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ACTIVE CONTROL OF BUILDINGS DURING EARTHQUAKES

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Abstract

The objective of this report is to provide an overview of the different types of control systems used in buildings, to discuss the problems associated with current active control mechanisms, and to show the cost-effectiveness of applying active control to buildings. In addition, a small case study investigates the feasibility and benefits of using embedded actuators in buildings. Use of embedded actuators could solve many of the current problems associated with active control by providing a wider bandwidth of control, quicker speed of response, increased reliability, and reduced power requirement. Though embedded actuators have not been developed for buildings, they have previously been used in space structures. Many similarities exist between large civil and aerospace structures indicating that direct transfer of concepts between the two disciplines may be possible. In particular, much of the Controls-Structures Interaction (CSI) technology currently being developed could be beneficially applied to civil structures. While several buildings with active control systems have been constructed in Japan, additional research and experimental verification are necessary before active control systems become widely accepted and implemented.

1 Introduction

Though buildings have historically been regarded as passive entities, current research activities in the field of civil engineering are aimed at creating actively controlled structures. Actively controlled structures promise to provide greater efficiency in resisting unpredictable load levels. Civil engineering structures are repeatedly subjected to randomly occuring environmental loads, many of which may be quite large, such as those due to earthquakes and high winds. Prediction of loading conditions on buildings has always presented a challenging problem. In the past, buildings were conservatively designed to withstand a certain, almost arbitrary, design load level. It was hoped that inherent overstrength of the structure due to these conservative design techniques would be sufficient to avoid collapse and excessive damage should the structure be subjected to loads greater than the design loads. However, we have witnessed on several occasions that this hypothesis is not accurate, with major destruction and loss of life experienced during earthquakes. It is no longer sufficient in building design to construct conservative structures with little understanding of how they will behave during an earthquake. Active control systems dynamically counteract loads, to avoid designing for all possible load levels. The concept of active control of buildings was prompted by the following factors [Soong 1990]:

- **Increased Flexibility**–Taller structures using lighter materials are being designed and constructed.
- **Increased Safety Levels**–Higher levels of reliability against damage and failure are expected today than in the past.
- **Increased Performance Requirements**–Buildings are housing more sensitive equipment and reactive materials requiring improved isolation from vibrations.

- **Better Utilization of Materials and Lower Cost**–With new concerns over the environment and available natural resources, it is no longer economically feasible to create massive, overconservative structures.

As part of the Langley Aerospace Research Summer Scholars (LARSS) Program, I conducted a literature search on the state-of-the-art in active control of civil engineering structures and developed a small case study to investigate the effectiveness of using embedded actuators to control earthquake induced motions in buildings. Embedded actuator characteristics which could resolve many of the problems associated with active control systems in buildings include a wide band of control, reliability, compactness, low cost, and a small power requirement. While additional hardware development and testing is necessary before embedded actuators may be used in buildings, they are shown in this study to be very effective in reducing building motions caused by earthquakes.

2 Background on Control of Buildings

The idea of actively controlling civil structures originated in 1960 when Eugene Freyssinet proposed using prestressed tendons as control devices in buildings and bridges. Then in 1965 Lev Zetlin designed several buildings, though they were never constructed, with active cables and jacks to control motions [Zuk 1980]. These pioneering ideas formed the foundation for the idea of actively controlling buildings. It was not, however, until the control theories for buildings were formalized by J.T.P. Yao in 1972 [Yao 1972], that intensive research in active control really started in the field of civil engineering.

Research related to the control of a variety of structural systems, such as bridges, dams, and lifelines, under different loading conditions such as wind and waves, has been conducted. However, the majority of the work in active control for civil engineering applications to date has been geared toward the control of buildings during earthquakes. Loads induced by earthquakes are very difficult to predict, thus presenting a major challenge to designers. Earthquakes are stochastic in nature ranging in acceleration levels from $0.1g$ to $1.2g$. While earthquakes contain both horizontal and vertical components, the effects of the vertical component are negligible compared to the large gravity loads which buildings must support. Thus, structural engineers are generally only concerned with the horizontal components of earthquakes which can produce large lateral forces in buildings. The lateral stability of buildings in earthquake zones is usually the governing design condition. Peak ground motion (acceleration, velocity, or displacement), duration of strong motion, and frequency content are all important characteristics of earthquake ground motion which affect structural response [Mohraz 1989]. Shorter, stiffer buildings generally respond with high floor accelerations during an earthquake which causes discomfort to occupants. And taller, more flexible structures generally respond with high interstory drift values (differential floor displacements) which could result in excessive damage, especially to nonstructural components such as windows, partition walls, and cladding. Active control is generally more beneficial in taller, more flexible structures to reduce displacements and thus mitigate damage.

Structural control as a means of protecting buildings during earthquakes has been a prominent field of research for the past two decades. While both Japan and the U.S. have been researching this topic, only Japan has actually implemented full-scale active control systems in buildings. U.S. researchers were, however, involved in the design and fabrication

Table 1: Buildings with Active Control Systems

Building	Year Completed	No. of Stories	Type of System
Kyobashi Seiwa	1989	11	Active Mass Damper
Takenaka Experimental Bldg.	1990	6	Active Bracing System & Active Mass Damper
Kajima Research Facility	1990	3	Variable Stiffness System
Sendogaya INTES	1992	13	Active Mass Damper
Hankyu Chayamachi	1992	24	Active Mass Damper
MM21	1993	70	Active Mass Damper

of the Takenaka active bracing system. Those buildings which contain active control systems are listed in Table 1 [Soong *et al* 1993].

In an effort to increase active control developments in the U.S., a panel was recently formed by the National Science Foundation to study and guide structural control research [Housner *et al* 1992]. The panel oversees seven committees which investigate the following areas: (i) Analytical Methods, (ii) Experimental Methods, (iii) Building Applications, (iv) Non-Building Applications, (v) Interdisciplinary Approaches, (vi) International Coordination, and (vii) Information Dissemination. Evidence that structural control of buildings is becoming an active area of research throughout the world includes the formation of an International Association for Structural Control and the organization of an International Workshop on Smart Control in June of 1993. In addition, 10% of the papers presented at the Tenth World Conference on Earthquake Engineering in Madrid in 1992 were related to structural control.

While the U.S. may be lagging in the implementation of active control systems, it is a leader in the area of passive control systems. There are more than 125 buildings in the world with passive control devices, the majority of which are located in the U.S. [Buckle 1993]. Though the emphasis of this report is on active control, a brief discussion on passive control systems is included for completeness. Base isolation and tuned mass dampers are the most widely used passive systems. The philosophy behind the tuned mass damper involves placing a concentrated mass in the structure to counteract motions induced by an earthquake. 'Tuned' simply means that the mass is positioned such that it controls a certain mode or modes of vibration of the structure; generally, the mass is placed near the top of the building to control its fundamental period. The mass usually weighs 2-5% of the entire structure and is free to slide or swing to counteract motions. Tuned mass dampers have been installed in several buildings including the John Hancock Building in Boston and the Citicorp Building in New York, both of which were retrofitted to reduce vibrations due to wind.

The idea behind base isolation is to mount the building on some type of flexible, or friction, bearing system which introduces additional damping to absorb earthquake motions before they reach the upper floors. Similar types of systems have previously been introduced in other engineering applications to isolate machinery and sensitive equipment. In 1909, the first patent for a base isolation system for a building was granted. It was not, however, until much later that base isolation became a popular method of reducing building motions.

Table 2: Passive vs. Active Control

	Passive	**Active**
Advantages	No external energy supply required	Wide frequency band of control
	Minimal maintenance required	Effective control of transient response
Disadvantages	Narrow frequency band of control	Large external energy supply required
	Ineffective control of transient vibrations	High level of maintenance required

Reasons for the recent acceptance of base isolation systems include [Mayes 1989]: (i) the development of elastomeric (rubber) pads and mechanical energy dissipators capable of resisting earthquake motions; (ii) the development of computer software to analyze the behavior of structures on nonlinear isolators; and (iii) the verification of base isolation systems by performing shaking table tests on model structures. The hysteretic properties of the materials in base isolation systems dissipate earthquake input energy. Elastomeric pads are the most common type of material used because the behavior of elastomers is well-understood and easy to predict. These pads have been found to reduce buildings motions by a factor of 5 to 10 [Mayes 1989]. Other, less widely used, types of base isolation systems include rollers, friction slip plates, cable suspension, and sleeved piles [Mayes 1989]. Base isolation seems to be best suited for relatively rigid structures of moderate height.

While passive control is a viable method for reducing buiding motions, it also has many limitations. One limitation is that passive systems are generally tuned to a single modal frequency. However, earthquakes have a wide frequency range which may excite many different structural modes, particularly in tall, flexible structures. In addition, though passive systems increase damping in the structure they are ineffective in controlling transient vibrations. Table 2 from [Iemura 1992] lists the advantages and disadvantages of both passive and active control systems. The remainder of this report is dedicated to the active control of building structures.

3 Types of Active Control Systems

3.1 Active Tendons

Active tendon control, first proposed by Freyssinet in 1960, is one of the most researched active control mechanisms. Analytical studies with active tendon control systems have been conducted for several types of civil structures including tall buildings ([Abdel *et al* 1983], [Juang *et al* 1980], and [Yang 1982]), bridges [Yang *et al* 1979], and offshore structures ([Reinhorn *et al* 1986] and [Prucz *et al* 1983]). Active tendon control involves applying forces to tendons or braces with electrohydraulic actuators. One of the reasons active tendon control has been such a favorable control mechanism is that braces and tendons are common structural elements. Thus little modification is required to implement active tendon control systems in conventional designs, or to retrofit existing structures. In addition, active tendon control can operate in both pulse and continuous modes [Soong 1990]. Numerous studies, both analytical and experimental, have been conducted regarding the optimal placement of actuators and sensors. However, a single set of forces is generally applied at the first floor of the structure since the large size and cost of hydraulic actuators prohibits their implementation on multiple floors.

As listed in Table 1, the Takenaka Experimental Building in Tokyo, Japan has a full-scale active tendon system. The Takenaka Building is a symmetric two-bay, six-story steel structure. It is constructed of box columns, W-section beams and a reinforced concrete floor slab (assumed rigid), with moment connections. It is a relatively flexible structure with fundamental periods of 1.0 second and 1.5 seconds in the strong and weak directions respectively [Soong *et al* 1992]. The active bracing system installed in the Takenaka Building consists of a pair of hydraulic actuators which apply forces to the first floor of the structure in both directions via four braces. Each of the actuators is capable of applying 685 kN of control force. Velocity sensors and accelerometers are installed in the structure to monitor its response behavior. Velocity feedback control algorithms are used with and without an observer. Time delays due to instrument phase shifts, on-line computation time, and actuator response time are also accounted for in the control algorithms [Soong *et al* 1992]. The active bracing system is able to reduce top floor displacements, top floor accelerations, and base shear values by 20–40%. However, the control system is generally ineffective from zero to four seconds, leaving initial vibrations essentially uncontrolled. Another problem with this type of control system is that the necessary control forces often exceed the capacity of the actuators [Soong *et al* 1992].

3.2 Active Mass Dampers

Active mass dampers are an adaptation of the passive tuned mass damper, in existence in several buildings throughout the U.S. and Japan [Soong 1990]. One disadvantage of the passive mass damper is that they are generally tuned to a single frequency. The main reason for developing active mass dampers is to control a wider frequency band. A single active mass damper is usually installed at the top of the structure due to economic limitations. A single damper (active or passive) placed at the top of a building is generally only effective in controlling the fundamental period of the structure since frequency of control is governed by placement of the actuators [Soong 1990]. Thus, in reality, there is little advantage to using an active rather than a passive mass damper, as far as frequency bandwidth is concerned.

Active mass dampers, like passive mass dampers, may be either a pendulum type mechanism or a sliding mass type mechanism. One advantage to active mass damper systems is that a smaller mass is required: 1-2% as opposed to 2-5% of the structural mass. In addition, the mass is generally variable. The mass is moved by hydraulic actuators to conteract undesirable motions. Most active mass damper systems are designed to control torsion as well as motions in the transverse directions of the building.

As listed in Table 1, there are several buildings constructed in Japan with active mass damper systems. These buildings have performed well with regard to reducing displacements and accelerations for improved comfort and reduced damage levels. The Kyobashi Seiwa Building, in particular, has been subjected to several hurricanes and moderate earthquakes with little damage [Soong *et al* 1992].

An active mass damper is installed in the Takenaka Experimental Building in addition to the active tendon control system discussed in the previous section so that the two systems may be compared directly. The active mass damper system in the Takenaka Building is a biaxial pendulum type system. The mass weighs approximately 6 tons which is 1/100 of the structural weight. The system is capable of generating 10 kN of control force with a stroke of ±1.0m [Soong 1990]. During a moderate earthquake in Tokyo in 1992, the maximum relative displacement measured at the top of the structure was 0.63 cm as compared to the estimated uncontrolled value of 2.16 cm [Housner *et al* 1992]. Both the active mass damper and active tendon control systems are found to reduce displacements by 20-40% on the average; however, the active tendon control system is more effective in reducing acceleration values and in controlling higher order modes.

3.3 Variable Stiffness Systems

The objective of the active variable stiffness system is to modify the stiffness of the structure such that its natural frequency is different than the earthquake input frequency [Housner *et al* 1992]. While some small experiments have been conducted [Kobori *et al* 1992], the active variable stiffness system is a relatively new concept. The stiffness of the building is changed by engaging or disengaging certain joints. The advantage of this type of system is that it requires only a small amount of external energy (12 volts of electricity is generally sufficient to control the switches at the joints) [Housner *et al* 1992]. However, in order to correctly adjust the stiffness, a very good understanding of the dynamic structural behavior is necessary. Further research is required in the area of system identification before active variable stiffness systems become accepted and implemented.

3.4 Hybrid Systems

Hybrid systems, which combine active and passive control mechanisms in the same structure, have been a recent area of much research. It is hoped that combining passive and active control systems will alleviate many of the problems associated with each separately. For example, the force required by the active systems may be significantly reduced in the presence of a passive system. In addition, uplift in the isolator may be reduced by applying active control forces [Housner *et al* 1992].

4 Problems Associated with Active Control Systems

Several political and social issues are involved in the development of active control systems. Civil engineers tend to be slow in embracing new technology and concepts, as is illustrated by the lethargic conversion from traditional Allowable Stress Design (ASD) to the new Load and Resistance Factor Design (LRFD) [Buckle 1993]. Testing and verification of active control systems must be performed in order to convince designers that this technology provides a viable method for reducing building motions. Of course, obtaining sufficient funds for testing, research, and implementation is also a major obstacle.

Additional issues related to active control which must be addressed before it becomes widely accepted include [Housner *et al* 1992]:

- **Cost**–Cost is a major issue in any engineering endeavor. The availability of reliable hardware and software systems at a reasonable cost is necessary.

- **Maintenance & Reliability**–While earthquakes threaten major destruction, they are rare events, meaning control systems are seldom turned on. The control systems must, however, be maintained to a level that they are reliable and fully operational at an instant's notice in the event of an earthquake.

Table 3: Likelihood of Damage During an Earthquake

δ = **drift index** **= interstory drift/story height**	**Likelihood of Damage During an Earthquake**
0.001	Nonstructural damage probable
0.002	Nonstructural damage likely
0.007	Nonstructural damage almost certain; Structural damage likely
0.015	Nonstructural damage certain; Structural damage likely

- **Robustness**-Active control sytems must also prove robust as it is difficult to predict true structural response and possible loading conditions.
- **External Energy Requirements**-External energy requirements present a challenging problem since during an earthquake, destruction of lifelines and power supplies is much more probable. It is desirable to reduce the reliance of active control systems on external power sources.

While there are still many problems associated with active control systems, much progress is being made toward the acceptance of this technology.

5 Cost-Effectiveness of Active Control Systems

Current design codes require that buildings resist earthquake forces without collapse, but allow certain levels of damage to be incurred, since it is economically infeasible to design a perfectly damage-proof structure. Savings gained by implementing active control result mainly from reduced damage costs and loss of operational time. Though buildings rarely collapse and sustain only minor structural damage during an earthquake, nonstructural damage is a major concern. The cost of nonstructural/architectural elements of a building generally greatly exceeds the cost of the structural components. It is likely that during even a moderate earthquake (magnitude 4-5) a building will sustain significant nonstructural damage. The scale shown in Table 3 was established by Farzad Naeim [Naeim 1989] to indicate the likelihood of damage during an earthquake. Though this scale is somewhat vague it shows that nonstructural damage is likely to occur at a very low interstory drift (differential floor displacement) values. Thus, active control systems which reduce building displacement responses will mitigate damage during an earthquake.

Wen and Ang outline three basic alternatives to seismic design [Wen *et al* 1992]. The design alternative currently followed, *alternative A*, is to conventionally design the structure, but also include an active control system. The active control system in design alternative A provides redundancy which increases the structural reliability. Design *alternative B*, on the other hand, refers to a method whereby the structure relies fully on a control system for lateral stability. During an earthquake, if the control system were to fail under alternative B, the structure would collapse. Complete reliance on active control is not currently possible due to insufficient testing and verification as well as psychological reasons. Design *alternative C* is a compromise between alternatives A and B. According to alternative C, a structure is designed with less seismic capacity than conventional design codes require, but enough capacity to withstand an earthquake without collapse. Thus, under alternative C there is a slightly lower initial structural cost due to the lower capacity requirement in addition to reduced damage costs. While alternative C is likely to prove slightly more cost-effective that alternative A, many issues must first be addressed. Precise quantitative information is required to determine the collapse point of the structure. And the reliability of the control system must be known. In addition, structural engineers are liable for design decisions, thus are unlikely to arbitrarily reduce structural capacity requirements without research and verfication regarding the safety of alternative C. While there are additional savings from reduced capacity requirements in alternative B and C, they will not be significant since only a small portion of the building cost is a result of the lateral support system (<10%). The bulk of a building's costs are in nonstructural components (partition walls, windows, wiring, etc.) and in the gravity load governed structural elements (floor slab and beams).

A life-cycle cost-effectiveness analysis may be used to assess the benefits of implementing active control systems. Considerations made in a life cycle analysis include: (i) load randomness, (ii) failure consequences, (iii) design life, and (iv) control system reliability [Wen *et al* 1992]. An expected life-cycle cost analysis adopted from research by Wen and Ang [Wen *et al* 1992] is presented here and applied to an alternative A design to illustrate the cost-effectiveness of active control systems. It is assumed for the analysis that earthquakes occur independently of one another according to a Poisson process with an occurrence rate ν. Also, the limit state is described in terms of a maximum response of the structure (i.e. displacement must be less than a certain value). 'Failure' means exceedance of the limit state values rather than total building collapse. The expected total cost over a predicted design life is:

$$E(C) = C_o + E(\sum_{i=1}^{\infty} C_f(t_i)P_f) + \int_0^t C_m(t)dt \qquad (1)$$

where: E = *expected value*

C_o = *initial cost of building including control system*

C_f = *cost of failure including damage cost and operational losses*

t_i = *time of the ith loading*

P_f = *probability of failure when loaded*

C_m = *cost of control system maintenance*

$$\begin{aligned} C_f(t_i) &= C_f \exp^{-\lambda t_i} \\ C_m(t_i) &= C_m \exp^{-\lambda t_i} \end{aligned} \qquad (2)$$

where: λ = *discount rate*

C_f *and* C_m *have units of dollars*

The calculation of P_f may be quite difficult, but theoretically it is calculated:

$$P_f = P(X > x_o|C)P(C) + P(X > x_o|\overline{C})P(\overline{C}) \qquad (3)$$

where: X = *maximum response*
x_o = *allowable maximum response*
C = *event that the control system works properly*
$\overline{C}$ = *event that the control system does not work properly*

By substituting Equation 2 into Equation 1 and defining a cost ratio, $r = C_f/C_o$, it is possible to obtain a ratio of the expected cost of a structure with control to one without control:

$$\frac{E(C_2)}{E(C_1)} = \frac{C_2}{C_1}\left(\frac{1+\frac{1}{\lambda}(r_2\nu p_2 + r_m)(1-e^{-\lambda t})}{1+\frac{1}{\lambda}r_1\nu p_1(1-e^{-\lambda t})}\right) \tag{4}$$

where: $E(C_2)$ = *expected life cycle cost with control*
$E(C_1)$ = *expected life cycle cost without control*
C_2 = *initial building cost with control*
C_1 = *initial building cost without control*
t = *building design life*
p_2 = *probability of 'failure' of the controlled system*
p_1 = *probability of 'failure' of the uncontrolled system*
r_2 = *cost ratio of 'failure' of the building with control*
r_1 = *cost ratio of 'failure' of the building without control*
r_m = *control system maintenance cost divided by the building initial cost*

See [Wen *et al* 1992] for a more detailed derivation of Equation 4.

Wen and Ang also include a parametric study to illustrate the cost-effectiveness of active control systems [Wen *et al* 1992]. A brief synopsis of this parametric study is included here. Assumptions made for the parametric study include: (i) the mean earthquake occurrence rate, ν, is 0.1 per year, (ii) seismic loading has a coefficient of variation of 60% and an extreme type I distribution, (iii) the limit state occurs at 60% of the maximum response since control systems are estimated to reduce motions by 30 to 50%, and (iv) the cost ratios for systems with and without control are the same since this study assumes design alternative A. Additional parameters are varied to determine their effect on the cost-effectiveness of active control systems.

The results of the parametric study indicate that active control is a cost-effective method of controlling building motions during an earthquake by reducing damage levels and loss of operation time. Assuming that the risk of exceeding the limit state in a conventional building (νp_1) is 0.001 (0.1%), for a cost ratio (C_f/C_o) of 10 or greater, active control is cost-effective for buildings with a design life of at least 10 years. And if the cost ratio is reduced to 5, active control is cost-effective for buildings with a design life of at least 15 years. Increasing the annual risk value (νp_1) to 0.01 (1%), active control is found to be cost-effective for buildings with a design life of at least 5 years and a cost ratio of greater than 0.5. The reliability of the control system has little effect on its cost-effectiveness, as long as it is within a reasonable range ($P(\overline{C}) < 20\%$). Cost-effectiveness of active control systems is reduced as the maintenance cost ratio approaches the cost of failure. Maintenance cost are assumed to be 1% of the control system cost for this study, and are generally quite low. These results show that active control is a cost-effective alternative for buildings in seismic regions. Buildings generally have a design life of 50–100 years, and cost-ratios range from 1–5 (C_f includes loss of service costs, damage costs, and dollar value changes). See [Wen *et al* 1992] for additional graphical results.

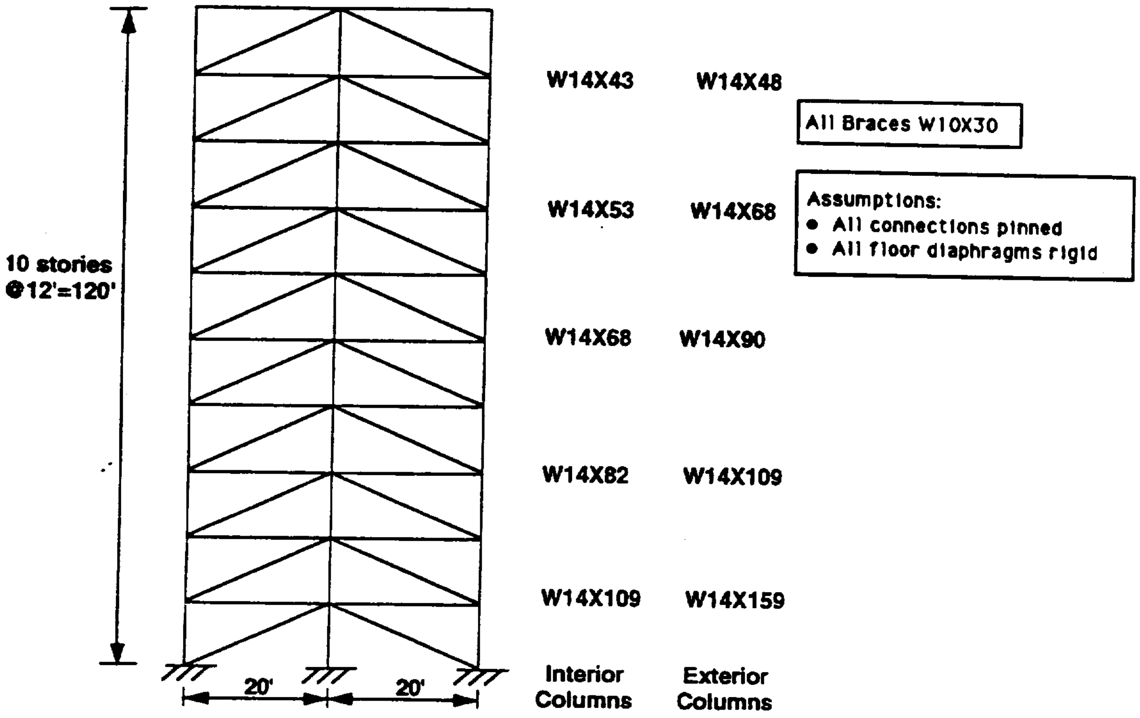

Figure 1: 10-story Braced Frame

6 Case Study

6.1 Description

The current active control mechanisms developed have limitations which reduce their benefits. One of the main reasons for developing active control systems is to control a wider frequency bandwidth. However, most of the current control systems have only slightly wider frequency bandwidths of control than passive systems. And while some improvement is noticeable, active control systems have not proven as successful at controlling transient vibrations as was hoped. In addition, current actuator systems require large amounts of external power, continual maintenance, and respond slowly. Many of these shortcomings are due to the fact that economic constraints limit the number of forces which can be applied to the building to control motions. This case study is meant to investigate the feasibility and benefits of using embedded actuators distributed throughout the building to control vibrations during an earthquake. It is hoped that this distribution of more, smaller actuators will achieve greater control of the building over a wider frequency bandwidth, more effectively control transient vibrations, prove more reliable, have a quicker speed of response, and require less power. The frame shown in Figure 1 is analyzed with both an active tendon control system and an embedded actuator system in order to compare the effectiveness of these two systems in controlling motions due to an earthquake.

The 10-story braced frame in Figure 1 was modified from an example in *The Seismic Design Handbook* [Naeim 1989]. It is designed according to conventional seismic design codes. A two-dimensional frame alone is analyzed, rather that the entire three-dimensional building, since it is generally assumed in building design that only a few frames actually resist the lateral earthquake forces. The frame has 10 12-foot high stories with 2 20-foot wide bays. The dimensions of the building are chosen so that the height-to-width ratio of the building is 3, meaning it is classified as a high-rise structure and considered more flexible. Active control is generally more effective in taller, more flexible structures. All members of the structure are W-sections made of A36 steel. All connections are assumed pinned, thus the frame acts as a truss with all lateral loads being resisted by the diagonal bracing elements. As is common in building analysis, the floors are assumed to act rigidly. The number of degrees of freedom of the structure is reduced to 10, one horizontal degree of freedom at each floor level.

Assuming that the floor diaphragms act rigidly greatly simplifies the development of the system matrices. The mass of the building, as well as live and dead loads, may be lumped at the floor levels according to appropriate tributary areas. Thus the mass of the frame is represented by a diagonal matrix. The stiffness of the frame is derived from the bracing elements since all of the connections are assumed pinned. The stiffness matrix of the frame is a function of the modulus of elasticity, area, length, and angle of the steel braces. Damping in the structure is assumed to be proportional to the mass and stiffness matrices according to:

$$\mathbf{C} = \alpha \mathbf{M} + \beta \mathbf{K} \tag{5}$$

where: $\mathbf{C}$ = *damping matrix*
$\mathbf{M}$ = *mass matrix*
$\mathbf{K}$ = *stiffness matrix*

The factors α and β are scalar weighting factors which are determined by assuming 3% of critical damping in the first two modes:

$$\left\{ \begin{array}{c} \alpha \\ \beta \end{array} \right\} = \left[\begin{array}{cc} \omega_2 & -\omega_1 \\ -\frac{1}{\omega_2} & \frac{1}{\omega_1} \end{array} \right] \frac{2\omega_1\omega_2}{\omega_2^2 - \omega_1^2} \left\{ \begin{array}{c} 0.03 \\ 0.03 \end{array} \right\} \tag{6}$$

where: ω_1 = *natural frequency of the first mode*
ω_2 = *natural frequency of the second mode*

While this process of determining the structural damping is somewhat arbitrary, experimental verification indicates adequate results in most cases. A damping ratio of between 1% and 5% is generally used for buildings, with taller, more flexible structures having lower damping values.

MATRIXx is used to compute the eigenvectors and eigenvalues of the system. The eigenvalue problem is $(\omega^2\mathbf{M} + \mathbf{K})\Phi = 0$. The natural frequencies and periods of the frame may then be computed from the eigenvectors and eigenvalues. The modal properties of the frame are listed in Table 4.

The general equation of motion for the frame in Figure 1 is as follows:

$$\mathbf{M}\ddot{x} + \mathbf{C}\dot{x} + \mathbf{K}x = f \tag{7}$$

where: x = *position vector*
$\dot{x}$ = *velocity vector*
$\ddot{x}$ = *acceleration vector*
f = *applied force* = $f_e + f_a$

Table 4: Modal Properties of the 10-story Braced Frame

Mode	**Natural Frequency (rad/sec)**	**Period (sec)**
1	3.4953	1.7976
2	10.4077	0.6037
3	17.0877	0.3677
4	23.3859	0.2687
5	29.1618	0.2155
6	34.2862	0.1833
7	38.6447	0.1626
8	42.1400	0.1491
9	44.6939	0.1406
10	46.2494	0.1359

f_e = *earthquake force vector* = $-\mathbf{M}\{1\}_{10x1}\ddot{x}_g$
$\ddot{x}_g$ = *earthquake ground acceleration vector*
f_a = *actuator force vector*

For this case study, the input "earthquake" ground acceleration time history is shown in Figure 2. The acceleration values from 0 to 3.4 seconds were taken from actual recorded ground motions during the 1940 Imperial Valley–El Centro Earthquake in California. The El Centro Earthquake is often used by researchers studying structural response because it has a relatively wide frequency content and duration. The frequency content of the input motion from Figure 2 is shown in Figure 3. The frequency content is determined by Fourier transformation of the time history. While the record shown in Figure 2 is not the full time history (the full time history is over 60 seconds long), its acceleration levels are representative of actual earthquake ground motion. The magnitude of the 1940 El Centro earthquake was 6.7 on the Richter scale. The full time history of the earthquake has a wider frequency bandwidth, with most of the energy content between 0.1 and 10 Hz, and a peak value at about 1.5 Hz [Mohraz *et al* 1989]. The 3.4 second input ground motion in Figure 2 is followed by 6 seconds with no input motion in order to observe the damping characteristics of the frame and control systems.

The state-space representation of the frame is derived from the equation of motion by defining the state-space vector as:

$$q = \begin{Bmatrix} x \\ \dot{x} \end{Bmatrix} \tag{8}$$

The following equation is obtained by rearranging the Equation 7 and using the state vector:

$$\dot{q} = \begin{Bmatrix} \dot{x} \\ \ddot{x} \end{Bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -(\mathbf{M}^{-1}\mathbf{K}) & -(\mathbf{M}^{-1}\mathbf{C}) \end{bmatrix} \begin{Bmatrix} x \\ \dot{x} \end{Bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix} \{f\} \tag{9}$$

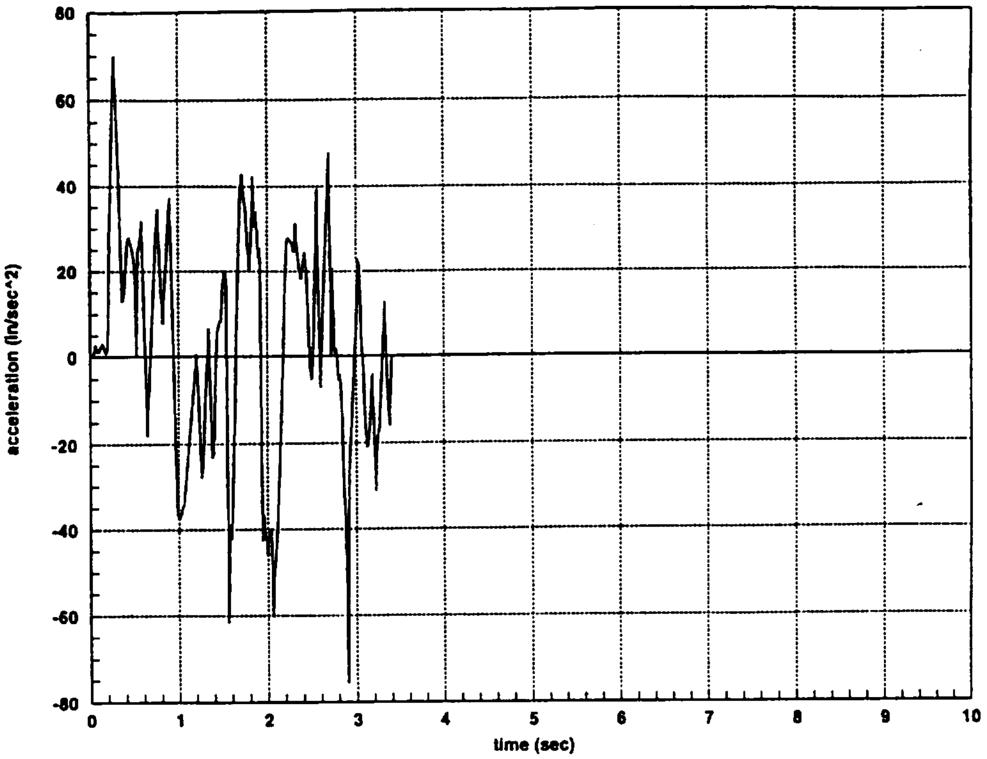

Figure 2: Input "Earthquake" Time History

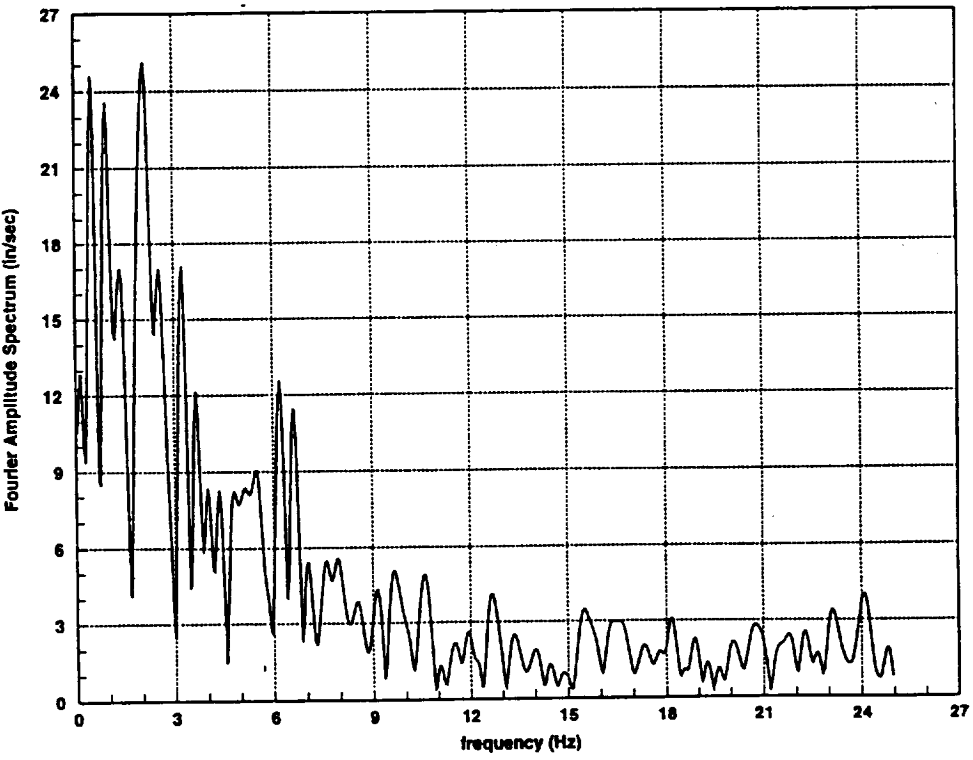

Figure 3: Input "Earthquake" Frequency Content

where: $\mathbf{0}$ = *matrix of zeros*
$\mathbf{I}$ = *identity matrix*

In this study, direct velocity feedback is used to control the system. While this is a simple technique and not the most effective control method, it guarantees stability. Using direct velocity feedback:

$$y = \begin{bmatrix} \mathbf{0} & \mathbf{I} \end{bmatrix} \begin{Bmatrix} x \\ \dot{x} \end{Bmatrix} \tag{10}$$

Thus, the state-space representation for this problem is:

$$\begin{aligned} \dot{q} &= \mathbf{A}q + \mathbf{B}f \\ y &= \mathbf{C}q \end{aligned} \tag{11}$$

where: $\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -(\mathbf{M}^{-1}\mathbf{K}) & -(\mathbf{M}^{-1}\mathbf{C}) \end{bmatrix}$
$\mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix}$
$\mathbf{C} = [\,\mathbf{0} \;\; \mathbf{I}\,]$
$\mathbf{D} = [\mathbf{0}]$

The block diagram representation of the control system for this case study is shown in Figure 4. The reference input is simply a vector of zeros indicating that a response of zero velocity is desired. Note that the actuators and sensors are assumed perfect, since this study is simply meant to compare two control systems rather than to obtain an exact analytical prediction of the behavior. The control simulations for this case study were run using MATRIXx with the SystemBuild Tool [MATRIXx 1991].

The uncontrolled motions of the frame when subjected to the 'earthquake' forces are shown in Figures 5, 6, and 7. The objective of implementing active control systems is to control these response so that damage is reduced and comfort levels are improved. During an earthquake, reduction of displacements and thus interstory drifts are generally deemed most important.

6.2 Linear Optimal Control

Classical linear optimal control theory is used in this study to determine the gain matrices. The objective of linear optimal control is to choose control forces, $u(t)$, to minimize a performance index, J, which for this study is [Soong 1990]:

$$J = \int_0^t [z^T(t)\mathbf{Q}z(t) + u^T(t)\mathbf{R}u(t)]dt \tag{12}$$

Q and **R** in Equation 12 are weighting matrices whose values indicate desired performance trade-offs. Large values in the **Q**-matrix relative to **R**-matrix values indicate that response reduction is more important than the magnitude of the control force required. On the other

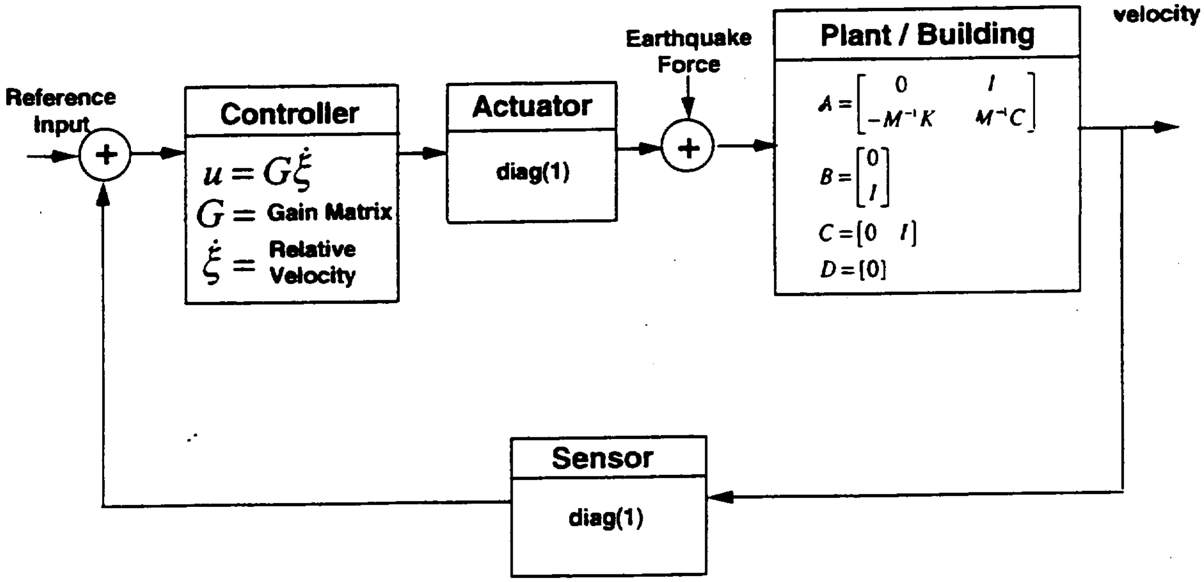

Figure 4: Block Diagram

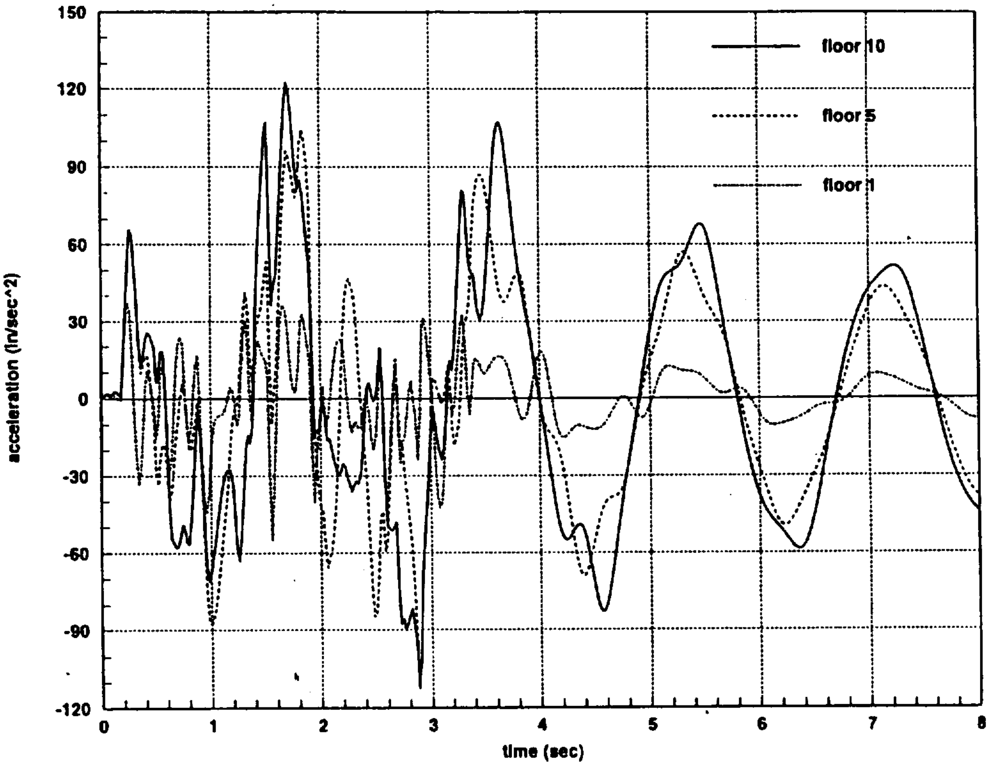

Figure 5: Uncontrolled Accleration Response

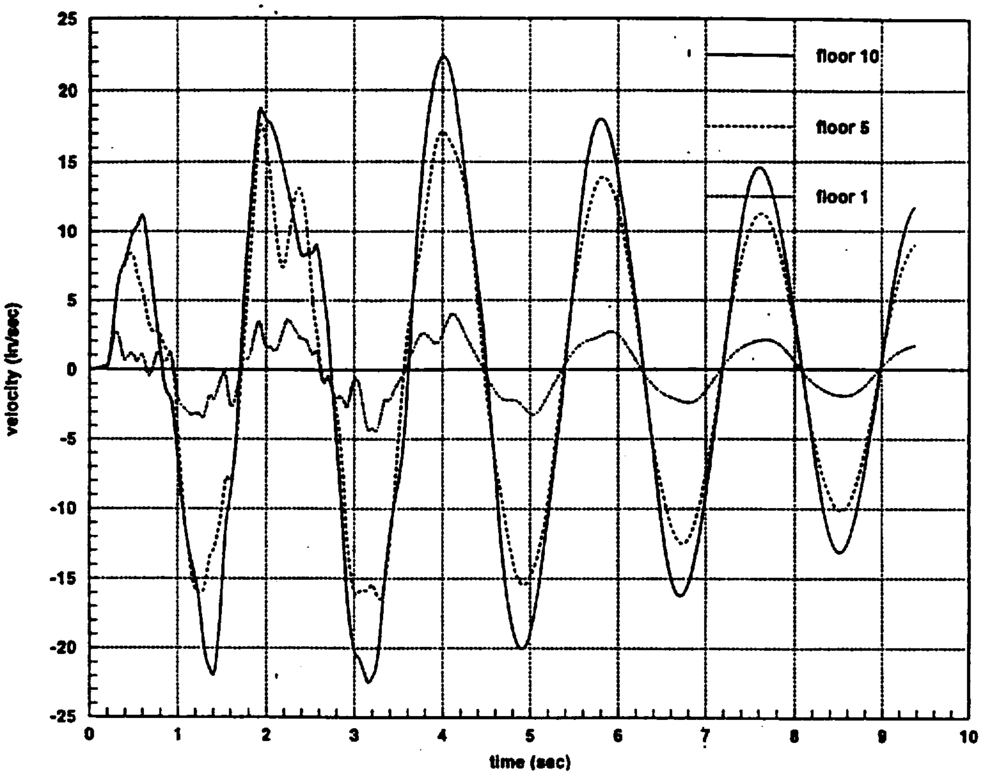

Figure 6: Uncontrolled Velocity Response

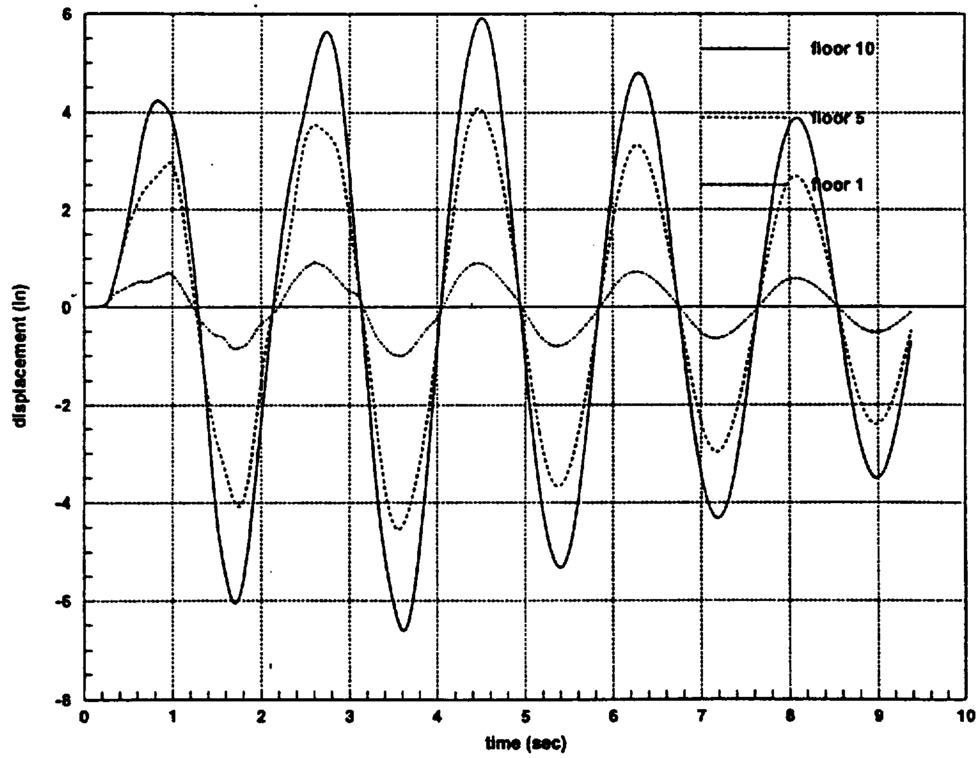

Figure 7: Uncontrolled Displacement Response

hand, large values in the **R**-matrix relative to the **Q**-matrix indicate that the magnitude of the control force is more important than response reduction. For this case study, both of the weighting matrices, **Q** and **R**, are proportional to the damping matrix of the frame since velocity feedback control is used.

The performance index of Equation 12 and the system equation of motion are combined with a Lagrangian multiplier, λ. By taking the first derivative of the resulting Lagrangian equation with respect to state and control variables and making appropriate substitutions, the following constraint equations are obtained:

$$\dot{\lambda}(t) = -\mathbf{A}^T\lambda(t) - 2\mathbf{Q}z(t) \qquad (13)$$

$$\lambda(t_f) = 0$$

$$u(t) = -\frac{1}{2}\mathbf{R}^{-1}\mathbf{B}^T\lambda$$

Assuming that the control vector is regulated by the state vector, $\lambda(t) = \mathbf{P}(t)z(t)$, results in the Riccati equation where $\mathbf{P}(t)$ is the Riccati matrix. In structural applications, $\mathbf{P}(t)$ remains relatively constant over the control interval [Soong 1990]. By assuming a constant Riccati matrix, the Riccati equation may be reduced to:

$$\mathbf{PA} - \frac{1}{2}\mathbf{PBR}^{-1}\mathbf{B}^T\mathbf{P} + \mathbf{A}^T\mathbf{P} + 2\mathbf{Q} = 0 \qquad (14)$$

An optimal gain matrix may be precalculated for a particular structure by solving Equation 14 for the Riccati matrix. The optimal gain matrix is computed directly from the Riccati matrix according to Equation 15

$$u(t) = -\frac{1}{2}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}z(t) \qquad (15)$$

6.3 Active Tendon Control

Active tendon control is first used to control the frame in Figure 1. Only the braces on the first floor of the frame are assumed to be connected to hydraulic actuators which apply the control forces. The gain matrix was chosen according to linear optimal control theory which is outlined in the previous section. Different gain matrices were calculated by varying the relative magnitudes of the weighting matrices until an acceptable control force was achieved. According to previous implementations of active control systems, hydraulic actuators in buildings are capable of generating approximately 175 kips of force [Soong *et al* 1992]. Since the braces of this frame are diagonal, a reasonable lateral control force which could be generated is assumed to be $\frac{4}{5}$ of 175 kips or approximately 140 kips. The control forces required by the active tendon control system for this case study are shown in Figure 8.

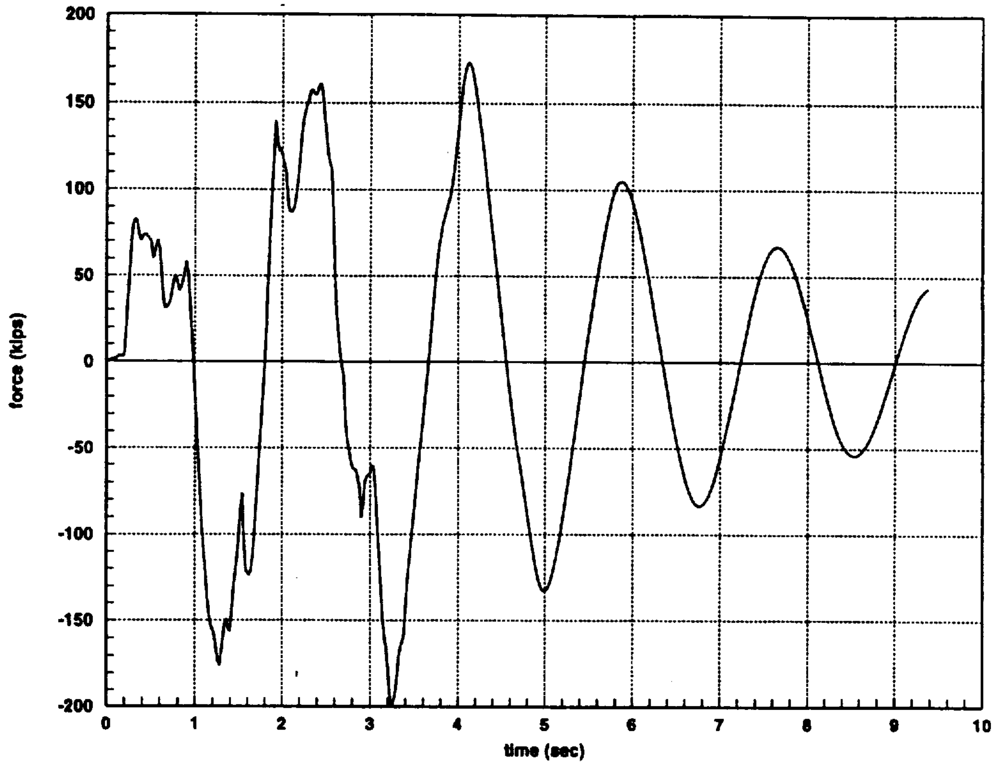

Figure 8: Active Tendon Control Forces

Figure 9 compares the uncontrolled and active tendon controlled displacement response of the top floor of the frame. The maximum top floor displacement is reduced from approximately 6.5 in to approximately 5.0 in, with steady-state reductions of 30-50%. A 30-50% reduction in steady-state displacement response is similar to previous analytical and experimental active tendon control studies. The uncontrolled vs. active tendon controlled acceleration, velocity, and displacement reponse histories are shown in Figures 9, 10, and 11. Active tendon control is most effective in controlling first floor responses, since the control force is applied directly to the first floor only. While active tendon control is relatively ineffective in controlling transient responses in the upper floors, it is capable of reducing steady-state vibrations by as much as 50%, even in the upper floors.

6.4 Embedded Actuator Control

Embedded actuator control is also used to control the frame in Figure 1, so that its effectiveness may be compared with that of the active tendon control system. Embedded actuators are incorporated directly into the structural members and distributed throughout the structure. Though embedded actuators have not been developed for building applications, they are currently used in space structures. In particular, piezoelectric actuators have been used in several flexible space structure systems [Amrane *et al* 1991], [Baz *et al* 1988], and [Preumont *et al* 1990]. Piezoelectric materials are used in space structures because they are wide band, reliable, compact, lightweight, relatively inexpensive, and require a small amount of power. Piezoelectric materials have coupled electrical and mechanical properties. If the piezoelectric material is mechanically deformed, it responds with an electrical signal. And an electrical signal applied to a piezoelectric material causes the material to deform.

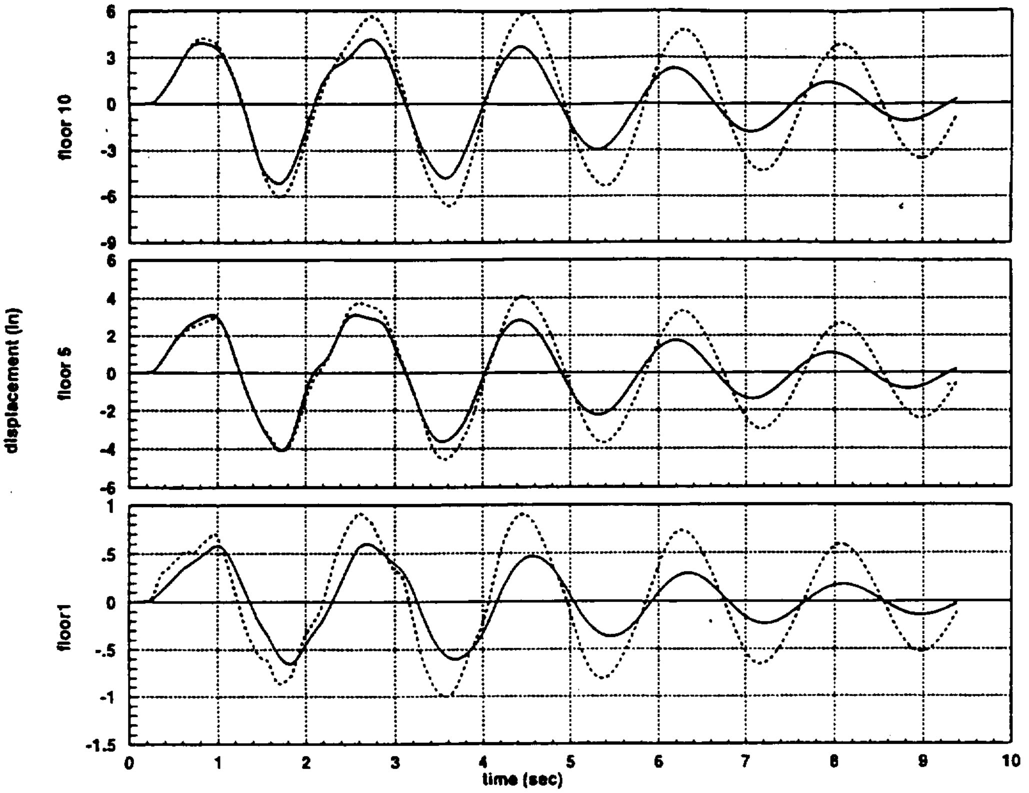

Figure 9: Displacement Response: Uncontrolled vs. Active Tendon Controlled

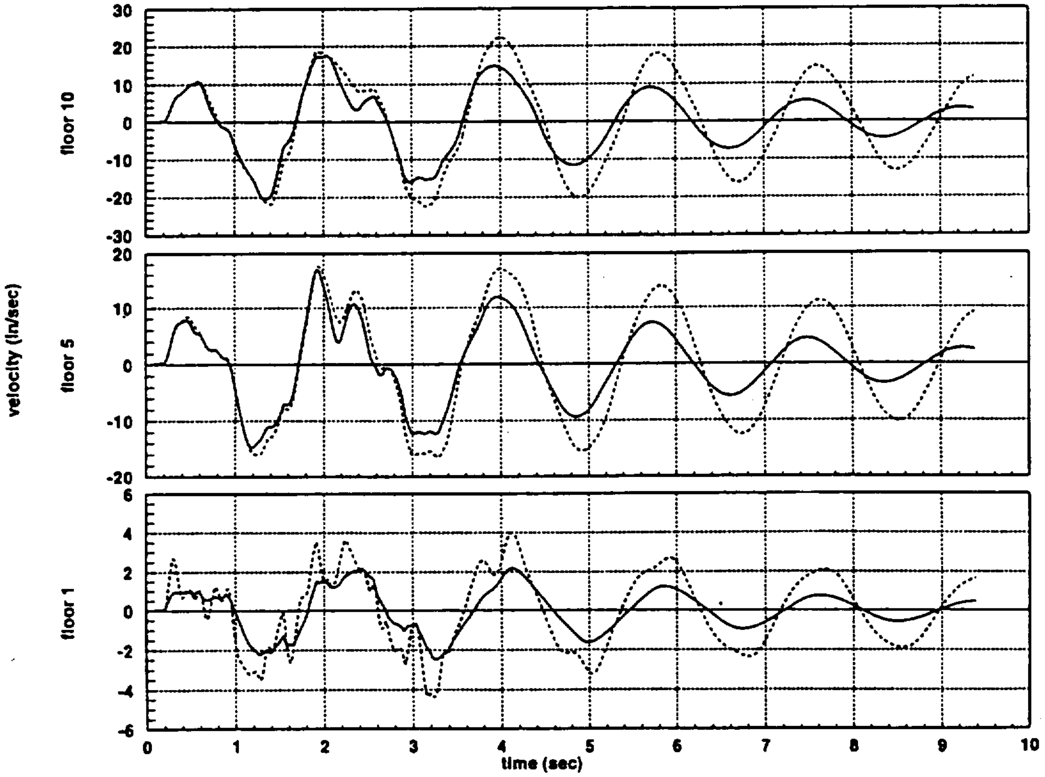

Figure 10: Velocity Response: Uncontrolled vs. Active Tendon Controlled

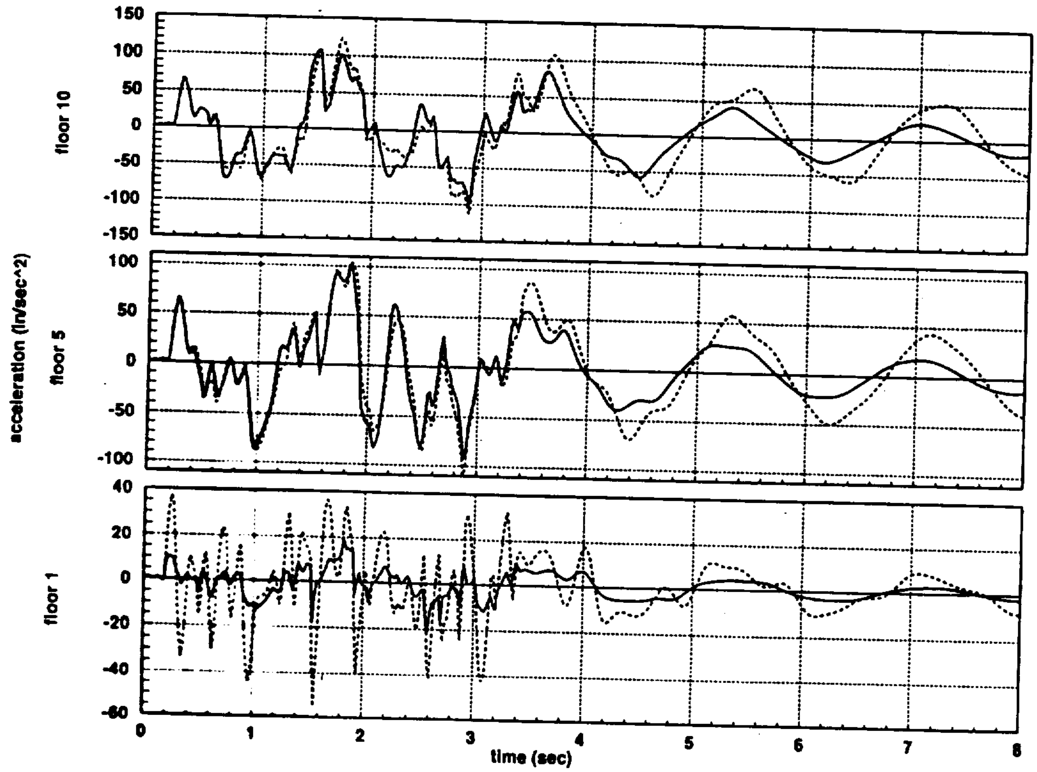

Figure 11: Acceleration Response: Uncontrolled vs. Active Tendon Controlled

Thus, piezoelectric materials may be used as both sensors and actuators. Ceramic disks of piezoelectric material may be stacked to form actuators. Further hardware developments need to be made before piezoelectric actuators may be used in buildings, as they are currently designed to control small vibrations. However, it may be possible in the future to produce large enough control forces by increasing the size and voltages of these devices. Other materials which may be considered for use as embedded or distributed actuators in buildings include electro-rheological fluids, electrostrictive materials, magnetostrictive materials, and shape-memory alloys [Gandhi *et al* 1992].

For this case study, embedded actuators are placed at each floor of the structure. Since embedded actuators have not previously been implemented in buildings, reasonable control limits are unknown. Thus, different gain matrices are chosen to show the effectiveness of embedded actuator control over a range of control force limits. Gain matrices are chosen by multiplying the weighting matrix, **Q**, by different scaling factors, α, and then solving the Riccati equation. The α–values are chosen between 100 and 4000, with higher values indicating that control effectiveness is important and lower values indicating that generation of small control forces is important. The results for different α–values are listed in Table 5. Graphical results showing the uncontrolled vs. embedded actuator controlled response for $\alpha = 1000$ are presented in Figures 13, 14, and 15 for comparison with the active tendon control system. In addition, the corresponding control forces are shown in Figure 12. Some reduction in transient acceleration and displacement responses are seen, but as with the active tendon control system reductions in steady-state responses are much greater.

Table 5: Response Reduction and Control Forces Required for Different α-values

Alpha (α)	Percent Top Floor Response Reduction			Control Force Required (kips)		
	disp.	vel.	accel.	1st Floor	5th Floor	10th Floor
100	21	18	8	11	8	5
200	24	22	10	12	10	6
500	27	30	25	18	12	9
1000	31	33	34	25	16	14
2000	39	39	38	28	18	15
4000	49	48	38	33	19	17

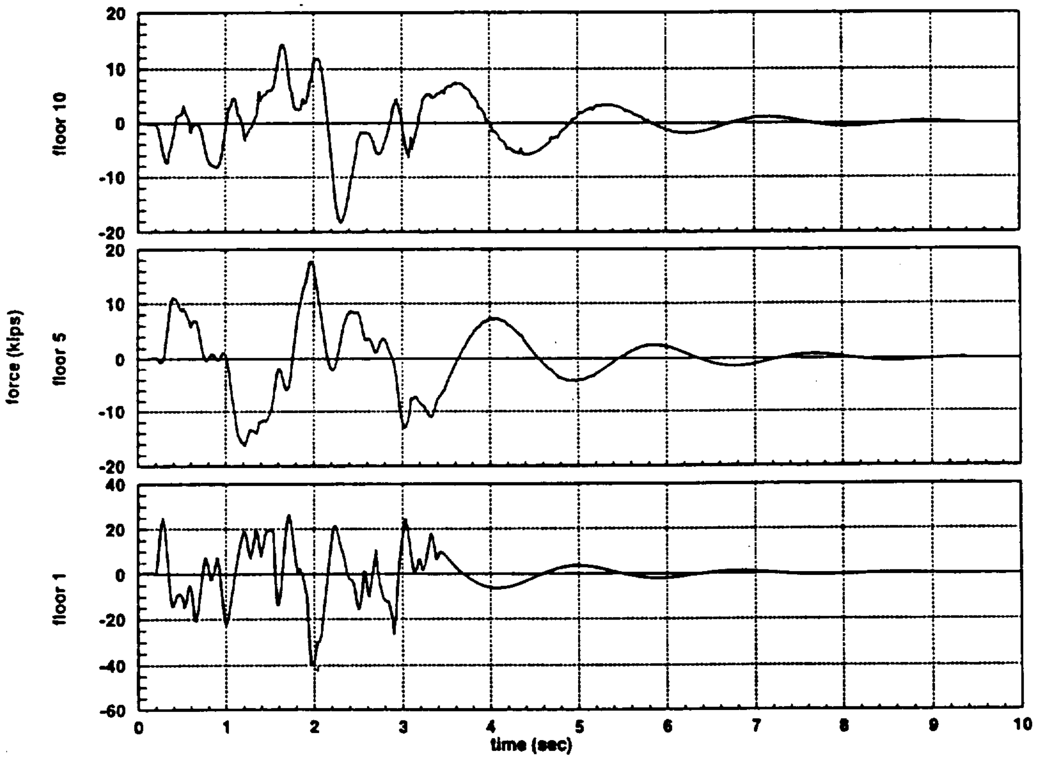

Figure 12: Embedded Actuator Control Forces

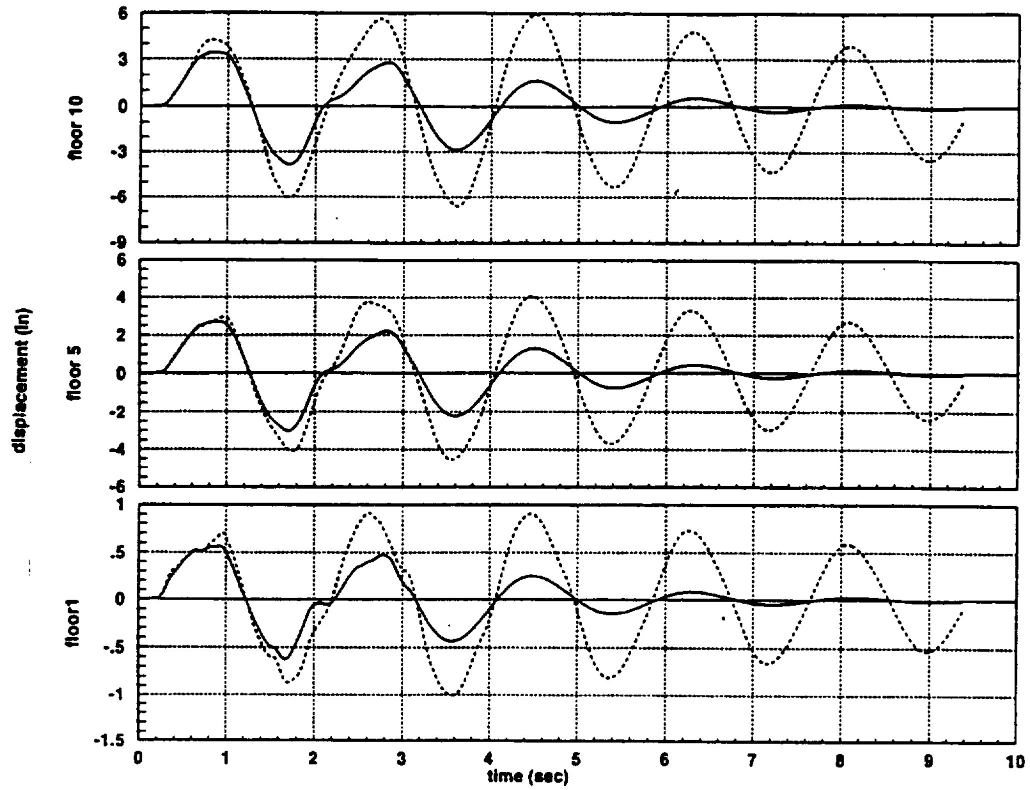

Figure 13: Displacement Response: Uncontrolled vs. Embedded Actuator Controlled

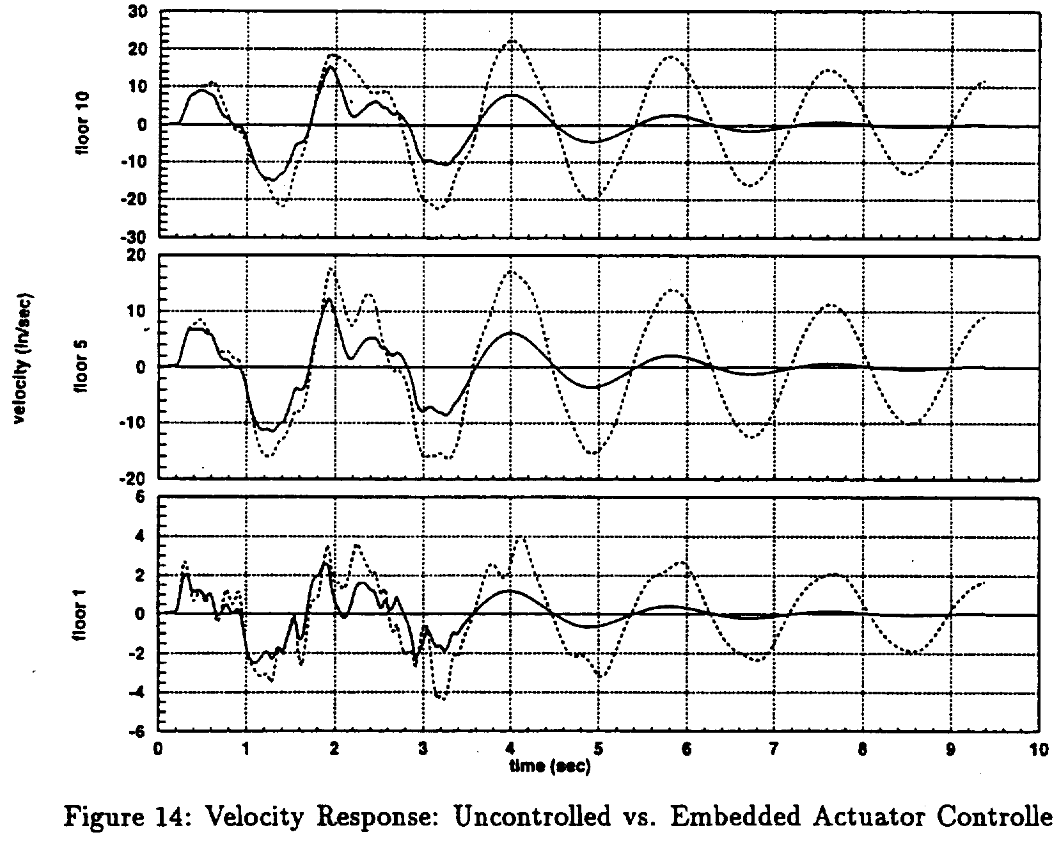

Figure 14: Velocity Response: Uncontrolled vs. Embedded Actuator Controlled

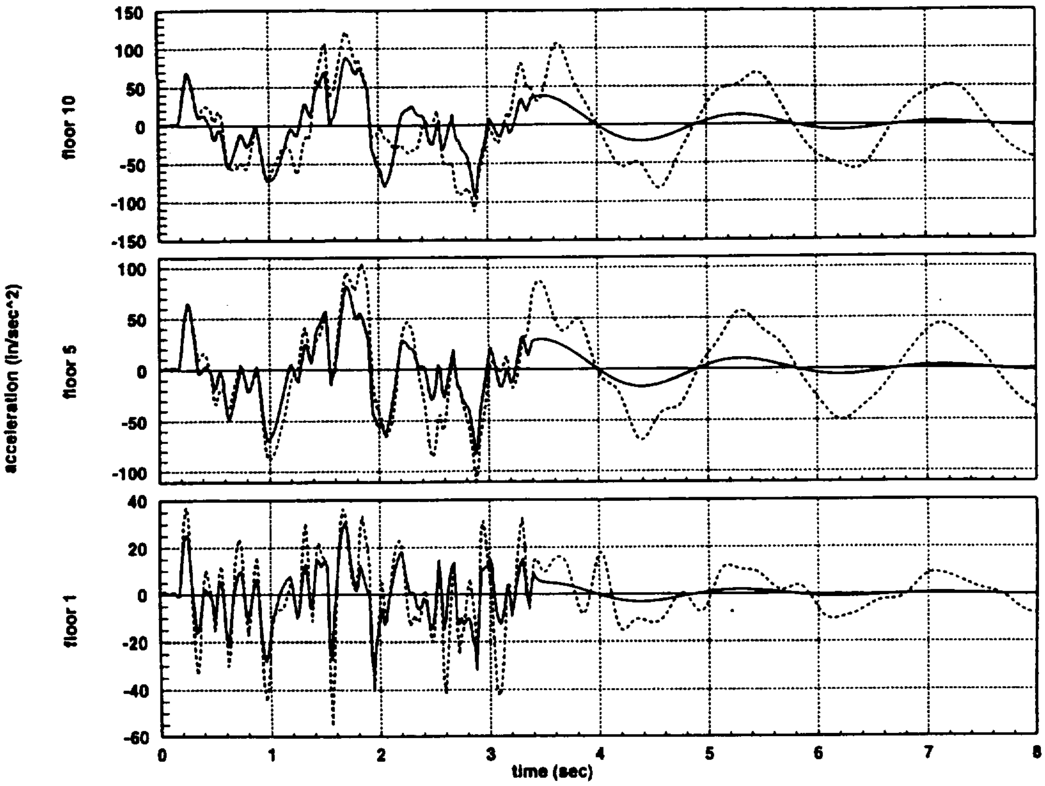

Figure 15: Acceleration Response: Uncontrolled vs. Embedded Actuator Controlled

6.5 Results

The fact that the practical limitations on the control forces of embedded actuators for buildings are unknown should be considered when comparing active tendon control and embedded actuator control systems. Some comparative observations between the two control methods are nevertheless useful. Top floor displacements are plotted in Figure 16 to show the possible improved reductions from using embedded actuators. Figure 16 shows the results for an α-value of 1000, which requires relatively high control forces. Figure 17, which compares results for an α-value of 200, is included to show that even with small control forces, embedded actuators reduce responses to levels similar to those attained by the active tendon system.

Additional benefits which may be achieved by embedded actuators include the fact that they require less power and respond more quickly. In addition, since they require less power, it may be feasible to use the embedded actuators to control wind-induced motions for improved occupant comfort. By using them to control wind-induced motions, concerns regarding reliability will be reduced, since the major concern with current active control systems is that they are rarely turned on. While this case study does not indicate a large improvement in the control of transient vibrations, a wider frequency of control is attainable with embedded actuators since they are distributed throughout the structure.

Figure 18 shows the maximum relative displacement values at each floor of the frame for the uncontrolled, active-tendon controlled and embedded-actuator controlled cases. Interstory drift, may be correlated with building damage levels as discussed in Section 5. The drift indices for the uncontrolled, active-tendon controlled, and embedded-actuator controlled cases are 0.007, 0.006, and 0.004 respectively. The drift index for the uncontrolled

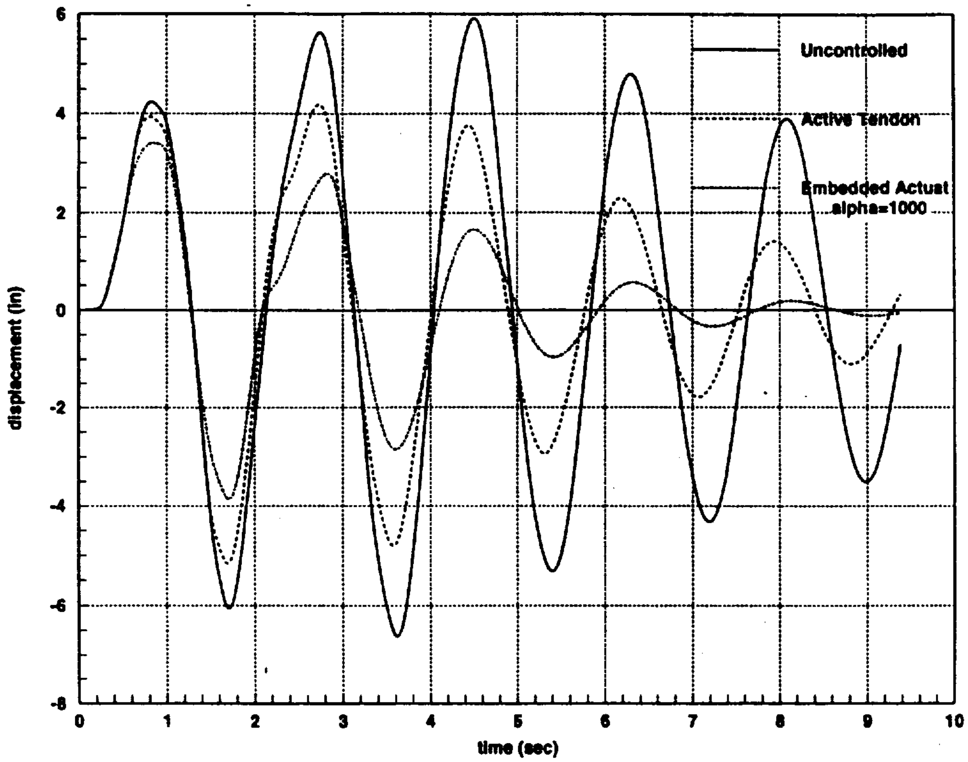

Figure 16: Top Floor Displacement Response $\alpha = 1000$

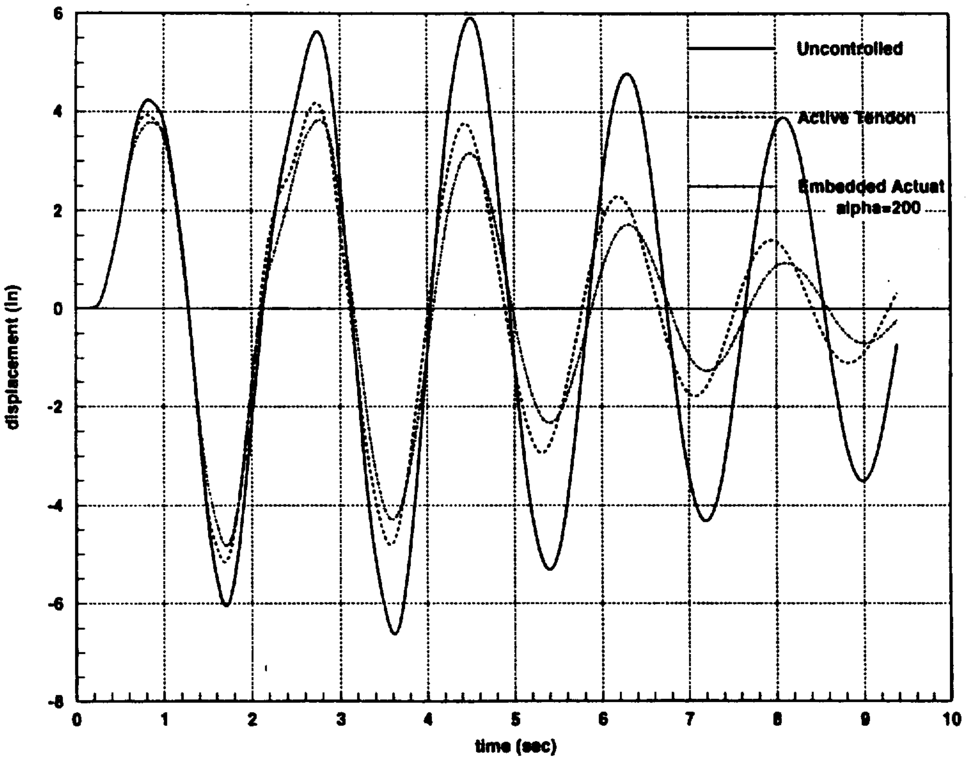

Figure 17: Top Floor Displacement Response $\alpha = 200$

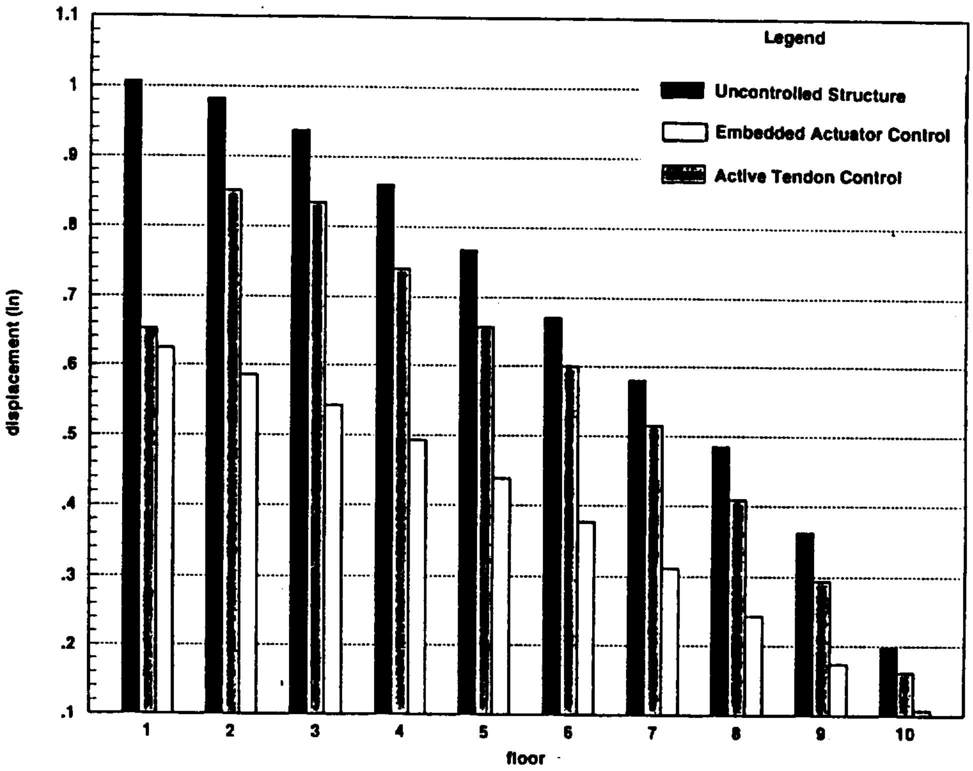

Figure 18: Maximum Relative Displacement

frame corresponds to a damage level of ***nonstructural damage almost certain; structural damage likely*** according to Table 3. The drift indices for the controlled cases, both active tendon and embedded actuator control, are smaller. Active control of the frame brings the damage level closer to ***nonstructural damage likely***. While this scale indicates that even with control some damage is possible, much less damage is likely to occur, making it a cost-effective alternative.

7 Active Control Research Needs

Research needs in the area of active control of buildings include [Housner *et al* 1992]:

1. Hardware development
2. Testing and verification
3. Methods for accurately predicting structural response
4. Development of integrated control-structure design and analysis tools
5. Investigation of local effects

Hardware development is essential in the advancement of active control systems. Actuators and sensors must be developed specifically for buildings, with emphasis on quick speed of response, cost and size. In addition, full-scale testing and verification should to be performed to convince designers and the public of the benefits of active control. Accurate prediction of structural behavior results in better control, particularly for variable stiffness systems. System identification methods for buildings are also currently being developed. In

Table 6: Comparison of LSS and LCES

	LSS	LCES
Size	*comparable*	
Type	*large dimensional models*	
Critical Resonant Frequencies	many closely packed throughout spectrum	few low frequency separated
Damping	$< \frac{1}{2}\%$	$\frac{1}{2} - 10\%$
Disturbances	*Large Deterministic:* maneuvers, docking, accidents *Small Stochastic:* solar pressure, gravity gradient	*Large Stochastic:* wind, earthquakes, waves *Small Deterministic:* machinery, people

addition, the complicated behavior of buildings is being investigated by studying the effects of soil-structure interactions, joint rigidities, and nonstructural components. Development of integrated control-structure design and analysis methodologies for buildings has begun, but requires further development before design alternative B becomes a viable options.

Many of the research needs outlined above for buildings are also being investigated for large space structures. Large, flexible space structures require active control systems to reduce vibrations. Though civil and aerospace engineering are two distinct disciplines, the basic underlying principles of all mechanically flexible structures and control systems are the same. Table 6 compares large space structures (LSS) and large civil engineering structures (LCES) [Balas 1980]. The differences which exist in the range of critical resonant frequencies and damping values are reduced as buildings become taller and more flexible. The main differences between LSS and LCES are the disturbances or loads applied to the structure. The loads applied to civil engineering structures are generally much larger; however, actuators with adequate force and stroke are able to control buildings just as small actuators control space structures. The similarities between LSS and LCES indicate that the transfer and sharing of technology between civil and aerospace engineering are possible. In particular, much of the CSI technology currently being developed may be beneficially applied to buildings.

8 Conclusions

The objective of this report was to provide an overview of the different types of control systems used in buildings, to discuss the problems associated with active control systems in buildings, and to show the cost-effectiveness of active control systems. The different types of active control systems include (i) active tendons, (ii) active mass dampers, (iii) variable stiffness systems, and (iv) hybrid systems. While each of these systems has advantages and disadvantages, in general there are many problems associated with active control systems designed for buildings. The problems associated with active control systems include cost, maintenance, reliability, robustness, and external energy requirement. Current research in the area of active control of buildings is directed at resolving these issues. The case study included in this report indicates that embedded-actuator control more effectively reduces building responses. However, further hardware development and testing are required before embedded actuators may be installed in buildings. While considerable progress has been made, much work remains to be done before active control systems become an accepted alternative to conventional design.

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13. ABSTRACT *(Maximum 200 words)*

The objective of this report is to provide an overview of the different types of control systems used in buildings, to discuss the problems associated with current active control mechanisms, and to show the cost-effectiveness of applying active control to buildings. In addition, a small case study investigates the feasibility and benefits of using embedded actuators in buildings. Use of embedded actuators could solve many of the current problems associated with active control by providing a wider bandwidth of control, quicker speed of response, increased reliability, and reduced power requirement. Though embedded actuators have not been developed for buildings, they have previously been used in space structures. Many similarities exist between large civil and aerospace structures indicating that direct transfer of concepts between the two disciplines may be possible. In particular, much of the Controls-Structures Interaction (CSI) technology currently being developed could be beneficially applied to civil structures. While several buildings with active control systems have been constructed in Japan, additional research and experimental verification are necessary before active control systems become widely accepted and implemented.

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20. LIMITATION OF ABSTRACT

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