DESIGN OF ROOF ISOLATION SYSTEMS WITH VARIABLE FRICTION DAMPERS

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ABSTRACT :

Using tuned mass dampers is a well known and effective way to protect buildings from earthquakes, winds and other types of dynamic excitations. Several structures with tuned masses have demonstrated enhanced behavior. Sometimes the tuned mass displacements relative to the roof is big enough, and in order to decrease it supplemental dampers are used. Another disadvantage of tuned mass dampers is that they contribute to the static loads acting on the building. A more effective way allowing similar improvement in structural dynamic response is implementation of roof isolation systems, which require no additional mass. The current study is aimed to investigate a roof isolation system incorporating variable friction dampers (VFD). The variable friction dampers have re-centering capacity and limit displacements of the isolated roof part relative to the upper floor diaphragm. A method for selection of the dampers properties is proposed. A numerical example has been carried out on a six-story frame building subjected to three natural earthquake records. A structure with the proposed system has an enhanced seismic behavior and proves the effectiveness of the VFD in limiting the isolated roof part displacements.

KEYWORDS: tuned mass, variable friction damper, seismic response, selection of dampers properties

1. INTRODUCTION

Using supplemental dampers for vibration reduction has been thoroughly investigated in the past few decades. Various damping devices were proposed in order to improve the structural response to earthquakes and to limit the damage caused to the structural elements. These devices dissipate energy in various ways, such as by yield of mild steel (Tyler, 1995, Tsai et al., 1993), sliding friction (Pall et al., 1993), viscoelastic behavior of polymers (Bergman et al., 1993), movement of a piston in viscous fluid (Constantinou and Symans, 1993, Seleemah and Constantinou, 1997), etc. A wide review of passive energy dissipation applications in buildingd has been done by Soong and Dargush (1997).

Tuned mass dampers (TMD) consisting of a mass and a spring-dashpot have been widely used in structural applications in order to reduce response of buildings and bridges to wind, earthquake, traffic (like pedestrians or railway trains) and other types of dynamic loads. These systems were proposed about a hundred years ago and are known as classic solutions for improving dynamic behavior of structures (Copra, 1995, Hart and Wang, 2000). An advantage of a TMD is that it is very simple and requires no obstructions closing the structural bays like in the case of using supplemental dampers connected between the floor diaphragms.

A mass in TMDs is tuned in resonance with the structures dominant frequency allowing significant reduction in structural dynamic response. Depending on the mass ratio, the tuning frequency and the damping capability the reduction in structural seismic response can be very significant. The improvement of seismic performance according is confirmed by theoretical and practical investigations (Nawrotzky, 2006). Many researchers in the last three decades have developed modern effective method for selection of optimal parameters of TMD systems (Warburton, 1981, Sadek et al., 1997).

Roof isolation is a special type of a TMD. It was proposed by Villaverde and Mosqueda (1999) in order to overcome the disadvantages of conventional TMD systems like relatively large mass, space required for installation, large relative displacements of the mass caused by setting it in resonance with the structures dominant frequency. The idea was to use a portion of the roof mass as the mass of the absorber. Elastomeric bearings usually used in base isolation systems (Kelly, 1993) were proposed to be used together with viscous dampers instead of springs in order to reduce the mass displacement and to provide additional energy dissipation. Later Villaverde (2002) has investigated a 13 – story building to gain insight into the size of the bearings and dampers needed to build an absorber, to estimate the maximal roof displacement and to prove the effectiveness of the proposed solution.

The authors propose an alternative roof isolation system, incorporating variable friction dampers (Ribakov et al., 2006) instead of viscous ones and elastomeric bearings. The proposed system is simple and has the same effect. A method for selection of variable friction dampers parameters is developed.

2. THE ROOF ISOLATION SYSTEM AND SELECTION OF ITS PARAMETERS

A building with a roof isolation system RIS) was described in details by Villaverde (2002). A schematic view of an RIS proposed in this study is shown in Figure 1. The system consists of an isolated roof slab (1), roof beam (2), column (3), auxiliary beam (4), sliding support (5) and a variable friction damper (6). The damper is aimed to limit the isolated roof. part displacement relative to the un-isolated one. According to Sadek et al. (1997), it is possible to obtain the parameters of a tuned mass damper as follows:

$$f = \frac{1}{1+\Phi_k m_a / M_b}\left(1-\xi_b\sqrt{\frac{\Phi_k m_a / M_b}{1+\Phi_k m_a / M_b}}\right) \qquad (2..1)$$

$$\xi_a = \Phi_k \left(\frac{\xi_b}{1 + m_a / M} + \sqrt{\frac{m_a / M_b}{1 + m_a / M_b}} \right) \tag{2.2}$$

where f is frequency ratio, Φ_k denotes the amplitude corresponding to the mass of the structure that supports the appendage in the mode shape of the structure without the appendage corresponding to the frequency ω_b, which is a natural frequency of a multi degree of freedom structure (equal to the natural vibration frequency of the absorber, ω_a), m_a is absorber mass, ξ_a and ξ_b are the absorber and the structures damping ratios, M_b is the generalized mass of the structure.

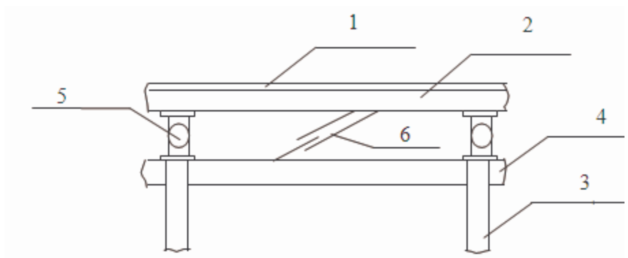

Figure 1. A roof isolation system with a variable friction damper

Villaverde (2002) has demonstrated that the above explained method can be successfully used for design of RIS. In this case the absorber mass is a part of the roof one, and according to this value the absorber´s stiffness and the viscous damper´s damping coefficient should be defined. Following Villaverde (2002), the damping ratio for the RIS is obtained from Eq. (2). The damping coefficient and the systems stiffness are obtained as follows:

$$c_a = 2\xi_a \omega_b m_a \tag{2.3}$$

$$k_a = f^2 \omega_b^2 m_a \tag{2.4}$$

3. BASIC LAYOUT AND FEATURES OF A VARIABLE FRICTION DAMPER

A various friction damper (VFD) proposed to be used as a part of a RIS has been developed earlier by Ribakov et al., (2006). It consists (Figure 2) of a rectangular section tube (7), a double wedge (8), two elastic strip elements (9), and a bolted connection clip (10). The wedge lies partly inside the tube and can move back and forth along its axis. The strips have a cantilever static scheme and are fixed to the tube by the connection clip, forming an elastic strip system. The stiffness of this system may be regulated by changing the location of the connection clip along the tube. The free ends of the cantilever strips are in contact with the inclined surface of the wedge.

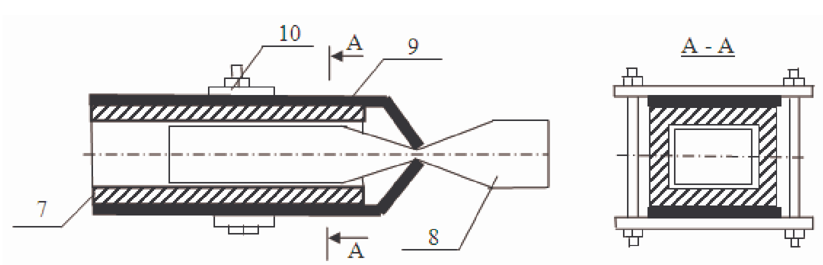

Figure 2. A variable friction damper

The damping force, F_D, can be obtained as a function of wedge displacement, x, as follows (Ribakov et al., 2006):

$$F_D = 2\,x / (C_u + C_v \cot \alpha) \tag{3.1}$$

where α is the wedge inclination angle, f is the friction coefficient on the surface between the wedge and the elastic strip elements,

$$C_u = \delta_{21} / \tan(\alpha + \rho) + \delta_{11} \quad \text{and} \quad C_v = \delta_{22} / \tan(\alpha + \rho) + \delta_{21} \tag{3.2}$$

$$\rho = \text{arc} \tan f \tag{3.3}$$

δ_{ij} (i = 1;2, j = 1;2) are the elastic strip elements flexibility coefficients; 1 and 2 are the horizontal and vertical directions, respectively.

4. DESIGN OF A ROOF ISOLATION SYSTEM WITH VARIABLE FRICTION DAMPERS

As it was mentioned above, a variable friction damper is proposed to be used as a part of a RIS instead of elastomeric isolators and viscous dampers (Villaverde, 2002). A method for selection of VFD parameters yielding equivalent structural seismic response (like in the case of a RIS with isolators and viscous dampers) is proposed. Assuming that the behavior of a building with viscous damped RIS incorporating isolators and of that with VFDs is similar, the following two demands may be taken into account for obtaining the VFD properties:

- the maximum isolated roof displacements relative to the unisolated roof part should be equal;
- the energy dissipated in a RIS with isolators and viscous dampers and in that with VFD are equal.

Let $d(t) = d_{\max} \cos(2\pi f_b t)$ be the isolated roof displacement relative to the unisolated part of the roof.
Here $f_b = \omega_b / 2\pi$ is the first natural vibration mode frequency, $d_{\max}$ is the maximum isolated roof displacement relative to the unisolated part of the roof. Then the energy dissipated in the RIS can be obtained as follows:

$$E_{RIS} = \int_0^{1/f_b} f_c(t)\dot{d}(t)dt = \int_0^{1/f_b} c_a \dot{d}^2(t)dt = 2\pi^2 f_b c_a d_{\max}^2 \tag{4.1}$$

where k_a and c_a are stiffness and damping coefficients calculated according to Equations (3) and (4), f_c is the damping force developed in the viscous device.

The theoretical relation between the displacement, transferred to the VFD, and the resulting damping force is governed by Eq. 5. The friction force changes sign when loading of the damper is followed by unloading. Therefore the corresponding lines have different slopes: slope k_L for loading and slope k_U for unloading (Figure 3).

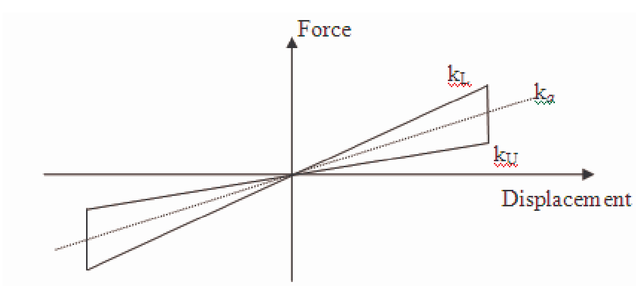

Figure 3. Relation between the damping force and the displacement in VFD (Ribakov et al., 2006).

Let the bisector of the angle between the upper and the lower slopes equals the RIS stiffness coefficient k_a. In other words let

$$k_a = \frac{k_U + k_L}{2} \tag{4.2}$$

Hence the VFD coefficients may be defined by means of a new parameter D ($0 \le D < 1$) using the following equations:

$$k_L = k_a(1 + D), \qquad k_U = k_a(1 - D) \tag{4.3}$$

The energy dissipated in the VFD can be obtained as follows:

$$P_{VFD} = 2\left(\int_0^{1/4 f_b} k_L d(t)\dot{d}(t)dt + \int_{1/4 f_b}^{1/2 f_b} k_U d(t)\dot{d}(t)dt \right) = d_{\max}^2 \frac{k_L - k_U}{4} = d_{\max}^2 \frac{k_a \cdot D}{2} \tag{4.4}$$

By equating the Eqns (4.1) and (4.4),

$$D = \frac{4\pi^2 f_b c_a}{k_a} \tag{4.5}$$

Eqns. (4.5) and (4.3) allow obtaining parameters of a VFD which will yield a seismic response of a structure with isolated roof similar to that with a RIS proposed by Villaverde (2002).

5. NUMERICAL EXAMPLE

To examine the efficiency of the proposed RIS with VFD and the method for selection of the VFD parameters, a numerical simulation of a six story building was carried out. A shear framed structure with stiff beams was analyzed (Figure 4). The structure is a steel frame. Steel ASTM A36 iss used for all shapes of columns and grids. The natural frequencies of the building are 1.083, 2.92, 4.799, 9.596, 7.93, and 6.478 Hz.

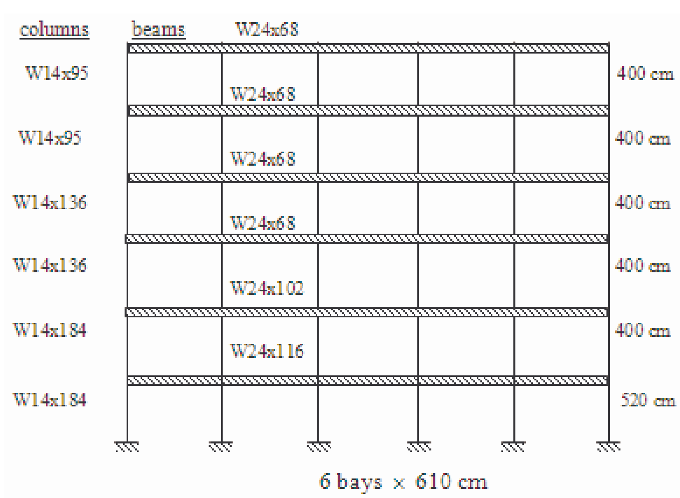

Figure 4. A six-story structure used for numerical analysis

An initial damping ratio of 2% was assumed for all vibration modes of the structure without the RIS. The following three natural seismic excitations were used as input in order to examine the behavior of the structure:

El Centro S00E, 1940, Kobe NF17, 1995, and Hachinohe 1968. The response of the structure was analyzed for the following three cases:
Case 1. Uncontrolled structure;
Case 2. A structure with RIS incorporating elastomeric bearings and viscous dampers (Villaverde 2002);
Case 3. A structure with the proposed RIS including VFD.
All simulations were performed with routines written in MATLAB (Palm, 2003, Tewari, 2002) using the improved fast simulation method (Agranovich at al., 2004). According to the method described by Villaverde (2002), the following optimal RIS parameters were obtained for the selected structure: $m_a = 7.5 \times 10^4$ kg-mass, $k_a = 3.54 \times 10^6$ N/m, $c_a = 1.546 \times 10^5$ N·sec/m . Following Eqn. (4.4), $D = 0.505$ and according to Eqn. (4.3), $k_L = 5330$ kN/m, $k_U = 1750$ kN/m.

Peak values of floor absolute displacements under the selected earthquakes are presented in Figure 5. It should be noted that for all earthquakes the peak response of the structure with the RIS is significantly improved compared to that of the uncontrolled one. The reductions in the peak absolute displacements of the structure with the RIS compared to the uncontrolled one varies from 33% to 50% (see Figure 5).

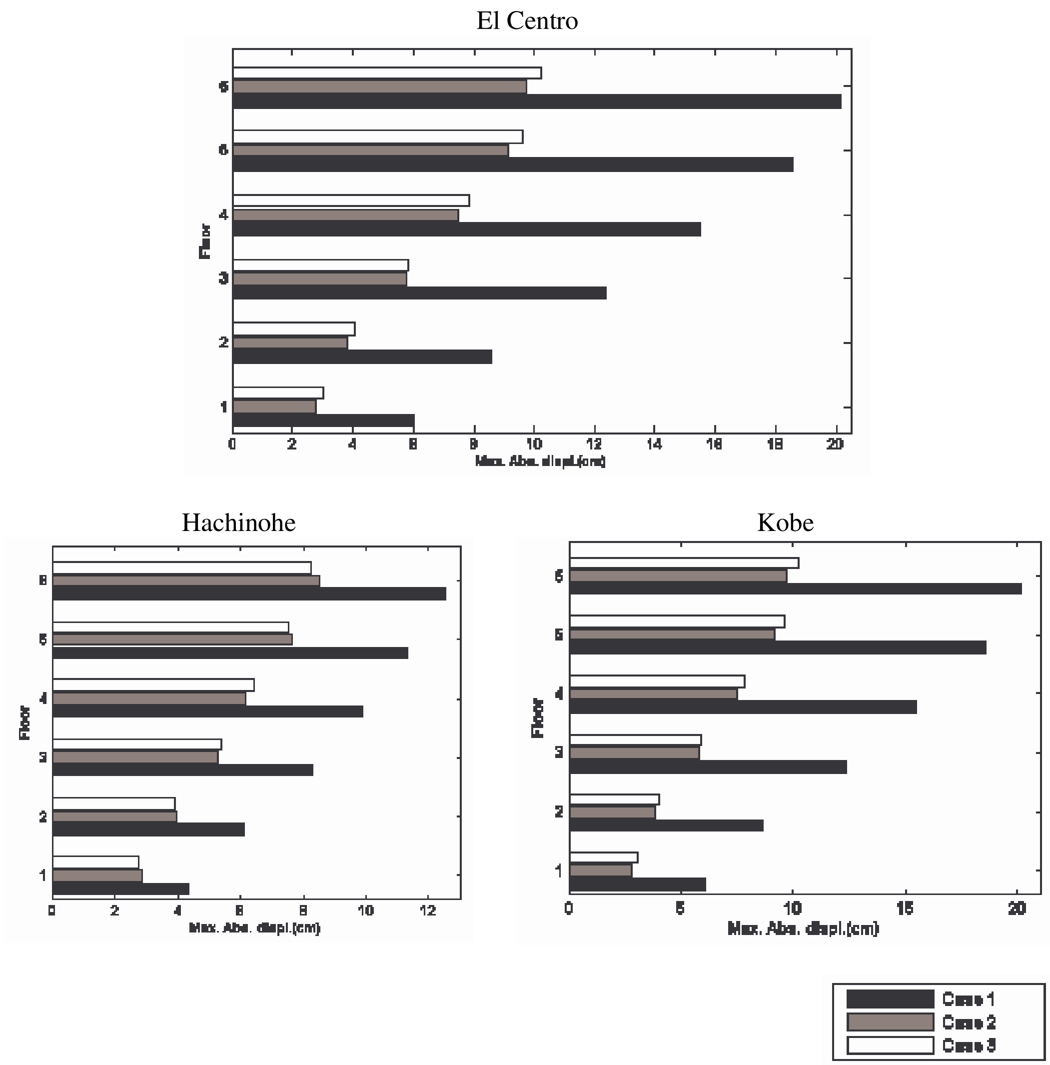

Figure 5. Peak absolute displacements of the building

6. CONCLUSIONS

Variable friction dampers were proposed to be used as a part of a roof isolation system. A method for selection of dampers parameters was developed. It was aimed to yield similar structural response to earthquakes like in the case when roof isolation systems incorporating elastomeric bearings and viscous dampers are used. Selection of VFD properties is based on the assumption that: the maximum isolated roof displacements relative to the unisolated roof part and the energy dissipated in a RIS with isolators and viscous dampers and in that with VFD are equal.

Numerical simulation of a six-story steel frame with two kind of roof isolation systems was carried out in order to prove the efficiency of the proposed method. The building´s response to three natural earthquake records was calculated. It was shown that using roof isolation allows significant reduction in structural response. Absolute peak floors displacements were reduced up to 50% in a structure with roof isolation system compared to an uncontrolled one.

Energy dissipated under the selected earthquakes in the roof isolation system with variable friction damper was similar to that in a roof isolation system with elastomeric bearings and viscous dampers. The peak displacements of the isolated roof part relative to the unisolated one were almost the same for both cases. There was no significant change in the peak base shear forces of the structure with two types of roof isolation systems. Hence the proposed method may be effectively used for design of structures with roof isolation systems incorporating variable friction dampers, providing enhanced structural response to earthquakes.

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