SEISMIC ISOLATION SYSTEMS BASED ON FRICTION-FRACTIONAL VISCOELASTIC DAMPERS

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ABSTRACT :

This work presents a study of some friction-viscoelastic damping systems for base isolation of structures. The systems are based on a friction-viscoelastic damping device made of a rotational friction damping device extended with a rotational fractional viscoelastic unit. The device is designed to dissipate seismic input energy and wind load and protect buildings from structural and non-structural damage during moderate and severe earthquakes as well as dynamic effects from wind. The damper device has been tested at DTU in Denmark, while intensive experimental tests have been carried out with the friction version of the damper at Takenaka research center in Japan. The comparison of results obtained from the experimental and numerical models show good agreement. Studying the response for static and dynamic loading has identified parameters influencing the response of a structure improved with a given damping system. The quality of the damping system is related to the structural response and an evaluation of the investigated damping systems is made. The damper device is easy to implement in structures. It is an economic device due to material availability. It can easily be replaced if damaged, which is unlikely to happen and it is easily readjusted in site. The frictional damper device has been installed in several buildings in Japan, Greece, India and Denmark.

KEYWORDS: Structural systems, structural response, friction-viscoelastic damper, base isolation, passive control, dampers.

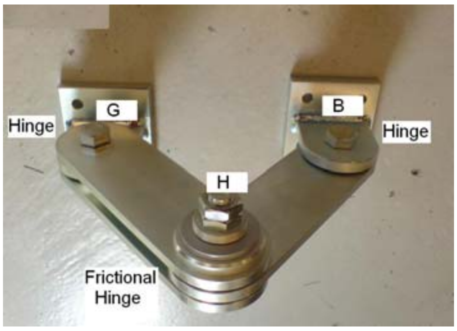
1. INTRODUCTION

Seismic isolation of a structure reduces the transfer of ground motion produced by an earthquake to the structure. Seismic isolation is typically obtained by a damping system acting as base isolation between the structure and the ground. Such damping systems are designed to protect structural integrity and prevent damages and injuries to the occupants by reducing seismic forces and deformations in the structure [1]. Several types of base isolation systems have been proposed and investigated see e.g. [2] and [3]. Friction dampers are often an essential component of these base isolation systems because they represent a high energy dissipation potential at low cost and are easy to install and maintain. Several friction devices have been tested experimentally [4],[5],[7],[8],[9] and some of these have been implemented in buildings around the world. Also viscoelastic dampers are often used in base isolation systems see e.g. [6].

The present paper concerns the development of a new rather inexpensive friction-viscoelastic damper and its application in damping systems for base isolation of a structure. The computational modeling of the base isolated structure is described and results from the simulations concerning essential structural design quantities are discussed.

2. DAMPING SYSTEM

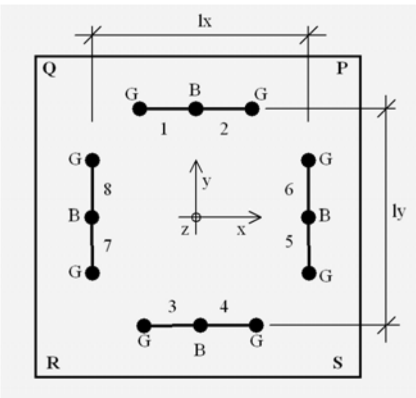
The friction damper (FD), see Figure 2.1, consists of two rigid plates HG and HB connected in the rotational hinge H. The moment-rotation behavior in H is elastic-frictional. When the damper is used for base isolation of a structure, the two other plate end points – the connection points - are moment free connected to ground (G) and structural base (B). When the distance between the connection points changes, the angle between the damper plates changes in the hinge H and the damper dissipates energy if the elastic rotation limit is exceeded, i.e. if sliding occurs in the hinge. Extending the friction damper, as AFV in figure 4.1, with another plate VC connected to AFV in the viscoelastic rotational hinge V, results in the friction-viscoelastic damper (FVD) considered in this paper.

(A) 

(B) 

Figure 2.1 (A) Friction damper, (B) Experimental setup at DTU Denmark for the friction damper.

An example on application of FDs or FVDs in a damping system for horizontal base isolation of a structure is shown in figure 2.2, where eight identical dampers are inserted between the structural base PQRS and the ground. One connection point of each damper is connected the structural base in a point B and the other connection point to the ground in a point G. The dampers are used in pairs to obtain symmetric behavior of the damper pair. Four pairs are used in the damping system to obtain symmetric behavior and to obtain damping resistance against both the two translation components in the horizontal plane (*x,y*-plane) and the rotation about the vertical axis (z-axis). This damping system (rhombic) is investigated here together with another damping system (triangular) with a three damper pair arrangement along the sides of an equilateral triangle.

(A) 

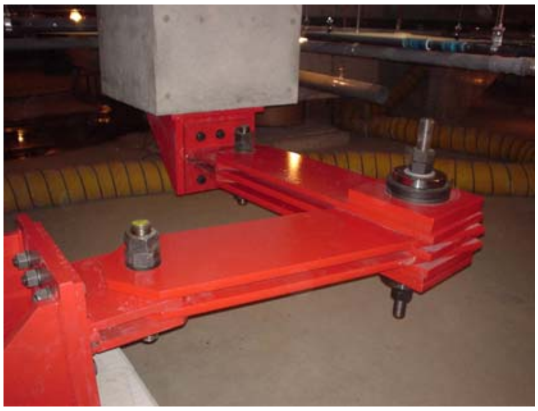
(B) 

Figure 2.2 (A) Double symmetric 8 damper system of FVDs. Each damper connects ground (G) and base (B).
(B) Friction damper device installed as part of Base Isolation System

3. DAMPER APPLICATIONS

Figure 3.1-2 show some buildings, where the pure friction version of the damper has been used for base isolation.

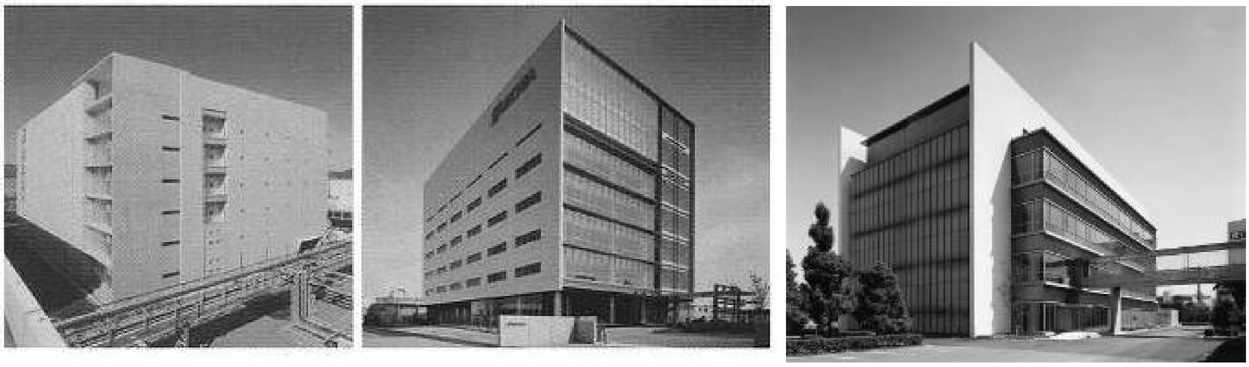


Figure 3.1 Several building projects of 5, 7 & 9 floors.

Figure 3.2 Three new towers of 40 floors and a finished residential tower of 44 floors.

4. MODELING

4.1 Friction-viscoelastic damper

The friction-viscoelastic damper with two energy-dissipating hinges Figure 4.1 consists of three rigid plates AF (length *a*), FV (length *b*) and VC (length *c*) connected in a frictional hinge F with the mutual angle v_f between the connected plates and in a viscoelastic hinge V with the mutual angle v_v (subscripts *f* and *v* for frictional respectively viscoelastic). When the length d of the damper, i.e. the distance between the connection points A and C increases *u* from the undeformed value d_0, the angles between the damper plates increase θ_f and θ_v in point F respectively V.

In the frictional hinge the elastic deformations are neglected, i.e. the moment-rotation (M_f-θ_f) relation is rigid-frictional with the sliding moment M_{sf}.

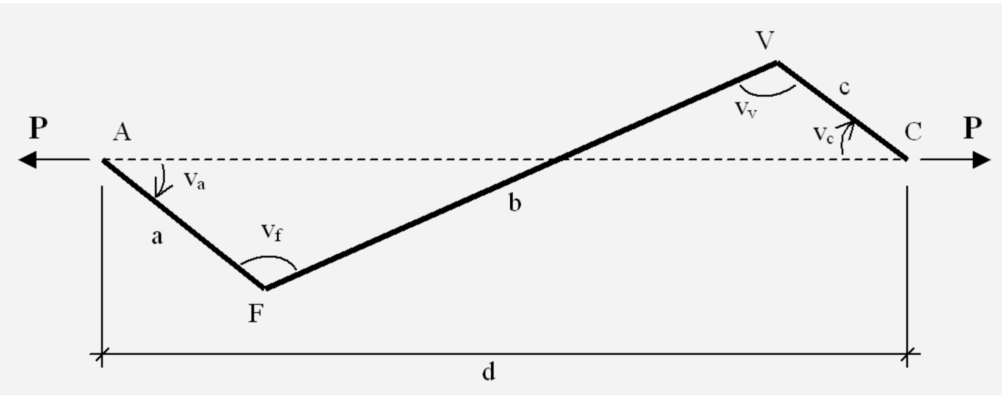


Figure 4.1 Geometry and notation for friction-viscoelastic damper.

The moment-rotation (M_v-θ_v) behavior in the viscoelastic hinge is fractional viscoelastic, i.e.

$$M_v(t) + a_v D^\alpha M_v(t) = k_v(\theta_v(t) + b_v D^\alpha \theta_v(t)) \tag{3.1}$$

where k_v, a_v, b_v, α are material constants, $0 < \alpha < 1$ and D^α the fractional derivative (see e.g. [10]).

Neglecting mass inertia forces in the damper, the force interaction between the damper and the surroundings is characterized by forces P in the external connection points along the connecting line, Figure 4.1. The essential damper behavior in relation to the structure in which the damper is used, is the *P-u* behavior. The friction-viscoelastic damper is discussed in more detail in [11,12].

4.2 Structural modeling

Representative for a typical several storey building structure is considered a structure, see Figure 4.2, consisting of a superstructure (s), a base (b), which is connected to the ground (g) through supports for vertical load, and an isolation system for horizontal loads. The isolation system is made of FVDs and an auxiliary system (a) connecting base and ground. The dampers are e.g. arranged as shown in figure 2.2.

As structural model is used a vertical shear beam with torsion about the beam axis (*z*-axis). The shear beam end nodes are located with node 1 in the base and node 2 in the superstructure. In each node 3 degrees of freedom (dof) exist: the translations u_x,u_y in the horizontal x,y-plane and the rotation r_z about the z-axis.

A first order mechanical theory is used for the structure except the FVDs, which are handled exact as described in section 4.1. The resulting governing equations are

$$\mathbf{M}\ddot{\mathbf{V}}^r + \mathbf{C}\dot{\mathbf{V}}^r + \mathbf{K}\mathbf{V}^r = \mathbf{R} + \begin{bmatrix} \mathbf{F}_d \\ 0 \end{bmatrix} - \mathbf{M}\ddot{\mathbf{V}}^g \tag{3.2}$$

where **M** is the mass matrix for the system, **C** the viscous damping matrix, **K** the stiffness matrix, **R** the external load vector, $\mathbf{F}_d$ the load vector from the forces on the base from all FVD's, **V** the DOF-vector and $\ddot{\mathbf{V}}^g$ represents the ground accelerations. Superscript r indicates relative motion and each dot a time differentiation.

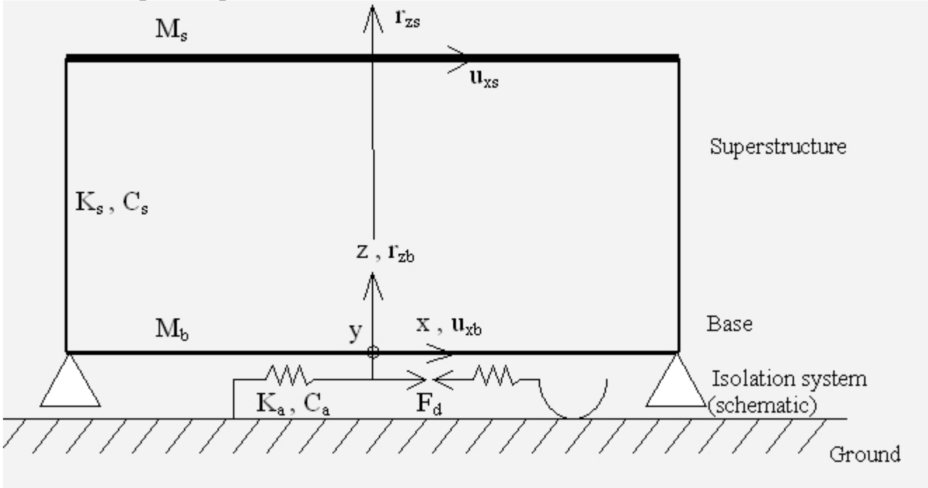


Figure 4.2 Structure with isolation system.

In the following the ground motion represents an earthquake and the structural behavior $\mathbf{V}(t)$ for $t > 0$ is determined from Eqn. 4.2 and the initial conditions $\mathbf{V}(0) = \dot{\mathbf{V}}(0) = 0$ corresponding to a structure initially at rest. Eqn. 4.2 with initial conditions is integrated numerically in time by the central difference method as further discussed in [11].

5. STRUCTURAL RESPONSE

The structure Figure 4.2 with isolation system - Figure 2.2 or the triangular version - is loaded by horizontal ground accelerations in the x-direction corresponding to an earthquake acceleration component (El-Centro with max acceleration 0.35g (g = gravity)) and some aspects of the structural response are studied. In the FVDs $a = b/2 = c$ and in the undeformed state $|v_a| = |v_f| = |v_v| = |v_c| = 60^0$. The elastic stiffness k_f of the frictional hinge is great compared with the elastic stiffness k_v of the viscoelastic hinge. The viscoelastic properties in the FVDs are determined by $a_v = 0.14, b_v = 13.07, \alpha = 0.243$ see (4.1). For the superstructure the undamped period is $T_s = 1\text{sec}$ and the viscous damping ratio $\zeta_s = 0.02$. The superstructure mass m is equal to the base mass. No auxiliary damping system is used.

The damper system is designed according to the following principles, which for simplicity are applied to closed dampers (both frictional hinge and the viscoelastic hinge closed).

The horizontal sliding load is equal to a specified part (r_{hor}) of the structural weight, i.e.

$$r_{hor} 2mg = n_{ac} \frac{M_{sf}}{a} \tag{4.1}$$

where n_{ac} is the number of initially contributing dampers ($n_{ac} = 4$ for the rhombic system, $n_{ac} = 4/\sqrt{2}$ for the triangular system). Here is considered $r_{hor} = 0.025, 0.05, 0.1, 0.2$.

A value is specified for the small vibration period T_b of the rigid structure with isolation system, i.e.

$$(\frac{2\pi}{T_b})^2 = \frac{n_{ac} k_{veff} / a^2}{2m} \tag{4.2}$$

where k_{veff} is the effective stiffness in the viscoelastic hinge at harmonic vibrations with period T_b. Here is considered $T_b = 2\sec$. Then a time window for integration of the viscoelastic material equal to 2sec is sufficiently.

In order to obtain a reasonable damper geometry the damper plate length should not be too small. Here is chosen $a \geq 0.3m$. Moreover to obtain some balance between the frictional part and the viscoelastic part of the FVD, the sliding moment M_{sf} has to be reached in the viscoelastic hinge for a not too large angle change θ_{vs} (as large as possible but not exceeding 20^0) in the viscoelastic hinge at reasonable strain rates. Here is chosen a harmonic vibration with period T_b as reference, i.e.

$$M_{sf} = k_{veff} \theta_{vs} \tag{4.3}$$

The damper designs based on Eqn. 5.1-3 and the above mentioned restrictions on a, θ_{vs} are shown in figure 5.1. For decreasing r_{hor} when a reach its lower limit, decreasing θ_{vs} compensates.

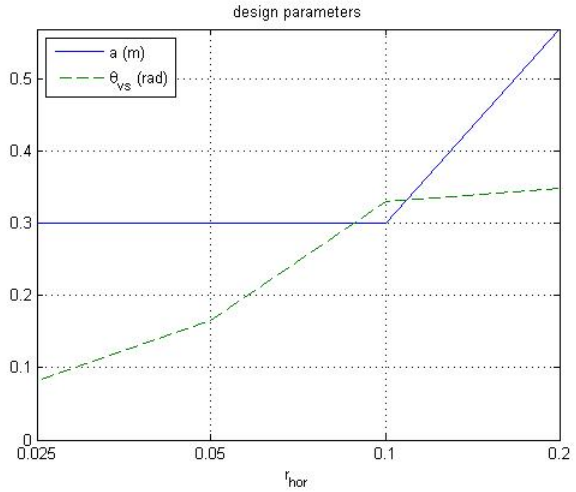


Figure 5.1 Damper design parameters as function of horizontal resistance.

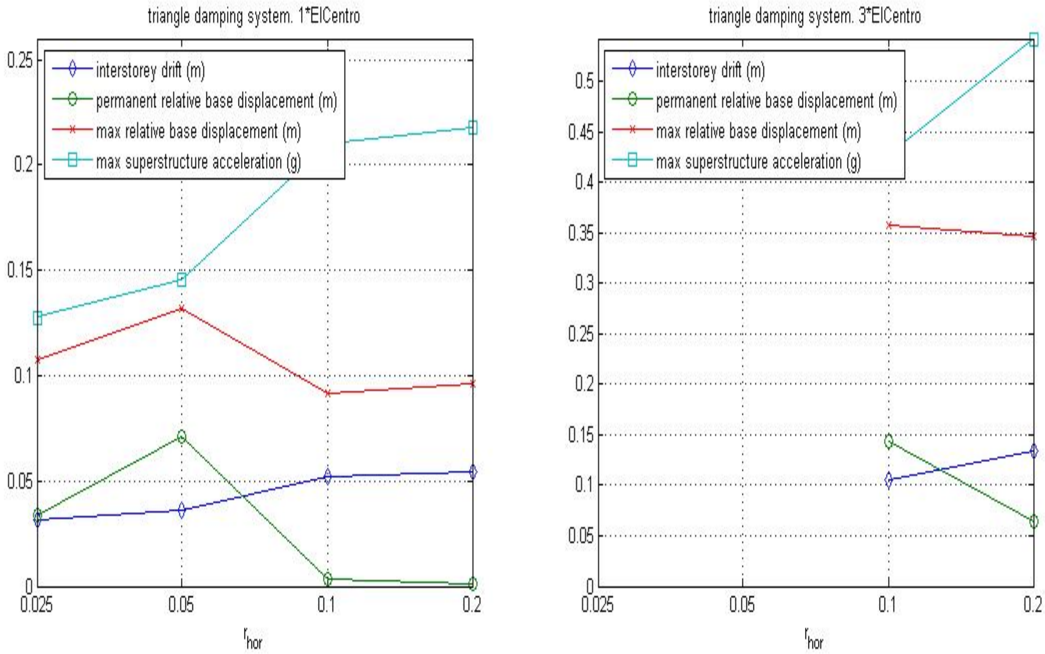


Figure 5.2 Behavior of structure with triangular damping system as function of horizontal resistance for El-Centro (left) and $3\times$El-Centro (right).

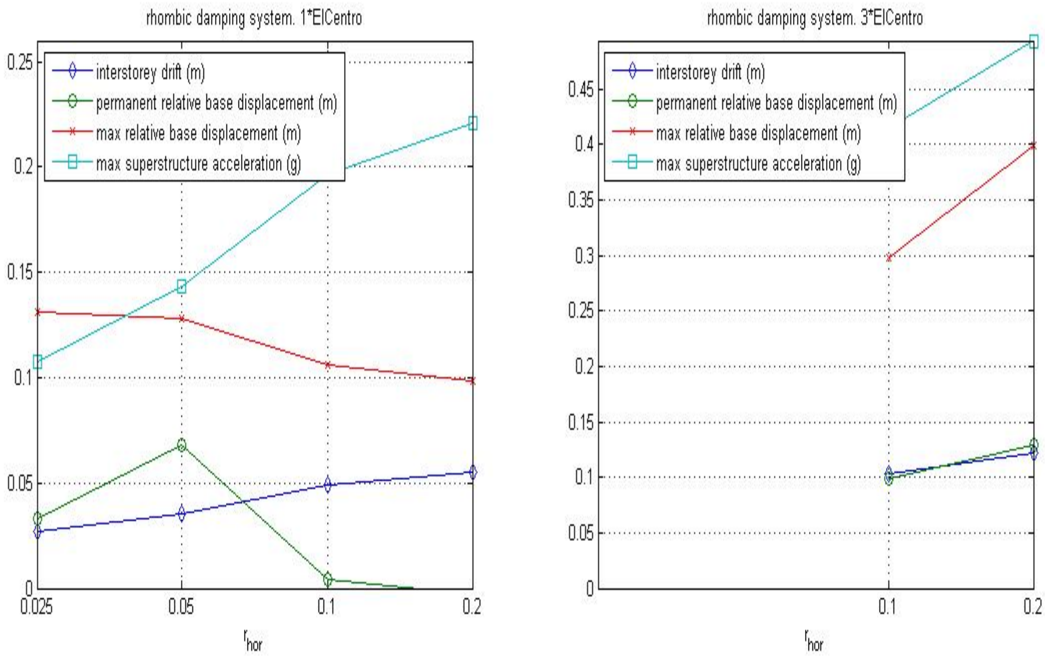


Figure 5.3 Behavior of structure with rhombic damping system as function of horizontal resistance for El-Centro (left) and $3\times$El-Centro (right).

The structural response quantities considered are

$$\text{interstorey drift} = \max_t |u_{xs}^r(t) - u_{xb}^r(t)|$$

$$\text{permanent relative base displacement} = u_{xb}^r(t_{after})$$

$$\text{max relative base displacement} = \max_t |u_{xb}^r(t)|$$

$$\text{max superstructure acceleration} = \max_t |\ddot{u}_{xs}^r(t) + \ddot{u}_{xg}(t)|$$

where $\max_t$ means the maximum over the earthquake and t_{after} means a time after the earthquake has finished and where the structure again is in rest.

In figure 5.2 (left) is shown how these structural response quantities depend on the chosen horizontal resistance using the triangular damping system. Figure 5.2 (right) shows the same for 3 times the ElCentro accelerations, but only for sufficient high values for the horizontal resistance because the damping system otherwise breaks down with closing frictional hinges. Figure 5.3 concerns the rhombic damping system and the conclusions are as for the triangular damping system. In total can be concluded that both damping system are useful possibilities for base isolation of structures against earthquakes.

6. CONCLUSIONS

A new friction-viscoelastic damper and its application in two damping systems for base isolation of a structure have been investigated. The experiments with the pure friction version of the damper have shown very stable behavior and also the full version behaves promising. The computational modeling of the damper and the structural analysis has indicated rather efficient damping systems and has also indicated its limitations. These systems are very effective in damping vibration caused by strong winds as well as earthquakes. The devices are easy to implement in structures. They are economic devices due to material availability.
Several of the new damping systems have been installed in projects in Japan, Greece, India and Denmark.

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