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Application of Fluid Damper Controlled Single Bay steel Buildings

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ABSTRACT

Finite element software package ANSYS Workbench v.12 is used to analyze a three story fluid damper controlled structure subjected to seismic loadings. The story building is not just assumed to be linear shear building system as previously considered. However, it is quite complex problem as material responded beyond elastically. Nonlinear property of steel material behaviors are pre assumed, turns out both of raw structures and fluid dampers are responded into nonlinearly to reveal the responses much realistically. In other words, the problem treated herein is nonlinear dynamic system. Dynamic responses not only elastically but also plastically for the material goes beyond yielded are investigated. The major purpose of the work is then to investigate the control effects of the structure as limited numbers of energy dissipation fluid dampers are installed in different combinations.

The contents of the paper are aimed for individual structure model. Basically, resistances to seismic wave of the building are increased as fluid dampers installed, specially installed at the lowest floor. For different structure models, it has to be re-analyzed to decide which combination of the installations is better for the structure. In the presented examples, Case 2 is the one much more suitable for the presented structure models in case both of comfort and safety are being considered.

Keywords: fluid dampers, nonlinear analysis, structural control, dynamic responses

1. INTRODUCTION

Structural control has been become a popular research topic, theoretical, and practical applications as well, has been greatly developed. Frankly, for the sake of human life concern, structural control aims to safe the structures not to be damaged, or even to be collapsed. As this situation being concerned, two of the questions in reality

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we should have to give the answer clearly. One is that the problem is structures behaviors basically dynamically instead of statically. All of the structural responses due to abnormal excitations such as severe earthquakes should be analyzed dynamically. The other problem is that as the structures under consideration experiences partially damage or near collapse, the structure and the materials already responded nonlinearly, particularly when materials responded beyond yielding point. So, unless dynamic and nonlinearity problems are being concerned, the analysis could be criticized unreality. Furthermore, many of the control devices installed in the controlled structures, such as energy dissipation dampers, or lead rubber bearing isolation devices, …, etc., are obviously behave nonlinearly responded devices. We are trying to emphasize these two problems, dynamic and nonlinearly property, herein when viscous dampers are installed in the structures for structural control purposes.

Finite element software package ANSYS Workbench v.12 proposed by Lee(2010) is used in the analyzed examples. Problems are analyzed dynamically and nonlinearly to investigate the better installation policies as fluid viscous dampers are installed in single bay structures for structural control purposes.

Property of viscous fluid damper is simulated by the Eq. (1) as shown following:

$$F_D = C\left|\dot{u}\right|^n sgn\left(\dot{u}\right)$$
$$sgn\left(\dot{u}\right) = \begin{cases} 1 & \dot{u} \geq 0 \\ -1 & \dot{u} < 0 \end{cases} \qquad (1)$$

Where F_D is the damping force of the damper applied; C is the damping coefficient; $\dot{u}$ is the relative velocity of the piston to the tube; n is the power of the velocity term, it is a value in-between 0.1 – 1.2 as suggested by Taylor(1996). Linear damper (n=1) is used herein in the examples. So, Eq. (1) is modified into Eq. (2).

$$F_D = C\left|\dot{u}\right| sgn\left(\dot{u}\right) \qquad (2)$$

2. ANSYS DYNAMIC ANALYSIS

Generally, structural dynamic system can be mathematically written in a motion equation as shown in Eq. (3).

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{Q\} \qquad (3)$$

Where $[M]$ is the mass matrix; $[C]$ is the damping coefficient matrix; $[K]$ is the structural stiffness matrix; $\{U\}$, $\{\dot{U}\}$, $\{\ddot{U}\}$ are the displacement, velocity, and acceleration vectors, respectively; $\{Q\}$ is the external loading vector.

Eq. (3) can be modified when dampers are installed in this nonlinearly motion equation as shown following:

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K(U)]\{U\}=\{Q\}-F_D(\dot{U}) \tag{4}$$

Where F_D stands for the damping force as dampers are excited.

Eq. (4) reveals that structural stiffness is not a constant. It is a function of displacement. To find the solution of Eq. (4), software package ANAYS Workbench is used by means of Transient Dynamic Analysis. Newmark method and modified HHT method proposed by Hilber etc. (1977) are the built-in solving method in the package.

2.1 Rayleigh damping

Retleigh damping is adopted. Damping coefficient $[C]$ is assumed to be function of mass matrix, $[M]$, and structural stiffness matrix, $[K]$, with the relation assumed in Eq. (5) by two of the parameters, α_R and β_R.

$$[C]=\alpha_R[M]+\beta_R[K] \tag{5}$$

Orthogonal transformation is then applied to transfer an n-d.o.f. motion equation into non-coupled linear equations. That is, the motion equation as shown in Eq. (6) can be transformed into Eq. (7).

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=\{Q\} \tag{6}$$

$$\{\phi\}^T[M]\{\phi\}\{\ddot{\xi}\}+\{\phi\}^T[C]\{\phi\}\{\dot{\xi}\}+\{\phi\}^T[K]\{\phi\}\{\xi\}=\{\phi\}^T\{Q\} \tag{7}$$

The non-coupled linear equation can be derived as shown in Eq. (8).

$$\{\ddot{\xi}_j\}+2\zeta_j\omega_j\{\dot{\xi}_j\}+\omega_j^2\{\xi_j\}=\{Q_j\} \tag{8}$$

Where $\{\xi\}$ is the displacement orthogonally transformed; $\{\zeta\}$ is the uncoupled damping ratio; $\{\omega\}$ is the system frequency; $\{\phi\}$ is the orthogonal eigenvector.

And, the term which damping stands becomes

$$\{\phi\}^T[C]\{\phi\}=\begin{bmatrix} \alpha_R+\beta_R\omega_1^2 & 0 & . & 0 \\ 0 & \alpha_R+\beta_R\omega_2^2 & . & 0 \\ . & . & . & . \\ 0 & . & . & \alpha_R+\beta_R\omega_n^2 \end{bmatrix} \tag{9}$$

By expanding Eq. (8) and Eq. (9), we obtain,

$$2\zeta_n\omega_n=\alpha_R+\beta_R\omega_n^2 \tag{10}$$

Substitute frequencies, obtained by model analysis, into Eq. (10), parameters α_R and β_R can be obtained. System model damping ratio is assumed to be 2% in the examples.

2.2 Damping ratio estimated by motion of free vibration

Motion equation for free vibration of a single d.o.f. system can be written as following,

$$m\ddot{u} + c\dot{u} + ku = f(t) \tag{11}$$

m , c , k , and $f(t)$ stand for mass, spring stiffness, damping ratio, and external loading function, respectively.

In case of damping coefficient is smaller than critical damping coefficient, the general solution of Eq. (11) can be written in the following function:

$$u = Ae^{-\zeta\omega t}\sin(\omega_d t + B) \tag{12}$$

$$\omega_d = \omega\sqrt{1-\zeta^2} \tag{13}$$

$$\zeta = \frac{C}{C_c} \tag{14}$$

$$C_c = 2m\omega \tag{15}$$

Where, *A* and *B* are real numbers; ω_d , C_c , and ζ stand for the damping frequency, critical damping coefficient, and damping ratio, respectively.

The ratio of adjacent peak displacement value of Eq. (12) gives us displacement ratio, R , written in Eq. (16).

$$R = \frac{u_{peak1}}{u_{peak2}} = \frac{u(t)}{u(t+T_D)} = e^{\zeta\omega_n T_D} = e^{\frac{2\pi\zeta}{\sqrt{1-\zeta^2}}} \tag{16}$$

Eq. (16) is rearranged to obtain damping ratio as shown in Eq. (17).

$$\zeta = \sqrt{\frac{(ln R)}{ln R - 4\pi^2}} \tag{17}$$

Eq. (17) is used to estimate the structural damping ratio, and the change of damping ratio of the controlled structures can be estimated as dampers are installed on the structures.

2.3 Application of Newton-Raphson method

Linearly approximated Newton-Raphson method proposed by Chopra (1995) is applied in ANSYS package. Displacement vector $\{u\}$ is obtained iteratively with time steps. Tangent stiffness $[K]$ is used to solve displacement difference $\{\Delta u\}$ in-between steps through Eq. (18) as following:

$$[K]\{\Delta u\} = \{\Delta F\} \tag{18}$$

As illustrated in Fig. 1, incremental $\{\Delta u\}$ is added to $\{u_0\}$ to get $\{u_1\}$, and then $\{u_1\}$ is substituted into structural stiffness equation, Eq. (19), to obtain $\{P_1\}$ and $\{F_1\}$.

$$[K(u_1)]\{u_1\} = \{F_1\} \tag{19}$$

Where P_1' is the intersection of ($u_1, F_0 + \Delta F$). The difference of the external force ($u_1, F_0 + \Delta F$) and the internal force (u_1, F_1) is nothing but the step residual force, it is

$$F_1^R = \{F_0 + \Delta F\} - \{F_1\} \tag{20}$$

Step residual force is obtained iteratively until F_1^R reaches the pre-assigned criterion.

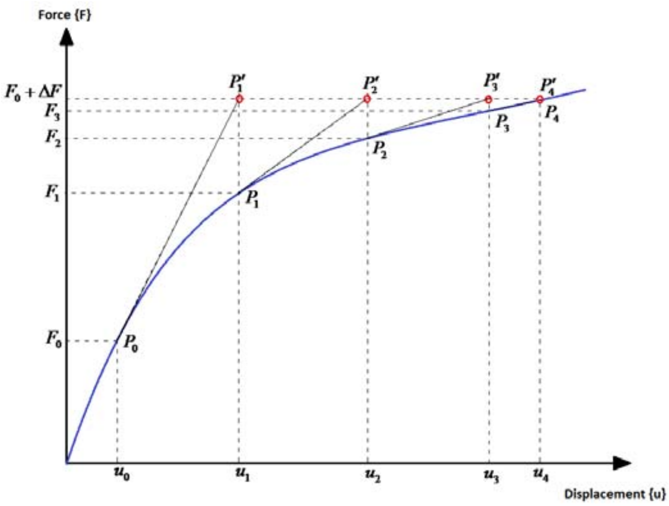

Fig. 1 Newton-Raphson iteration

3. EXAMPLE DESCRIPTIONS

A 3-storys single bay steel structure subjected to 0.5 and 0.884 1940 El-Centro earthquake is selected as the structure to be analyzed and to be controlled. The reason of 0.884 El-Centro earthquake is selected is because the raw structure collapsed at this excitation. Dampers with C=10,000 N-s/m are used as the energy dissipation devices. Six dampers are installed in the structure by different installations as shown in Fig. 2, and listed in Table 1. Different installations are indicated as case0 (raw structure, without control) and case1, case2, case3, case4, case5, respectively. Frame dimensions are 5m for column to column distances; 3m for story height. Yielding stress and ultimate stress of steel material are assumed to be 250MPa and 460MPa. Stress-strain relationship is assumed as shown in Fig. 3. Wide flange cross section as shown in Fig. 4 is adopted for the columns and beams in the example. Floor thickness is assumed to be 0.05m. Acceleration of 1940 El-Centro earthquake as shown in Fig. 5 is applied as the excitation to the structures. As finite element analysis is executed, line body elements are used for columns and beams, while surface body elements are used for floors.

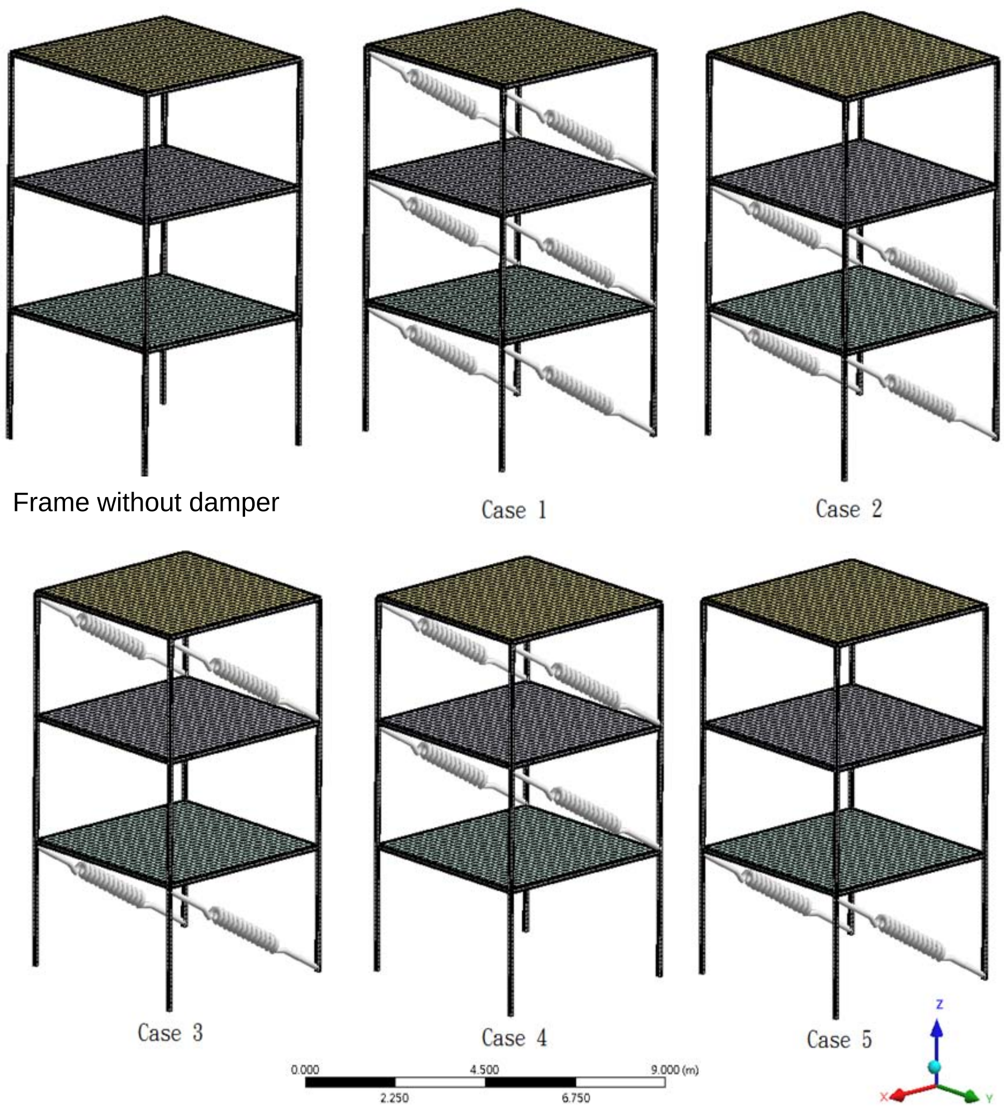

Fig. 2 Structures analyzed in the example

Table 1 Damper installation cases

Number of dampers / Floor / Cases	1st	2nd	3rd
Frame without damper	0	0	0
Case 1	2	2	2
Case 2	4	2	0
Case 3	4	0	2
Case 4	0	4	2
Case 5	6	0	0

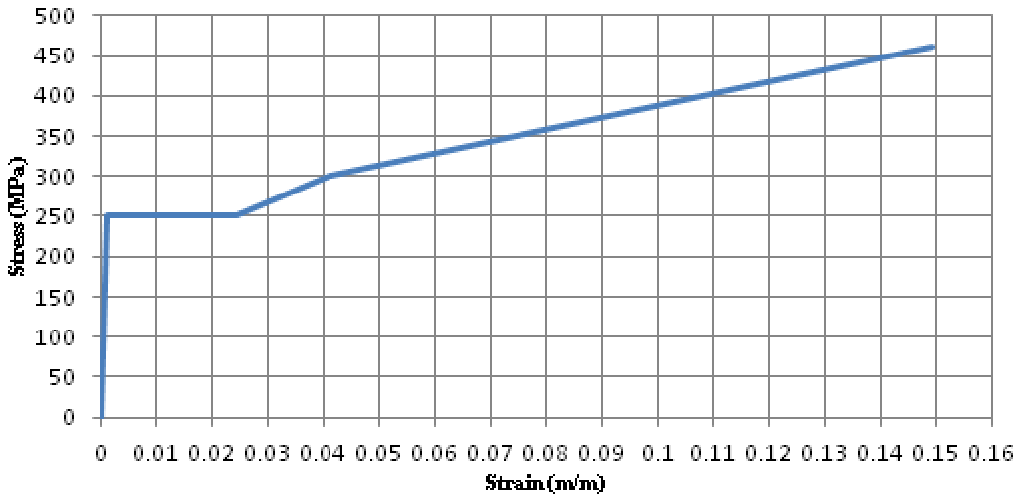

Fig. 3 Material stress-strain relationship

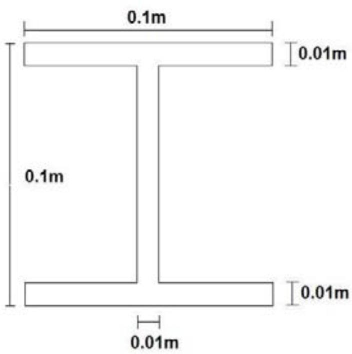

Fig. 4 Wide flange cross section adopted

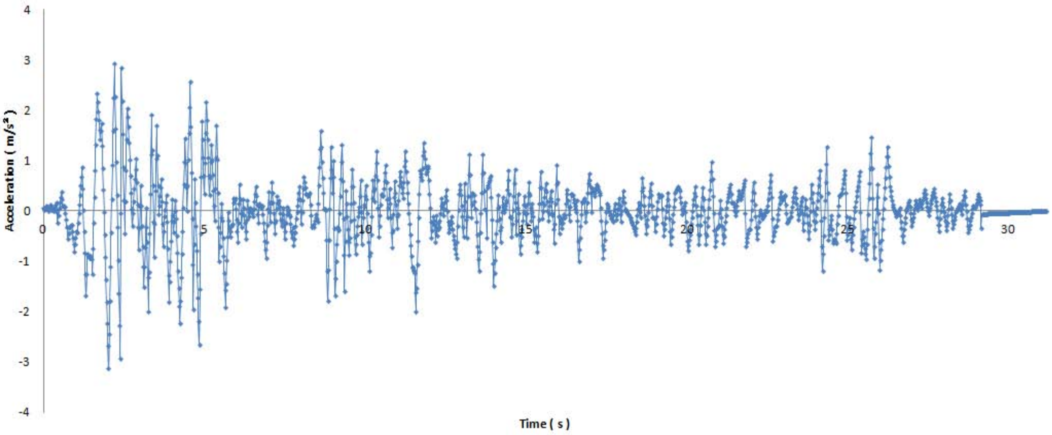

Fig. 5 1940 El Centro earthquake

4. EXAMPLE RESULTS

4.1 Control efficiency

Efficiency of control (*EOC*) is defined in Eq. (21) as following:

$$EOC = \frac{NC - WC}{NC} \times 100\% \quad (21)$$

Where, *NC* is the responses of raw structure (non-control); *WC* is the responses of controlled structures with dampers installed.

The shadowed blocks in the following tables of control efficiency indicates the best installation case which gives the best control efficiency.

4.2 Energy relate to control capacity

Amount of energy (strain energy and kinetic energy) of the structures analyzed can be obtained as an output value by ANSYS Workbench package. No matter whether the structural material responds beyond yielded or not, different installation of damper leads different responses of the controlled structures. Total energy from the Workbench output, control efficiency can also be estimated. Smaller amount of the total energy imply the better of the control result.

4.3 System damping ratio

By means of free vibration of the controlled cases with the material maintained totally elastically, system damping ratio can be estimated through Eq. (17). The system damping ratio for the without controlled raw structure is ζ_0 = 0.02076, while the system damping ratio of the five controlled frames with different installation of dampers are ζ_1 = 0.067586, ζ_2 = 0.08324, ζ_3 = 0.06799, ζ_4 = 0.06726, and ζ_5 = 0.08261, respectively. It shows the system damping ratios increased greatly for all of the control cases.

4.4 Control results --- 0.5 El-Centro earthquake applied

Control efficiency in terms of system maximum stress is listed in Table 2.

Table 2 Control efficiency in terms of system maximum stress

Responses	Maximum stress (MPa)						Control efficiency (%)				
	Frame without damper	Case 1	Case 2	Case 3	Case 4	Case 5	Case 1	Case 2	Case 3	Case 4	Case 5
Compressive stress	399.03	367.73	349.18	355.33	381.73	337.69	7.84	12.49	10.95	4.34	15.37
Tensile stress	338.41	302.96	285.39	290.34	317.17	273.64	10.48	15.67	14.20	6.28	19.14

Responses including maximum displacement, maximum velocity, maximum acceleration, maximum floor relative displacement, maximum floor relative velocity, and maximum floor relative acceleration are displayed in Fig. 6 to Fig. 11, respectively.

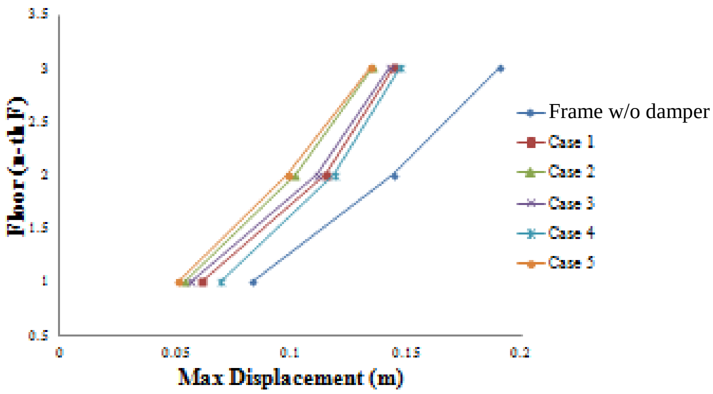

Fig. 6 Maximum displacement --- 0.5 El-Centro earthquake

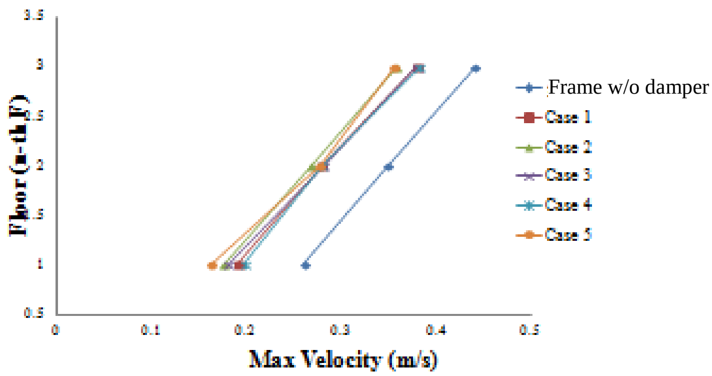

Fig. 7 Maximum velocity--- 0.5 El-Centro earthquake

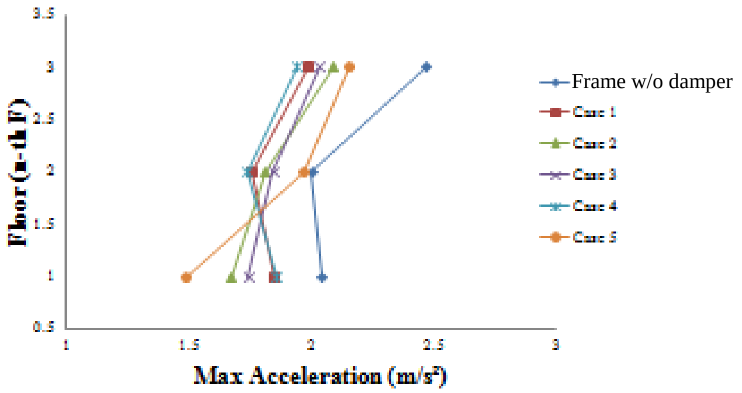

Fig. 8 Maximum acceleration--- 0.5 El-Centro earthquake

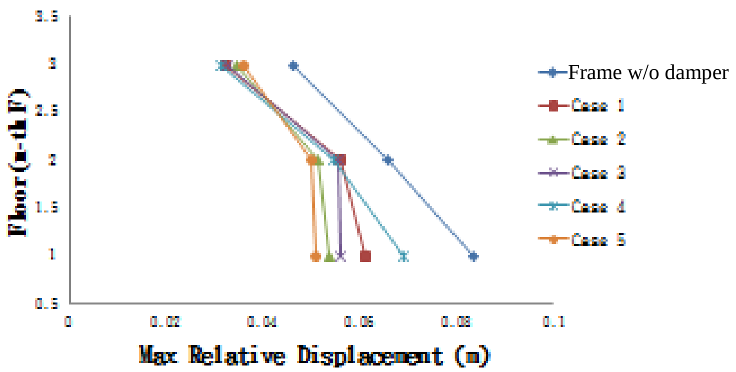

Fig. 9 Maximum relative displacement --- 0.5 El-Centro earthquake

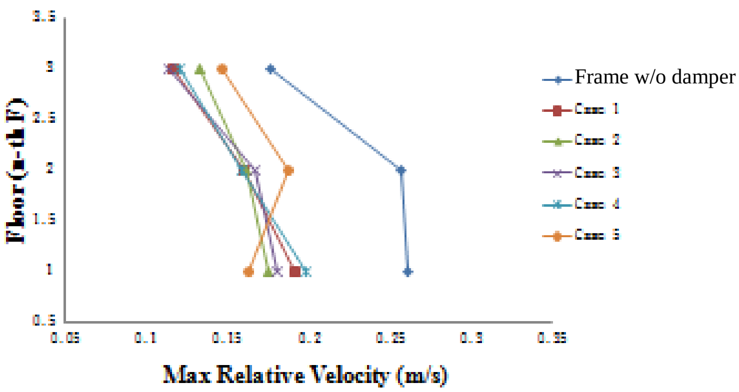

Fig. 10 Maximum relative velocity--- 0.5 El-Centro earthquake

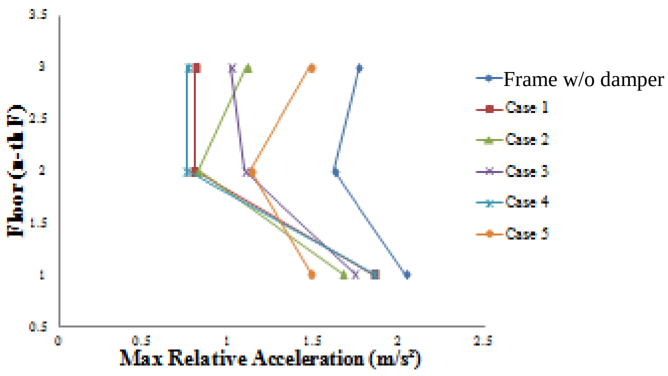

Fig. 11 Maximum relative acceleration--- 0.5 El-Centro earthquake

Time history of energy dissipation for each of the controlled cases is plotted in Fig. 12.

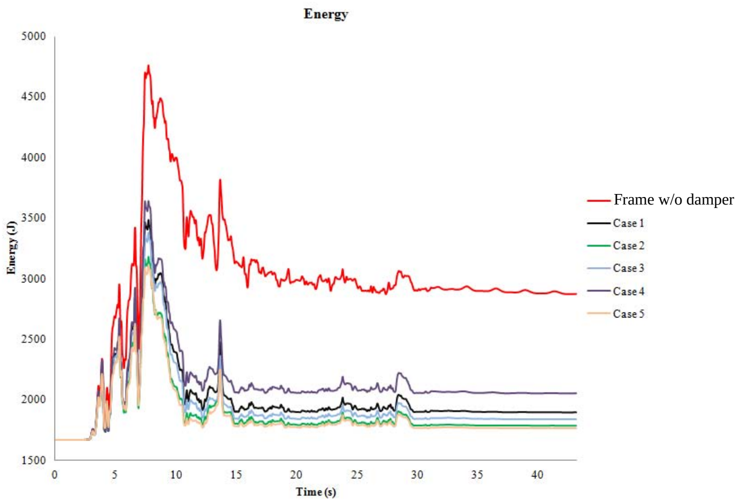

Fig. 12 Time history of energy dissipation --- 0.5 El-Centro earthquake

4.5 Control results --- 0.884 El-Centro earthquake applied

The value of NC in Eq. 21 is the collapse displacement for the raw structure when 0.884 El-Centro earthquake applied. Control efficiency in terms of system maximum stress is listed in Table 3.

Responses including maximum displacement, maximum velocity, maximum acceleration, maximum floor relative displacement, maximum floor relative velocity, and maximum floor relative acceleration are displayed in Fig. 13 to Fig. 18, respectively.

Time history of energy dissipation for each of the controlled cases is plotted in Fig. 19.

Table 3. Control efficiency in terms of system maximum stress

Responses	Maximum stress (MPa)						Control efficiency (%)				
	Frame without damper	Case 1	Case 2	Case 3	Case 4	Case 5	Case 1	Case 2	Case 3	Case 4	Case 5
Compressive stress	445.45	411.60	406.65	405.66	415.25	404.75	7.60	8.71	8.93	6.78	9.14
Tensile stress	400.41	356.01	350.46	349.58	360.99	345.97	11.09	12.47	12.69	9.84	13.60

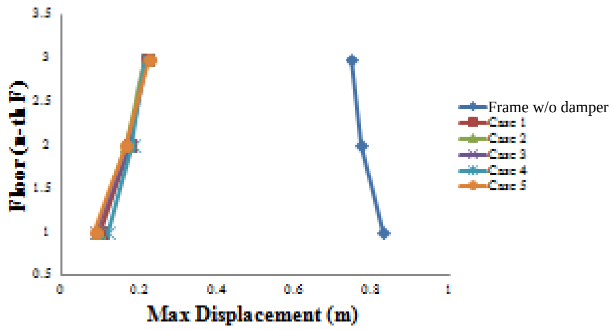

Fig. 13 Maximum displacement --- 0.884 El-Centro earthquake

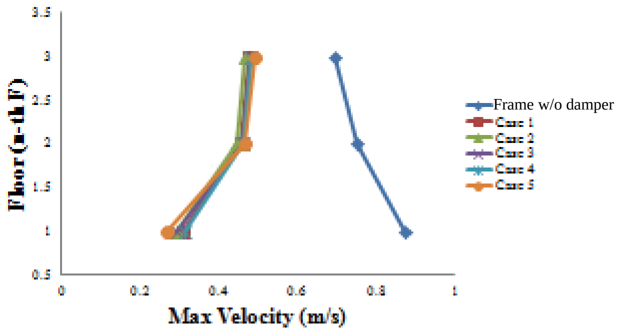

Fig. 14 Maximum velocity--- 0.884 El-Centro earthquake

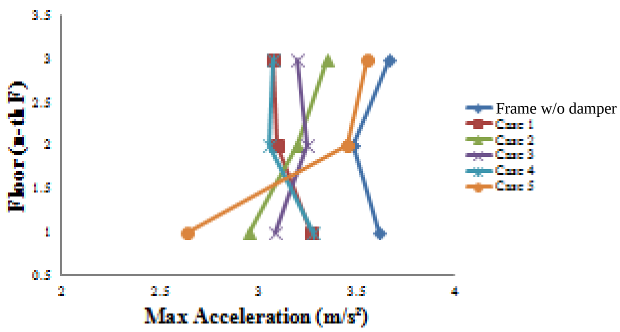

Fig. 15 Maximum acceleration--- 0.884 El-Centro earthquake

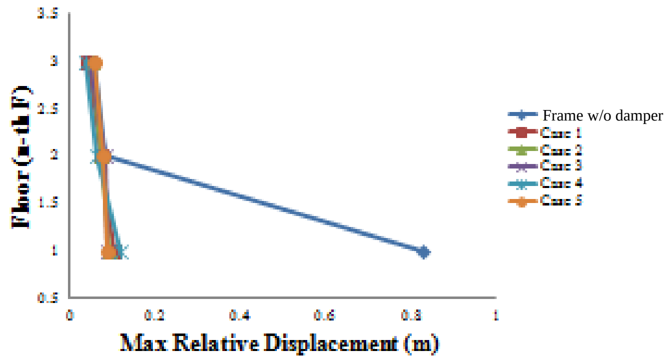

Fig. 16 Maximum relative displacement --- 0.884 El-Centro earthquake

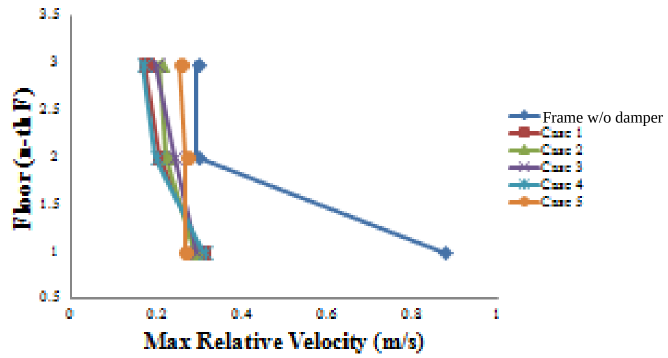

Fig. 17 Maximum relative velocity--- 0.884 El-Centro earthquake

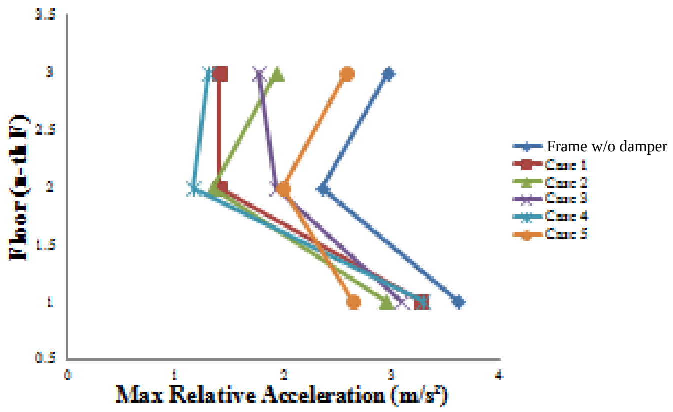

Fig. 18 Maximum relative acceleration--- 0.884 El-Centro earthquake

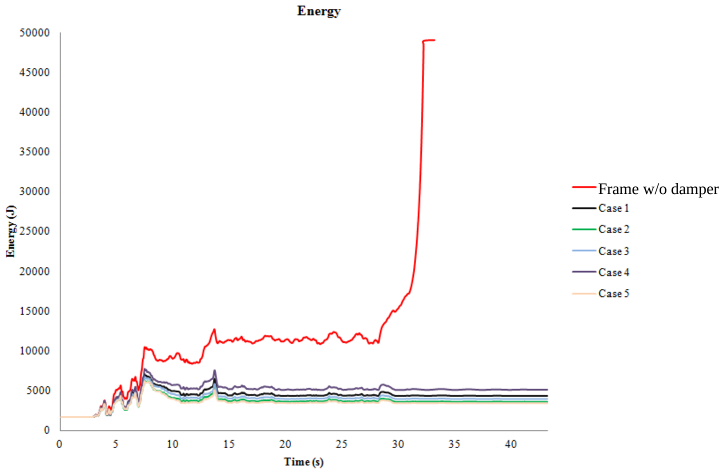

Fig. 19 Time history of energy dissipation --- 0.884 El-Centro earthquake

5. CONCLUSIONS

Nonlinearly responded controlled structure is analyzed. Nonlinear phenomenon cause by material responded beyond yield and viscous dampers induced control affects. By means of ANSYS Workbench package, the controlled structures are analyzed by finite element method.

Control efficiency can be estimated not only from the responses such as displacement, velocity, acceleration,…, etc. of the controlled structures, but also can be estimated from the combined stresses at the critical points of the structure, or even from the energy aspect. The smaller the total energy (strain energy and kinetic energy) displayed, the higher control efficiency obtained.

According to the total energy displayed by the different control cases in the example herein, both of 0.5 and 0.884 El-Centro earthquake applied, the total energy displayed can be listed orderly as case 0 ＞ case 4 ＞ case 1 ＞ case 3 ＞ case 2 ＞ case 5. And this order is same as maximum combined stress is considered when the controlled structures subjected to 0.5 El-Centro earthquake. While, it gives another order, case 0 ＞ case 4 ＞ case 1 ＞ case 2 ＞ case 3 ＞ case 5, when 0.884 El-Centro earthquake is applied as maximum combined stress is concerned.

Most of the damper installed control cases show the practical positive control results. A typical example taken from case 2 is given in Fig. 20, the time history of displacement at the third floor with respect to ground. A collapsed raw structure is controlled safely as we expected. Some of the marked points, Δ, ∗, x, +, etc., indicated the first yield and the maximum displacement point in the raw structure, and in the controlled case. Obviously, the maximum displacement instant in the raw structure means the collapse occurrence of the structure.

Analysis of the raw structure shows the maximum floor relative responses occurred at first story. The following analysis shows the system responses improved a lot when the dampers are installed at first story. But, still, our suggestion is, the locations of the damper installation are necessary to be decided case by case with precise analysis. A three story single bay steel frame with certain dimension is selected as the analyzed structure in the example. The conclusions could not be applied directly to high-rise buildings. Some of the general impression of installing the damper at the lowest or lower stories could not be always true.

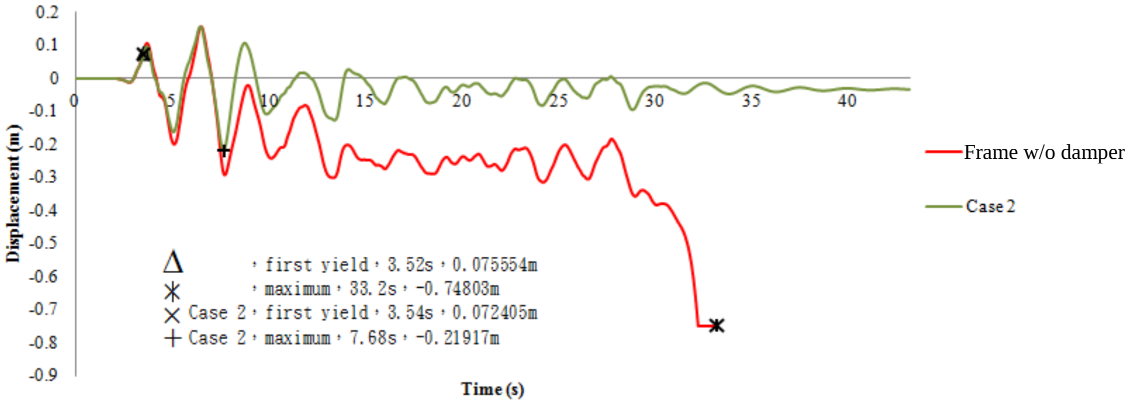

Fig. 20 Displacement of the 3rd floor to ground, control case 2
--- 0.884 El-Centro earthquake

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