and of the structure.

(b) Active control of a structure with a sliding system by reducing the frictional force between the foundation and ground to close to zero. This can be accomplished by connecting an active controller in the direction of motion such that the structure will slide freely.

(c) An active tendon/sliding hybrid system for reduction of interstory displacements and absolute accelerations at each floor of the structure.

(d) The use of hybrid systems as "absolute" stabilizers in protecting sensitive equipment in a vibrational environment.

While some small-scale hybrid control experiments have been carried out, its feasibility still awaits verification using more realistic model structures under realistic conditions. Cost associated with hybrid systems is another important consideration.

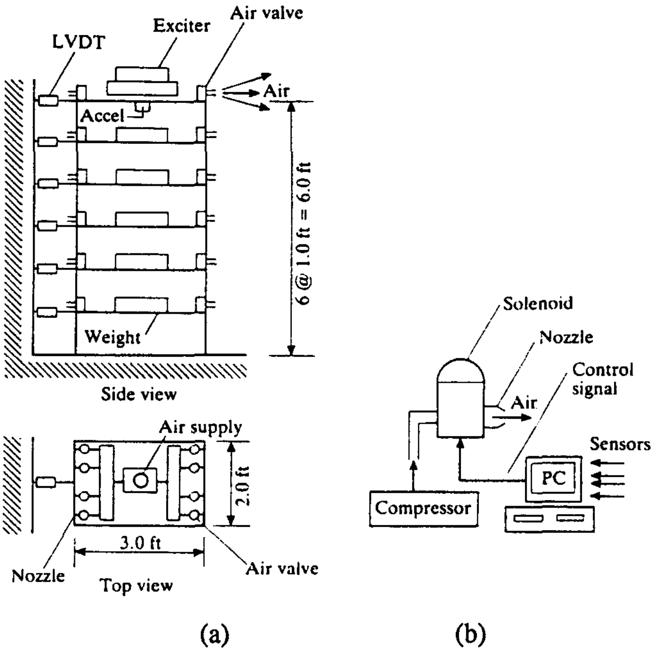


Figure 9 Pulse Control System
(a) Control Configuration; (b) Pneumatic Control
[Traina et al., 1988]

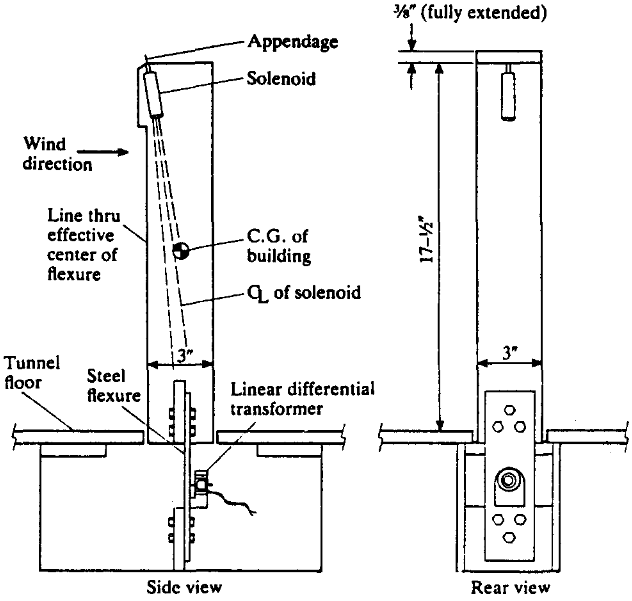


Figure 10 Schematic Diagram of Aerodynamic Appendage

FULL-SCALE IMPLEMENTATION AND TESTING

As alluded to earlier, full-scale implementation of active control devices in buildings has taken place. Recently, a full-scale active mass driver system has been installed on the top floor of the eleven-story Kyobashi Seiwa building in Tokyo, Japan (Fig. 11). The active mass driver, shown in Fig. 12, is a pendulum-type dual-mass system capable of controlling torsional as well as lateral vibration of the slender structure due to strong wind or moderate earthquakes. The first mass, weighing approximately four tons, is used for lateral motion control and the second mass, weighing approximately one tone, is used for torsional control. This system, designed primarily for comfort control of building occupants, has performed well under several hurricanes and modest earthquakes encountered since installation.

Another active mass damper was recently fabricated and is being tested on top of a dedicated full-scale 600-ton test structure depicted in Fig. 13. The biaxial AMD, shown in Fig. 14, is of the pendulum type with a fail-safe regulator. It weighs 6 tons, approximately 1/100 of the structural weight, and has a maximum stroke of ±1.0 m with a maximum control force of 10 tons. During a recent earthquake in Tokyo, the maximum relative displacement at the top floor was observed to be 0.63 cm as compared with 2.16 cm, which is the estimated maximum value had the system not been activated.

In addition, a full-scale active bracing system has been fabricated and installed in the same dedicated test structure as described above. As shown in Figs. 15 and 16, the ABS consists of four actuators attached to bracings on the first floor. Similar to the AMD, it is designed to provide motion control in either of the two directions.

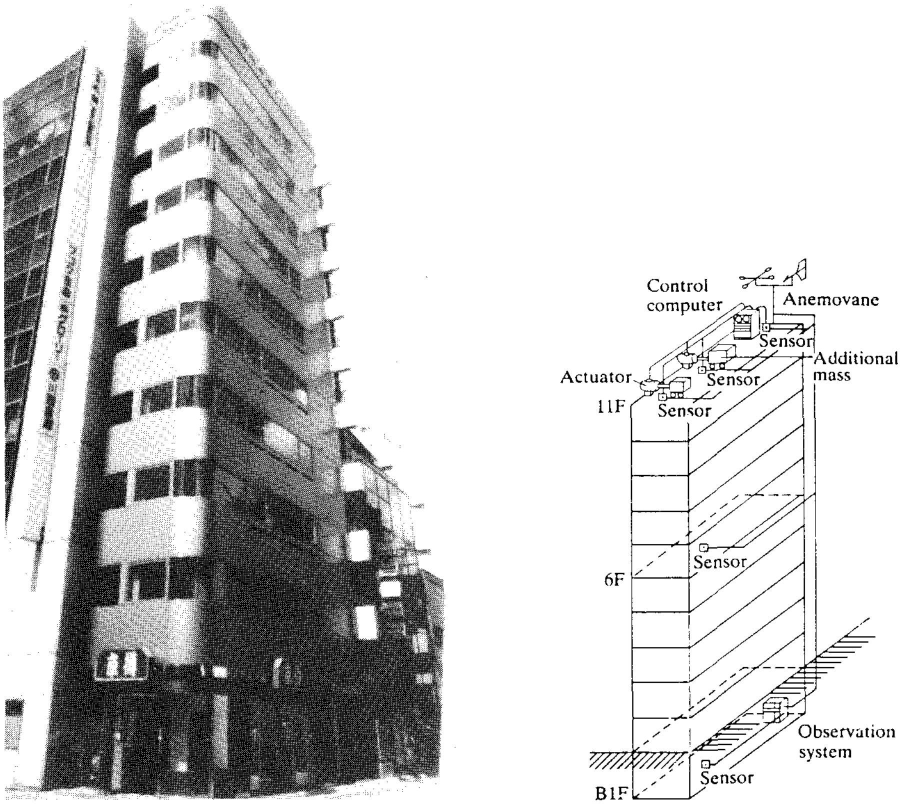
Again, the advantage of having the performance of two active systems evaluated using the same structure is obvious. In addition to providing the same base parameters for performance comparisons, this arrangement allows the calibration of the ABS and AMD systems by using one of the systems as motion inducer and the other as motion controller. Even without actual seismic motion, much of the performance characteristics can be assessed using this calibration method. During the calibration period, several feasible control algorithms can be evaluated and control parameters refined.

Performance observations of these systems under actual ground motions are being carried out by deactivating one of the systems for a period of six months in order to allow performance assessment of the other system. A total three-year observation period is planned under this activation-deactivation scheme.

FUTURE RESEARCH AND CONCLUDING REMARKS

With extensive experimental work and full-scale testing underway, active structural control research for seismic applications has entered an exciting phase. Faced with increasing demands on reliability and safety, active structural control can be an eminently logical alternative in insuring structural integrity and safety to more traditional approaches.

At the same time, however, a large number of serious challenges remain and they must be addressed before active structural control can gain general acceptance by building owners and by the civil engineering and construction professions at large. Some of these issues are discussed below.



(a) (b)

Figure 11 Kyobashi Seiwa Building with AMD (Courtesy of Kajima Corporation)
(a) Kyobashi Seiwa Building; (b) AMD System

CAPITAL COST AND MAINTENANCE

Maintenance is certainly necessary for active systems and this is an important issue particularly due to the fact that, when active control is only used to counter large seismic and other environmental forces, it is likely that the control system will be infrequently activated. The reliability of a system operating largely in a standby mode and the related problems of maintenance and performance qualification become an important issue.

Cost, however, is not likely to be an obstacle. Recent phenomenal advances in allied technology such as computers, electronics and instrumentation all reflect favorably on the cost factor. Based on recent experiences in the fabrication of full-scale systems, active systems can in fact be more economical when used in strengthening existing structures than, for example, the use of base isolation systems. This is largely due to the fact that active systems can be designed such that they are not structurally invasive. More studies, however, are needed to address the cost issue in more concrete terms.

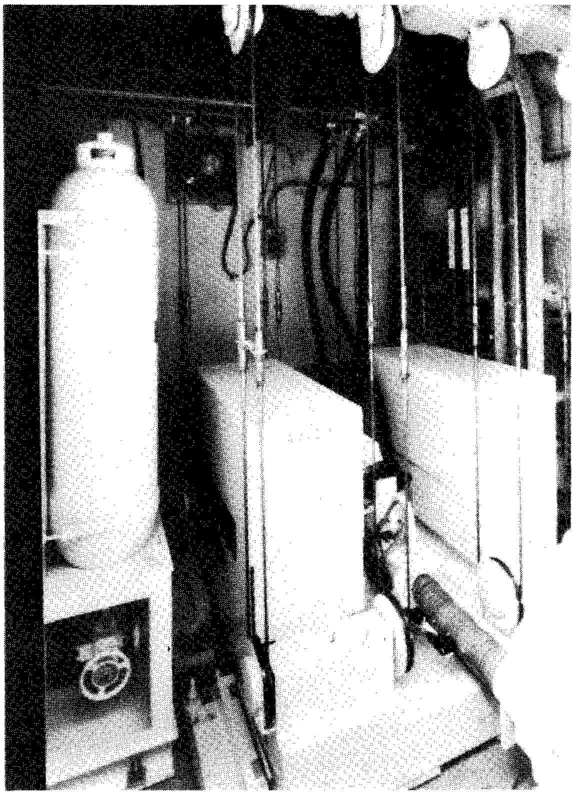


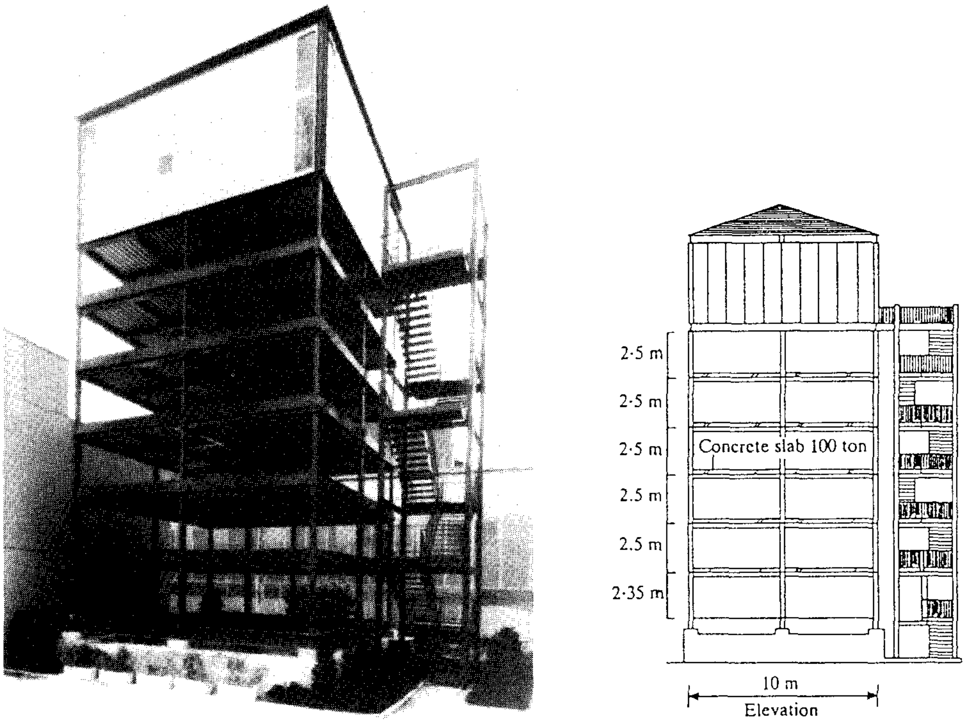
Figure 12 View of AMD (First Mass Portion)
(Courtesy of Kajima Corporation)

RELIANCE ON EXTERNAL POWER AND RELIABILITY

Active systems rely on power sources and, when these sources in turn rely on all the support utility systems, this power dependence on the part of an active system presents serious challenges since the utility systems, unfortunately, are most vulnerable at the precise moment when they are most needed. The scope of the reliability problem is thus considerably enlarged if all possible ramifications are considered.

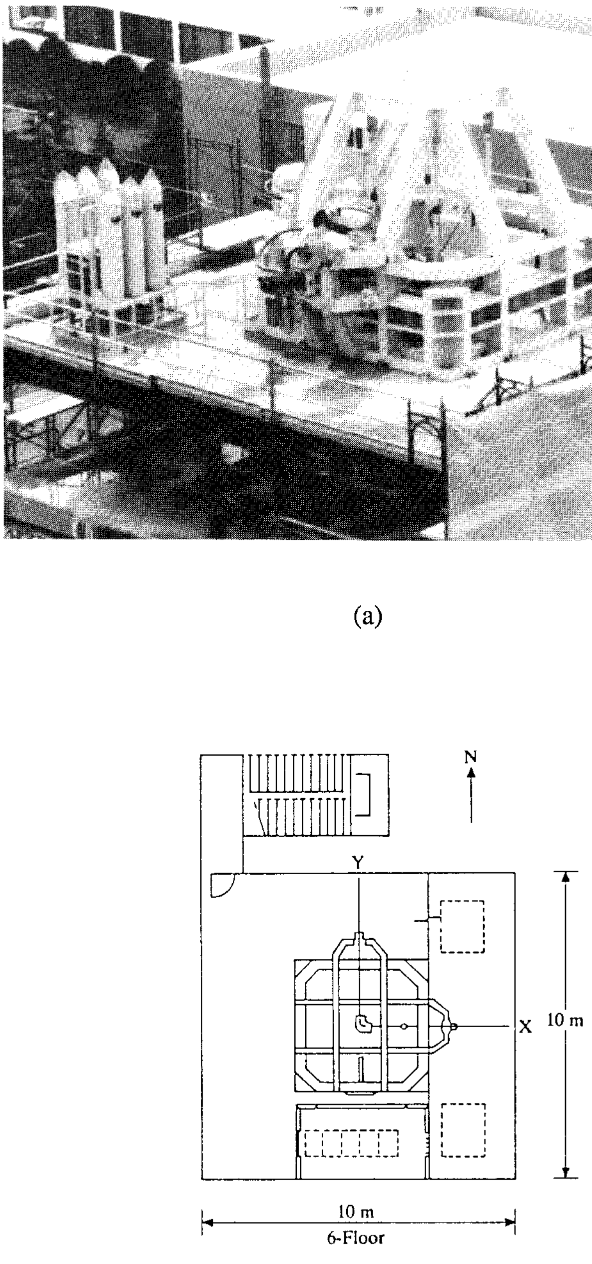
It should be noted that this problem has been addressed in the design of the full-scale active bracing system discussed in the preceding section. Since the control interval for earthquake-excited motions is of the order of one minute or less for each episode, the power requirement of this system is such that it can be supplied by currently available accumulators. This design strategy would eliminate its dependence on external power at the time of control execution.

On reliability, not to be minimized is the psychological side of this issue. There may exist a significant psychological barrier on the part of the occupants of a structure in accepting the idea of an actively controlled structure, perhaps leading to perceived reliability-related concerns.



(a) (b)

Figure 13 Full-Scale Dedicated Test Structure
(Courtesy of Takenaka Corporation)



(a)

(b)

Figure 14 View of AMD on Top of Test Structure (Courtesy of Takenaka Corporation)

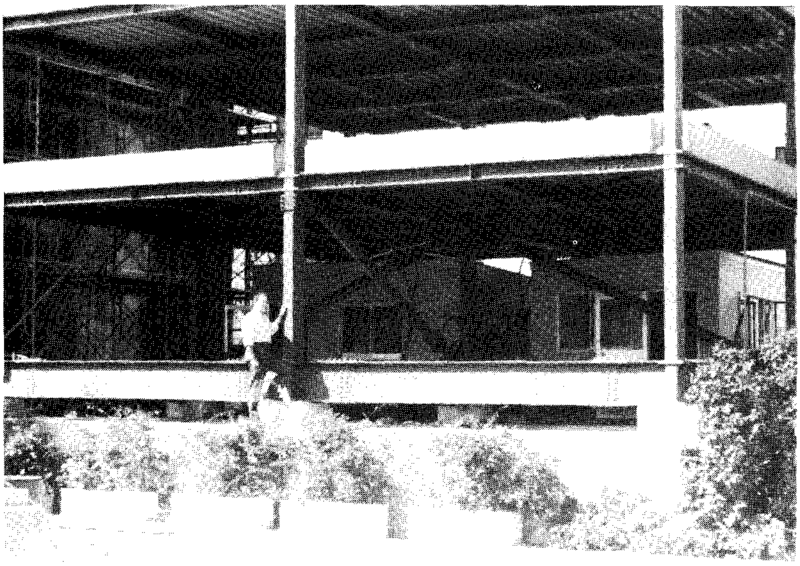


Figure 15 Active Bracing System in Test Structure

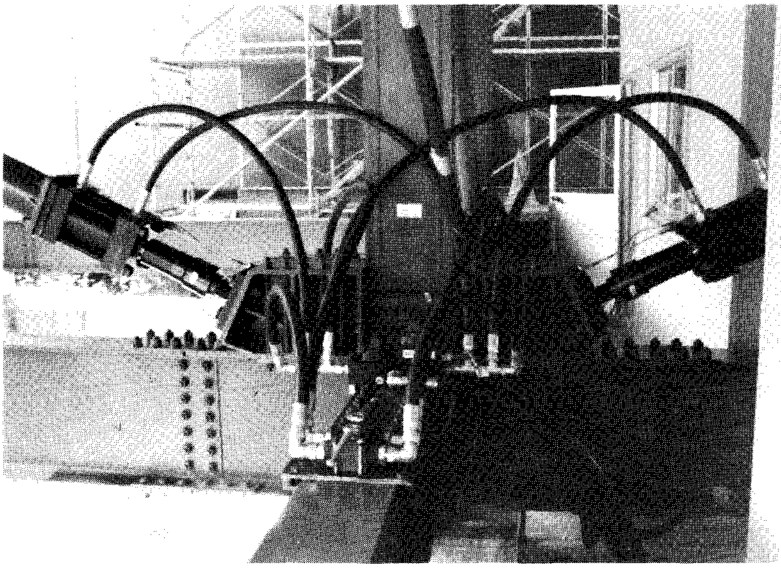


Figure 16 Close-up View of Actuators

NONTRADITIONAL TECHNOLOGY

Since the concept of an active-controlled structure is a significant departure from traditional structural concepts, obstacles exist with respect to its acceptance by building owners and by the profession. This is particularly true when structural safety is to rely upon an active control system. More full-scale demonstration projects are thus needed for purposes of concept verification and education.

SYSTEM ROBUSTNESS

As demanded by reliability, cost and hardware development, applicable active control systems must be simple. Simple control concepts using minimum number of actuators and sensors may well deserve more attention in the near future. Simple control, of course, does not mean simple problems. Since civil engineering structures are complex systems, this inherent incompatibility gives rise to a number of challenging problems from the standpoint of system robustness, controllability and effectiveness.

ACTIVE VS. PASSIVE CONTROL

While some progress has been made in this direction, more comprehensive studies are certainly needed in order to realistically evaluate the relative merits of alternative structural protection techniques on the basis of practical criteria such as performance, structural type, site characteristics and cost-effectiveness. However, to find answers to these questions are more long-term tasks since they will depend on specific structural applications, hardware details and a variety of other issues, many of which need to be better understood and further developed.

Finally, it is remarked that, in view of considerable interest that has been generated in this research area, a U.S. Panel on Structural Control Research has been formed under the auspices of the National Science Foundation. The Panel has the responsibility of:

(a) Facilitating the transmission of information concerning state-of-the-art developments in the field.

(b) Identifying and prioritizing needed research and development.

(c) Developing preliminary plans for analytical and experimental advancement in the field.

(d) Developing plans for the performance of full-scale testing and demonstration.

The Panel members are:

F. Conati, MTS Systems Corporation
W. Hall, University of Illinois
G.W. Housner, California Institute of Technology
S.F. Masri, University of Southern California
M. Shinozuka, Princeton University
T.T. Soong, State University of New York at Buffalo
B.K. Wada, Jet Propulsion Laboratory

The organization of the U.S. Panel is illustrated in Fig. 17. As shown in this figure, working groups in several key areas are in place and active researchers in these areas are invited to participate.

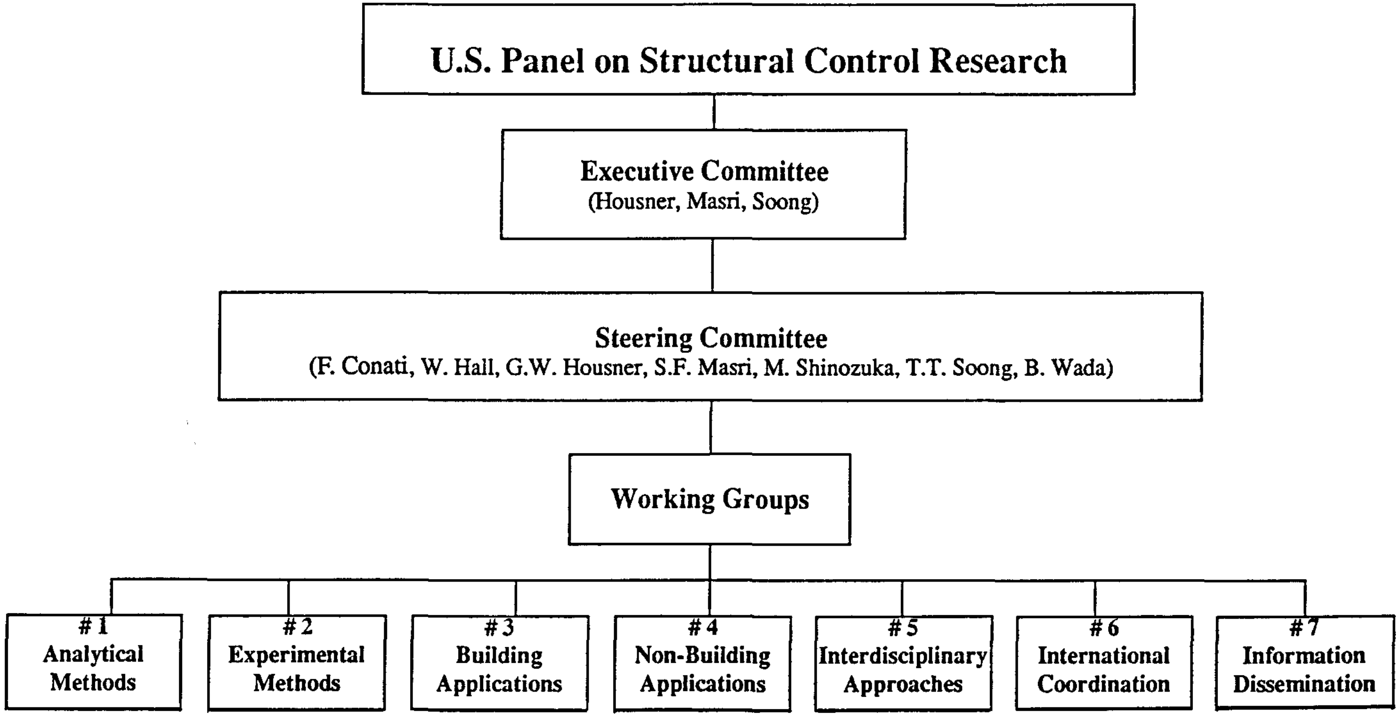


Figure 17 Organization of U.S. Panel on Structural Control Research

In addition, the U.S. Panel works closely with its Japan counterpart in the development of a joint US-Japan research agenda in the active and hybrid control program areas.

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REFERENCES

Agababian Assoc., (1984a). *Validation of Pulse Techniques for the Simulation of Earthquake Motions in Civil Structures*, AA Rept. No. R-7824-5489, El Segundo, CA.

Agababian Assoc., (1984b). *Induced Earthquake Motion in Civil Structures by Pulse Methods*, AA Rept. No. R-8428-5764, El Segundo, CA.

Chung, L.L., Reinhorn, A.M. and Soong, T.T., (1988). "Experiments on Active Control of Seismic Structures," *ASCE J. Eng. Mech.*, Vol. 114, pp. 241-256.

Chung, L.L., Lin, R.C., Soong, T.T. and Reinhorn, A.M., (1989). "Experimental Study of Active Control of MDOF Seismic Structures," *ASCE J. Eng. Mech.*, Vol. 115, pp. 1609-1627.

Kelly, J.M., Leitmann, G. and Soldatos, A.G., (1987). "Robust Control of Base-Isolated Structures Under Earthquake Excitations," *J. Optim. Th. Appl.*, Vol. 53, pp. 159-180.

Kobori, T., (1988). "State-of-the-art Report: Active Seismic Response Control," *Proc. Ninth World Conference on Earthquake Engrg.*, Vol. VIII, pp. 435-446, Tokyo/Kyoto, Japan.

Kobori, T., Kanayama, H. and Kamagata, S., (1988). "A Proposal of New Anti-seismic Structure with Active Seismic Response Control System," *Proc. Ninth World Conference on Earthquake Engineering*, Vol. VIII, pp. 465-470, Tokyo/Kyoto, Japan.

Kobori, T. et al., (1990). "Experimental Study on Active Variable Stiffness System - Active Seismic Response Controlled Structure," *Proc. Fourth World Congress of Tall Buildings and Urban Habitat*, Hong Kong.

Kuroiwa, H. and Aizawa, S., (1987). Private Communication.

Masri, S.F., (1988). "Seismic Response Control of Structural Systems: Closure," *Proc. Ninth World Conference on Earthquake Engrg.*, Vol. VIII, pp. 497-502, Tokyo/Kyoto, Japan.

Masri, S.F., Miller, R.K., Dehghanyar, T.J. and Caughey, T.K., (1989). "Active Parameter Control of Nonlinear Vibrating Structures," *The Journal of Applied Mechanics*, Trans. ASME, Vol 56, September, pp. 658-666.

Miller, R.K., Masri, S.F., Dehghanyar, T.J. and Caughey, T.K., (1987). "Active Vibration Control of Large Civil Engineering Structures," *ASCE J. Eng. Mech.*, Vol. 114, pp. 1542-1570.

Reinhorn, A.M., Soong, T.T. and Wen, C.Y., (1987). "Base Isolated Structures with Active Control," *Proc. ASME PVD Conf.*, PVP-127, pp. 413-420, San Diego, CA.

Reinhorn, A.M. and Manolis, G.D., (1989). "Recent Advances in Structural Control," *Shock and Vibration Digest*, Vol. 21, pp. 3-8.

Reinhorn, A.M., Soong, T.T., et al., (1989). *1:4 Scale Model Studies of Active Tendon Systems and Active Mass Dampers for Seismic Protection*, Tech. Rep. NCEER-89-0026, National Center for Earthquake Engineering Research, Buffalo, NY.

Roorda, J., (1980). "Experiments in Feedback Control of Structures," *Structural Control*, (H.H.E. Leipholz, ed.), North Holland, Amsterdam, pp. 629-661.

Soong, T.T. and Skinner, G.T., (1981). "Experimental Study of Active Structural Control," *ASCE J. Eng. Mech., Div.*, Vol. 107, pp. 1057-1068.

Soong, T.T., (1988), "State-of-the-art-Review: Active Structural Control in Civil Engineering," *Engineering Structures*, Vol. 10, pp. 74-84.

Soong, T.T., (1990). *Active Structural Control: Theory and Practice*, Longman, London, and Wiley, New York.

Traina, M.I., Masri, S.F., et al., (1988). "An Experimental Study of Earthquake Response of Building Models Provided with Active Damping Devices," *Proc. Ninth World Conference on Earthquake Engineering*, Vol. VIII, pp. 447-452, Tokyo/Kyoto, Japan.

Yang, J.N. and Soong, T.T., (1988), "Recent Advances in Active Control of Civil Engineering Structures," *J. Prob. Eng. Mech.*, Vol. 3, pp. 179-188.