SEISMIC BEHAVIOR OF NEW VISCO PLASTIC DEVICE EQUIPPED WITH STEEL CORES AND VISCOELASTIC SOLID

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SUMMARY

This paper presents the preliminary results of an analytical and finite element investigation into the effectiveness of a new Visco-Plastic energy dissipation device. This new device, which is fabricated from readily available structural steel rods and viscoelastic solids, has a wide range of application in building and bridge structures. Input energy due to seismic excitation is dissipated by yielding of steel cores and shear strain in viscoelastic layer. One of the important abilities of the proposed energy dissipating device is its good performance under cyclic loading and high speed of repair. This is such a manner that after an intermediate or strong earthquake without need of foreman and extra equipment, only with changing the ductile steel cores used in the device, the repairing process of structure can be accomplished very fast.

Keywords: Visco-plastic device, steel cores, passive energy dissipation.

1. INTRODUCTION

The research and development of structural control against wind and earthquake have achieved significant progress over the last three decades (Chan et al. 2008). Structural control can broadly be classified into three categories. Passive, active, and semi active are the three most commonly used classifications of vibration-control systems, either as isolators or absorbers. A vibration control system is said to be active, passive or semi-active depending on amount of external power required for the vibration control system to perform its function. A passive vibration control consists of a resilient member and an energy dissipater either to absorb vibratory energy or to load the transmission path of the disturbing vibration (Korenev and Reznikov. 1993).

The mechanisms used for passive energy dissipation are based on yielding of metals, friction sliding, phase transformation of metals, fluid orificing, and deformation of viscoelastic solids. Passive energy systems that depend primarily on friction or yielding are called displacement-dependent systems. Such a system is typically configured in a manner that increases the lateral stiffness of the structure and consequently reduces its deformation demand. However, increasing the stiffness may damage the building contents due to excessive acceleration. High stiffness often increases base shear, and bending moment at column bases as well. Under larger levels of ground motion, performance of this system is improved due to added energy dissipation and due to force limiting characteristics of the device. Examples of displacement-dependent devices include hourglass shape ADAS damper (Bergma et al. 1987) or its triangular variant the TADAS damper (Tsi et al. 1993), honeycomb damper (Kobori et al. 1992) and the slit damper (Benavent and Akiyama. 1998; Chan et al. 2008; Oh et al. 2009)

Velocity-dependent device, like viscoelastic dampers (Shen and Soong. 1995) and viscous fluid damper (Symans and Constantinou. 1998) dissipate energy through forces proportional to the velocity of the motion. Velocity-dependent devices provide damping and sometimes stiffness to the structures and are used to dissipate energy for all levels of excitation while displacement-dependent devices usually provide stiffness and energy dissipation takes place under moderate and strong excitation only. Beside the displacement-dependent and velocity-dependent devices, other classes of passive energy devices have been developed that use either abilities of mentioned devices. Lead viscoelastic dampers (Zhou et al. 2008) and visco-plastic dampers (Ibrahim et al. 2006) are examples of these devices.

Since it is important to restore building and the function of the effected urban area as quickly as possible after an earthquake, in this paper it is tried to develop a new visco-plastic damper with high speed in being repaired after a moderate or strong ground motion.

2. DETAIL DESCRIPTION OF THE DEVICE

The device proposed in this study combines and enhances many of the proven characteristics of both displacement-dependent and velocity-dependent devices. The device is fabricated from readily available materials. Moreover, the device dissipates energy under all levels of vibrations. At low levels of excitation the device works as a viscoelastic damper and the energy is dissipated through amplified shear strain. For a high level of vibration, it operates as a combined viscoelastic and metallic yielding device. In addition to the energy dissipation, the device provides stiffness to structure through the steel core elements and the stored stiffness of the viscoelastic material.

The device consists of a viscoelastic solid material bonded into place between two steel plates or shapes, some steel cores, high strength bolts, nut and washers, main chassis and some special nuts to fix the steel cores in the bottom flange hole. Detail of the proposed device is shown in Fig. 1.

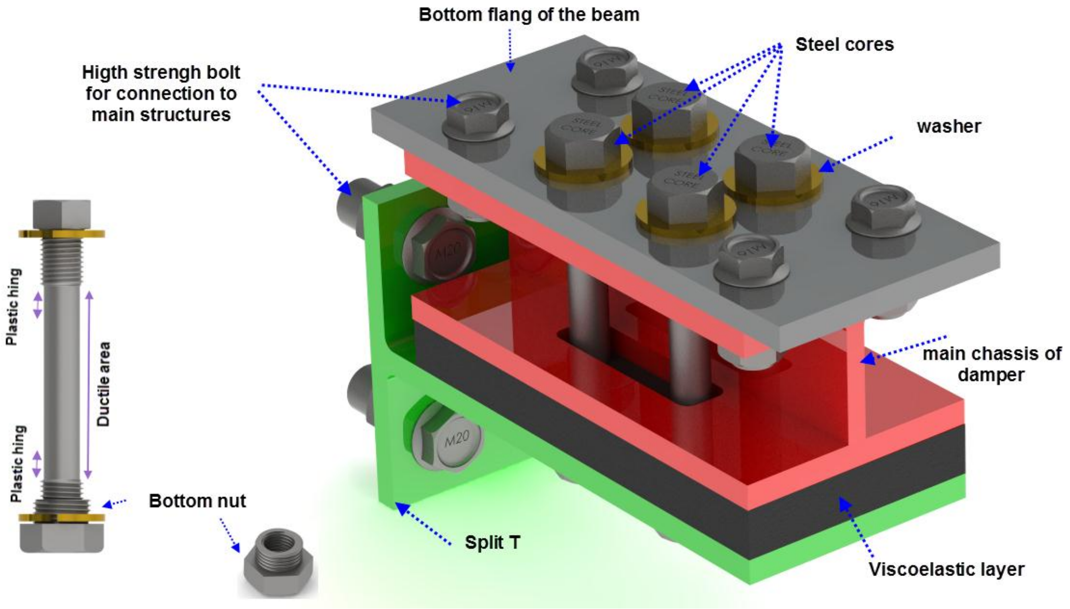

Figure 1. Detail of the proposed visco-plastic device

The proposed passive energy device does not need a complex technology for production and installation. Figure 2. shows how the proposed device can be attached to the beam to column joint. As an another application, this device can also be used in chevron bracing systems.

3. PRELIMINARY DEVICE DESIGN

Under small relative displacements between the two supports (bottom plate and top plate), the steel core behave as a series of partially fixed-ended beams and deform in double curvature. The elastic bending moment in the steel cores is shown in Fig. 2a. Under sufficient displacement, plastic hinges

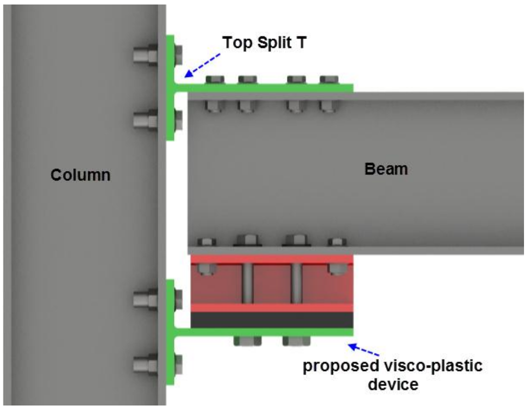

Figure 2. used of proposed visco-plastic device in beat to column joint

form at both ends of each steel core. Consequently, the mechanical characteristics of the Visco-Plastic Damper (VPD) can be described in terms of the ductile area length in steel cores, steel cores diameter, rubber properties and rubber layer thickness.

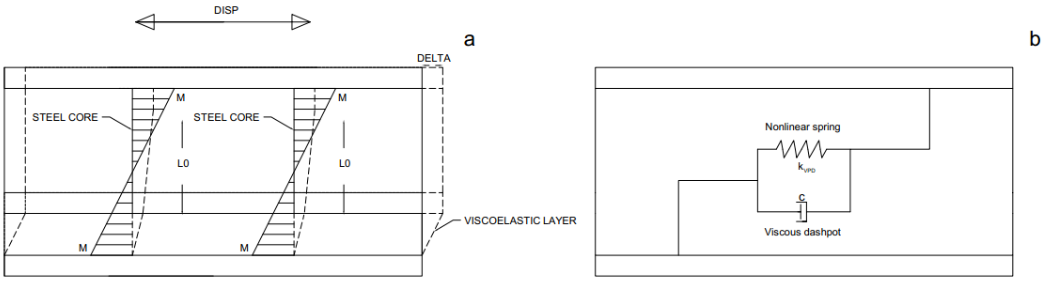

Figure 3. (a) Moment and deformation in steel cores (b) simple mechanical model

Assuming elastic–perfectly-plastic behavior in the steel cores, yield load P_y and ultimate load P_u can be determined based on a plastic mechanism analysis. Consequently:

$$P_{ysc} = \min\left(P_{yb}\ ,P_{ysh}\right) = \min(n\frac{17}{160}\frac{\pi D^3}{l_0}\sigma_y\ ,n\frac{3\pi D^2}{16\sqrt{3}}\sigma_y) \tag{2.1}$$

And

$$P_{usc} = \min(P_{ub}\ ,P_{ush}) = \min(n\frac{17}{160}\frac{\pi D^3}{l_0}\sigma_u\ ,n\ \frac{3\pi D^2}{16\sqrt{3}}\sigma_u) \tag{2.2}$$

where n is the number of steel cores in the device, l_0 is the effective length of ductile area, D is the steel core diameter, σ_y is the yield stress of steel and σ_u is the ultimate stress of steel. In the elastic–perfectly-plastic behavior of steel, the yield stress and ultimate stress are the same and consequently, the steel core's yield and ultimate loads are identical. In Eqs. (1) and (2), the first term means that the yielding of the steel cores is governed by the flexural moment, while the second term relates the yielding of the steel cores to shear force. The elastic stiffness of the steel cores K_{esc}, can be determined by assuming that the steel cores are partially fixed at their ends. It is given by,

$$K_{esc} = cn\frac{12EI}{{l_0}^3} = cn\frac{12E\pi D^4}{64{l_0}^3} \tag{2.3}$$

where E is the Young's modulus and c is a stiffness coefficient to be calibrated from experiment or finite element analysis.

Additional to steel core, other sources of energy dissipation are provided by the viscoelastic layers. For a linear viscoelastic material under a sinusoidal shear stress $\tau(t)$ with a frequency ω, the shear strain $\gamma(t)$ will lag behind the stress by a phase angle δ as

$$\gamma(t) = \gamma_0 \sin \omega t, \quad \tau(t) = \tau_0 \sin(\omega t + \delta) \tag{2.4}$$

where τ_0 and γ_0 are the stress and strain amplitudes, respectively. If the strain is plotted against stress, one will obtain an elliptical hysteresis loop as shown in Fig. 4.

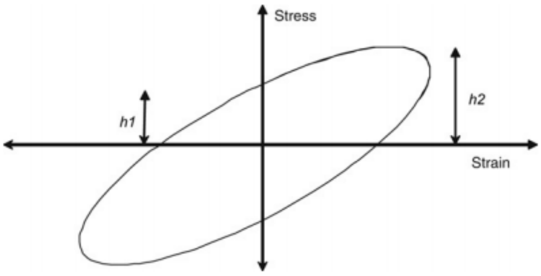

Figure. 4. Typical stress-strain curve of the rubber specimen under harmonic loading (Ibrahim et al. 2006)

Viscoelastic material (VEM) is often characterized by storage G' and loss $G"$ shear moduli to represent the elastic and viscous properties, respectively. The ratio of the loss to storage modulus is the loss factor η or the so-called tangent eta ($\tan \eta$) which is also used along with G' to describe the material

$$\eta = \frac{G"(\omega)}{G'(\omega)} \tan \delta \tag{2.5}$$

Also $\sin \eta$ can be calculated by:

$$\sin \eta = \frac{h_1}{h_2} \tag{2.6}$$

Where h_1 and h_2 are the stress at zero strain and the maximum strain, respectively, as shown in Fig. 4 (Ibrahim et al. 2006).

The viscoelastic layer can be characterized by storage K' and loss $K"$ stiffnesses and are related to G' and $G"$ as

$$K' = \frac{G'A}{h}, \ K" = \frac{G"A}{h} \quad and \quad \eta = \frac{K"}{K'} \tag{2.7}$$

where A is the total shear area of the VEM layer (Gopalakrishna and Lai. 1998). $K"$ can be further related to the viscous damping constant, C, and damper operating frequency, ω as

$$C = \frac{K"}{\omega} = \eta \frac{K'}{\omega} \tag{2.8}$$

According to the above equation the proposed visco-plastic device can be modeled by a nonlinear spring and a viscous dashpot as shown in Fig. 3b. The stiffness of the nonlinear spring is equal to sum of the steel cores stiffnesses and the viscoelastic layer's storage stiffness. These stiffnesses are parallel to each other. Figure 5. describes the combination of these stiffnesses.

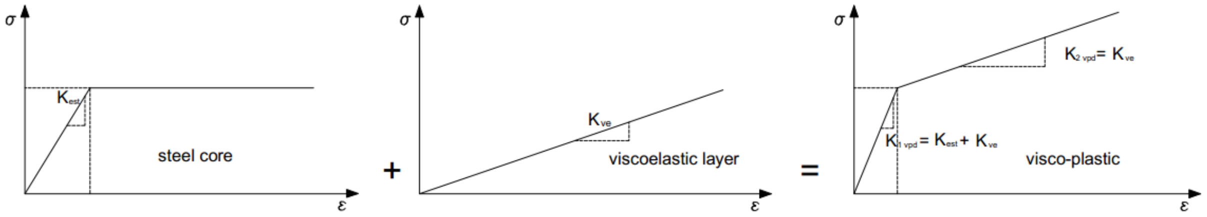

Figure 5. Schematic scheme for stiffness in steel core, viscoelastic layers and visco-plastic device.

3. FINITE ELEMENT ANALYSIS OF THE PROPOSED DEVICE

A finite element analysis was conducted to determine the stiffness and energy dissipation capacity of the proposed visco-plastic device. The specimen in this analysis consists of four steel cores and a viscoelastic layer 20mm in thickness. The steel material behavior is assumed to be elastic-perfectly plastic. The yield stress of steel equals 250Mpa, the Young modulus is 2.1E5 Mpa and the Poisson ratio is equal to 0.3. For the device model, the viscoelastic behavior of rubber was modeled using the experimental results conducted on a viscoelastic damper by Shen and soong (Shen and soong. 1995) . al Elastomers, like rubbers, are classified as hyperelastic materials. Hyperelastic materials have the ability to deform elastically up to large strains. The stress-strain curve is highly nonlinear but elastic. Hyperelastic behavior is important when the strain range is very high (over 200-500%). The viscoelastic layers in the proposed device experience shear strains under 100%. Therefore for the modeling of viscoelastic layer, a simple elastic model can be used with a Young modulus equal to 3100 Mpa and a Poisson ratio equal to 0.495.

By performing several finite element analyses with various D/L ratios, and by using a curve fitting process, the following equation is derived for the effective length of steel cores.

$$b = 0.91 - 0.4\frac{D}{l} \qquad (3.1)$$

Then,

$$l_0 = bL \qquad (3.2)$$

where, L is the total length of the ductile area in the steel cores. Also to evaluate c coefficient in Eq. 2.3, the values of K_{esc} for two cases, theory and analysis, were calculated and are presented in Table 3.1. As is observed, for a D/L ratio more than 0.16, the c parameter quickly decreases. With adjustment of the thickness of the upper and lower plates of the device, the c parameter is determined as 0.4 approximately. Chen et. al (Chan et al. 2008) determined this coefficient for slit damper as 0.3. The force-displacement curve due to bending of steel cores for the D/L ratio of 0.136 and displacement amplitude of 20mm for theory and analysis cases are presented in Fig. 6. A good agreement between the theory and analysis results is observed.

Table 3.1. Calculating stiffness coefficient in VPD

D/L Ratio	**K_{anal}**	**K_{FEM}**	**c**
0.136	7515	3240	0.43
0.145	9854	4068.4	0.41
0.163	16196	6001	0.37

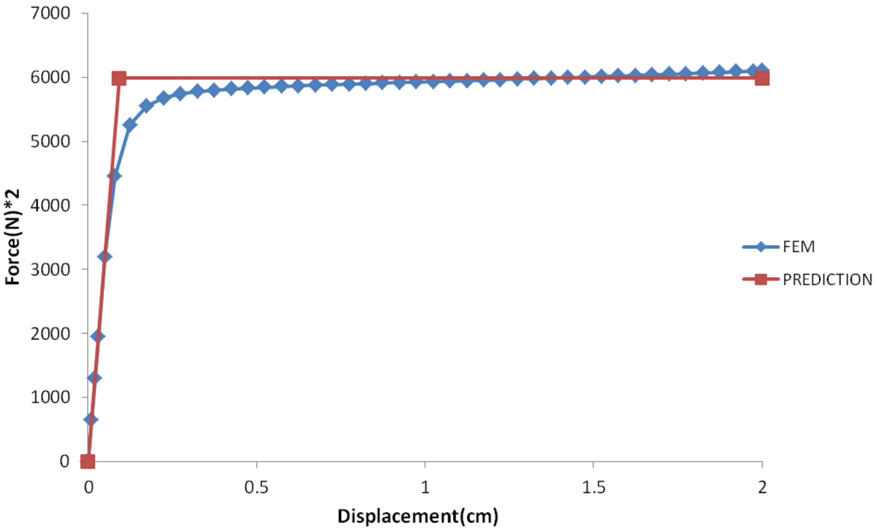

Figure 6. Force-displacement curve for steel cores

Also the force–displacement curves of the proposed device for various loading speeds of 2, 4, 10 and 20mm/s for specimens with D/L ratio equal to 0.136 are shown in Fig. 7. With increase of the loading speed, the initial and secondary stiffnesses of the device increases too. In a loading speed equal to 20mm/s, the portion of the force absorbed by viscoelastic layers, is 150% larger than the portion absorbed by steel cores.

The force-displacement curve of the device under a sinusoidal harmonic excitation with maximum amplitude 15mm and excitation frequency 3 Hz is shown in Fig. 8, along with the value of the energy dissipated by creep in viscoelastic layers and dissipated plastic energy in the steel cores (see Fig. 9.).

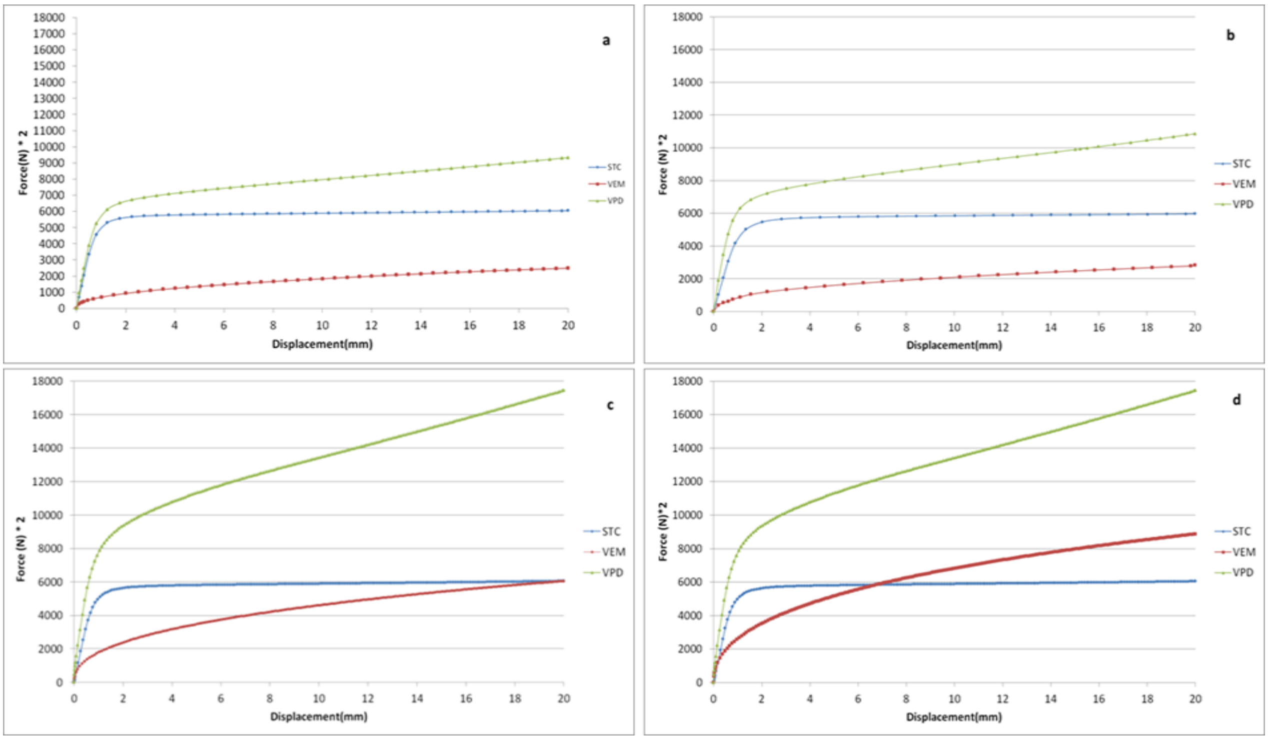

Figure 7. Force-displacement curves for the visco-plastic device for various loading speeds. (a) v=2mm/s (b) v=4mm/3 (c) v=10mm/s (d) v=20mm/s

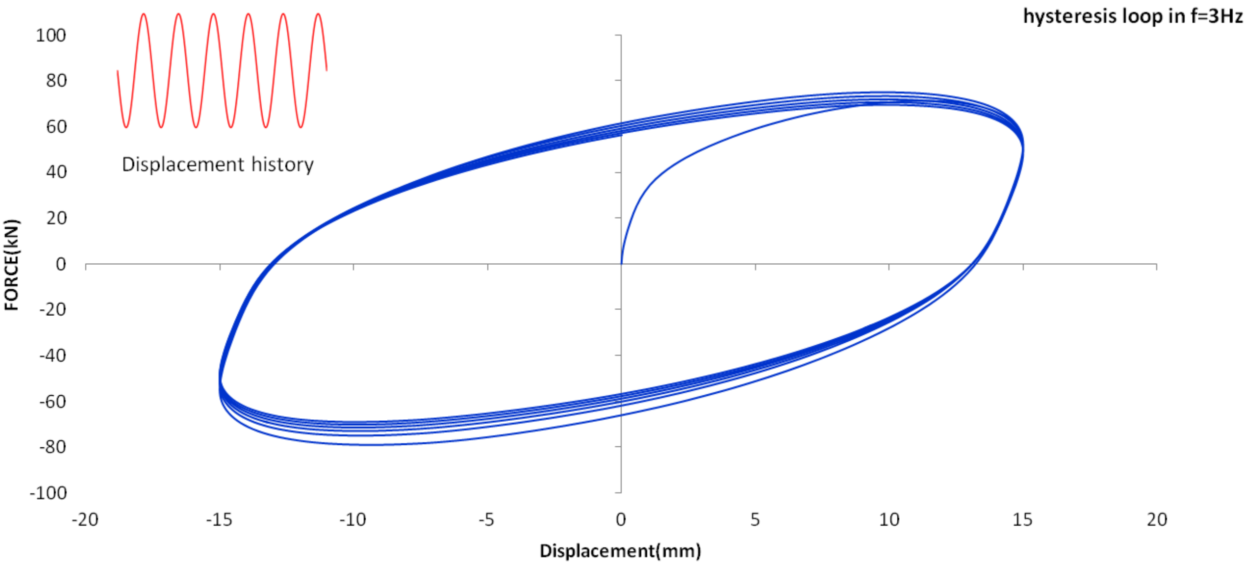

Figure 8. Hysteresis loop for visco-plastic damper at frequency 3Hz.

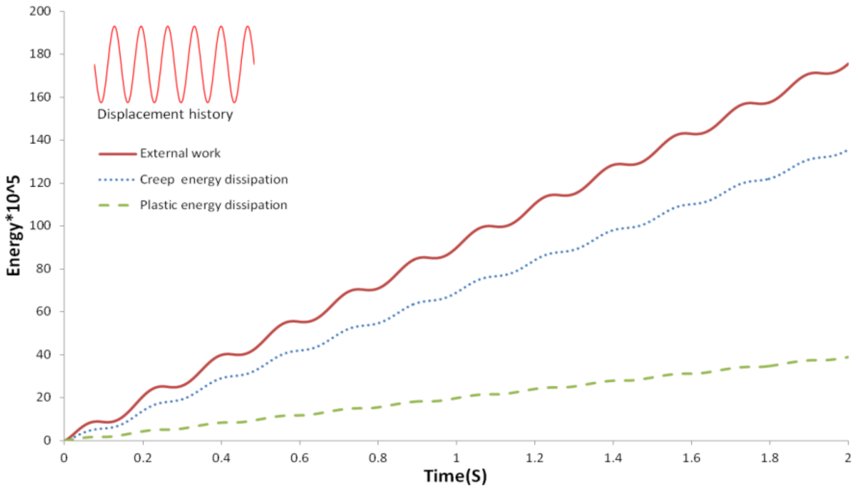

Figure 9. Energy value in the visco-plastic damper under sinusoidal harmonic excitation.

According to the above curve, at a frequency equal to 3 Hz, the creep energy dissipation is larger than the plastic energy dissipation. Since in the viscoelastic material a higher excitation frequency leads to a higher loss and storage modulus, the stiffness and energy dissipation capacity of the device increases.

5. Conclusions

A new visco-plastic energy dissipation device is introduced to protect structures under seismic loads. The device is constructed from readily available materials and can be easily assembled in most structural steel fabrication plants. The device consists of a viscoelastic solid material bonded into place between two steel plates or shapes, some steel cores, high strength bolt, nuts and washers, main chassis and some special nuts to fix the steel cores in the bottom plate hole. The device has shown a good hysteresis behavior under sinusoidal harmonic excitation and possesses the ability to be repaired quickly. It means that the yielded bolts can be substituted easily after moderate or strong earthquakes.

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