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A NEW "VISCO-PLASTIC" PASSIVE ENERGY DEVICE

Finley A. CHARNEY[1] and Yasser E. IBRAHIM[2]

SUMMARY

This paper reports the preliminary results of an analytical investigation into the effectiveness of a new "Visco-Plastic" energy dissipation device. This new device, which is fabricated from readily available structural steel shapes and viscoelastic solids, has a wide range of application in building and bridge structures. For the 13th World Congress, emphasis is placed on seismic applications.

For suppression of floor and wind vibrations, and for control of vibrations associated with small to moderate seismic activity, the Visco-Plastic device acts as a viscoelastic damper. One of the special features of the device is that small axial deformations in the device are geometrically amplified, producing relatively large deformations in the viscoelastic solid material. These amplified deformations produce a uniform axial strain through the entire volume of this material, thereby maximizing the efficiency of the device. For more extreme seismic events, the steel shapes in the device may yield in combined axial force and bending. The yielding behavior is controlled by the shape of the device and by the stabilizing presence of the viscoelastic materials.

In addition to providing energy dissipation, these dampers also supply stiffness to the structural system. The added stiffness may be controlled by the shape and proportioning of the device.

INTRODUCTION

Performance Based earthquake Engineering (PBE) is based on the concept that a seismic resistant design that relies on explicit evaluation of certain performance criteria at a variety of associated hazard levels will result in more predictable behavior of structures during earthquakes, particularly when compared to designs that are based on the current prescriptive approaches. While damage may be more reliably predicted and controlled using PBE, damage still occurs. Hence, performance based engineering does not necessarily result in *improved* performance. The best way to obtain improved performance is to minimize the inelastic deformation demands on the structure itself by, for example, using seismic isolation, auxiliary energy dissipation, or a combination of the two. Of course, the ideal approach to minimizing damage is to design the seismic protective system within the context of performance based engineering.

[1] Associate Professor, Virginia Tech, Blacksburg, Virginia, USA
[2] Graduate Student, Virginia Tech, Blacksburg, Virginia, USA

Regardless of the design approach, structures survive earthquakes by absorbing, dissipating, or reflecting energy. Given this realization, there are three basic types of seismic resistant systems: *Traditional*, *Seismically Isolated*, and *Seismically Controlled*.

The *Traditional* approach is to dissipate seismic input energy through inelastic deformation of appropriately detailed regions of the structure. This method, which is embraced by current building codes, including the 2003 International Building Code, ICC [1], may also be referred to as the *Damage Based* approach because survival of the system depends on repeated yielding of primary structural components. Systems of this type include steel, concrete, or composite moment resisting frames, braced steel frames, or reinforced concrete structural walls. The main disadvantage of this approach is that damage to structural and nonstructural elements is difficult to predict, and may be severe, even under low to moderate ground motions. Excessive damage observed in many buildings during relatively moderate earthquakes, such as the 1994 Northridge, California earthquake, has led to a complete reassessment of seismic resistant design procedures (SEAOC [2], ATC [3], FEMA [4]).

The second type of system is the *Seismic Isolated* or *Base-Isolated* system (Naeim and Kelly [5]). The basic concept of this system is to support the structure on laterally soft springs which increase the period of vibration of the structure well beyond the strong components of ground motion, thereby reflecting the seismic input energy away from the structure. Structures supported on isolated systems are expected to survive large earthquakes with minimal damage to the superstructure. One disadvantage of this system is that the electrical-mechanical-plumbing systems at the base of the structure must be designed to accommodate large displacements. Dampers (or lead cores) may be used in association with the isolators for the purpose of limiting the isolation system displacements. The IBC does not have provisions for seismically isolated structures, but does make reference to ASCE 7-02 (ASCE [6]), which has such provisions.

The third type of system is the *Seismically Controlled* system, in which the structural system is augmented with mechanical devices. The devices may be actively controlled, semi-actively controlled, or passive. Active systems require a reliable external source to power computer controlled hydraulic actuators. Semi-active systems also require a power source to dynamically change the physical properties of the semi-active devices, but the power requirements are much smaller than for active systems (Symans and Constantinou [7]). Passive control systems use no external power and dissipate seismic energy through friction, metallic yielding, or viscoelasticity. Passive systems that depend primarily on friction or yielding are called displacement-dependent systems, and those that depend primarily on viscoelasticity are termed velocity-dependent systems. Several comprehensive references are available on the behavior, analysis, and design of passive systems (e.g., Constantinou et al. [8] and Hanson and Soong [9]). Current building codes do not have procedures for designing seismically controlled buildings. However, an appendix to Chapter 13 of the 2000 NEHRP Provisions (FEMA [10]) has procedures for analyzing and designing certain passive energy dissipation systems.

Displacement-dependent passive energy dissipation systems are typically configured in a manner that increases the lateral stiffness of the structure and provides energy dissipation through sliding friction or metallic yielding. Under low levels of ground motion the energy dissipation component of the devices is inactive, and the increased stiffness, acting alone, will result in lower system deformations. However, the added stiffness may lead to higher component force demands (producing premature yielding), and high story accelerations (causing damage to contents). Under larger levels of ground motion, performance is improved due to the added energy dissipation and due to the force-limiting characteristics of the device. Examples of displacement-dependent systems include a variety of friction devices (Cherry and Filiatrault [11]; Nims et al. [12]), ADAS Devices (Dargush and Soong [13]; Tsai et al. [14]) and the Unbonded Steel Brace (also known as the Buckling Restrained Brace) (Wada et al. [15]). An important advantage of many of the displacement-dependent systems is that they are made from readily available materials and may be assembled in ordinary steel fabrication plants. The visco-plastic device shares this advantage.

Among the most commonly utilized velocity-dependent systems are viscoelastic dampers (Bergman and Hanson [16]; Chang et al. [17]), and viscous fluid dampers (Symans and Constantinou [18]; Symans et al. [19]). Viscoelastic devices typically consist of a solid viscoelastic copolymer which has been bonded to steel plates. Energy is dissipated through large shear strains in the viscoelastic material. Implementation of viscoelastic dampers causes a small increase in structural stiffness due to the inherent storage stiffness of the viscoelastic material. One of the primary advantages of the viscoelastic damper, and the viscous fluid damper described below, is that it dissipates energy under all levels of ground motion. The visco-plastic device shares this advantage.

Viscous fluid dampers dissipate energy by forcing a viscous fluid through orifices which have been machined into a piston head. The piston is housed in a cylinder filled with liquid silicone or a similar type of oil. Movement of the structure during an earthquake drives the piston head through the fluid. Depending on the shape of the orifice, the force-velocity relationship of the damper may be linear or nonlinear. Another type of viscous fluid device, called a viscous damping wall, dissipates energy by dragging a plate through a "wall" which contains a viscous fluid (Reinhorn and Li [20]). Structures augmented with viscous fluid dampers typically have the same lateral stiffness as the base structure without the dampers because the devices have no inherent stiffness when excited over a certain frequency range which typically includes the fundamental frequency of the structure.

In some situations, viscous dampers or other passive energy dissipation devices are implemented into a special mechanism that amplifies the effect of the devices (Charney and McNamara [21]). Such amplification is particularly useful when the devices are used in very stiff structures, or when it is desirable to use the devices to mitigate low level excitation, such as wind induced vibration. The visco-plastic device inherently contains a displacement amplification system.

One of the main goals of designing passive dissipation energy systems is to obtain an optimum balance of added damping and stiffness. Unfortunately, it may be difficult to obtain such a balance because the damping and stiffness component of the device may not be independently controlled by the designer. The device proposed in this research overcomes this disadvantage by providing a sufficient number of parameters such that both the stiffness and the energy dissipative characteristics of the device can be controlled. Furthermore, as indicated above, the visco-plastic device shares many of the advantages of existing passive damping devices.

DESCRIPTION OF THE VISCO-PLASTIC DAMPER

The device proposed herein, called a Visco-plastic Damper (VPD), combines and enhances many of the proven characteristics of both displacement-dependent and velocity-dependent devices. It works as a viscoelastic damper at low levels of excitation, and for extreme levels of vibration, operates as a combined viscoelastic and metallic yielding device. As illustrated in Figure 1, the device consists of two steel plates or shapes, bent as shown, with a viscoelastic solid material bonded into place between the plates. When an axial compressive force is applied along the longitudinal axis of the device, the device shortens by an amount δ. Concurrent with this shortening is an expansion of the mid-span transverse dimension of the device, h. Due to the bent configuration of the plates, the transverse expansion of the device is several times the axial shortening. This expansion is quantified as $\eta\delta$, where η is a geometric amplification factor. Such amplification is highly desirable, and as mentioned earlier, has been previously utilized with a variety of devices. When the transverse dimension of the VPD expands or contracts, the entire volume of viscoelastic material is subjected to a near-uniform axial strain. Behavior of the VPD in tension is similar to that in compression, except that the viscoelastic material is in compression when the device is in tension.

For low-level seismic vibrations, the viscoelastic component of behavior will be sufficient to provide the required control, where vibration suppression is provided by both the axial stiffness and the viscoelastic damping characteristics of the device. It should be noted that, due to the "pre-buckled" bent shape of the plates, the axial stiffness of the device is significantly less than the stiffness that would be obtained if the same plates were used in a straight configuration. This is an advantage of the VPD because excessive added stiffness may act as a "seismic attractor," increasing base shears and increasing response accelerations, which result in damage to contents and nonstructural components.

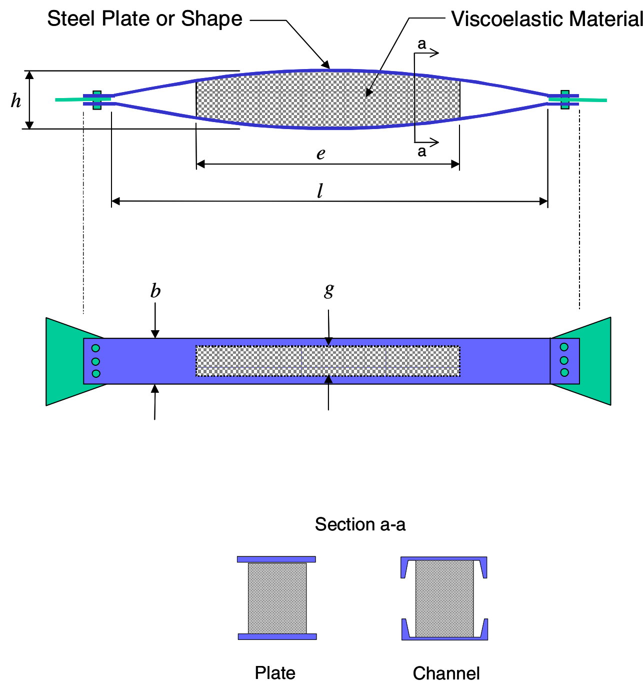

Figure 1: Details of Proposed VPD

For high level seismic vibrations, an additional source of energy dissipation in the VPD is provided by axial-flexural yielding of the central portion of the steel plates. This yielding occurs when the device is in tension or compression. When the device is in compression, the pre-buckled symmetry of the plates and the rigidity of the viscoelastic material will prevent uncontrolled inelastic buckling of the steel plates. This behavior is similar to that exhibited by unbonded steel braces (Clark et al. [22]). Additionally, a restraining mechanism may be placed in the device which limits the amount of transverse expansion that may occur when the device is under compression. When placed into a structural system it is expected that the devices would be used in pairs, where one device is in tension and the companion device is in compression.

There are a number of parameters that may be manipulated to control the behavior of the device. These parameters include:

- Length (l), width (h) and breadth (b) of the device
- Aspect ratio, (h/l) of the device
- Initial bent shape of the plates (straight, circular, parabolic, transcendental)
- Size and profile of steel sections (plate, channel, tee)
- Hysteretic behavior of steel
- Extent (e) and thickness (g) of viscoelastic material
- Solidity of viscoelastic material. To reduce stiffness, holes may be cored into the material
- Static constitutive behavior of viscoelastic material
- Dynamic constitutive behavior of viscoelastic material
- Bonding of the viscoelastic material to the plates (bonded vs. unbonded)

While essentially a "high technology" device, the VPD is constructed from readily available materials, can be assembled in most structural steel fabrication plants, is projected to have a relatively low cost, and should require little if any maintenance. Unlike many other passive energy dissipation devices, the VPD should operate without need for replacement for all applications except the most extreme seismic loading. Preliminary analysis of the device, as described in the next section, has shown that the device is very effective, particularly when compared to existing devices that employ viscoelastic solid materials.

SIMPLIFIED PRELIMINARY ANALYSIS

In order to investigate the behavior of the device and its effect on the response of structures under different seismic loads, a simplified analytical model was developed using the SAP2000 finite element analysis program [23]. Several discrete dampers were used to represent the viscoelastic material. To model these elements in SAP2000, NLINK elements are used. The NLINK element consists of a spring in series with a dashpot, which represents a Maxwell model. This was converted to a Kelvin model by using a high stiffness in the spring component of the Maxwell model, and adding a second linear spring parallel to the full Maxwell model. The steel elements are assumed to behave elastically during this analysis.

Single-Story steel frame

In this study the device was attached to a single-story one-bay steel frame to investigate the effect of different device parameters on its effectiveness. These parameters are the damping constant of the discrete dashpots, the stiffness of the springs, the cross section of the steel elements and the aspect ratio of the device. To perform this parametric study, the steel frame was analyzed under a harmonic excitation for a quarter cycle and then allowed to vibrate freely.

One of the most important parameters to be considered is the damping constant, C, of the dashpot that is used to represent the viscous damping characteristic of the filler material. This damping constant depends on a variety of factors, including the viscoelastic material type, the tributary cross sectional area of filler material represented by the dashpot, and the transverse thickness of that material. Four different values of C were exercised to cover a reasonable range of viscous behavior that can be provided by the filler material.

The second parameter to be investigated is the stiffness, K, of the linear spring placed in parallel with the dashpot. These springs represent the storage stiffness of the viscoelastic material. Many parameters affect the spring stiffness, such as the modulus of elasticity of the filler material, the tributary area, and the transverse thickness of the viscoelastic material represented by the spring. Three reasonable values of K were used.

The effect of cross section of the steel elements was considered. Three cross sections were chosen, C10x20, C12x25 and C15x50. The last parameter in this investigation that affects the behavior of the device is its shape. Three cases are considered with aspect ratio, h/L, of 1/6, 1/8 and 1/12, where h is the maximum transverse thickness of the device and L is the device span. The bent shape of the plates was a half sine wave in each case.

From the results of these analyses, it was observed that increasing the loss modulus of the filler material increases the overall damping effect, leading to a reduction in floor displacement and base shear. The results also illustrate the influence of the elastic properties of the viscoelastic filler material on the efficiency of the VPD. Fillers that are too flexible lead to premature yielding of the steel component, and fillers that are too stiff minimize the displacement amplification factor η, inhibit damping, inhibit yielding, and cause excessive axial stiffness of the devices.

It was also observed that the larger the cross section of the steel elements, the smaller the floor displacement obtained. This result is expected because the axial stiffness of the device increases, and hence, the lateral stiffness of the frame increases. On the other hand, increasing the size of the steel section reduces the transverse displacement of the device, which reduces deformational velocity in the filler material, and lowers the effective damping ratio provided by the device. Regarding the device shape, it is noticed that the as the aspect ratio increases, the horizontal stiffness provided by the device is reduced while the effective damping provided by the VPD is increased.

Multi-Bay Multi-Story Steel Frame

In order to investigate the effectiveness of the device on the response of multi-story structures, the five-bay nine-story (plus one basement level) steel frame designed for the SAC building project (Gupta and Krawinkler [24]) was utilized. The device was attached to the frame at each floor through the use of an inverted chevron brace. The model and the arrangement of the devices are shown in Figure 2. For all analysis it was assumed that the entire steel structure, including the chevron brace, remained elastic.

Prior to performing a ground motion based response history analysis, a parametric study was conducted on the frame to determine the best device parameters to improve the response under a harmonic excitation. According to the results of this analysis, the damping constant C was set to be 1 k-sec/in, the spring stiffness K was set to be 0.4 k/in, the steel elements were C10x20, and the aspect ratio was 1/12. Large displacement and P- δ effects were considered for the whole analysis. As before, the analysis was performed using SAP2000.

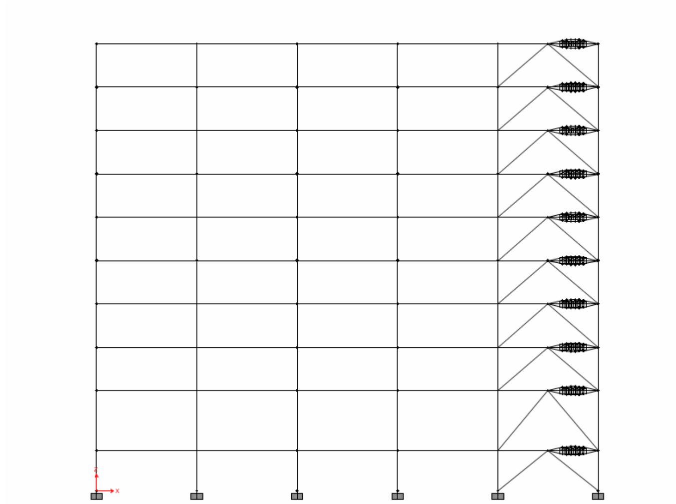

Figure 2: A Nine-Story Steel Frame with VPD Devices

The 9-story model of this structure was analyzed with and without the devices under harmonic excitation and under unscaled records of the El Centro and Northridge earthquakes. The results of these analyses are shown in Figures 3a through 3f. As may be observed, the device was very effective in reducing both displacement and base shear. Table 1 summarizes the response improvement due to the use of VPD.

In traditional viscoelastic damper applications, the standard VE damper is relying on obtaining the damping through the shear strains developed in the viscoelastic material. In this device, the damping is mainly obtained through the amplified tensile and compression strains. It is interesting to compare the efficiency of this device with the standard type of viscoelastic dampers. To accomplish this comparison, the several dashpots and springs that were placed in a vertical configuration in the VPD were placed in a horizontal configuration. In effect, the amplification of deformation which arises from the unique shape of the VPD was eliminated. The comparison between the effectiveness of both orientations of dashpots and springs was performed for the structure subjected to harmonic excitation as well as the unscaled records of the El Centro and Northridge earthquakes.

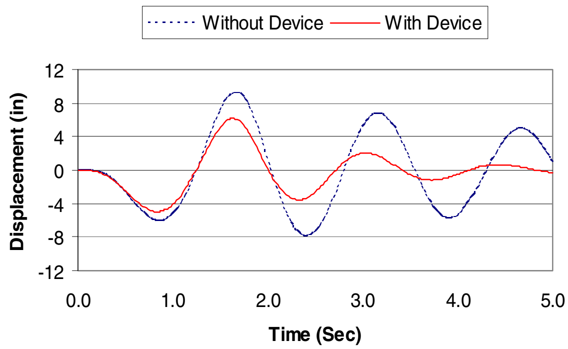

Figure 3a: Top floor displacement under harmonic excitation

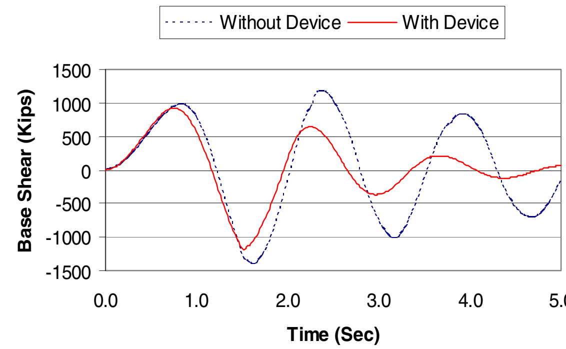

Figure 3b: Base shear under harmonic excitation

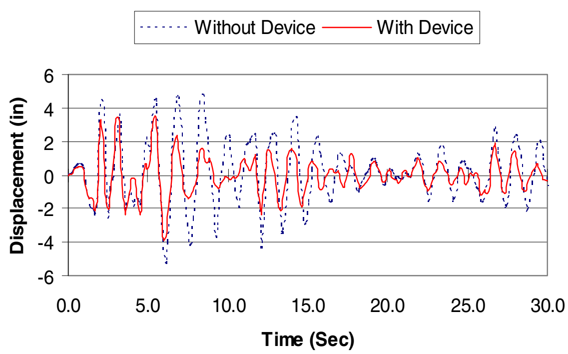

Figure 3c: Top floor displacement under El Centro earthquake

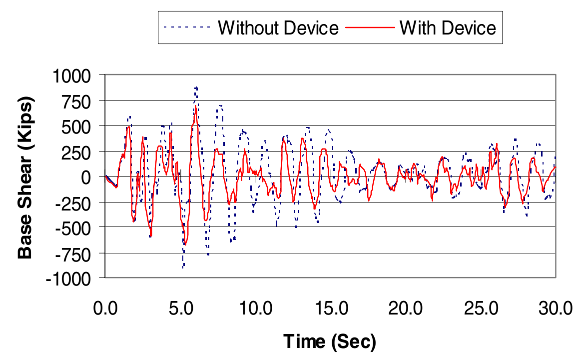

Figure 3d: Base shear under El Centro earthquake

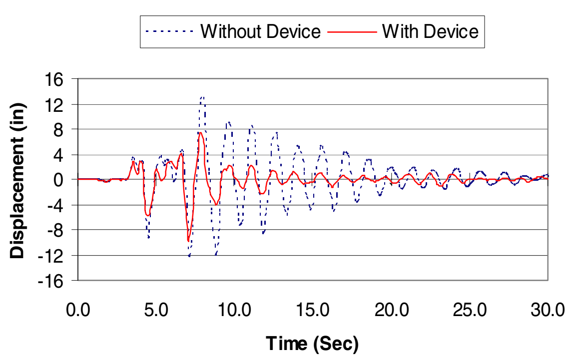

Figure 3e: Top floor displacement under Northridge earthquake

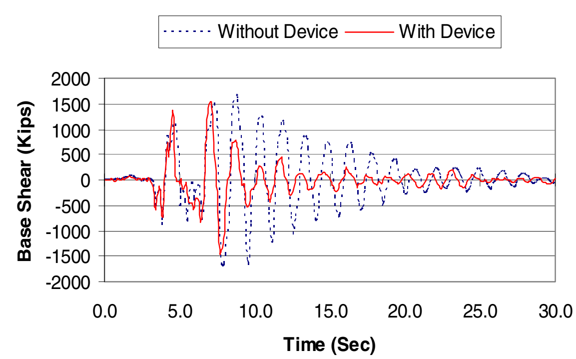

Figure 3f: Base shear under Northridge earthquake

Figures 4a through 4f represent the comparison between the structural responses using the standard VE damper configuration and the VPD under the different ground excitations. In all cases, the VPD showed better response improvement than the standard VE damper. The top floor displacement and base shear are reduced under the different ground excitations. Table 2 summarizes the reduction in structural response due to the use of the new device instead of the standard VE damper. Although using the device introduced better response under different cases, there is not much reduction in the maximum floor displacements and story shears occurring during the first pulse of response when the system was subjected to the harmonic ground motion. However, the superiority of the new device can be clearly seen in later cycles.

Table 1: Summary of Response Reduction for Systems With and Without the VPD

Excitation	% reduction in top floor displacement	% reduction in base shear at max. top floor displacement	% Average reduction in floor displacements at max. top floor displacement	% Average reduction in story shears at max. top floor displacement
Harmonic	33.2 %	15.6 %	31.7 %	33.6 %
El Centro	27.4 %	23.7 %	34.6 %	20.6 %
Northridge	24.7 %	8.3 %	2.1 %	18.2 %

Table 2: Summary of Response Reduction for System with Components in VPD and Traditional Configuration

Excitation	% reduction in top floor displacement	% reduction in base shear at max. top floor displacement	% Average reduction in floor displacements at max. top floor displacement	% Average reduction in story shears at max. top floor displacement
Harmonic	30.9 %	16.9 %	0.63 %	0.37 %
El Centro	32.3 %	34.7 %	24.3 %	33.8 %
Northridge	12.3 %	25.3 %	3.74 %	15.6 %

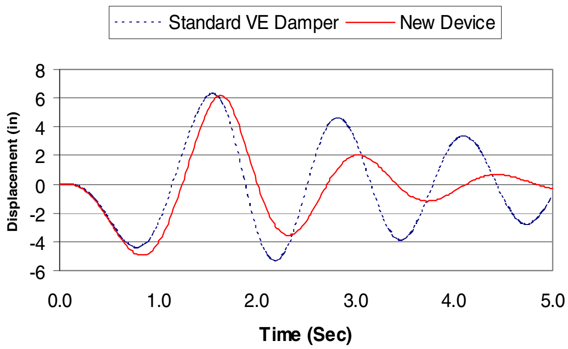

Figure 4a: Top floor displacement under harmonic excitation

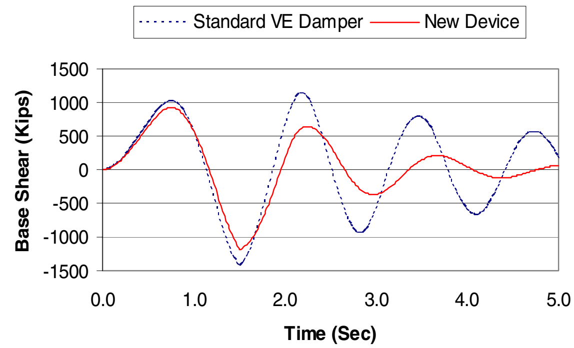

Figure 4b: Base shear under harmonic excitation

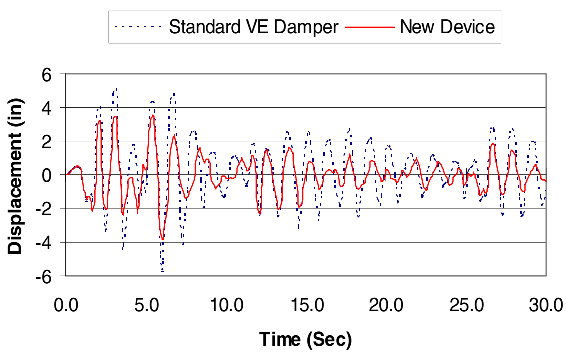

Figure 4c: Top floor displacement under El Centro earthquake

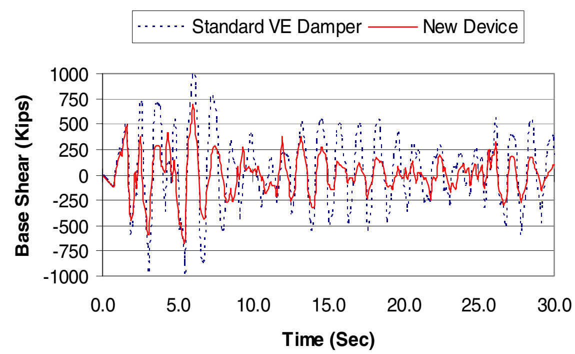

Figure 4d: Base shear under El Centro earthquake

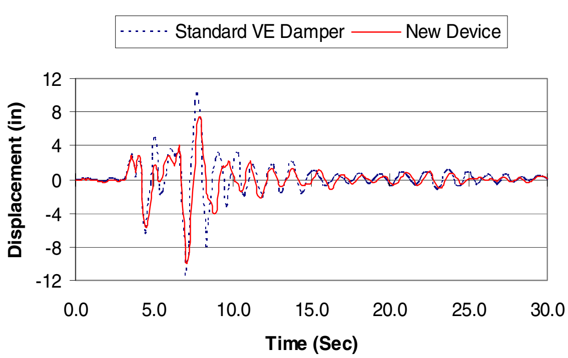

Figure 4e: Top floor displacement under Northridge earthquake

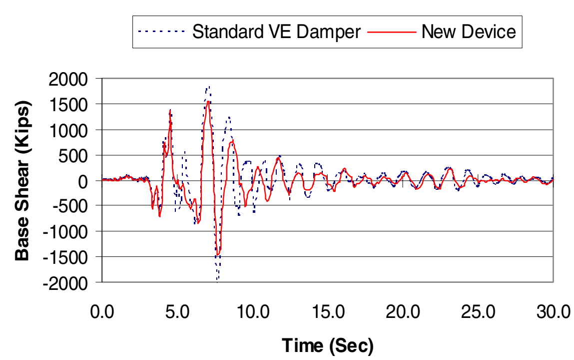

Figure 4f: Base shear under Northridge earthquake

DETAILED FINITE ELEMENT ANALYSIS of VPD

Due to the pre-buckled shape of the steel elements of the device, it is necessary to model the VPD using a full large displacement formulation, where equilibrium equations are formed in the displaced geometry. The steel elements of the VPD were modeled to behave elastically during the previously described SAP2000 analyses. This ignores the important source of energy dissipation which occurs through axial-flexural yielding of the steel element of the device. Accordingly, a more detailed and accurate analysis of the device is needed. A finite element analysis using ABAQUS [25] was conducted to determine the actual behavior of the device under dynamic loads. In this model, the rubber block is modeled using three-dimensional solid elements considering the viscoelasticity and hyperelasticity of the rubber material. Steel elements are modeled using a Von Mises yield criterion and appropriate strain hardening rules. Large displacement and P-delta effects are included in the analysis. The model is analyzed under dynamic harmonic axial forces. The deformation contours from one of the ABAQUS analyses is shown in Figure 5.

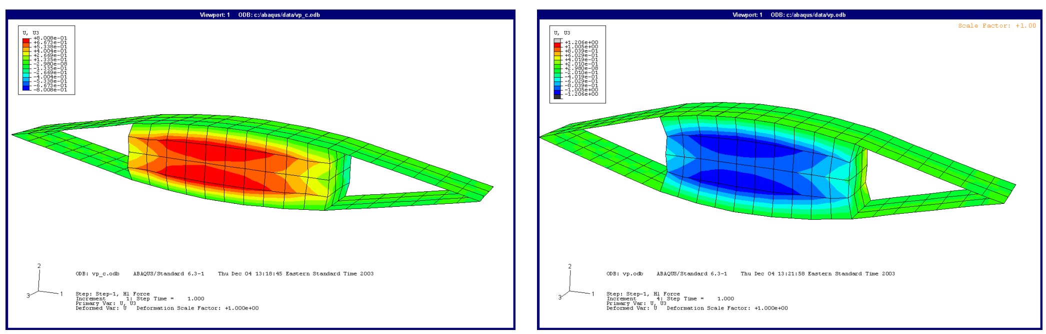

Figure 5: ABAQUS Models of VPD in Tension (left) and Compression (right)

Rubber block modeling

To model the rubber block, C3D8R elements were used. These elements are three dimensional, eight-node, linear, reduced-integration continuum elements, which are suitable for large-strain analysis. Hybrid elements are used to model the incompressibility of rubber materials with Poisson ratio as high as 0.5.

Hyperelasticity

To model the hyperelastic behavior of rubber in ABAQUS, results of uniaxial and biaxial tension-compression tests are required. Raos [26] presented experimental results of these tests on Synthetic Butadiene rubber, SBR. Table 3 and 4 present the results of these tests, which are used in the model.

Viscoelasticity

The time-dependent material constants needed to define the viscoelasticity are obtained from Quigley et al. [27] based on relaxation tension and compression tests data conducted on carbon black filled, highly saturated nitrile rubber (HNBR) (Touchet et al. [28]). The tension test was performed on a specimen of dimensions 15.24 by 2.54 cm. The specimens were pulled at rate of 20%/s to the specified strain levels. Six strain levels were specified as 5%, 10%, 50%, 100%, 150% and 180%. For the stress relaxation test in compression, cylindrical specimens 2.86 cm in diameter and 1.27 cm high were used. The specimens were compressed at rate of 20%/s to the specified strain levels, which are 5%, 10%, 15% and 20% strains. Quigley et al. developed four different prony series from collocation method and a nonlinear regression analysis, based on either small or large tensile strains relaxation data, in addition to a prony series constructed from dynamic data. These prony series were compared to the results of experimental relaxation test conducted on HNBR and all of them showed good results especially for those based on large strains. In this model, the prony series developed from the collocation methods is used. The material constants used in the ABAQUS model are shown in Table 5.

Table 3: Uniaxial test data

Stress (N/mm2)	Strain %
-2.60	-50
-1.80	-40
-1.20	-30
-0.70	-20
-0.30	-10
0.00	0
0.30	25
0.60	50
0.80	75
0.92	100
1.05	125
1.15	150
1.30	175
1.48	200

Table 4: Biaxial test data

Stress (N/mm2)	Strain %
-3.15	-40
-1.80	-30
-1.00	-20
-0.40	-10
0.00	0
0.30	25
0.75	50
1.00	75
1.25	100
1.55	125
2.20	150
3.00	175

Table 5: Time-dependent material constants (Quigley et al. [27])

τ_K (sec)	$g_{K} * 10^{-2}$
0.01	9.884
0.1	-5.362
1	25.19
10	4.023
100	16.53

Steel elements

The steel elements are modeled as S4R elements, which are 4-node linear reduced integration shell elements with finite membrane strains.

One of the advantages of modeling the device in ABAQUS is the availability of considering the inelastic behavior of the steel elements. In order to do so, the elastic-plastic behavior of steel is encountered. To model the plasticity in ABAQUS, true stress and true strain must be used instead of the nominal stress and strain. Table 6 summarizes the calculations used for the modeling of the steel elements.

Dynamic loads

In order to investigate the behavior of the device under dynamic loads, the model is analyzed under a dynamic concentrated forces acting along the longitudinal axis of the device. The forces are harmonic taking the form of $A \sin (2\pi t)$, where A values of 10, 20 and 40 kips were used.

Results

Figure 6a through 6f show the device response under these harmonic loads. The figures show the external work, energy dissipated through the viscoelastic material for VPD, and the energy dissipated through the inelastic behavior of the steel plates of the VPD. Moreover, the amplification of the horizontal deformations, which is the main concept behind the device, is shown for the different loading amplitudes. It is clear that small horizontal deformations can be amplified to increase the energy dissipation through the VE material and the steel elements

For small levels of strains, the steel elements remain elastic and the energy is basically dissipated through the strains in the VE material. As the device is stressed by higher stresses, larger strains are developing allowing to inelastic behavior of the steel elements. Accordingly, a new source of energy dissipation is introduced. Under high levels of stresses, severe yielding occurs leading to significant energy dissipation, which is desired under such levels of large seismic loads and strong earthquakes.

Table 6: Stress and strain for steel (ABAQUS / Standard [25])

Nominal stress (MPA)	Nominal strain	True stress (MPA)	True strain	Plastic strain
200	0.00095	200.2	0.00095	0
240	0.025	246	0.0247	0.0235
280	0.05	294	0.0488	0.0474
340	0.1	374	0.0953	0.0935
380	0.15	437	0.1398	0.1377
400	0.2	480	0.1823	0.18

CONCLUSIONS

A new visco-plastic energy dissipation device is introduced to protect structures under seismic loads. The device is constructed from readily available materials that can be assembled in most structural steel fabrication plants. The device consists of a viscoelastic material sandwiched between two steel plates or shapes. First, the device is modeled as several discrete dashpots and springs using SAP2000. Visco-plastic devices are attached to two structures, one-story single-bay and nine-story five-bay steel frames. The structures are analyzed under harmonic excitation as well as real records of El Centro and Northridge earthquake excitations. Second, a detailed finite element model of the device is constructed and analyzed under dynamic harmonic axial forces using ABAQUS. The model considers the viscoelasticity, hyperelasticity of the viscoelastic material and the inelastic behavior of the steel plates using a Von Mises yield criterion and appropriate strain hardening rules. Large displacement and P-delta effects are included in the analysis.
According to the results of these analyses, the following conclusions are obtained:

1. The VPD device is very controllable since it has many design parameters that can be selected carefully in order to optimize its use to dissipate energy for different structures. These parameters include the aspect ratio of the device, *h*/*L*, the dimension of the viscoelastic material, the type and cross section of the steel elements, the type of the viscoelastic material used placement of the device, i.e. horizontally or diagonally, and the location of the device throughout the structures to which the dampers be attached.
2. A small axial deformation along the device axis can be geometrically amplified considerably to produce large strains in the viscoelastic material, which increases the energy dissipation.
3. Under low levels of excitations, such as wind induced vibrations the VPD dissipates energy through the tensile and compression strains developed in the viscoelastic materials. However, for extreme levels of vibration, like strong earthquake excitations, a significant source of energy dissipation is encountered through the yielding of the steel elements in addition to the viscoelastic energy dissipation.

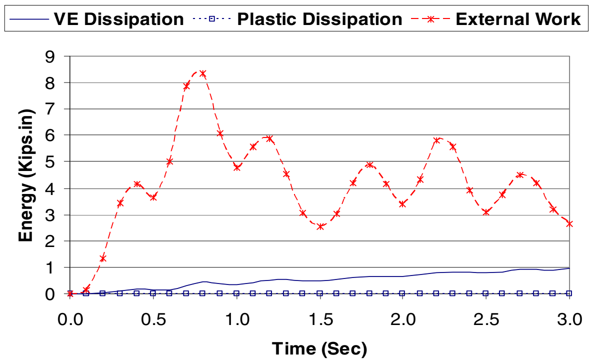

Figure 6a: Energy dissipation under two periodic forces with 10-Kips amplitude

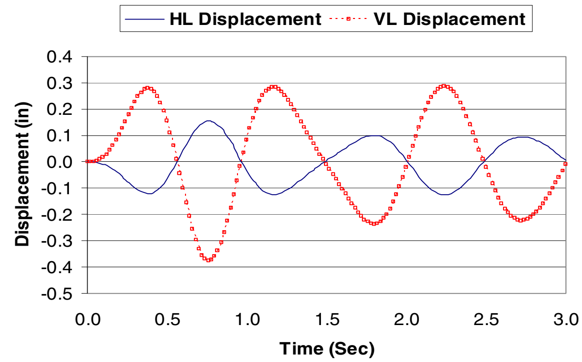

Figure 6b: Deformation amplification under two periodic forces with 10-Kips amplitude

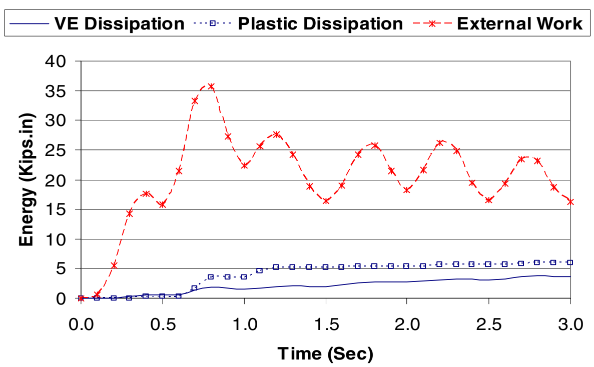

Figure 6c: Energy dissipation under two periodic forces with 20-Kips amplitude

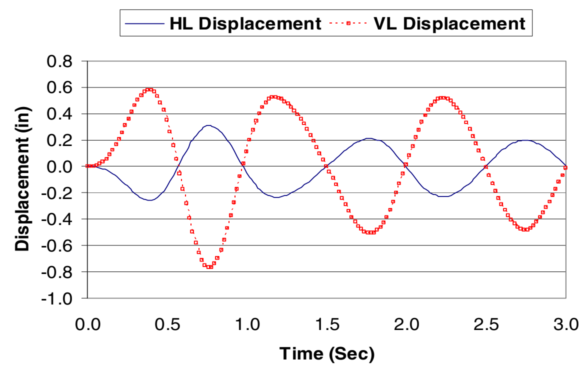

Figure 6d: Deformation amplification under two periodic forces with 20-Kips amplitude

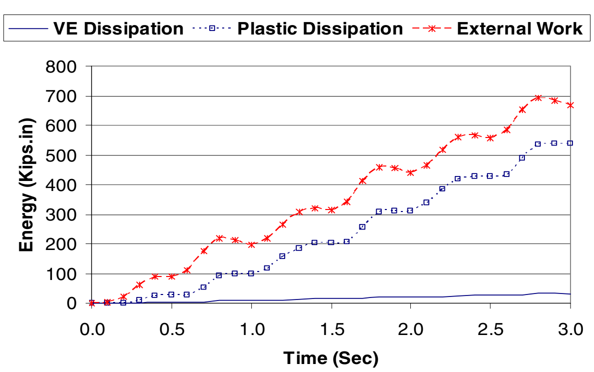

Figure 6e: Energy dissipation under two periodic forces with 40-Kips amplitude

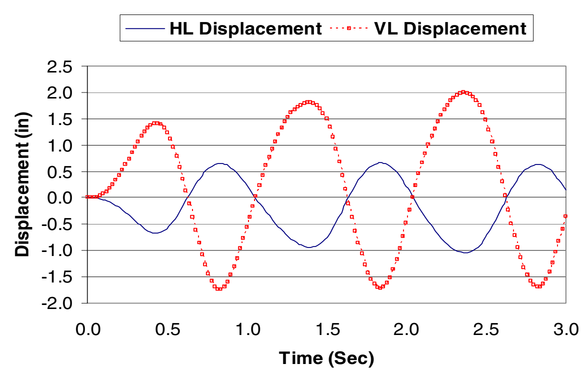

Figure 6f: Deformation amplification under two periodic forces with 40-Kips amplitude

4. The VPD improved the response of different structures significantly under different seismic excitations. Structures with VPD's had significantly lower peak displacements and lower peak base shears than systems without the devices. Also, Placement of viscoelastic material in a VPD configuration was more effective than placement in a traditional configuration (wherein the viscoelastic material is stressed in direct shear). The increase in VPD efficiency is attributed to the amplification of deformations in the viscoelastic material. Amplification factors η as high as 3.0 were observed in some analyses.

FUTURE WORK

1. The viscoelastic material to be sandwiched by the steel elements of the device needs to be carefully selected. There are many rubber types can be used such as natural rubber, high-damping natural rubber, synthetic rubber and styrene butadiene rubber. The damping properties of the rubber can be improved considerably by reinforcing the rubber by certain fillers like carbon black and silica. To choose the best suitable viscoelastic material for the device, test specimens of such materials will be tested under uniaxial and biaxial in addition to creep or relaxation tension and compression tests.
2. Prior to finalizing the design of the VPD, three detailing requirements must be addressed. These are the design of the connections at the two ends of the device, the proper manner for bending the steel plates, and the determination of whether the viscoelastic material must be bonded to the steel, or whether the steel may be "bent around" the viscoelastic material, causing a precompression, and thereby eliminating the need for physical bonding. If it is determined that the filler must be bonded to the plates, additional tests will be performed to test the effectiveness of the bond.
3. Having selected the suitable viscoelastic material and the appropriate design of the device, visco-plastic devices will be constructed at approximate one-half scale and then tested using a uniaxial seismic shaking table to drive the device. The tests will be performed with pseudo-static and dynamic cyclic loading applied along the axis of the device. The imposing motion will be harmonic at frequencies ranging from zero to 5 HZ. The purpose of this testing is to check the device behavior in elastic and inelastic range and compare it with the results of the finite element model.
4. Full-scale visco-plastic devices will be constructed at the NEES Fast Hybrid Testing (FHT) at the University of Colorado at Boulder and then tested similar to the previous testing. After that a physical substructure will be combined with a finite element model substructure and tested dynamically. Such testing combines real-time physical experiment with on-line model-based simulation in order to evaluate the seismic performance of structural systems.

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