

SEISMIC ISOLATION WITH A NEW FRICTION-VISCOELASTIC DAMPING SYSTEM

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SUMMARY

This work presents a study on the parameters that govern the performance of a friction-viscoelastic damping system for base isolation of structures. This system is based on a friction-viscoelastic damper made of a friction damper extended with a viscoelastic unit. The device is designed to dissipate seismic input energy and protect buildings from structural and nonstructural damage during moderate and severe earthquakes.

The damper has been tested at DTU in Denmark and later on experimental tests have also been carried out with the pure friction damper at Takenaka research center in Japan. The comparison of results obtained from the experimental and numerical models shows good agreement.

Studying the response for static and dynamic loading has identified the parameters influencing the response of a structure improved with the damping system. The numerical studies have demonstrated that the overall response is mainly affected by damper properties as geometry, frictional sliding moment and viscoelastic properties combined with the structural natural frequencies.

The device is easy to manufacture and implement in structures. It is an economic device due to material availability. It can easily be replaced if damaged, which is unlikely, and it can easily be readjusted after use.

The friction dampers have been installed in a new 5 storey RC building in Japan.

KEY WORDS: structural systems, structural response, experimental testing, active and passive control, evaluation and retrofit, friction-viscoelastic damper, base isolation

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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]. The number of projects with such systems is increasing in different places around the world and the base isolation systems have proved their value through many earthquakes.

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] and [5], 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 a damping system for base isolation of a structure. The damper can easily be manufactured and installed in a short time without a need of qualified staff. The friction version of the damper has been installed in a new 5 storey RC building in Japan. In the following a computational model is set up for the mechanical behavior of the damper and this is combined with a computational modeling of the damping system and the structure loaded by an earthquake. Next this model is used for determination of essential structural design quantities as a function of earthquake intensity.

2. DAMPING SYSTEM

The friction damper (FD), see Figure 2.1 and 2.2, 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.



Figure 2.1: Friction damper.

Extending the friction damper, as AFV on 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.



Figure 2.2: 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 on Figure 2.3, 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). Of course many other arrangements are possible, e.g. a three damper pair arrangement along the sides of a triangle.



Figure 2.3: Double symmetric 8 damper system of FDs or FVDs. Each damper connects ground (G) and base (B).

3. FRICTION DAMPER TESTS

A large capacity friction damper (force capacity 120 kN) has been built and tested at DTU in an 250 kN Instron machine as shown on Fig 2.2. Loads with different frequencies and displacement amplitudes have been applied. The test results indicates a stable performance over many cycles as shown in Figure 3.1 for 100 cycles with the frequency 0.5 Hz and the displacement amplitude 25 mm. This good performance is owing to the use of a special friction pad material between the damper plates in the frictional hinge. Further investigations support this conclusion [7], [8], [9].



Figure 3.1: Experimental displacement cycle test of friction damper.

Another case is the friction dampers for a new 5-storey RC laboratory building in Japan, see Figure 3.2, which needs 8 dampers installed in the basement as base isolation Figure 3.3. Tests have been conducted, see Figure 3.4, through a hydraulic actuator with a capacity 500kN, stroke 1016 mm and a force transducer with maximum load of 500kN as follows:

- 50 mm amplitude (5 tests) to adjust clamping force to get required slip force
- 300 mm amplitude (4 tests) to inspect period dependency
- 480 mm displacement (2 tests) by static loading
- 480 mm amplitude (1 test) to confirm the limit displacement
- 300 mm amplitude (2 tests) to inspect direction dependency

The required capacity for the dampers have been achieved. Beside these tests other tests have been conducted on a scaled model with different temperatures to evaluate the damper's temperature independence.

The installation of a damper Figure 3.5 needs two workers in less than one day.



Figure 3.2: Building base isolated with friction dampers.



Figure 3.3: Layout of damper locations at base of building.



Figure 3.4: Experimental tests of friction damper at Takenaka Research Center, Japan



Figure 3.5: The friction damper after installation in the building base.

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.



Figure 4.1: Geometry and notation for friction-viscoelastic damper.

The moment-rotation $(M_f - \theta_f)$ behavior in the frictional hinge is elastic-frictional as shown on Figure 4.2a with an elastic stiffness k_f and the sliding moment M_{sf} , i.e.

$$\dot{M}_{f} = 0 \qquad for \ abs(M_{f}) = M_{sf} \ and \ M_{f}\dot{\theta}_{f} > 0$$

$$\dot{M}_{f} = k_{f}\dot{\theta}_{f} \quad otherwise \qquad (4.1)$$

where a dot over a symbol means differentiation $\frac{d}{dt}$ with respect to time *t*.

The moment-rotation $(M_{\nu}-\theta_{\nu})$ behavior in the viscoelastic hinge is fractional viscoelastic, i.e.

$$M_{\nu}(t) + a_{\nu}D^{\alpha}M_{\nu}(t) = k_{\nu}(\theta_{\nu}(t) + b_{\nu}D^{\alpha}\theta_{\nu}(t))$$

$$(4.2)$$

where k_v, a_v, b_v, α are material constants and where the fractional derivative of a time dependent variable y(t) is defined by (see e.g. [10])

$$D^{\alpha} y(t) = \frac{1}{\Gamma(1-\alpha)} \frac{d}{dt} \int_{0}^{t} \frac{y(\zeta)}{(t-\zeta)^{\alpha}} d\zeta$$
(4.3)

The harmonic behavior of the fractional viscoelastic material is illustrated on Figure 4.2b.



Figure 4.2: Behavior of frictional hinge (a) and of harmonic loaded viscoelastic hinge (b).

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 determined as follows.

From statics of the deformed damper (hinge connections in the connection points A and C)

$$Pa\sin v_a - M_f = 0 \tag{4.4}$$

$$Pc\sin v_c - M_v = 0 \tag{4.5}$$

Specifying the direction at point C of AC and the position of point C determined from point A along the damper give 3 geometrical conditions

$$v_a + v_f - v_v - v_c = 0 (4.6)$$

$$a\cos v_a - b\cos(v_a + v_f) + c\cos v_c - u - d_0 = 0$$
(4.7)

$$a\sin v_{a} - b\sin(v_{a} + v_{f}) + c\sin v_{c} = 0$$
(4.8)

The above mathematical description (4.1-8) breaks down, when a damper hinge straightens or closes. Moreover if the damper becomes static instable internally. In the first case an infinite large force is possible in the direction of the damper plates. In the second case a snap back type behavior occurs giving a sudden finite state change. Both types of behavior are unacceptable from an application point of view, i.e. the limitations of mathematical model can be accepted.

The numerical handling of (4.1-8) is as follows. From a solution $P, M_f, M_v, v_a, v_f, v_v, v_c, u$ to the above equations (4.4-8) and the constitutive conditions in F and V (4.1-2) is determined a new solution $P, M_f, M_v, v_a, v_f, v_v, v_c$ for a given increase Δu in u by the Newton-Raphson method. For integration of the fractional derivative (4.3) a time window equal to a half cycle is reasonable, see also [10].

4.2 Structural modeling

Representative for a typical several storey building structure is considered a structure, see Figure 4.3, 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 arranged as shown on Figure 2.3.

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.



Figure 4.3: Structure with isolation system.

Using a first order mechanical theory for the structure except the FVDs, which are handled exact as described in section 4.1, the notation in the following is as follows. **M** is a mass matrix, **C** a viscous damping matrix, **K** a stiffness matrix and **V** a dof-vector. A subscript on these quantities specifies the related structural unit, e.g. \mathbf{M}_s is the mass matrix for the superstructure and **K** the stiffness matrix for the total system (superstructure + base + isolation system).

The natural vibration problem (periods T_s) for the superstructure (with fixed base) has some importance as reference. It is governed by

$$\mathbf{M}_{s} \ddot{\mathbf{V}}_{s} + \mathbf{C}_{s} \dot{\mathbf{V}}_{s} + \mathbf{K}_{s} \mathbf{V}_{s} = 0$$
(4.9)
where $\mathbf{V}_{s}^{T} = [u_{xs} u_{ys} r_{zs}].$

Assuming that the damping in the superstructure is connected to the superstructure deformation and not its rigid body motion and neglecting the mass of the isolation system, the equations for the dynamic behaviour of the total system can be formulated as

$$\mathbf{M}\ddot{\mathbf{V}} + \mathbf{C}\dot{\mathbf{V}} + \mathbf{K}\mathbf{V} = \mathbf{R} + \begin{bmatrix} \mathbf{F}_d \\ 0 \end{bmatrix} + \begin{bmatrix} \mathbf{C}_a\dot{\mathbf{V}}_g + \mathbf{K}_a\mathbf{V}_g \\ 0 \end{bmatrix}$$
(4.10)

where

$$\mathbf{V}^{T} = [\mathbf{V}_{b}^{T} \ \mathbf{V}_{s}^{T}] = [u_{xb} \ u_{yb} \ r_{zb} \ u_{xs} \ u_{ys} \ r_{zs}]$$

$$(4.11)$$

$$\mathbf{M} = \begin{vmatrix} \mathbf{M}_b & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_s \end{vmatrix} \tag{4.12}$$

$$\mathbf{C} = \begin{bmatrix} \mathbf{C}_s + \mathbf{C}_a & -\mathbf{C}_s \\ -\mathbf{C}_s & \mathbf{C}_s \end{bmatrix}$$
(4.13)

$$\mathbf{K} = \begin{bmatrix} \mathbf{K}_s + \mathbf{K}_a & -\mathbf{K}_s \\ -\mathbf{K}_s & \mathbf{K}_s \end{bmatrix}$$
(4.14)

(4.15)

 $\mathbf{R} = \text{external load vector}$

 $\mathbf{F}_d = \text{load vector from the forces on the base from all FVDs}$ (4.16) with the horizontal ground motion

$$\mathbf{V}_{g}^{T} = \left[u_{xg} \ u_{yg} \ r_{zg}\right] \tag{4.17}$$

With a prescribed ground motion it is appropriate to introduce relative displacements \mathbf{V}^r of the system defined as the displacements beyond a rigid body motion \mathbf{V}^g of the system following the ground motion, i.e.

$$\mathbf{V}^r = \mathbf{V} - \mathbf{V}^g \tag{4.18}$$

$$\mathbf{V}^{gT} = [\mathbf{V}_g^T \ \mathbf{V}_g^T] \tag{4.19}$$

Inserting (4.18) in (4.10) modifies the governing equation to

$$\mathbf{M}\ddot{\mathbf{V}}^{r} + \mathbf{C}\dot{\mathbf{V}}^{r} + \mathbf{K}\mathbf{V}^{r} = \mathbf{R} + \begin{bmatrix} \mathbf{F}_{d} \\ \mathbf{0} \end{bmatrix} - \mathbf{M}\ddot{\mathbf{V}}^{g}$$
(4.20)

because the internal forces are independent of a rigid body motion of the system.

In the following the ground motion represents an earthquake and the structural behavior $\mathbf{V}(t)$ for t > 0 is determined from (4.20) and the initial conditions $\mathbf{V}(0) = \dot{\mathbf{V}}(0) = 0$ corresponding to a structure initially at rest.

The equation (4.20) with initial conditions are integrated numerically in time by the central difference method. The time step Δt is typically chosen to 0.01 sec. Then the load from the ground acceleration in (4.19) typically specified per 0.02 sec and interpolated linearly in each intermediate interval is handled reasonably. Moreover the numerical stability of (4.20) is secured, because the natural structural periods included in (4.20) typically are much larger than Δt . Finally the transition between elastic and sliding behavior in the damper is handled sufficiently accurate without special precautions. Of course, halving the time step does not change the computational results essentially.

5. STRUCTURAL RESPONSE

The structure Figure 4.3 with isolation system Figure 2.3 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 $|v_a| = |v_f| = |v_v| = |v_c| = 60^\circ$. 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 (4.2). For the superstructure mass m is equal to the base mass. No auxiliary damping system is used, i.e. $K_a = C_a = 0$.

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.

$$r_{hor} 2mg = n_{ac} \frac{M_{sf}}{a}$$
(5.1)

where the number of contributing dampers $n_{ac} = 4$ (initially only damper 1-4 gives resistance). Here is considered $r_{hor} = 0.15, 0.3$ the low respectively the high resistant system.

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

$$\left(\frac{2\pi}{T_{h}}\right)^{2} = \frac{n_{ac}k_{veff} / a^{2}}{2m}$$
(5.2)

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 certain 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 specified angle change θ_{vs} in the viscoelastic hinge at a harmonic vibration with period T_b , i.e.

$$M_{sf} = k_{veff} \theta_{vs}$$
(5.3)

Here is chosen $\theta_{vs} = 20^{\circ}$.

For the two above defined designs, (5.1-3) gives a = 0.427m in the low resistant system and a = 0.854m in the high resistant system. These two designs are investigated below.

To illustrate the behavior of the symmetric 8 damper system, the high resistant version is subjected to a slow (no inertia forces, no time effects in viscoelastic hinges) 5/4 displacement cycle in the x-direction (with no time effects is k_v changed to k_{veff} in this slow cycle case). The resultant force component P in the displacement direction in the damping system is shown as function of the displacement u on Figure 5.1a. Each slope discontinuity on the P-u curve corresponds to a phase shift in one or more dampers (elastic \rightarrow sliding or reverse). With $Pa/M_{sf} = 1$ as an approximate measure for the sliding strength of a single damper, the non-dimensional loads 4-5 at first (sliding in elongating dampers 1,3) and second (also sliding in shortening dampers 2,4) slope discontinuity are easily understood.



Figure 5.1: Behavior of friction-viscoelastic damping system. a) 5/4 slow cycle. b) 3/2 small cycle.

The viscoelastic behavior is tested in a small amplitude harmonic cycle test without inertia forces. Then no sliding occurs in the frictional hinges and the geometric non-linearities are without importance, i.e. the behavior is essentially linear and can be verified against an exact harmonic solution as shown on Figure 5.1b.



Figure 5.2: Behavior of high resistant structure as function of earthquake intensity.



Figure 5.3: Behavior of low resistant structure as function of earthquake intensity.

In order to investigate the influence of earthquake intensity on structural response are the ground accelerations multiplied with a factor - the ground acceleration factor -. The structural response quantities considered are

interstorey drift = max $|u_{xs}^{r}(t) - u_{xb}^{r}(t)|$ (5.4)

permanent relative base displacement = $u_{xb}^r(t_{after})$ (5.5)

max relative base displacement = $\max_{t} |u_{xb}^{r}(t)|$ (5.6)

max superstructure acceleration = $\max_{t} |\ddot{u}_{xs}^{r}(t) + \ddot{u}_{xg}(t)|$ (5.7)

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.

On Figure 5.2 is shown for the high resistant structure how these structural response quantities are increased with the ground acceleration factor. Figure 5.3 shows the same for the low resistant structure, but only up to a ground acceleration factor equal to 4 because the damping system breaks down for a ground acceleration factor equal to 6, where a frictional hinge closes.

6. CONCLUSIONS

A new rather inexpensive friction-viscoelastic damper and its application in a damping system for base isolation of a structure have been investigated. The experiments with the pure friction version of the damper have shown that it has a stable behavior and that it can easily be manufactured and installed in a short time without a need of qualified staff. The computational modeling of the damper and the structural analysis has indicated a rather efficient damping system and has also indicated its limitations.

REFERENCES

- 1. Housner GW, Bregman LA, Caughey TK, Chassiakos AG, Claus RO, Masri SF, et al. "Structural control: Past, present and future." Journal of Engineering Mechanics 1997; 123(9):897-971.
- Skinner RI, Robinson WH, McVerry GH. "An Introduction to Seismic Isolation. England": John Wiley & Sons, 1993.
- 3. Chopra A K. "Dynamics of Structures." USA : Prentice-Hall. 1995.
- Aiken ID, Kelly JM. "Earthquake simulator testing and analytical studies of two energy-absorbing systems for multistory structures." Report No. UCB/EERC-90-03, University of California, Berkeley, 1990.
- Constantinou MC, Reinhorn AM, Mokha AS, Watson R." Displacement control device for baseisolated bridges." Earthquake Spectra 1991; 7(2):179-200.
- Kelly JM. "The role of damping in seismic isolation" Earthquake Engng. Struct. Dyn. 1999; 28:3-20.
- 7. Mualla, I.H. "Experimental Evaluation of a New Friction Damper Device", 12th World Conference on Earthquake Engineering, Auckland, New Zealand, 2000.
- 8. Mualla, I. H. "Parameters Influencing the Behavior of a New Friction Damper Device ",SPIE's 7th International Symposium on Smart Structures & Materials, SS2000, CA, USA, 2000.
- I. H. Mualla, L.O. Nielsen, B. Belev, W. I. Liao, C. H. Loh, A. Agrawal, "Performance of Friction-Damped Frame Structure: Shaking Table Testing and Numerical Simulations",7th U.S. National Conference on Earthquake Engineering, Boston, USA, 2002.
- 10. Koh CG, Kelly JM. "Application of Fractional Derivatives to Seismic Analysis of Base-Isolated Models" Earthquake Engng. Struct. Dyn. 1990; 19:229-241.