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Paper No. 1530. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SEISMIC VIBRATION CONTROL OF BUILDING STRUCTURES USING ACTIVE MEMBERS

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ABSTRACT

This paper aims to investigate the possible use of a control system which combines the concept of active members and a direct output feedback method to mitigate seismic vibration of building structures. An active member, by the definition of this paper, is an added structural member in which an actuator, a sensor and a simple controller are highly integrated. By integrating these fundamental devices of control all together, the active members will be less vulnerable to environmental influence; moreover, each active member can be used as an independent control mechanism. In this study, an output feedback control algorithm called the Modal Truncated Output Feedback (MTOF), suitable for the active member control, is adopted. With this algorithm, the failure or malfunction of one active member will not impair the whole control system. A building structure controlled by the proposed control system is used as a numerical example. It is shown that the concept of active members and the MTOF control algorithm together form a very stable, effective, and reliable control system for vibration control of seismic buildings.

KEYWORDS

Active control; building structures; active members; output feedback control; modal truncation

INTRODUCTION

The possible use of active control as a means for structural protection against seismic loading has received considerable attention in recent years (Soong, 1988; Yang and Soong, 1988; Chung *et al.*, 1988; Soong et al., 1991). The most common control mechanism considered in this research field includes structural braces, tendons, active tuned mass dampers etc. Success in applying the technique of active control to seismic structures is really based on several factors. In general, it requires that control hardware and control algorithm be robust, fail-safe, and easily maintained. These are of great importance, particularly considering that a control system used in seismic protection is usually operating in a standby mode for most of its life time, which usually lasts tens of years; its direct hardware (such as actuators, sensors and controllers, etc.) and supporting systems (such as hydraulic pumps, piping, cabling, power sources, etc.) may be exposed to harsh environmental conditions during earthquakes and also in normal times. In view of this, this paper investigates the possible use of a relatively new control mechanism, namely, active members, as internal dampers to mitigate seismic structural response.

The concept of active members has been proposed and studied in such research field as space programs whose applications call for structures to be precise, diverse in use, light in weight, and easily maintained (Fanson, 1989; Wada, 1990; Anderson *et al*,1990; Lu *et al.*, 1993). An active member, by general definition, is a structural member in which an actuator, a sensor and a simple controller (or processor) are highly integrated, so that an active member can (1) provide the structure with a control force, (2) sense its own mechanical change, e.g., length change or rate of length change, and (3) compute the required control forces and give the commands to the actuators. Such an arrangement requires less complicated cabling and connections, so active members are more easily maintained and less vulnerable to influence from the surrounding environment. Furthermore, since each active member contains all the fundamental ingredients that a control system needs, i.e., the sensor, actuator and controller, it can be used as an independent control unit in case the other active members malfunction.

The performance of any control system greatly depends on the selected control algorithm. In the case of a large civil structure, it is not practical to control each degree of freedom (DOF) of the structure by using an active member. Therefore, the fundamental problem of controlling a civil structure with active members is that of controlling a large dimension system with a limited number of actuators and sensors. In this work, a direct output feedback control algorithm called the Modal Truncated Output Feedback (MTOF), suitable for the application of active member control, was adopted from Lu *et al.* (1993). Implementation of the algorithm, whose control goal is to suppress the motion of the selected vibration modes of the controlled structure, merely requires a small number of active members, compared with the number of DOFs of the controlled structure. The algorithm is one of the direct output feedback control methods; i.e., the sensor outputs are directly multiplied by an appropriately determined gain matrix to form the control commands; thus no state estimator or filter is needed. Because of this computational simplicity, the algorithm only requires a very simple controller or processor attached to each active member. Furthermore, with this control algorithm, the control system is very reliable, so that the failure or malfunction of any active member will not impair the whole control system, as will be demonstrated by an example.

DYNAMIC EQUATION OF SEISMIC BUILDINGS WITH ACTIVE MEMBERS

The seismic behavior of an *n*-story shear-type building can be characterized by the displacements of the *n* story slabs relative to the ground. Let ξ be a column matrix containing these relative displacements, and let matrices $\mathbf{M}_S$, $\mathbf{C}_S$ and $\mathbf{K}_S$ be the mass, damping and stiffness matrices of the building structure without control; then, the dynamic equation of a building equipped with active members may be expressed by

$$\mathbf{M}_s \ddot{\xi} + \mathbf{C}_s \dot{\xi} + (\mathbf{K}_s + \mathbf{K}_a)\xi = -\mathbf{M}_s \mathbf{1}\ddot{x}_g + \mathbf{B}\ diag(k_i)\ \mathbf{v_0} \tag{1}$$

where $\mathbf{K}_a$ represents the stiffness matrix contributed by the added active members. Also, note that in equation (1), there are two force terms at the right hand side. The first term represents the seismic loading which consists of the ground acceleration $\ddot{x}_g$, the constant column matrix **1** for matrix expansion and the mass matrix $\mathbf{M}_S$. On the other hand, the second force term which is generated by the control action is composed of three matrices: (1) **B**, the actuator placement matrix which is related to the locations and orientations of the active members; (2) $diag(k_i)$, the diagnal stiffness matrix whose *i*th diagonal element, k_i, is equal to the stiffness of the *i*th active member; (3) $\mathbf{v}_0$, the column matrix of control commands which lists the control elongations or contractions of active members and is decided by the controller. It is understood that for most of structural control applications, the number of control devices is usually less than the number of the structural degrees of freedom to be controlled. For building structures, this implies that the number of active members will be less than the number of stories, *n*. In such a case, the values of active member stiffness in the diagonal matrix $diag(k_i)$ corresponding to the stories without intalled active members must be set to zero. Furthermore, these null elements can be removed from $diag(k_i)$; consequently, the dimensions of $diag(k_i)$ can be reduced. Assume that an *n*-story building is controlled by

r active members ($r < n$); then, the dimensions of $diag(k_i)$ can be reduced to $(r \times r)$. Accordingly, the dimenions of matrices **B** and $\mathbf{v}_0$, whose original dimensions are $(n \times n)$ and $(n \times 1)$, can be reduced to $(n \times r)$ and $(r \times 1)$. Hereafter, the matrices $diag(k_i)$, **B** and $\mathbf{v}_0$ appearing in the equations will represent the matrices with reduced dimensions .

MODAL TRUNCATED OUTPUT FEEDBACK (MTOF) CONTROL

Consider a direct velocity feedback control law, where the control command vector, $\mathbf{v}_0$, is proportional to the rates of the total length changes of the active members, which is directly measured by the sensors embedded in the active members, i.e.,

$$\mathbf{v}_0 = \mathbf{F}_v \dot{\mathbf{v}} \tag{2}$$

where $\mathbf{F}_v$ is the velocity feedback gain matrix, and $\dot{\mathbf{v}}$ contains the rates of the length changes of the active members. Now, since the actuator and the sensors are collocated in pairs in the active members, we have $\dot{\mathbf{v}} = \mathbf{B}^T \dot{\xi}$, where $\mathbf{B}^T$ is the sensor placement matrix and is equal to the transpose of the actuator placement matrix **B** in equation (1). Using the result $\dot{\mathbf{v}} = \mathbf{B}^T \dot{\xi}$ in equations (1) and (2), one can obtain the equation of dynamics for the controlled building:

$$\mathbf{M}_s \ddot{\xi} + (\mathbf{C}_s + \mathbf{C}_c)\dot{\xi} + (\mathbf{K}_s + \mathbf{K}_a)\xi = -\mathbf{M}_s \mathbf{1}\ddot{x}_g \tag{3}$$

where

$$\mathbf{C}_c = -\mathbf{B}\, diag(k_i)\, \mathbf{F}_v\, \mathbf{B}^T \tag{4}$$

Note that the $(n \times n)$ matrix $\mathbf{C}_c$ is a matrix of augmented damping due to the control, in contrast with the inherent structural damping $\mathbf{C}_S$. By properly selecting the gain matrix $\mathbf{F}_v$, the damping matrix can be augmented to some desired values. In this study, the control algorithm MTOF, adopted from Lu *et al.* (1993), was employed to compute the gain matrix. The computation is briefly introduced as the follows.

Let r denote the number of selected structural vibration modes to be controlled, and let ω_i and $\mathbf{n}_i$ ($i = 1,2,\ldots, r$) represent, respectively, the free vibration frequencies and the free vibration mode shapes (normalized with respect to the mass matrix $\mathbf{M}_S$) of those selected modes. Using the MTOF control method, the gain matrix $\mathbf{F}_v$ is determined by

$$\mathbf{F}_v = -diag(k_i)^{-1}(\mathbf{N}^T\mathbf{B})\, diag(2\zeta_i^d \omega_i - 2\zeta_i \omega_i)(\mathbf{B}^T\mathbf{N}) \tag{5}$$

where

$$\mathbf{N} = [\, \mathbf{n}_1, \mathbf{n}_2, \ldots, \mathbf{n}_r] \tag{6}$$

and ζ_i^d (where i =1,2,...,r) are the desired (design) damping ratios decided by the control designer while ζ_i (where i =1,2,...,r) are the inherent structural damping ratios. The gain matrix $\mathbf{F}_v$ is designed in such a way that once it is substituted into the dynamic equation of the controlled structure (i.e., equation (3)), the dynamic equation can be decoupled into several modal equations with the desired modal damping ratios ζ_i^d, assuming that the influence of the un-controlled modes can be neglected in these modal equations.

OPTIMAL PLACEMENT OF ACTIVE MEMBERS

In the real world, truncation of uncontrolled modes in the design stage as mentioned above will inevitably introduce the effects of so-called control and observation spillover. With these effects, the structure may not behave as originally designed. However, it was proved by Lu *et al.* (1993) that the amount of spillover is related to the locations of the active members. The spillover effect can be minimized by properly selecting the locations of active members. For truss type structures, Lu and Utku (1993) have proposed two search schemes which help the designer find the optimal location(s) for placing single and multiple active members, respectively, so that the spillover effect can be minimized. In this study, these schemes were modified and applied to building structures:

Scheme 1. Placement of a single active member: For the case where one single active member is installed in a building to control one vibration mode, say the j-th mode, the optimal location for this active member is the story where the maximum story drift occurs due to the static mode shape, $\mathbf{n}_j$, of the building.
Scheme 2. Placement of multiple active members: When r active members are used to control r selected vibration modes, one may assume that each of the r controlled modes is controlled by one of the r active members, independently, and then using Scheme 1 r times, one may find the r best locations for the r active members.

ISSUES ABOUT CONTROL STABILITY, PERFORMANCE AND RELIABILITY

Usually, before a control system can be synthesized and applied to a real seismic structure, the following issues must be carefully examined: (1) Is the stability of the control algorithm used easily affected by the inevitable modeling error or the system parameter uncertainties? (2) How well does the control system perform, as compared with the designed performance? Does it reach the desired control goal, such as increasing the modal damping ratios of the selected modes? (3) How reliable is the control system in terms of its simplicity, maintenance easiness and fail-safe mechanism?

To answer the above questions related to the proposed control system, let us first consider the stability issue. As mentioned previously, one of the merits of using active members as control devices is the collocation of actuators and sensors. Such an arrangement makes the stability of the control system very insensitive to parameter uncertainties and the modeling error. (For the MTOF control algorithm, the modeling error includes the modal truncation error.) Using Liapunov's stability theorem, Lu *et al.* (1993) has proven that for the controlled system shown by equation (3), the stability of the system is guaranteed as long as the structural matrices, $\mathbf{M}_S$ and $\mathbf{K}_S$, are symmetric positive definite, and matrix $\mathbf{C}_S$ is positive definite (most civil structures will meet these conditions) regardless of the existence of modeling errors or parameter uncertainties. Next, consider the system performance issue. It is known that due to the spillover effect, the control goal set in the design stage may not be exactly achieved by the MTOF algorithm. However, by properly selecting the locations of the active members, the control goal can be closely achieved. This will be seen in the numerical example that follows.

Finally, the issue of system reliability will be discussed. As previously defined, an active member integrates an actuator, a sensor and a simple controller into one unit. In other words, an active member contains all the fundamental ingredients that a control system requires, so that each active member can actually be operated as an independent control unit or in conjunction with other active members operated as a control group. Because of this feature and the implementation of the MTOF control algorithm, the malfunction of some active members or the breaking of connections (or cabling) between active members will not impair the whole control system. Again, the numerical example in the next section will show the superiority of this feature.

NUMERICAL RESULTS

A 2-dimensional 6-story building controlled by active members and the MTOF algorithm will be illustrated in this section. It is assumed that the building is uniform; i.e., the structural properties for every story are identical. In the following simulation, the values of these properties were taken as: the mass and stiffness for each story = 2200 kg and 7.28×10^5 N/m; the height and width of each story = 2.5 and 6 m. Also, the first ten second record of the NS component of the El Centro earthquake (El Centro site, Imperial Valley earthquake, May 1940) was used as the ground excitation.

It was assumed that each active members was placed diagonally across the story panel and posed like a diagonal brace. In order to show the influence of control more clearly, no inherent structural damping was assumed in this example. All the damping was generated exclusively by the active members. The goal of the control was set to increasing the damping ratios of the building's first three vibration modes from 0% to 10%. Since by the MTOF control algorithm, the number of active members required has to be equal to that of the controlled modes, three active members were needed to achieve the above mentioned control goal. As determined by the search Scheme 2 proposed previously, the optimal locations for these three active members were: the first (for the control of the first mode), the fifth (for the second mode), and the third (for the third mode) stories, respectively. The active members placed in these stories were labeled in sequence as members 1,2 and 3.

Also, in order to investigate the reliability of the proposed control system, two kinds of failure modes were considered in this study: (A) Certain active members are completely damaged, while others are still workable. (B) The connections (for the exchange of sensor signals) between certain active members are broken, but the members themselves are still workable. In this mode, the control system is split into several independent and parallel control sub-systems.

Table 1 lists various control cases (including the damaged ones) and their resulting modal properties (frequencies and damping ratios) of the first three modes. In the table, the control case labeled M123 represents the undamaged control system, which is designed to control modes 1, 2, and 3, simultaneously. For failure mode A, case M12 represents the situation when the active member designed to control the third mode has broken down. In the same way, the case M1 implies that active members 2 and 3 have been damaged. On the other hand, for failure mode B, two cases labeled M1M23 and M1M2M3 are considered. The former one means that two independent control sub-systems have formed by breaking the connection between the active member 1 and active members 2 and 3. Similarly, the latter case, M1M2M3, signifies that three control sub-systems have been formed, with each sub-system controlling one active member and one vibration mode.

The maximum building responses and the maximum control action (i.e., the maximum control elongations and forces of active members) in these control cases are also listed in Table 2. Note that all the values in Table 2 have been non-dimensionalized by dividing the values by the proper values indicated in the table footnote. From Tables 1 and 2, it is seen that: (1) When the control system is undamaged (case M123), the resulting damping ratios for all the three modes are very close to their desired values, i.e., 10%. This implies that the control system is very effective, regardless of the spillover effect. (2) When failure mode A occurs, the resulting damping ratios decreases while the maximum control elongation of the undamaged active members increases. This implies that the undamaged members have taken over all the control job, although control performance has declined. (3) At the occurrence of failure mode B, although the resulting damping ratios of the first two modes have increased beyond the desired values, the maximum elongation of the first active member has increased, also. This means that the increase of the damping ratios is at the expense of overshooting the first active member.

In order to investigate the control results in the time domain, the time histories of the 6th floor acceleration due to the above control cases are considered and depicted in Figs. 1 ~ 3. From Fig. 1, which compares the response of the uncontrolled system with that of the controlled system, M123 (the undamaged control case), it is obvious that the seismic response of the 6th floor has been very effectively suppressed by the proposed control system. Figs. 2 and 3 mainly show the influence of failure modes A and B, respectively, on the structural response. From these two figures, it is seen that: (1) Even with partial failure, the control system still performs very well in all of the control cases except case M1. (2) From Fig. 2, the significant difference between cases M12 and M1 implies that control of the second mode is crucial to the suppression of the 6th floor motion.

Fig. 4 shows the length changes (computed by the controller and driven by the embedded actuators) of all three active members in the undamaged control case (M123). It is shown that the three active members share the control load equally, although in some instances their elongation is out-of-phase (positive for elongation and negative for contraction). For purposes of comparison, in Figs. 5 and 6, the length change of active member 1 in all of the control cases with partial failure is shown. It is observed that, in all the partially impaired cases, the required control effort (elongation) increases. The increase of the control effort does not guarantee the control performance, as can be seen in the case M1 (by Figs. 2 and 5). Nevertheless, from Figs. 3 and 6, it is realized that, for failure mode B, the increase of the control effort enable the control performance to remain as good as that of the undamaged case, M123.

CONCLUSIONS

In this study, a control system combining the concept of active members and the modal truncated output feedback (MTOF) algorithm has been proposed for the mitigation of seismic motion in building structures. The control system does not require any filter or state estimator, so it can be easily implemented. Also, from the numerical example given, it has been proven that the control system is very effective in suppression of the building's seismic motion even with a small number of active members, provided that the active members are placed in their optimal locations. It has also been shown that the control system is stable even in the presence of the spillover effect and is very reliable even when a portion of the control hardware is impaired.

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Table 1 Modal properties of the 6-story building for various control cases

Failure mode	Control Case	Mode #	Freq. (Hz)	Damping Ratio (%)	Control Case	Mode #	Freq. (Hz)	Damping ratio (%)
no damage	no control	1	0.72	0.00	M123	1	0.75	9.84
		2	2.13	0.00		2	2.22	9.74
		3	3.41	0.00		3	3.61	9.70
A	M12	1	0.76	8.35	M1	1	0.77	7.76
		2	2.21	9.56		2	2.45	5.72
		3	3.97	2.53		3	3.93	2.61
B	M1M23	1	0.77	12.50	M1M2M3	1	0.77	10.96
		2	2.58	12.72		2	2.68	17.07
		3	4.06	3.04		3	4.09	2.48

Table 2 Structural responses and control actions of various control cases

Failure mode	Control Case	Floor	Max. Acceleration[1]	Max. Displacement[1]	Active Member	Max. Elongation[2] (%)	Max. Control Force[3] (%)
no damage	M123	6	0.236	0.633	1	0.121	0.414
		4	0.117	0.546	2	0.104	0.445
		2	0.264	0.575	3	0.121	0.436
A	M12	6	0.412	0.650	1	0.153	0.592
		4	0.123	0.615	2	0.137	0.549
		2	0.286	0.623	3	damaged	damaged
A	M1	6	0.273	0.664	1	0.214	0.811
		4	0.504	0.672	2	damaged	damaged
		2	0.464	0.702	3	damaged	damaged
B	M1M23	6	0.214	0.552	1	0.160	0.622
		4	0.112	0.503	2	0.094	0.375
		2	0.198	0.496	3	0.096	0.365
B	M1M2M3	6	0.217	0.580	1	0.155	0.602
		4	0.119	0.527	2	0.105	0.410
		2	0.229	0.522	3	0.063	0.243

1. Divided by the max. acceleration or displacement values of the uncontrolled case.
2. Divided by the total length of the active member (i.e., $\sqrt{6^2+2.5^2}=6.5$ m).
3. Divided by the total weight of the building (i.e., $2200\times6\times9.8=129360$ N).

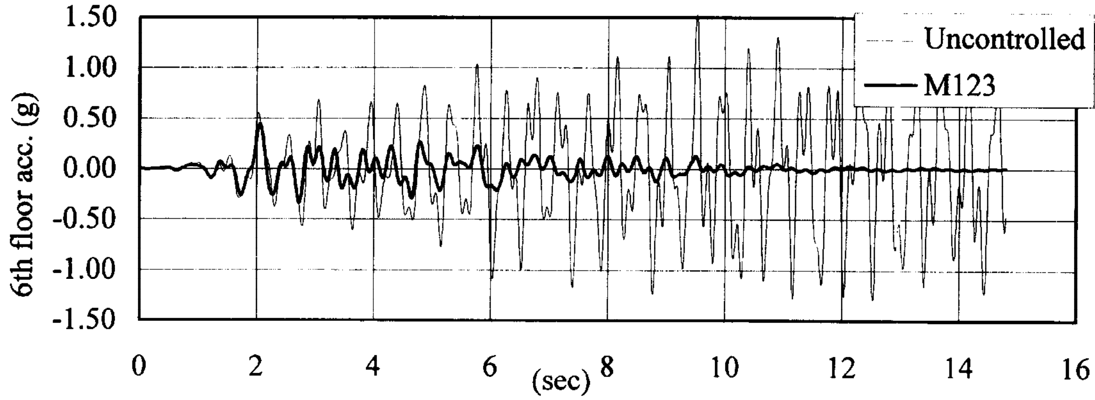

Fig. 1 Acceleration of the 6th (top) floor

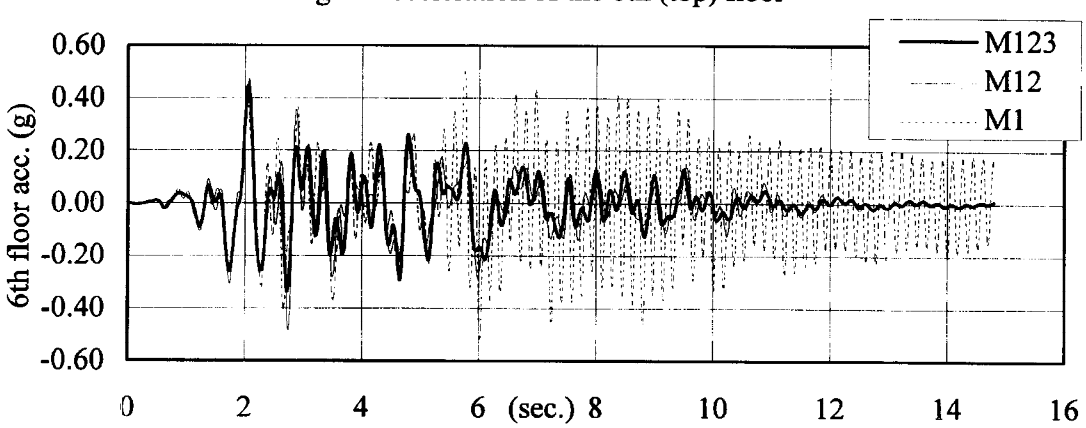

Fig. 2 Acceleration of the 6th (top) floor - with failure mode A

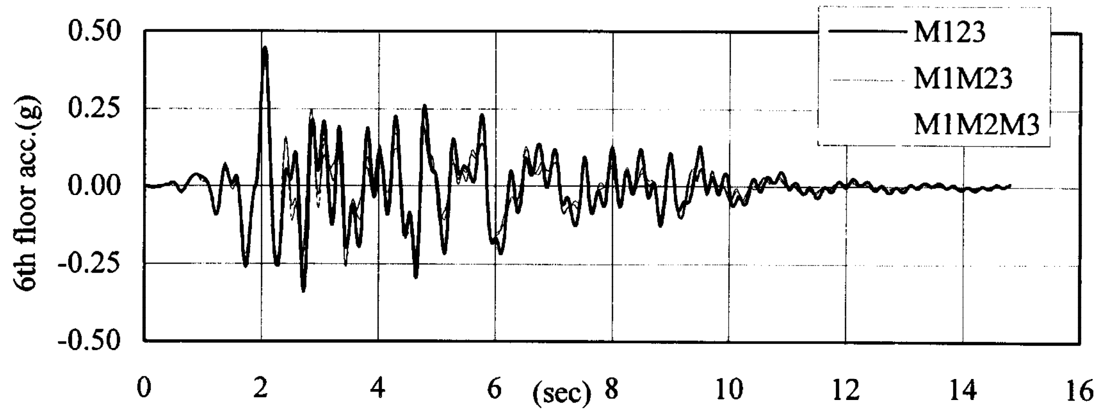

Fig. 3 Acceleration of the 6th (top) floor - with failure mode B

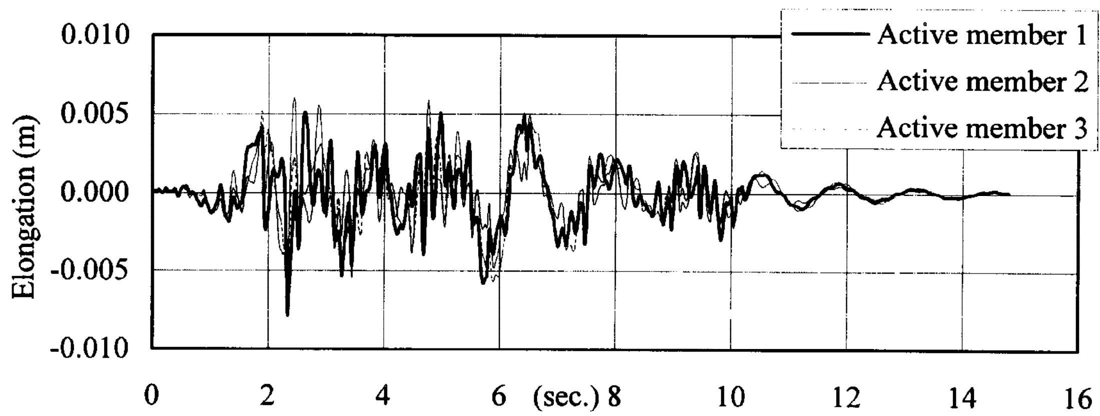

Fig. 4 Elongation of active members in the (undamaged) control case, M123

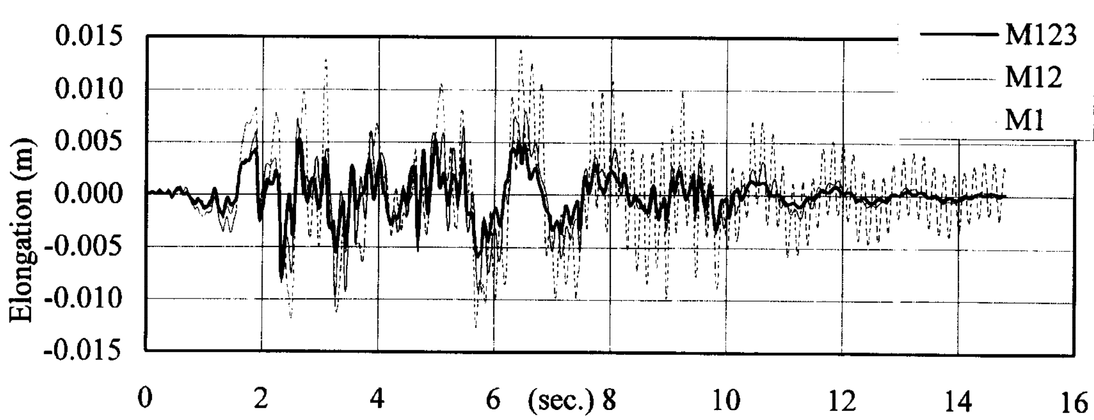

Fig. 5 Elongation of active member 1 - with failure mode A

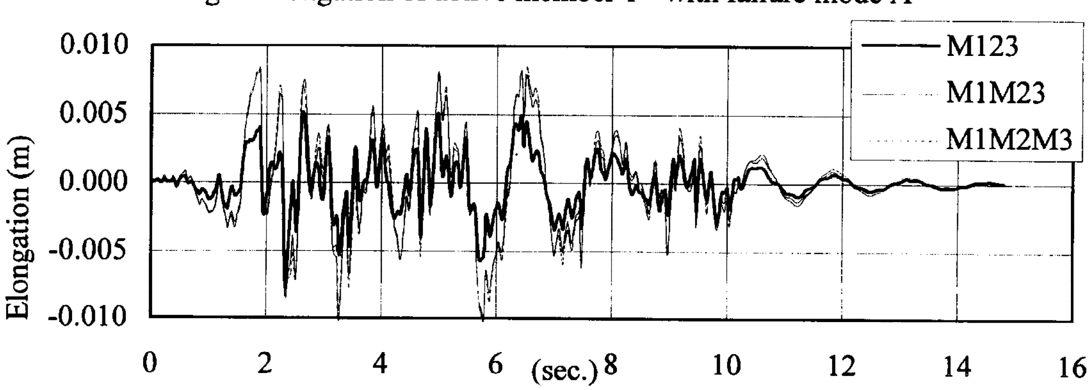

Fig. 6 Elongation of active member 1 - with failure mode B