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Coupled Truss Walls with Damped Link Elements*

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ABSTRACT

A new structural concept is proposed for the seismic design of tall buildings. The system combines the inherent stiffness and strength of the conventional truss system with the energy absorption characteristic of supplemental damping elements. The damping elements are strategically placed and configured to form the linking elements of a coupled vertical truss system. While the force resistance system of the truss wall is in parallel, the damped link beam is in series with the component of the truss stiffness contributed to the coupled wall action. The mechanics of the behavior of the proposed concept is explained. A series of time history dynamic studies are performed to gauge the performance of the proposed concept in comparison with the conventional damping arrangement. The result of the study indicates that the proposed damped link concept provides superior performance in comparison to the conventional approach.

KEYWORDS

Seismic Design, High-rise, Low-rise Structure, Energy Absorption Device, Damper, Optimization

INTRODUCTION

Damping elements have been proven to be an effective method to absorb a significant portion of the seismic energy transmitted through the building and, as a result, minimizing the stress and strain of the structural members participating in resisting the seismic motion. While various methods of dampening of a structure have been under extensive studies, their optimum locations and configurations were not exposed to the same level of scrutiny. This paper presents a new approach for a better utilization of supplemental damping elements within a structural system.

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* US Patent 6,397,528 B1

The fundamental concept lay within the notion of how to tap into the stored potential energy of a structure. This is achieved by attempting to maximize the relative velocity of the end nodes of a damper for a given inter-story velocity and sway. This is a function of geometry of the structure, position of the damper and the concept of the damper-structure interaction. This paper explores the interaction and correlation of the structure’s nodal degrees of freedom along the axis of the damper’s action.

The following describes two different approaches of utilizing a damper in a structure. The first approach is the current conventional method of placing the damper, and the second approach is the proposed method presented in this paper to increase the efficiency of the dampers. First, the difference between the two systems is explained. Then, the result of dynamic studies is presented. Dynamic studies are performed, using a sub-assemblage model, including damper elements, in order to assess the effectiveness of the dampers for the conventional as well as the proposed system. Observing the steady state response history of the systems under impulse loading revealed the level of effectiveness of the dampers as a percentage of the critical damping. The efficiency of the two methods is studied and compared using a series of parametric studies. While the finding of this paper would apply equally to viscous and friction dampers, the specific examples are related to viscous dampers.

Conventional Damper Bracing System

In this approach, dampers are placed within a panel formed by two columns and two intersecting horizontal beams and they are generally stacked vertically, see Fig.1. The arrangement of the damper could take many different forms; however, their fundamental behaviors are similar. The energy absorbed by a viscous damper is a function of its relative velocity and its viscous properties. The damper relative velocity is also a function of the relative movement and interaction of degrees of freedom of the panel nodes immediately surrounding the damper

Fig. 2 represents the structural model for a one-story module of a structure utilizing conventional arrangement of damper system. Dampers are placed in the bay –I. Bay –II represents the stiffness associated with a structural system based on a frame, truss or a wall system. Fig. 3 shows the typical sway mode of the system under the external lateral excitation.

In order to simulate the effect of the axial flexibility of columns supporting the module at a level above the ground, vertical springs are placed at the support of the columns. The lateral inter-story sway and velocity Ux and U’x are composed of two components. One is based on the equivalent shear deformation (local bending and shear deformation of frames and axial deformation of diagonals), and the other is the rocking component of deformation (rotation created by the axial deformation of columns).

$$Ux = Uax + Uvx \tag{1}$$

$$U'x = U'ax + U'vx \tag{2}$$

Only Uvx and U’vx contribute to the velocity and displacement of the dampers on Fig.2. Thus, damper forces are directly a function of Uvx for viscous dampers and U’vx for friction dampers. Uvx and U’vx may be obtained as follows:

$$Uvx = Ux - Uax \tag{3}$$

$$U'vx = U'x - U'ax \tag{4}$$

The effectiveness of the damper is directly related to U'vx and Uvx. As the contribution of U'ax and Uax increases for a constant Ux and U'x, the value of U'vx and Uvx reduces. This effect is more pronounced at the upper level of a high rise building where the axial deformation is at its maximum. Thus, the effectiveness of the dampers is reduced at the upper levels of a high-rise building for a constant inter-story sway of the building.

The relationships above could also be explained by considering the angular rotation and velocity of α, α_a , α_v , and β as shown in Fig.3. The damper force and absorbed energy are functions of the degree of distortion of the panel as shown in Fig.3. The panel distortion could be measured by the internal angle β or by its distortion angle from the angle of rest position, α_v . From Fig.3, the following relationship could be obtained:

$$\alpha_v + \beta = 90^o \qquad (5)$$

$$\alpha_v = \alpha - \alpha_a \qquad (6)$$

The following describes the system's energy under an external dynamic load F(t):

$$Ei = \int F(t)\, du = \int F(t)\, u'\, dt \qquad (7)$$

$$Ed = \int Fd\,(t)\, du = \int Fd(t)\, u'\, dt, \qquad (8)$$

where $Fd(t) = C\, u'$ and, $u' = f(\, U'vx)$

$$Es = \int fs\, du = \int fs\, u'\, dt = \int K\, u\, u' dt \qquad (9)$$

$$Ek = \int fi\, du = \int mu''\, u'\, dt \qquad (10)$$

$$Ei = Ed + Es + Ek \qquad (11)$$

Proposed Coupled Truss Wall with Damped Link Element System

This system attempts to improve the effectiveness of the dampers by increasing the dampers differential velocity for a given inter-story sway and velocity. This is accomplished by reversing the direction of the axial velocity of the columns adjacent to the dampers. This increases the net differential velocity of the damper. This could be physically achieved by modifying the placement of the dampers by placing them between two lateral systems comprised of truss system, frame system or wall system, or any combination of them (see Fig. 5). The dampers in effect become link damped beams or elements connecting the two structural "truss/wall" systems. The term "truss/wall" is meant to emphasize that the elements must independently have relatively significant structural resistance to lateral force.

Typically the damper velocity and energy absorption are functions of the inter-story lateral movement and velocity of the structure. However, in this system there is also an additional significant contribution from vertical velocity generated by the differential axial shortening of the columns located at the ends of the damped linked beam.

Dampers could be placed in a variety of configurations along the height of the building between the two lateral panels. The concept of tapping on the potential energy of the column’s axial deformation remains paramount to the success of this system.

The following explains the basic mechanics of this concept. Fig.6 shows a typical module demonstrating the essential behavior of the system. It is clear from the superposition of the nodal displacement that:

$$Ux = Uvx - Uax \quad (12)$$

$$U'x = U'vx - U'ax \quad (13)$$

Therefore,

$$Uvx = Ux + Uax \quad (14)$$

$$U'vx = U'x + U'ax \quad (15)$$

The relationships above could also be explained by considering the angular rotation and velocity of α, α_a , α_v , and β as shown in Fig.5. The damper force and absorbed energy are functions of the degree of distortion of the panel as shown in Fig.3. The panel distortion could be measured by the internal angle β or by its distortion angle from rest angle, α_v . From Fig.3, the following relationship could be obtained:

$$\alpha_v + \beta = 90^o \quad (16)$$

$$\alpha_v = \alpha + \alpha_a \quad (17)$$

The fundamental difference between this proposed concept and the conventional approach is demonstrated by equations 4 and 15 in lateral sway terms; as well as equations 6 and 17 in angular rotation terms. U’ax reduces the U’vx and the damper velocity in conventional systems for a given U’x. This is due to creation of rigid body rotation of the damper panel in the direction of U’x movement, see Fig.3. However, in the proposed damping configuration, U’ax increases the U’vx and the damper velocity for a given U’x. This is due to creation of rigid body rotation of the damper panel in the opposite direction of U’x movement, see Fig.6.

The various energies of the system to an external excitation follow equations 7 through 11 considering velocity and panel distortion relationship derived in equation 12 to 17.

Dynamic Analysis using Damping Elements: One Story Module

A series of computer models were created to study the effective damping values for both systems as described above. Fig. 8 & 11 show computer generated models for both systems. Dampers were modeled explicitly using SAP2000 structural analysis program. The effective damping value as percentage of critical damping was obtained by measuring the decay rate of the transient time history response to impulse loading. The sensitivity of the damper system to the vertical spring supports was obtained by performing a sensitivity study for the range of spring support as shown in Table-1. Fig. 9 & 12 show the deflected shape of model #B4M (for the conventional system) and model #A4M (for the coupled truss wall system) respectively. Fig 10 & 13 show the time history of displacement response for models B4M & A4M respectively.

Fig. 14 and 15 show the effective damping ratio (as percentage of critical damping) as a function of support's spring constant for both coupled truss walls with damped element system and conventional damped system. The damping values are also shown for a normalized frequency value of 1 Hz as shown in Table-2. This is only for a better comparison of the effective damping values for a constant frequency and stiffness.

For a conventional damping system, the effective damping ratio reduces as the spring constant reduces. This means that the same damping unit at the upper floors of a building exhibits a lower efficiency under similar inter-story sway and velocity conditions. This behavior is clearly shown in Fig 15, which illustrates the effective damping ratio as a function of support spring constant.

However, for the proposed coupled truss wall system with damped link element system, the effective damping ratio increases as the spring constant reduces. This means that the same damping unit at the upper floors of a building exhibit higher efficiency under similar inter-story sway and velocity conditions. This behavior is also shown in Fig 15, which demonstrates the effective damping ratio as a function of support spring constant.

The proposed concept of coupled truss wall system with damped link elements allows one to tap into the potential energy of the columns and convert them into damping energy. This would result in further reduction of member stresses and strains as well as acceleration and sway of the building.

Dynamic Analysis using Damping Elements: Multi-Story System

Three structures of 10, 20, and 40 stories high are studied using the concept explained above. Each structure is studied twice, once using conventional arrangement of dampers and second using the proposed arrangement. Figures 16a, b, c and 17a, b, c, show the computer models used in this study. Damper properties are identical to table-1. In addition to the truss system which is modeled explicitly a shear stick element is model the balance of stiffness provided by moment frame or additional truss systems. In order to compare the dynamic behavior of the structures, each model is exposed to an impulse loading at the roof level. A time history analysis is performed for each case. The response displacement time history is plotted in Figures 17a, b, c and 18a, b, c. Table-3 summarizes the effective damping for the first modes for each case. It is clear that the proposed damper arrangement significantly improves the response of the system by optimizing the effective damping of the system. This concept utilizes the damper similar to a link beam in a shear wall or coupled truss system. This eliminates the need for providing the dampers at every level as called for by recent SEAOC provisions for structural design with energy absorption system. The system in figure 17a is also studied by eliminating every other damper as shown in figure 20. The time history result shows that by using even half of dampers in comparison to conventional arrangement the effective damping is 100% higher. This concept demonstrates that a few strong dampers placed strategically in the structure could also provide an efficient seismic design for the structure.

TABLE- 1

TEST #	DESCRIPTION	Ky (K/IN)	WT (K)	COL SIZE	DIAGONAL	DAMPER-C	DAMPER-K

			KIP			K/FT/SEC	K/FT
A4M	COUPLED DAMPED TRUSS	1000	24000	W14X500	W14X61	600	100000
A5M	COUPLED DAMPED TRUSS	10000	24000	W14X500	W14X61	600	100000
A6M	COUPLED DAMPED TRUSS	100000	24000	W14X500	W14X61	600	100000
A7M	COUPLED DAMPED TRUSS	1000000	24000	W14X500	W14X61	600	100000
B4M	CONVENTIONAL DAMPED SYSTEM	1000	24000	W14X500	W14X61	600	100000
B5M	CONVENTIONAL DAMPED SYSTEM	10000	24000	W14X500	W14X61	600	100000
B6M	CONVENTIONAL DAMPED SYSTEM	100000	24000	W14X500	W14X61	600	100000
B7M	CONVENTIONAL DAMPED SYSTEM	1000000	24000	W14X500	W14X61	600	100000

TABLE- 2

				FREQ. NORM.			NORMALIZED
TEST #	DESCRIPTION	Ky (K/IN)	DAMPING	DAMPING	PERIOD	FREQ.	FREQ.
			%CR	%CR	SEC.	HZ	HZ
A4M	COUPLED DAMPED TRUSS	1000	14	8.77	1.59	0.629	1.004
A5M	COUPLED DAMPED TRUSS	10000	5.7	5.41	1.05	0.952	1.004
A6M	COUPLED DAMPED TRUSS	100000	4.4	4.40	0.996	1.004	1.004
A7M	COUPLED DAMPED TRUSS	1000000	4	4.02	0.99	1.010	1.004
B4M	CONVENTIONAL DAMPED SYSTEM	1000	5.9	3.79	1.77	0.644	1.004
B5M	CONVENTIONAL DAMPED SYSTEM	10000	4.7	4.35	1.08	0.928	1.004
B6M	CONVENTIONAL DAMPED SYSTEM	100000	4.2	4.20	0.999	1.003	1.004
B7M	CONVENTIONAL DAMPED SYSTEM	1000000	4	4.02	0.99	1.010	1.004

TABLE- 3

# of Story	Conventional Damper Arrangement	Proposed Coupled Wall with Damped Link Element
40 Story	0.025	0.095
20 Story	0.038	0.127
10 Story	0.047	0.117

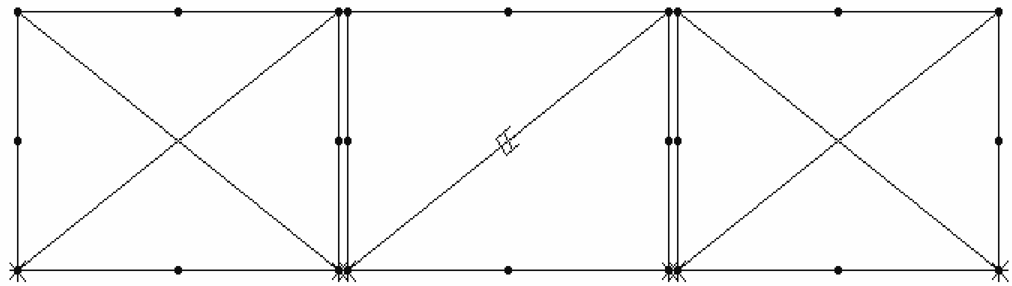

Fig. 8 Conventional Damping Arrangement, B4m

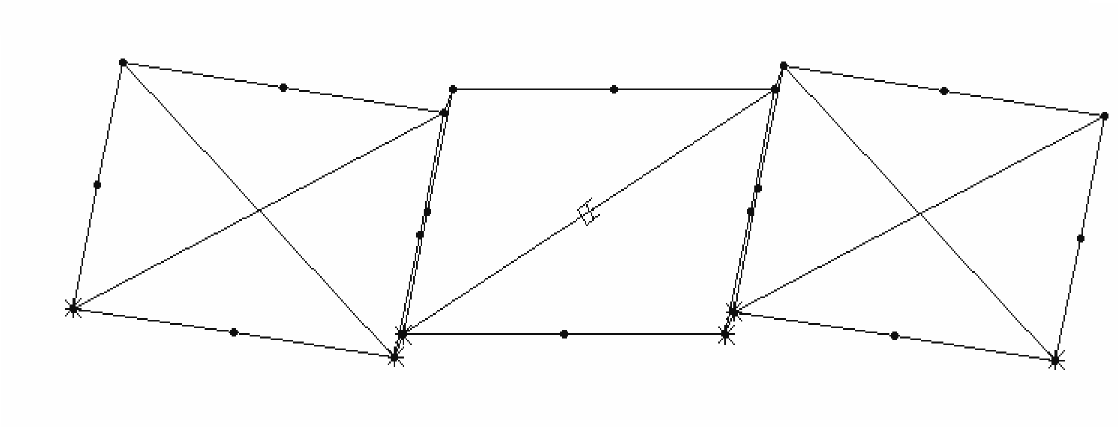

Fig. 9 Deformed Shape, B4M

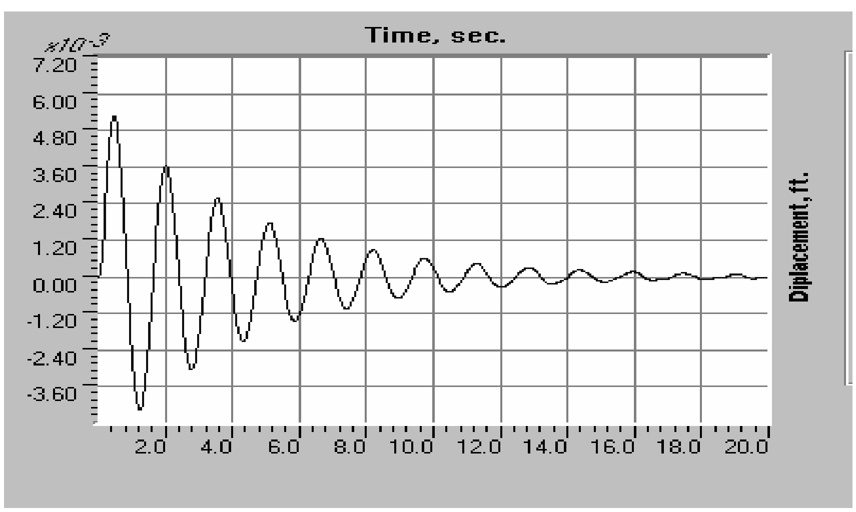

Fig. 10

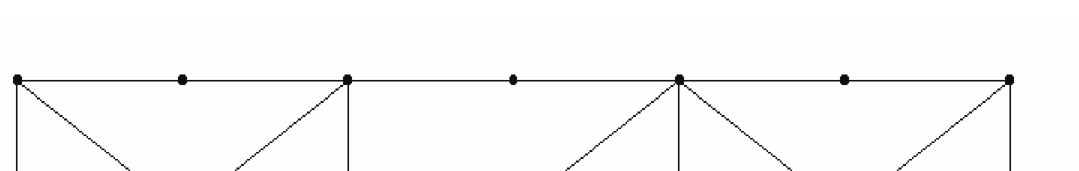

Fig. 11 Proposed Damper Arrangement

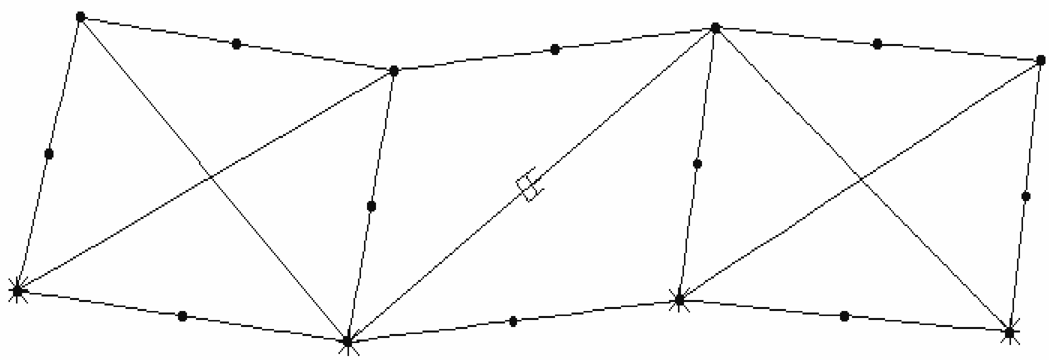

Fig.12 Deformed Shape

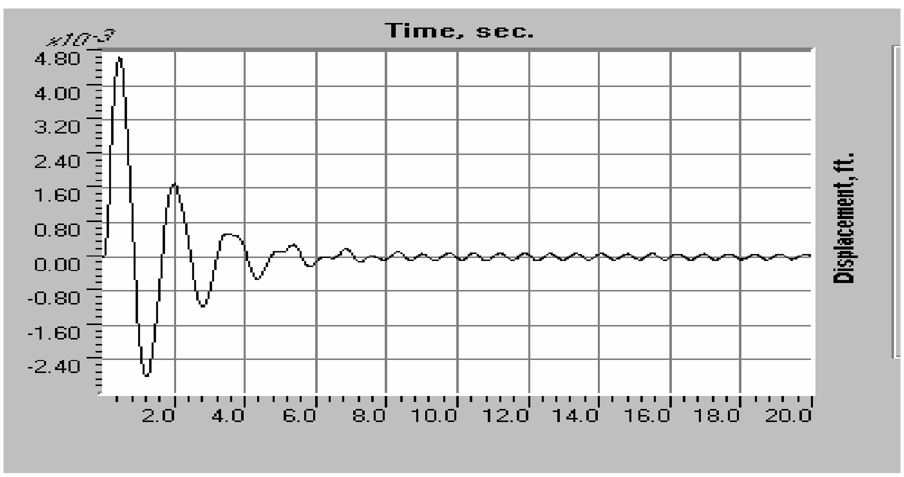

Fig.13

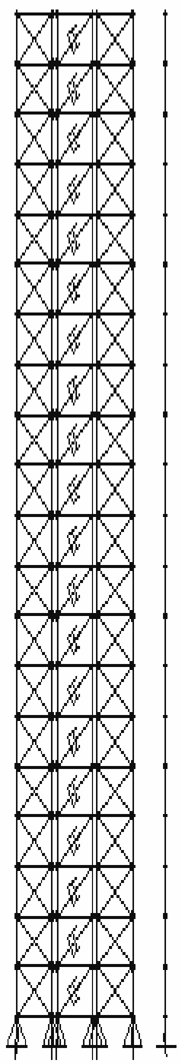

Fig.16a: BD40:
40 Story building

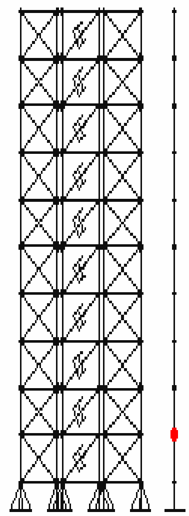

Fig.16b: BD20:
20 Story Building

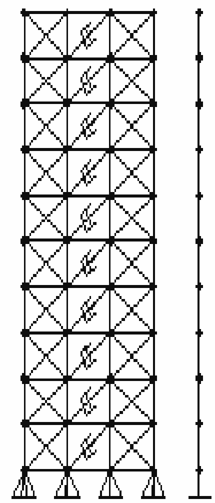

Fig17b: AD20:
20 Story Building

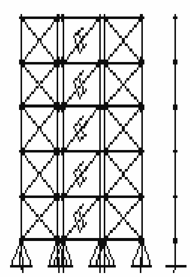

Fig.16c: BD10:
10 story Building

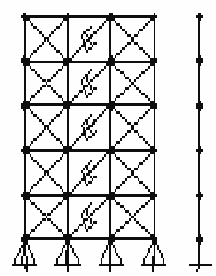

Fig.17c: AD10:
10 Story Building

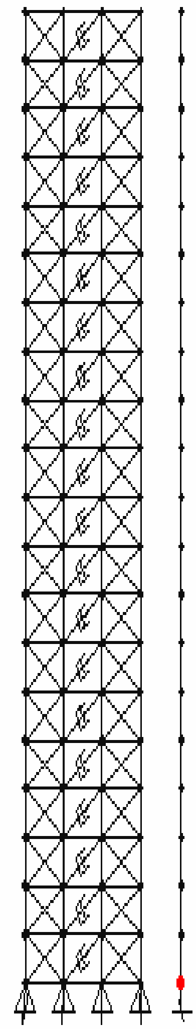

Fig.17a: AD40:
40 Story Building

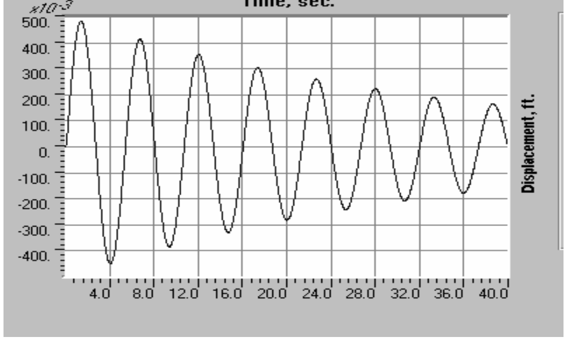

Fig.18a: BD40: 40 Story building

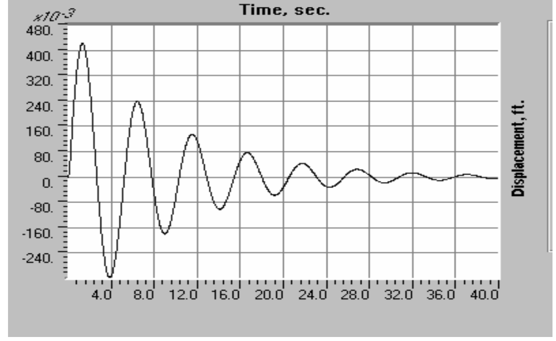

Fig.19a: AD40: 40 Story Building

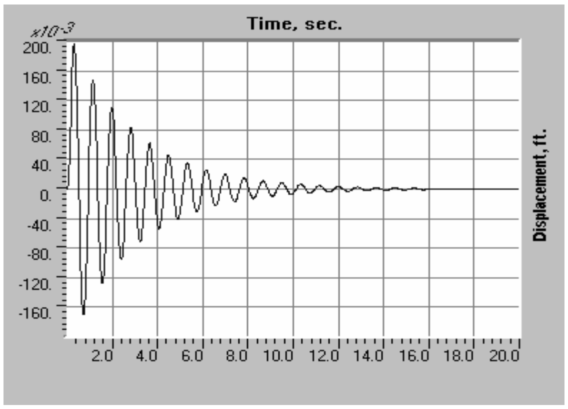

Fig.18b: BD20: 20 Story Building

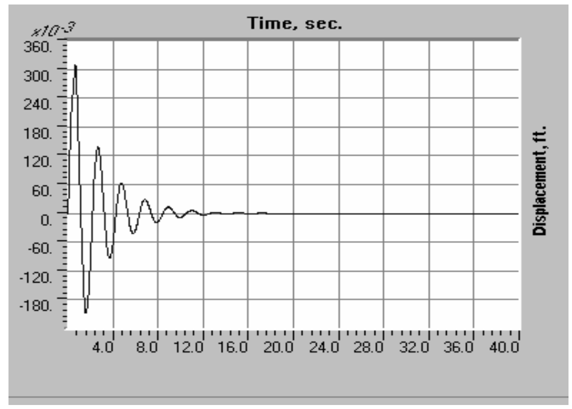

Fig.19b: AD20: 20 Story Building

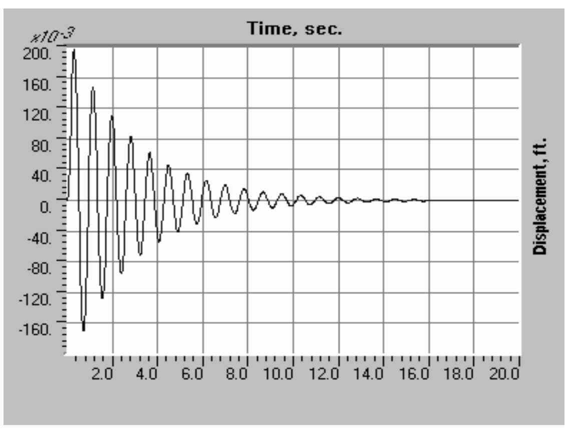

Fig.18c: BD10: 10 story Building

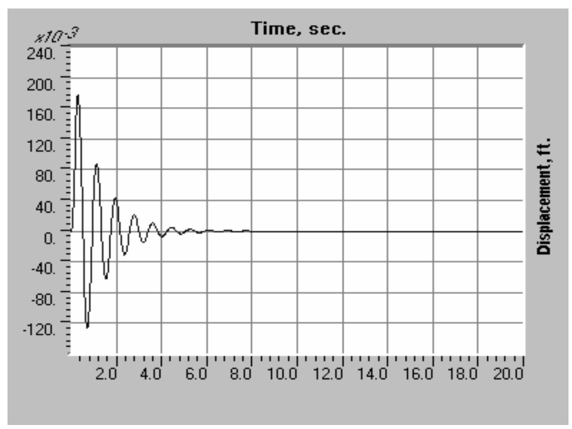

Fig.19c: AD10: 10 Story Building

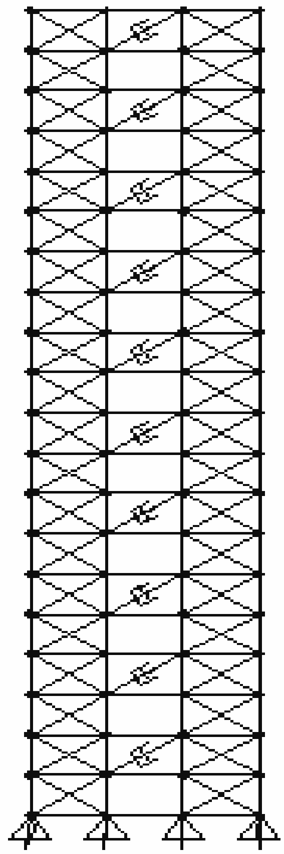

Fig. 20: Coupled Truss Wall with Damped Link Element at selected levels