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Active Tendons for Seismic Control of Buildings

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Abstract**—**In this study, active tendons with Proportional Integral Derivation type controllers were applied to a SDOF and a MDOF building model. Physical models of buildings were constituted with virtual springs, dampers and rigid masses. After that, equations of motion of all degrees of freedoms were obtained. Matlab Simulink was utilized to obtain the block diagrams for these equations of motion. Parameters for controller actions were found by using a trial method. After earthquake acceleration data were applied to the systems, building characteristics such as displacements, velocities, accelerations and transfer functions were analyzed for all degrees of freedoms. Comparisons on displacement vs. time, velocity vs. time, acceleration vs. time and transfer function (Db) vs. frequency (Hz) were made for uncontrolled and controlled buildings. The results show that the method seems feasible.

Keywords**—**Active Tendons, Proportional Integral Derivation Type Controllers, SDOF, MDOF, Earthquake, Building.

I. INTRODUCTION

ADVANCED construction methods and durable construction materials are insufficient for an important structure when it exposes with extreme external impacts. In order to minimize these huge impacts, control strategies are widely used in huge structures. Control methods become more popular with the help of development at technology and computers.

Huge dynamic impacts can be result of earthquakes, huge storms, explosions and other external forces. Earthquake factor is the most important one because of its international importance.

Structural control strategies have two main type and these are passive and active systems. Also hybrid and semi-active systems are used in buildings.

In this study, active tendon control was virtually analyzed on two different model buildings. One of these models was a single degree of freedom system (SDOF) which was experimentally examined before by Chung, Reinhorn and Soong. [1] The other system was a three storey multiple degree of freedom system (MDOF) which was also experimentally examined by Chung, Lin, Reinhorn and Soong. [2]

Different earthquakes and their various records were examined in order to see near and far fault effect and benefits of the control system under different conditions. Effects of 1999 Duzce and 1992 Erzincan Earthquakes were examined.

II. CONTROL SYSTEM

A. Active Tendon Control

These systems consist of four pre-stressed cables, two activators and a control element. In order to control more than one degree, additional four pre-stressed cables, two activators and a controller is also needed for each degree. While half of the cables and activators exist on one side of the building, the others exist on the opposite side.

B. Proportional Integral Derivation (PID) Type Controllers

Proportional Integral Derivation type controllers were chosen in order to produce control signal data (u) which is also known as displacements of the activators. These controllers use feedback strategy and have three actions. P-action is introduced for increasing the speed of response. D-action is introduced for damping purposes. I-action is introduced for obtaining a desired steady-state response. [3] Parameters for these actions were found by a using trial method.

Equation of these controllers is given in (1) in which K_p (Proportional gain), T_i (Integral time) and T_d (Derivation time) are the coefficients of controller.

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt} \right) \tag{1}$$

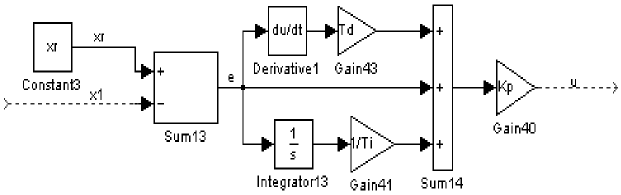

Fig. 1 Block diagram of PID controller prepared with Matlab Simulink [4]

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III. BUILDING MODELS AND EQUATIONS OF MOTION

A. Single Degree of Freedom System (SDOF)

Model of the SDOF system with active tendons and changes of tendon forces are shown in Fig. 2. Horizontal displacement of the system is x_1 and $\ddot{x}_g$ is the ground acceleration. R is the pre-stress force of each tendon during static state. In dynamic state, while one of the crosswise tendons is being tensed by tensile force, the other one is being unloaded because of compressive force. Absolute value of control force must be smaller than pre-stress force because tendons cannot carry compressive force.

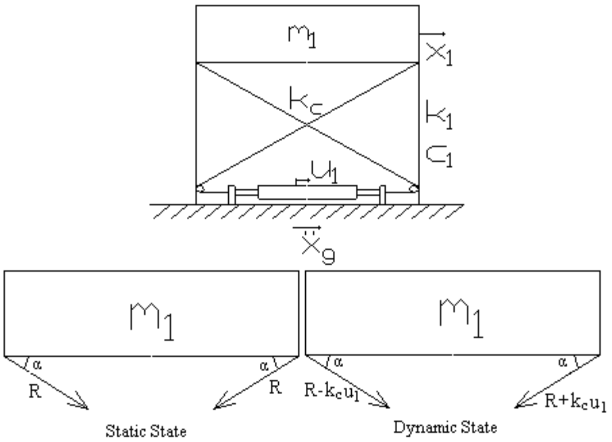

Fig. 2 Model of SDOF system with active tendons and control forces [4]

TABLE I
PROPERTIES OF THE SDOF MODEL AND TENDONS[1]

Symbol	Quantity	Numerical Value
m_1	mass of the SDOF system	2924 kg
k_1	stiffness of the SDOF system	1390000N/m
c_1	damping coefficient of the SDOF system	1581Ns/m
α	angle of tendons	36 °
k_c	stiffness of tendons	372100N/m

Numerical values of the SDOF model can be seen in Table I. Equation of motion for uncontrolled building is shown in (2). Equation 3 is for the SDOF system with active tendons. Horizontal control force is $-k_c u_1 \cos\alpha$ for each tendon.

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1 x_1 = -m_1\ddot{x}_g \tag{2}$$

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1 x_1 = -m_1\ddot{x}_g - 4k_c u_1 \cos\alpha \tag{3}$$

B. Multiple Degree of Freedom Systems (MDOF)

In Fig. 3, 4 and 5, three cases of the tendon placement are shown. In Case A, tendons exist only in first storey. Tendons exist in all floors in Case B and C, but in Case C, all activators are placed on the ground floor.

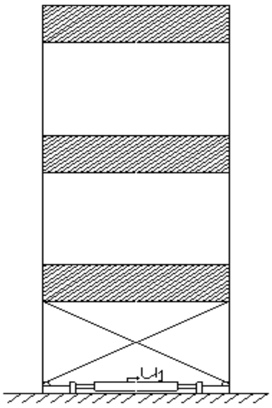

Fig. 3 Model of MDOF system with active tendons for case A [5]

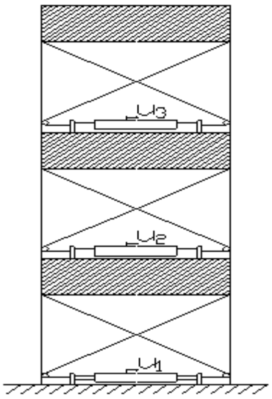

Fig. 4 Model of MDOF system with active tendons for case B [5]

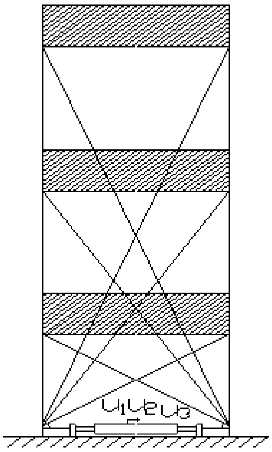

Fig. 5 Model of MDOF system with active tendons for case C [5]

M (mass matrix), K (stiffness matrix) and C (damping matrix) are shown in (4), (5) and (6) respectively [2]. Tendon properties are the same with the SDOF system. Angle of tendons are 36, 55, 65 degrees for Case C and 36 degrees for other cases.

$$[M]=\begin{bmatrix}981 & 0 & 0\\ 0 & 981 & 0\\ 0 & 0 & 981\end{bmatrix}\ \text{(Kg)} \qquad (4)$$

$$[K]=\begin{bmatrix}2741700 & -1641600 & 369100\\ -1641600 & 3022200 & -1624800\\ 369100 & -1624800 & 1333600\end{bmatrix}\ \text{(N/m)} \qquad (5)$$

$$[C]=\begin{bmatrix}382.8 & -57.3 & 61.7\\ -57.3 & 456.9 & -2.6\\ 61.7 & -2.6 & 437.5\end{bmatrix}\ \text{(Ns/m)} \qquad (6)$$

If pre-stress forces at the tendons are R, the tendon forces during dynamic state are shown in Fig. 6,7 and 8. Equations of motion were given in space state form. Equation 7 is for Case A, (8) is for Case B and (9) is for Case C.

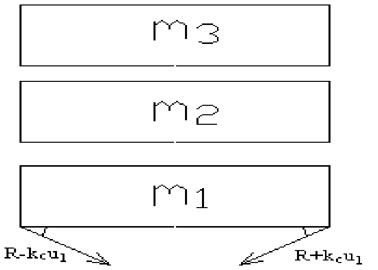

Fig. 6 Tendon forces at dynamic state for all case A [4]

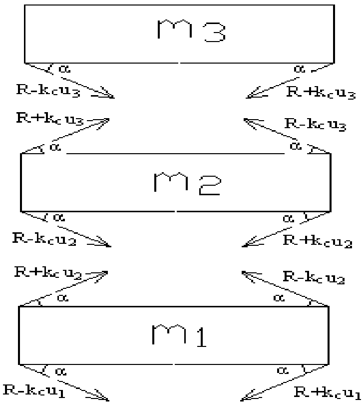

Fig. 7 Tendon forces at dynamic state for all case B [4]

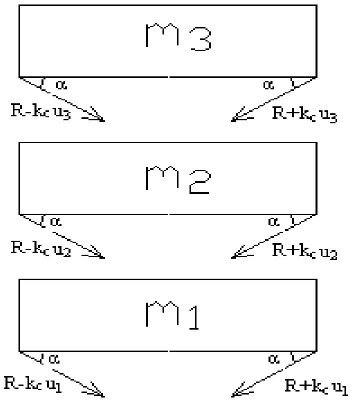

Fig. 8 Tendon forces at dynamic state for all case C [4]

$$[M]\underline{\ddot{X}}+[C]\underline{\dot{X}}+[K]\underline{X}=-[M][1]\ddot{x}_g-4k_c\cos\alpha\begin{bmatrix}u_1\\ 0\\ 0\end{bmatrix} \qquad (7)$$

$$\begin{aligned}&[M]\underline{\ddot{X}}+[C]\underline{\dot{X}}+[K]\underline{X}=-[M][1]\ddot{x}_g\\ &+4k_c\cos\alpha\begin{bmatrix}-1 & 1 & 0\\ 0 & -1 & 1\\ 0 & 0 & -1\end{bmatrix}\begin{bmatrix}u_1\\ u_2\\ u_3\end{bmatrix}\end{aligned} \qquad (8)$$

$$[M]\underline{\ddot{X}}+[C]\underline{\dot{X}}+[K]\underline{X}=-[M][1]\ddot{x}_g-4k_c\begin{bmatrix}u_1\cos\alpha\\ u_2\cos\beta\\ u_3\cos\theta\end{bmatrix} \qquad (9)$$

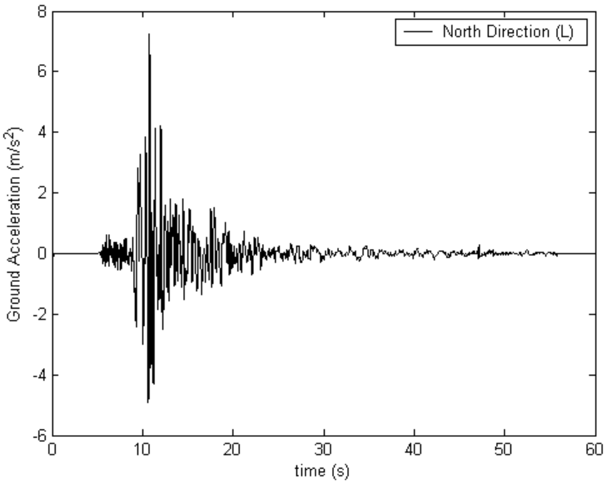

Fig. 9: Duzce Earthquake (1999)-Bolu Ground Acceleration Record (North direction) [6]

IV. EARTHQUAKE ACCELERATION RECORDS

Maximum ground acceleration of the 1999 Duzce Earthquake's Bolu record was nearly 8 m\s^2 in east-west direction but in the north-south direction, the record is more critical because of dense distribution in stroke time. Bolu record of 1999 Duzce Earthquake can be seen in Fig. 9 and 10. Bolu is nearly 50 km away from the center of earthquake and close to the fault.

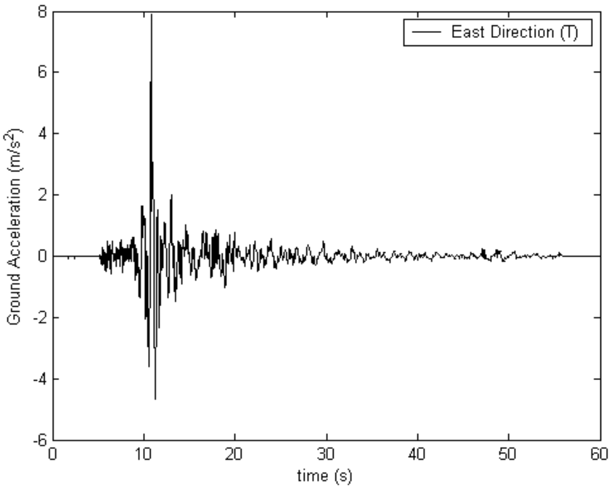

Fig. 10: Duzce Earthquake (1999)-Bolu Ground Acceleration Record (East direction) [6]

Sakarya record of the same earthquake can be seen in Fig. 11 and 12. Maximum ground acceleration of this record is much smaller than the other one because Sakarya is far from the fault. Because of local soil conditions, this record is longer than the other record.

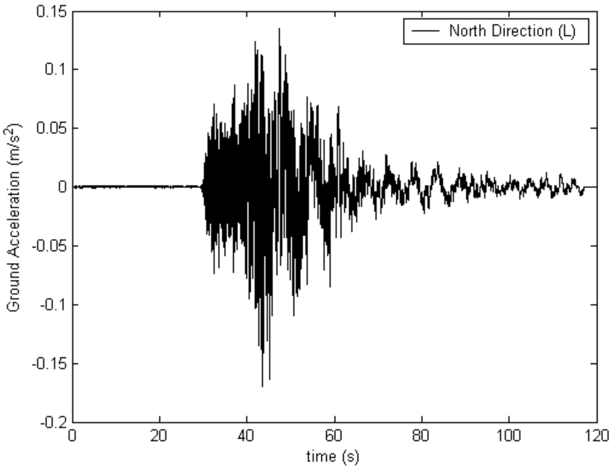

Fig. 11: Duzce Earthquake (1999)-Sakarya Ground Acceleration Record (North direction) [6]

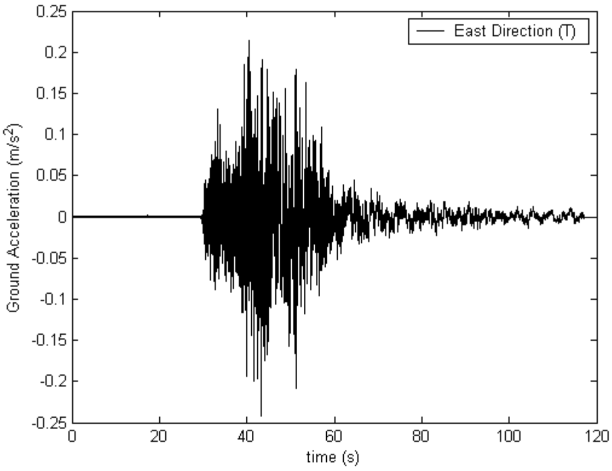

Fig. 12: Duzce Earthquake (1999)-Sakarya Ground Acceleration Record (East direction) [6]

Maximum ground acceleration of 1992 Erzincan Earthquake was lower than Duzce Earthquake but acceleration record of Erzincan Earthquake is very dense. Acceleration is stable at some times in east-west direction. Ground acceleration record of 1992 Erzincan Earthquake is given in Figure 13 and 14.

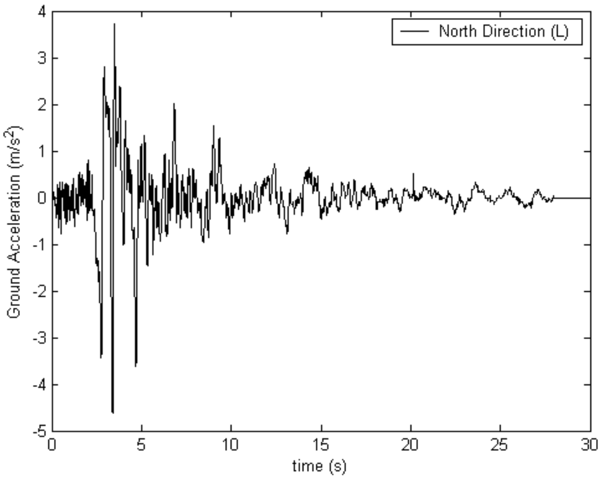

Fig. 13: Erzincan Earthquake (1992)-Erzincan Ground Acceleration Record (North direction) [6]

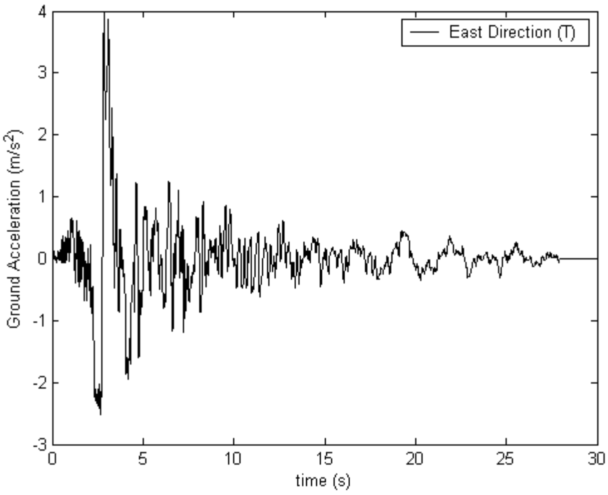

Fig. 14: Erzincan Earthquake (1992)-Erzincan Ground Acceleration Record (East direction) [6]

V. SYSTEM ANALYSIS

Matlab Simulink models were constituted for equations of motion and Runge-Kutta method was chosen for solver. Also, M-files were constituted for all models in order to obtain time and frequency domain graphics.

A. Single Degree of Freedom System (SDOF)

Controller parameters were accepted by using a trial method. These parameters are K_p = -0.6, T_d = 0.6 s and T_i = 0.01 s for the single degree of freedom system.

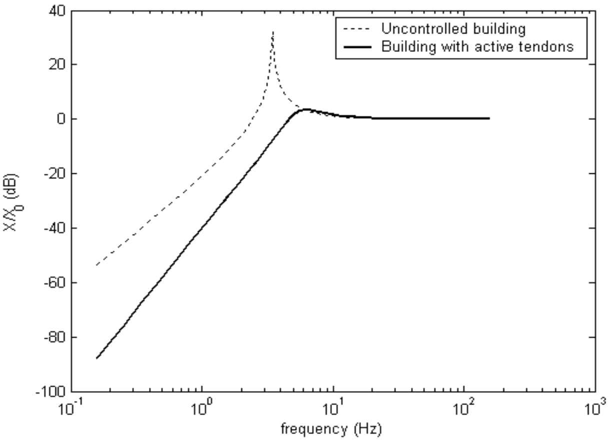

Fig. 15 Transfer function vs. frequency graph of single degree of freedom system [4]

Transfer function vs. frequency graph of the single degree of freedom system can be seen in Fig. 15. Natural frequency of single degree of freedom system is 3.47 Herz.

Displacement of the single degree of freedom system under two different earthquake acceleration records can be seen in Fig. 16. Active tendons are very useful in damping the vibrations.

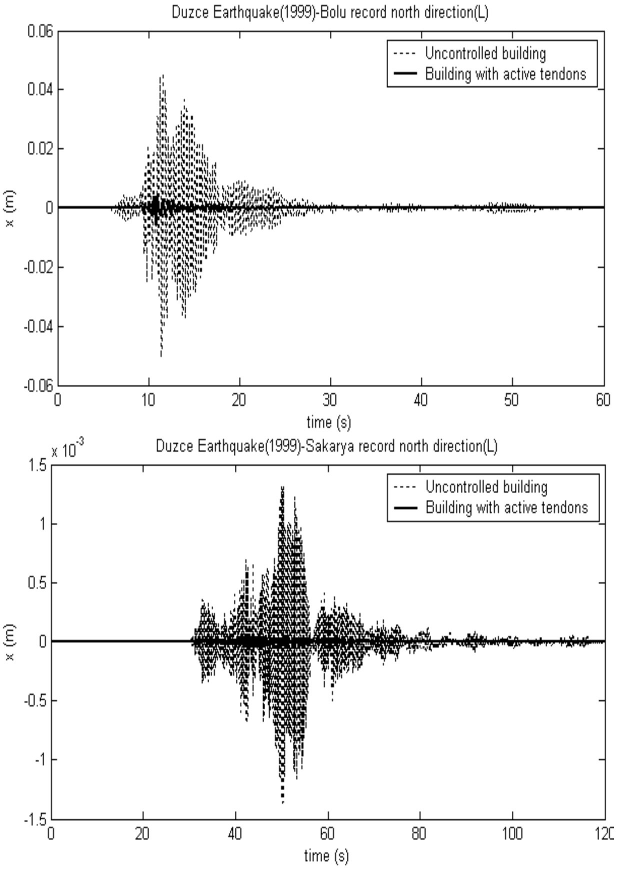

Fig. 16 Displacement of the single degree of freedom system [4]

B. Multiple Degree of Freedom System (MDOF)

Controller parameters are the same as SDOF system for Case A. The displacement graph of first storey (uncontrolled building-Case A) under Duzce Earthquake-Bolu acceleration records can be seen in Fig. 17. Results of the controlled system in Case A for the first storey are quiet good but tendons are not very useful for other floors as seen in Fig. 18.

The K_p value of controllers at the third storey for Case B is the same with the SDOF system, but Kp is 2 times for controllers at second floor and 3 times for controllers at first floor in order to produce equal control forces for all stores. Other controller parameters are the same as the SDOF system.

For Case C, all reaction forces of tendons are supported by the foundation but tendon angles are bigger for upper storey. Angles are α=36, β=55 and θ=65 degrees. Control forces are smaller for upper floors because of cosines of angles. In order to obtain same results of Case B, K_p is 1.4 times for controllers at second floor and 1.9 times for controllers for the third floor.

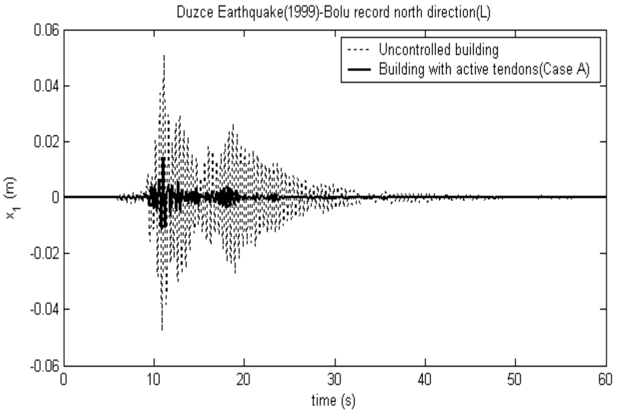

Fig. 17 Displacement of first storey (Case A) [4]

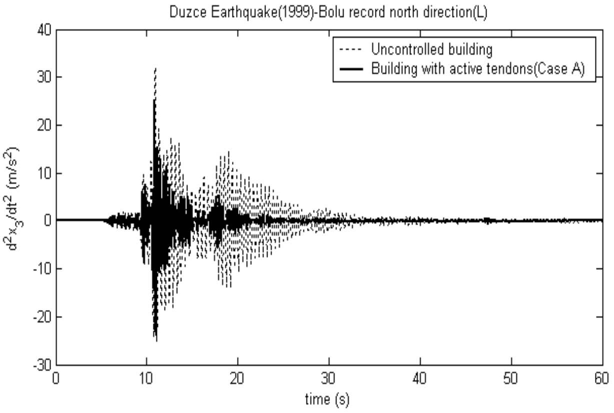

Fig. 18 Acceleration of third storey (Case A) [4]

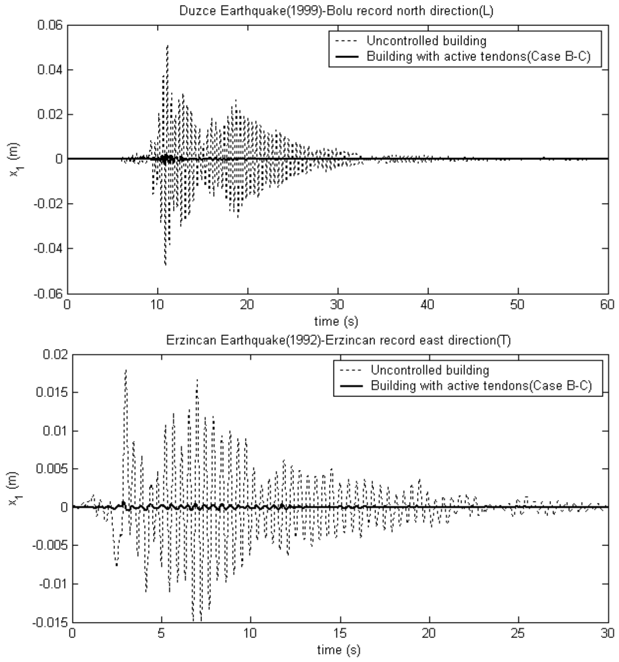

Fig. 19 Displacement of first storey (Case B and C) [4]

The results of cases B and C are better than Case A as seen in Fig. 19. Also, upper floors are controlled as well as the first floor as seen in Fig. 21.

Transfer function vs. frequency graph of multiple degree of freedom system can be seen in Fig. 20. The natural frequencies of multiple degree of freedom system are 2.237, 6.804 and 11.487 Hz.

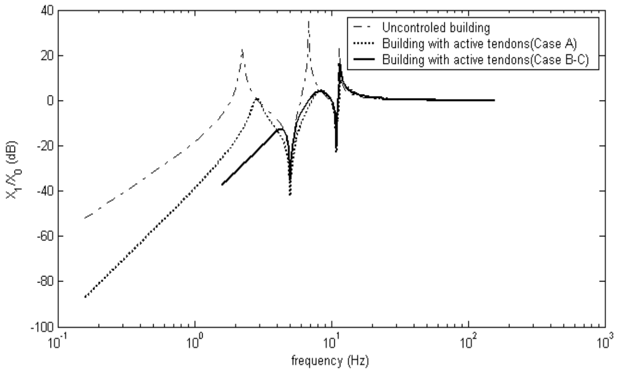

Fig. 20 Transfer function vs. frequency graph of multiple degree of freedom system [4]

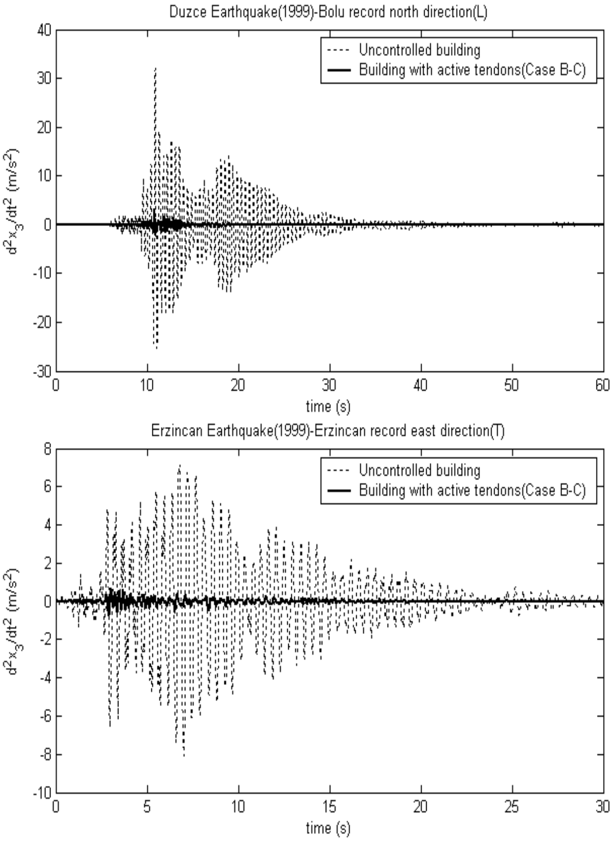

Fig. 21 Acceleration of third storey (Case B and C) [4]

VI. CONCLUSION

The results of the controlled single degree of freedom system show that the method seems feasible under different ground accelerations.

For multiple degree of freedom systems, placement of active tendons at first storey is insufficient. Only the results at first storey are quiet well. System can be more effective if active tendons are applied to all floors.

Active tendons at upper floors have a side effect. Tendons have reaction forces and these forces which are opposite to the direction of main control forces. But, in Case C, these reaction forces are supported by the ground so that the maximum tendon force is smaller than Case B. Maximum tendon force is the biggest in Case A as seen in Fig. 22.

Case C has more than one side effect. Tendons are very long and there are six activators on the ground so that the application of this method is not practical. Also, the vertical components of control forces are bigger than other cases because of the increase of the tendon angles. These forces may also be harmful for the columns.

Tendons are useful for all ground acceleration records used for multiple degree of freedom systems. Consequently, the best case is B. The results of Case B are well enough to control a building under extreme ground accelerations. Also, Case B is more practical to apply.

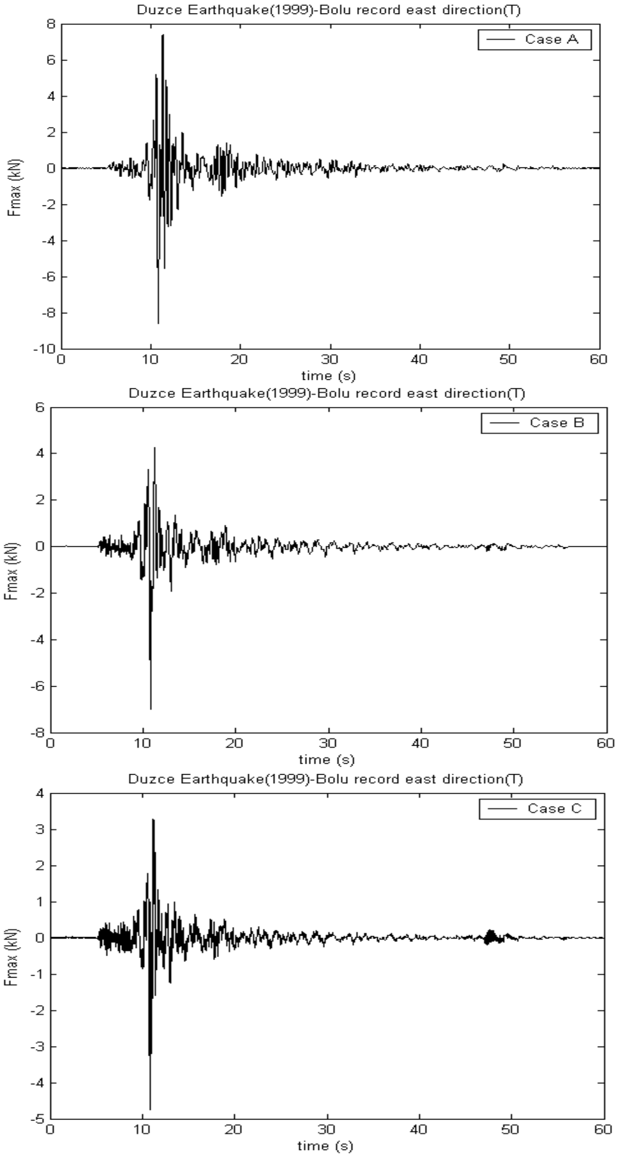

Fig. 22 Force at one tendon in different cases [4]

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