Earthquake design for controlled structures

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ABSTRACT. An alternative design philosophy, for structures equipped with control devices, capable to resist an expected earthquake while remaining in the elastic range, is described. The idea is that a portion of the earthquake loading is undertaken by the control system and the remaining by the structure which is designed to resist elastically. The earthquake forces assuming elastic behavior (elastic forces) and elastoplastic behavior (design forces) are first calculated according to the codes. The required control forces are calculated as the difference from elastic to design forces. The maximum value of capacity of control devices is then compared to the required control force. If the capacity of the control devices is larger than the required control force then the control devices are accepted and installed in the structure and the structure is designed according to the design forces. If the capacity is smaller than the required control force then a scale factor, α, reducing the elastic forces to new design forces is calculated. The structure is redesigned and devices are installed. The proposed procedure ensures that the structure behaves elastically (without damage) for the expected earthquake at no additional cost, excluding that of buying and installing the control devices.

KEYWORDS. Response spectrum analysis; Structural control; Earthquake engineering.

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INTRODUCTION

Over the past few decades various control algorithms and control devices have been developed, modified and investigated by various groups of researchers. The works of Yao, 1975, Housner et al., 1994, Kobori et al., 1998, and Soong 1998 are representative [1-4]. There have been some attempts to connect the control forces with the design codes. Yang et al. 2003 [5] suggested the maximum control force to be a percentage of the building weight, while Cai et al., 1997, [6] give this force as a portion of the seismic force. Lee et al., 2004, [7] determined the upper limit of control force based on the response spectrum of the external earthquake.

During the past years the design philosophy of new structure was to design stiff structures with high strength to resist the earthquake in the elastic range. After that the design philosophy moves one step further. Using the ductility of the material, structures were designed to resist lower level of earthquake forces within the elastic range but to have adequate ductility in order to face the attack of stronger earthquakes and prevent them from collapse. This drives to lighter structures compared to the previous structures and more economical. However, the capacity design and the reinforcement details increased the cost. Taking in account the cost of repair of the retrofitting of structure, after a strong earthquake, the design of ductile structures should be under consideration.

The design philosophy proposed here is to use control devices installed in the structure and provide a reservoir of strength, stiffness or damping, necessary for preventing the structure from damage when an expected earthquake will occur. Thus, the control system will drive the structure to behave in the elastic range when it is attacked by the expected earthquake and no damages will occur. As far as the cost is concerned, it is possible to achieve substantial savings by avoiding retrofit of structure during the lifetime of structure and utilize these savings for installing a control system. A systematic procedure to achieve the above objective is proposed in this work.

DESIGN PROCEDURE FOR STRUCTURES EQUIPPED WITH A CONTROL SYSTEM

The evolution of the design philosophy of structures passes through different stages. Fist the engineers design stiff and massive structures in order to behave elastically during the expected earthquake. As years passed and damages were observed after earthquakes the design philosophy was moved from the resistance of structure to energy dissipation capacity of the structural elements and design of structures with an overall ductile behavior. This drives engineers to perform capacity design for structures. This philosophy is nowadays included in all current design regulations. However, observing the damages to the structures that were designed with the latter philosophy and making calculations, the repair cost of the capacity design emerged and came into consideration. The answer to the previous consideration is the new and proposed design philosophy where the structure is oriented to capacity design equipped with control devices that will absorb a portion of seismic energy induced to the structure and as a result to keep the structure in the elastic range. The three design philosophies are depicted in Fig. 1. The proposed design procedure for the spectrum is calculated in such a way that one portion of earthquake forces is taken by the structure and the remaining ones are taken by the control devices.

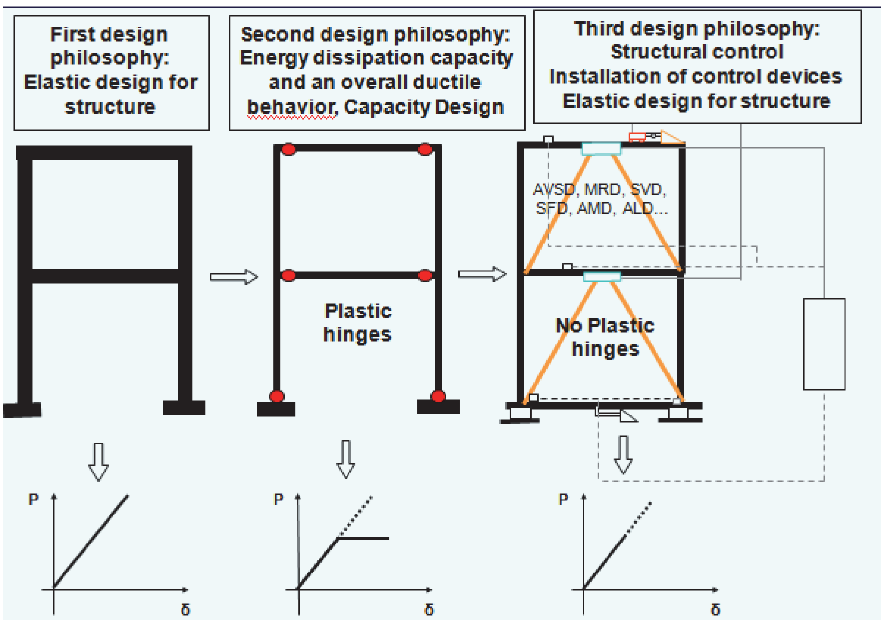


Figure 1: The three design philosophies of design of structures.

Initially, the controlled structure is designed based on a design spectrum provided by the pertinent code (Eurocodes) with a specific level of ductility. The required control forces that will take a portion of earthquake forces are calculated as the difference from forces obtained from the elastic spectrum to those obtained from the design spectrum. The maximum value of capacity of the control devices is compared with the required control force. If the capacity of the control devices is larger than the required control force then the control devices are accepted and installed into the structure. If the capacity is smaller than the required control force then a control device with larger capacity should be chosen or more devices per floor should be installed

In case the maximum available control device capacity is smaller than the required control force, or, there is a limitation to the number of control devices, then using an iterative procedure, a scale factor, α, higher than the value 1/q that reduces the elastic response spectrum is calculated. The structure is redesigned based on the new reduced spectrum by scale factor, a, and then the devices are installed into the structure. The flow chart of the procedure is shown in Fig. 2 with a solid line.

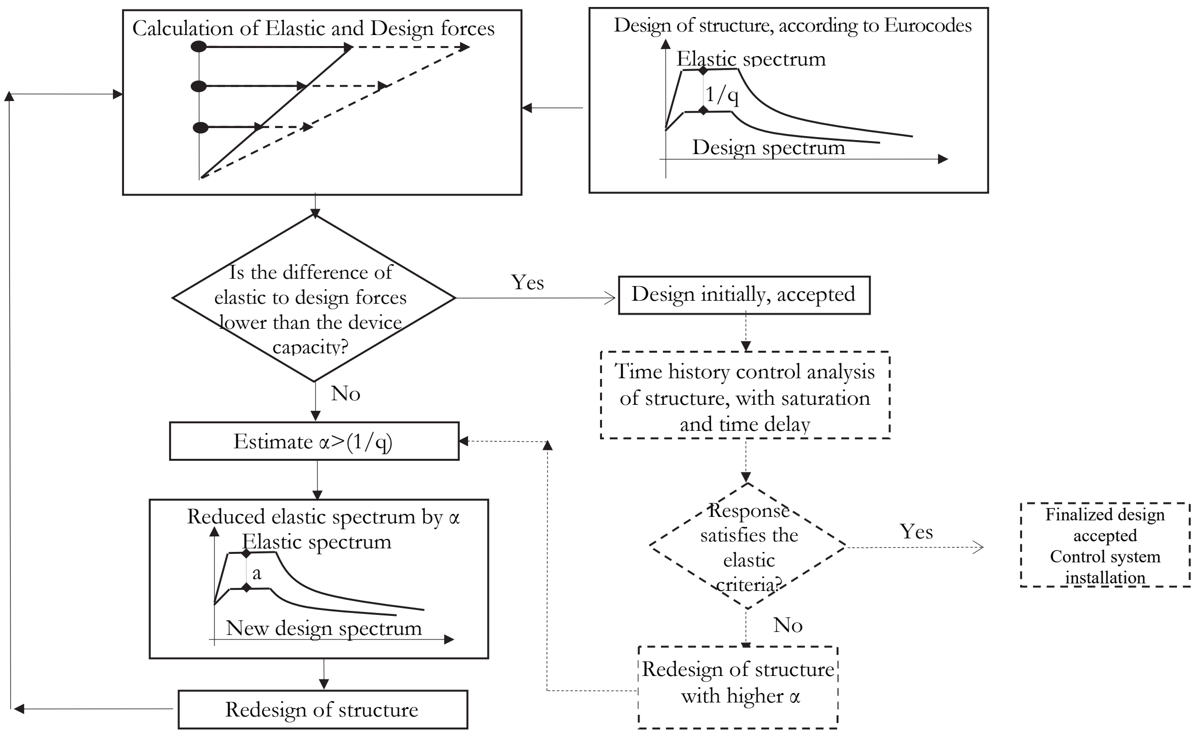


Figure 2: The flow chart of the proposed design procedure.

Estimation of scale factor, a.

From the elastic seismic forces and the maximum capacity of the control device a scale factor α is obtained and applied on the elastic spectrum. Knowing the mass and initial stiffness of the structure the eigenmodes Φ_i, eigenperiods T_i or eigenfrequencies f_i and the corresponding damping ratios ξ_i of the uncontrolled system are obtained.

The participation factor ψ_i, and elastic seismic forces $F_{q,el,i}$ for the i^{th} eigenmode are given as:

$$\psi_i = \frac{\mathbf{\Phi}_i^T \mathbf{ME}}{\mathbf{\Phi}_i^T \mathbf{M\Phi}_i}, \quad i=1,...,n \tag{1}$$

$$\mathbf{F}_{q,el,i} = \mathbf{M\Phi}_i \psi_i S_{e,i}(T_i, \xi_i), \quad i=1,...,n \tag{2}$$

where E is the direction matrix for the earthquake and $S_{e,i}(T_i, \xi_i)$ is the elastic spectral acceleration. The maximum elastic seismic forces $F_{q,e}$ for each degree of freedom are obtained combining the Square Root of Sum Squares method (SRSS) the elastic seismic forces from each eigenmode, thus:

$$\mathbf{F}_{q,e} = \sqrt{\sum_{i}^{n} \mathbf{F}_{q,e,i}^{2}} \tag{3}$$

If $F_{d,max}$ is the maximum control device capacity (maximum possible control force), then the maximum control force that can be applied on the system is:

$$\mathbf{F}_{d,max} = \mathbf{E}_f F_{d,max} \tag{4}$$

where E_f is the location matrix for the control devices on the structure. Assuming that one part, up to $F_{d,max}$, of elastic seismic forces are carried by control devices, the remaining seismic forces which go directly and force the structural elements are:

$$\mathbf{F}_{q,\,new} = \begin{cases} \mathbf{F}_{q,e} - \text{sign}(\mathbf{F}_q)\mathbf{F}_{d,max} & \text{if} \quad \left|\mathbf{F}_q\right| \geq \mathbf{F}_{d,max} \\ 0 & \text{if} \quad \left|\mathbf{F}_q\right| < \mathbf{F}_{d,max} \end{cases} \tag{5}$$

$\mathbf{F}_{q\ new}$ is a vector with n forces, where n is the degree of freedom of the system. These forces correspond to a reduced spectral acceleration. From Eq. (2) this new spectral acceleration $S_{d,i,new}(T_i, \xi_i)$, corresponding to new seismic forces, can be obtained:

$$S_{d,i,new}(T_i, \xi_i) = \frac{\left(\mathbf{M}\mathbf{\Phi}_i\right)^{-1} \mathbf{F}_{q,new}^{T}}{\psi_i}, \quad i=1,...,n \tag{6}$$

The reduction factor α can be obtained by dividing the new spectral acceleration $S_{d,i,new}(T_i, \xi_i)$ by the corresponding initial one:

$$\alpha_i = \frac{S_{d,i,new}(T_i, \xi_i)}{S_{e,i}(T_i, \xi_i)}, \quad i=1,...,n \tag{7}$$

The elastic spectrum is scaled using the maximum value of α_i and the structure is redesigned based on the reduced spectrum. The value of a is:

$$\alpha = \max(\alpha_i) \tag{8}$$

In order to ensure a linear behavior of the structure, dynamic control analysis is performed for a range of earthquakes (high and low frequency characteristics), with saturation control and time delay. If the response satisfies the elastic criteria, then the value of α is accepted, otherwise it is slightly increased and the above procedure is repeated. The flow chart of this procedure is shown in Fig. 2 with a dashed line.

The equation of motion of a controlled structural system with n degrees of freedom subjected to an earthquake excitation ag in the state space approach is:

$$\dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{B}_g a_g + \mathbf{B}_f \mathbf{F} \tag{9}$$

The matrixes X, A, B_g, B_f are given by

$$\mathbf{X} = \begin{bmatrix} \mathbf{U} \\ \dot{\mathbf{U}} \end{bmatrix}_{2n\times 1}, \quad \mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K}_{new} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}_{2n\times 2n}, \quad \mathbf{B}_g = \begin{bmatrix} \mathbf{0} \\ -\mathbf{E} \end{bmatrix}_{2n\times 1}, \quad \mathbf{B}_f = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{E}_f \end{bmatrix}_{2n\times 1} \tag{10}$$

where M and C denote the mass and damping matrices of the structure, respectively, K_{new} is the new stiffness matrix of the redesigned structure, and F is the control force matrix. The control force F is determined by linear state feedback as follows:

$$\mathbf{F} = -\mathbf{G}_1\mathbf{U} - \mathbf{G}_2\dot{\mathbf{U}} = -\begin{bmatrix}\mathbf{G}_1 & \mathbf{G}_2\end{bmatrix}\begin{bmatrix}\mathbf{U} \\ \dot{\mathbf{U}}\end{bmatrix} = -\mathbf{GX} \tag{11}$$

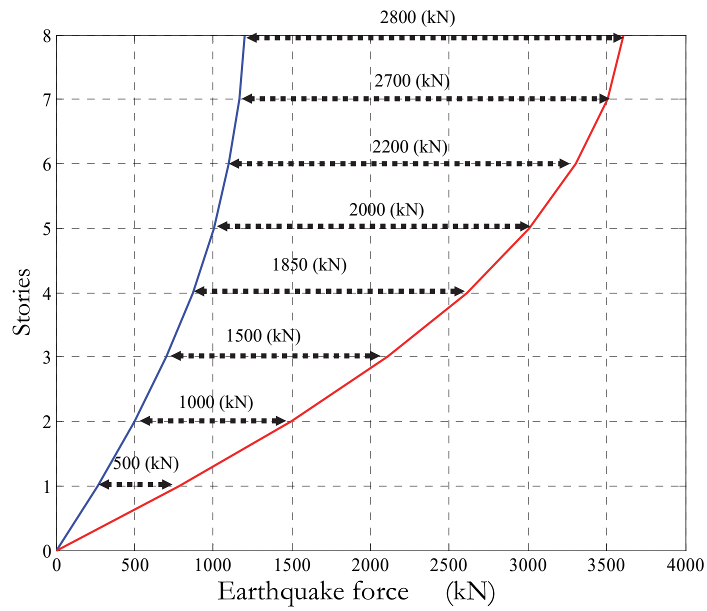
G is the gain matrix, which will be calculated by pole assignment method and according to the desired poles of the controlled system.
If the response obtained for the controlled system satisfies the design criteria, then the reduction by q or by a scale factor, α, is accepted. In this work a representative design criterion was used, that the story drift does not exceed h/300 (where h is the story height). This value does not cause member yielding. In a similar way, additional design criteria concerning the rotation and strength of structural members can be used. The above procedure was tested for a number of numerical simulations, and some representative examples are presented next.

RESULTS AND DISCUSSION

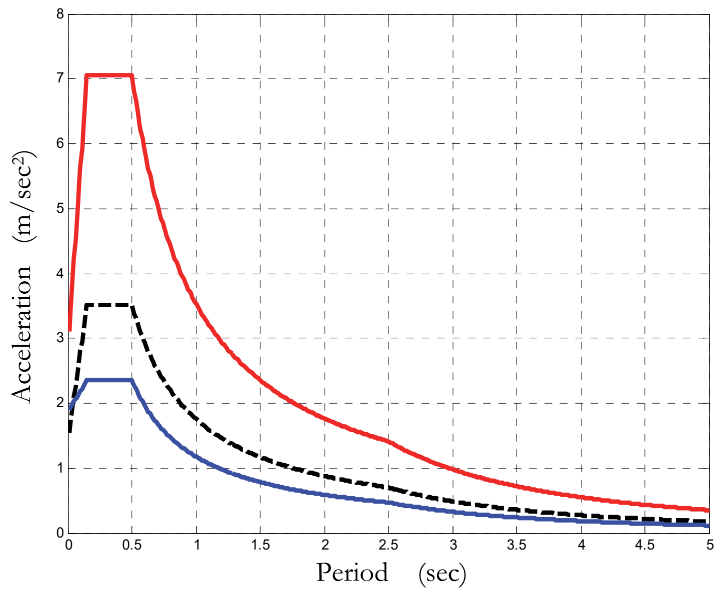
The proposed approach is demonstrated by means of numerical example where an eight-story building, described in the work of Yang et al, 1995 [7], is analyzed. Initially the elastic and design spectra are calculated based on Eurocode 8 (EC8) seismic code.
Based on those spectra and on dynamic characteristics of building the seismic forces $F_{q,i}$ for each eigenmode and their combination are calculated for both elastic and design spectrum. The seismic forces which are obtained from elastic and design spectrum and their differences are shown in Fig. 3(a). Assuming that the control devices are installed on each floor and the maximum capacity is 1000kN, following the proposed procedure the scale factor α is calculated to be equal to 0.49 or the equivalent reduction from the elastic spectrum 1-α which is equal to 51%. The elastic and design spectra and the reduced spectrum by 51% from the elastic spectrum, for which the structure will be redesigned, are illustrated in Fig. 3(b).
In order to ensure that the structure remains in the elastic range after redesigning, dynamic time control analysis history, with saturation control and time delay, for a wide range of earthquakes should be performed. The numerical simulations were performed in Simulink toolbox of Matlab software. The numerical simulation of the control scheme is described in Fig. 3(c).
The response (displacement and acceleration) of the system subjected to Athens earthquake 1999 were calculated. From the numerical results it was seen that full compensation of the displacements was achieved. According to the work of Yang et al. (2003) when one control force corresponds for each degree of freedom then complete compensation of the response can be achieved and the response state vector can be reduced to zero. Another reason that the relative displacements are near to zero is that the elastic response spectrum of the Athens earthquake are lower than the elastic spectrum that was used initially for the design procedure. The acceleration is equal to the external signal and the building behaves like executing a rigid body motion. The control forces are identical, with maximum value at 917 kN and rms value at 134 kN, because the mass of each story is the same. The storey drift between the floors was not exceeded the limit value h/300=10 mm. Time history of displacement and the acceleration from 8th floor for the controlled and uncontrolled structure is shown in Fig. 4.

SUMMARY AND CONCLUSIONS

A procedure to design a structure equipped with control devices is described. The structure is designed based on a reduced spectrum. A scale factor α which multiplies the elastic spectrum and produces a reduced spectrum is proposed. The design philosophy is that one part of seismic forces are taken by control devices and to the rest of earthquake forces taken up from the structure. The numerical results indicate that reduction of the spectrum can be achieved using control devices. The cost of repairing the post-earthquake damages of an uncontrolled structure which was design based on ductility demand can be considered as a motivation to install a control system which will keep the structure in the elastic range. The control system is acceptable if the results obtained from the dynamic control analysis keep the structure within the elastic limit. Design criteria such as inter-story drift which shouldn't exceed a specific value that causes yielding of the structural members could be used in order to ensure elastic behavior.



(a)



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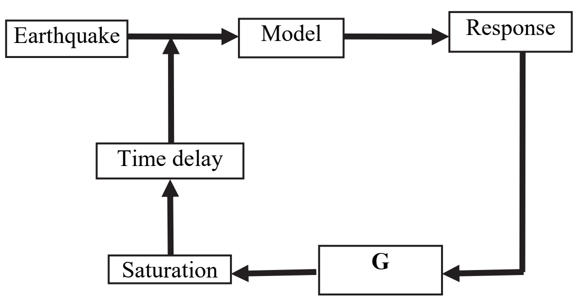
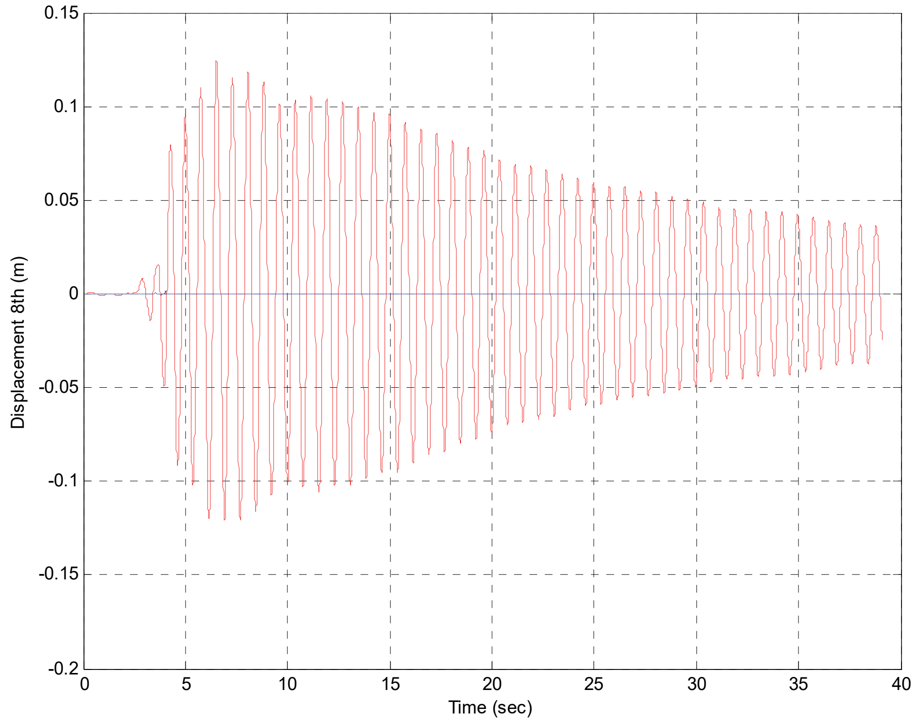


(c)

Figure 3: The difference between elastic and design forces for each story, (a), the elastic and design spectrum, (solid lines), and the reduced elastic spectrum (dash line) for the structure with control devices, (b). Model and control scheme in Simuling toolbox (c).

(a)



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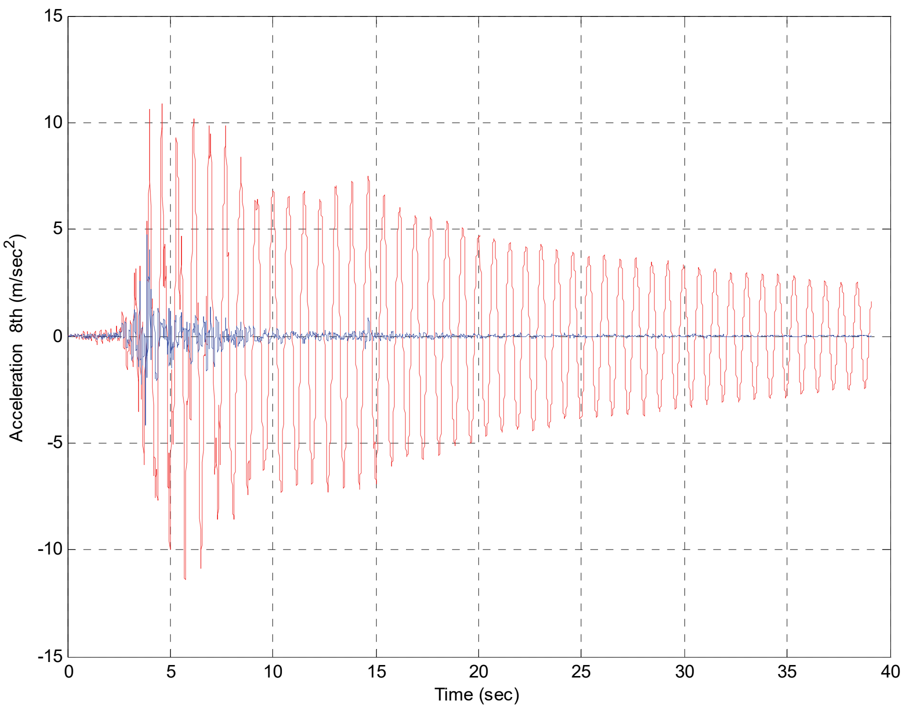

Figure 4: Displacement and the acceleration from 8th floor for the controlled and uncontrolled structure.

The proposed procedure was applied to 8-story building and the numerical results show the effectiveness of the procedure. The control system helps the structure not only to reduce the maximum response (displacements and accelerations) and keep it in the elastic range, but also to perform at much lower level than the maximum response values. This is proved by comparison of the root mean square (rms) values with the maximum values of response. The proposed design procedure seems to be an effective tool for designing controlled structures although further numerical research and experimental verification are needed. Additionally, the methodology should be applied to a space and irregular structures with significant participation of higher modes and with torsional effects.

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