DRY FRICTION DAMPING OF MULTISTORY STRUCTURES

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SUMMARY

Earthquake responses of 20-story framed structures with interfloor dry (Coulomb) friction dampers are presented in spectral form. Elastic stiffness and magnitude of the slip force in the dampers are related to stiffness and mass of the structures in a systematic way. Near optimum combinations of damper slip force ratio and stiffness ratio are found to greatly reduce response of buildings having a wide range of periods. A telescoping steel diagonal strut is statically tested as a friction damper at 13.5 tons force. It is concluded that friction damping has promise for practical application. More development work and dynamic testing are necessary.

INTRODUCTION

Damping is effective in reducing the response of a structure to an earthquake because, at any instant, when ground acceleration pulses are imparting kinetic energy to the structure, most of the energy which had been imparted by earlier pulses has been dissipated. Thus the total vibrational energy at any instant is reduced, and the buildup of vibrations of large amplitudes can be prevented. Damping can be accomplished by the radiation of energy into the ground and the air, by the distortion and sliding of nonstructural elements and building contents, by the distortion of structural elements, or by the action of auxiliary energy dissipators.

At the present time most framed structures are designed so that under strong shaking, with little damping from nonstructural sources, portions of the structural members must undergo inelastic deformations which lengthen the effective periods of the structures and provide a certain amount of energy dissipation. This paper examines auxiliary dampers which would come into action and dissipate energy at lower levels of deformation, while the structural frame is still elastic, thus reducing building sway, structural and nonstructural damage, and ductility and energy dissipation requirements for structural members.

Ideally, damping capacity should be distributed throughout every element of volume of the structure; in practice auxiliary dampers must be attached at discrete points, and thus new forces are imposed, possibly resulting in more taxing conditions for some members than if there were no auxiliary dampers. This paper does not examine the effects of such extra local loading, nor does it examine if any member is adequate, but views the structure as an assembly of masses connected by an elastic frame. More detailed analysis of member forces and better balancing of member properties, recognizing the presence of dampers, is a subject for future investigation.

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CLASSIFICATION OF FRICTION DAMPED STRUCTURES

The major factors affecting the earthquake response of a building are the building's vibrational periods and the fraction of vibrational energy dissipated per cycle, both of which in reality are functions of amplitude. In this study of friction damping, 20-story buildings of different periods were created by multiplying all masses of a basic building (which has appeared in previous studies[1,2,3,4]) by the ratio $(T_1/2.21)^2$, where T_1 is the fundamental period of a new building, and 2.21 sec. is the fundamental period of the basic building (Fig. 1). The basic building was designed according to the 1965 Uniform Building Code. Within each story of a building there was assumed a friction damper which elastically resists interfloor displacement up to its slip force, F_i, after which slipping occurs (Fig. 2). The slip force of each story's damper was made equal to a constant, F/W, times the total building weight above that story, W_i, and the elastic stiffness of the damper, K_{Di}, was made equal to a constant, STFCON, times the story stiffness of the frame, which was defined by

$$K_{Fi} = \sum_{j=i}^{20} K_{ij}. \quad K_{Di} = \text{STFCON} \times K_{Fi}. \quad W_i = \sum_{j=i}^{20} \text{mass}_j \times g.$$

In any one building, the stiffness ratio, STFCON, and the slip force ratio, F/W, were both kept constant for all dampers. Thus, the buildings studied were classified by three numbers: T_1, the fundamental period of the elastic building without dampers; F/W, the ratio of damper slip force to weight above the damper; and STFCON, the ratio of damper stiffness when not slipping to story stiffness of the frame. These damper properties would be those in the horizontal direction if the dampers were diagonal.

The frame's stiffness matrix was reduced to 20 x 20, relating to horizontal floor displacements. The effects of axial forces, shear deformations, soil-structure interaction, $P - \Delta$, and inelastic frame behavior were ignored. When any story's damper was not slipping a 2 x 2 matrix representing damper stiffness was added appropriately to the frame's stiffness matrix, which was adjusted each time any damper changed its state. Response was computed using the technique of assumed linear variation of acceleration across any short time interval, which was made less than one third of the shortest period of vibration when all dampers were locked[5]. Table 1 gives representative periods. It is seen in Fig. 2 that the frame-damper combination has bilinear stiffness. When the 20-story structure was reduced to a one-story structure, results agreed with Iwan's[6]. Other tests indicated the computer code was working properly. Fig. 3 illustrates free vibrations of a friction damped structure.

SPECTRA OF EARTHQUAKE RESPONSE

Figs. 4 and 5 show examples of friction damped response spectra and viscous damped response spectra for 20-story buildings under El Centro 1940 N-S excitation. In viscous damped buildings the fraction of critical damping, n, is the same for all modes. Base shear coefficient (Fig. 4) includes the shear in the dampers. It is seen that stiffness of friction dampers can be quite important, and in general the stiffer the damper the smaller the response. When STFCON = 1, approximate minima of response are produced when F/W = 0.06 for T_1 = 2 sec. For shorter period buildings optimum F/W is greater and for longer period buildings it is smaller, 0.02 for T_1 = 5 sec. These responses to this excitation are approximately the same as those resulting from 10% to 20% or more viscous modal damping. Surprisingly, in some cases increased F/W can result in increased response, sometimes greater than if there were no damping. This is because friction dampers stiffen a structure as well as absorb energy. Increased F/W can result in almost undamped vibrations of a structure whose periods have been shifted towards the dominant periods of the ground motion.

In the cases studied here residual displacements after the earthquake were insignificant. Doubling the intensity of the earthquake produced less than doubled response when F/W was large and more than doubled response when F/W was small (Fig. 6). These results depend on the ratio of F/W to earthquake intensity expressed as a fraction of gravity.

It was concluded that modest interfloor damper forces, in some cases only a few percent of the gravity forces, could be quite effective in reducing building response if damper properties are properly matched to the properties of the structure.

A TELESCOPING FRICTION DAMPING STRUT

A telescoping friction damping strut (Fig. 7) consists of 2 pieces of steel tube surrounded by 1/4" thick plates which are pressed against it by spring loaded clamps. Alternate plates are connected to opposite ends of the tube. As the tube changes length, as a diagonal in building frame, energy is consumed through friction by the plates slipping along each other. Disc springs (Belleville washers) prevent rapid loss of clamping force as wear occurs. Powdered oil shale (quartz and clay, with streaks of hydrocarbon) sprinkled onto the plates before assembly has been found to result in smooth noiseless slipping, even after thousands of inches of slipping, when heavy wear has occurred.

A friction damper placed in the lowest story of one bay of the frame in Fig. 1, capable of damping 3 bays, with STFCON = 1, would consist of a tube 8" x 8" x 1/2", with 3 layers of plates on each side. With F/W = 0.06, the strut should slip at a force of 320 kips. Laboratory work on a smaller version of this damper (27 kips slip force, slipping on only one surface per face), with a clamping force of 1,100 lbs per bolt, 2.80" diameter springs, resulted in a friction coefficient of approximately 0.5, producing 550 lbs. friction force per bolt-rubbing surface. To produce 320 kips, 25 clamping bands (Fig. 7) would be required. Fig. 8 shows how, due to wear, slip force changed with distance slipped in the laboratory test, which was conducted at frequencies of from 0.05 Hz to 0.3 Hz, with stops for cooling every 360 inches. Slip in a long intense earthquake would probably not exceed 40 inches.

DIRECTIONS OF FUTURE WORK

An extrusion damper, in which solid lead is forced back and forth through a narrowed opening, produces a force-deflection relationship similar to the friction damper[7]. The computer results would pertain to the extrusion damper as well as the friction damper. While the extrusion damper has been well tested, the friction damper has not, and further work is needed to answer questions about relaxation of the disc springs after many years, corrosion of the rubbing surfaces, performance of multiple rubbing surfaces, wear due to many years of movement in strong winds, behavior of the damper when twisted or bent, other forms of friction dampers, such as walls or diaphragms, and the uniformity of slip force from one damper to the next. Additional computer studies of friction damped structures should be made to consider other ground motions, soil-structure interaction, and detailed behavior of members locally influenced by the dampers.

ACKNOWLEDGEMENT

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TABLE 1. Vibrational Periods of Building With All Dampers Locked

Period (seconds)	T_1	T_2	T_3	T_4	T_{20}
No dampers	2.00	0.822	0.495	0.355	0.0403
Dampers, STFCON = 0.1	1.79	0.747	0.452	0.324	0.0387
Dampers, STFCON = 1.0	1.11	0.487	0.296	0.214	0.0294
Dampers, STFCON = 10	0.563	0.230	0.128	0.0878	0.0126

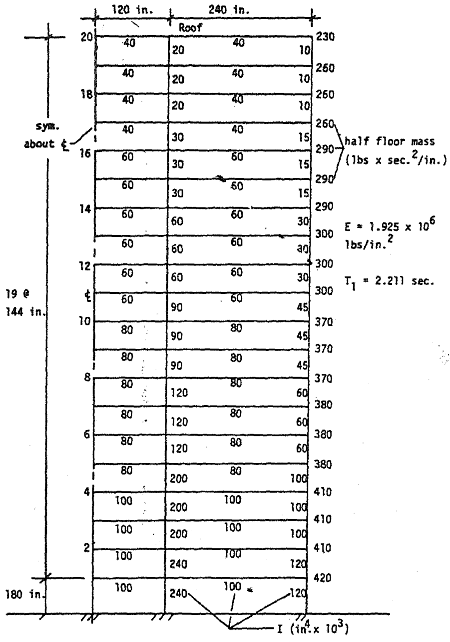

FIG. 1 Basic Building Frame and Floor Masses.

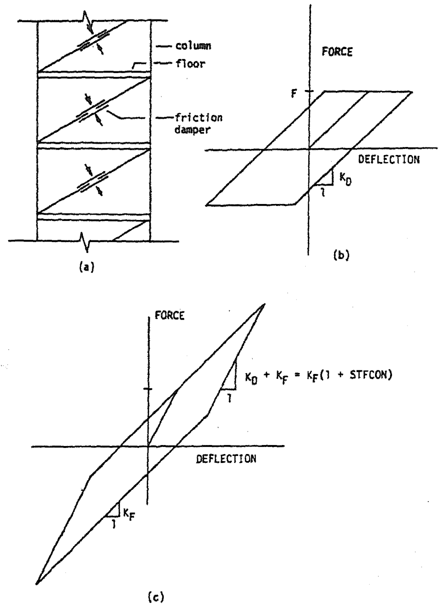

FIG. 2 - (a) Friction Dampers in Elastic Frame; (b) Stiffness Characteristics of Damper; (c) Stiffness Characteristics of Frame-Damper Combination.

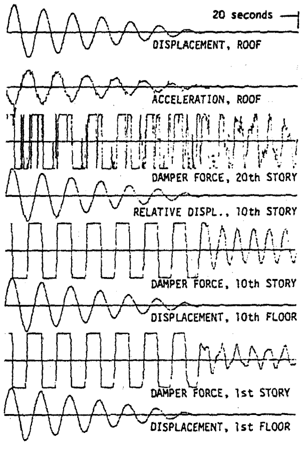

FIG. 3 - Free Vibration of a Friction Damped 20-Story Building. T_1 = 2 sec., F/W = 0.06, STFCON = 1.

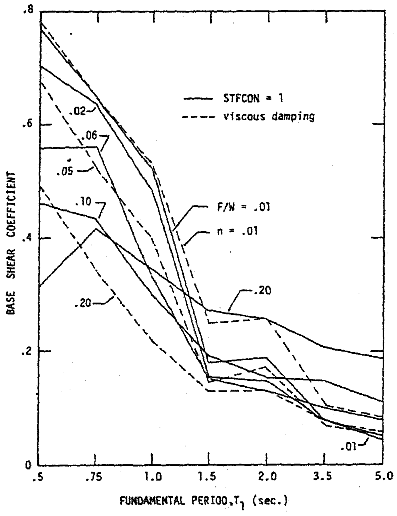

FIG. 4(a) - Response Spectra of Friction Damped and Viscous Damped 20- Story Buildings, El Centro 1940 N-S.

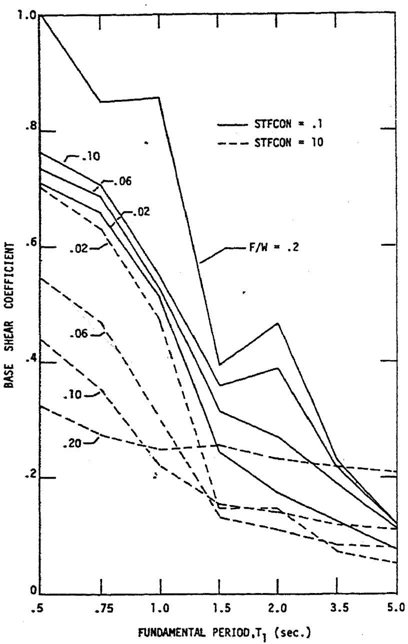

FIG. 4(b) - Response Spectra of Friction Damped 20-Story Buildings, El Centro 1940 N-S.

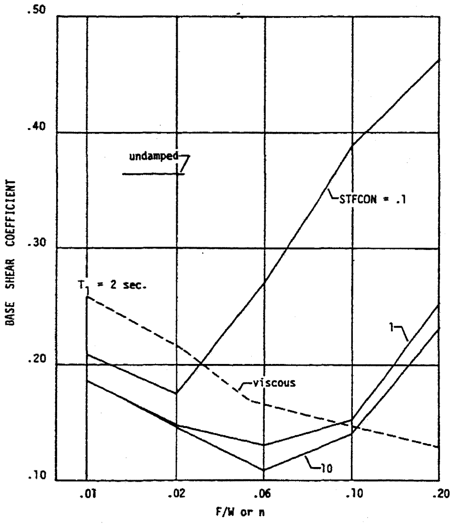

FIG. 4(c) - Response Spectra of Friction Damped and Viscous Damped 20-Story Buildings, El Centro 1940 N-S.

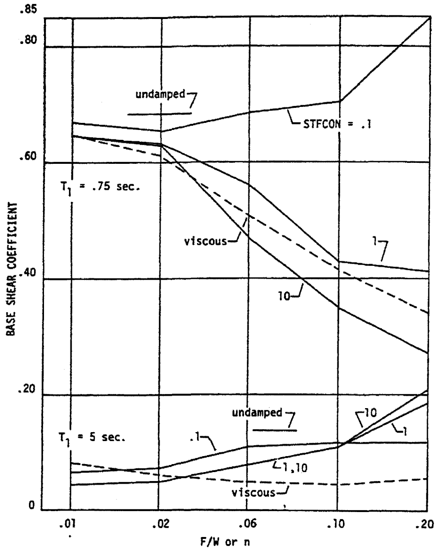

FIG. 4(d) - Response Spectra of Friction Damped and Viscous Damped 20-Story Buildings, El Centro 1940 N-S.

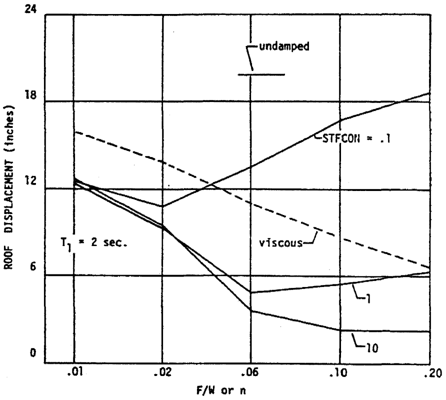

FIG. 5(a) - Response Spectra of Friction Damped and Viscous Damped 20-Story Buildings, El Centro 1940 N-S.

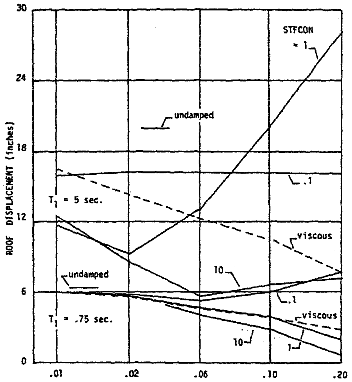

FIG. 5(b) - Response Spectra of Friction Damped and Viscous Damped 20-Story Buildings, El Centro 1940 N-S.

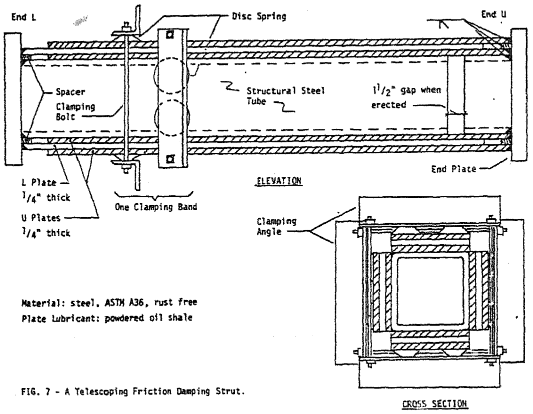

FIG. 7 - A Telescoping Friction Damping Strut.

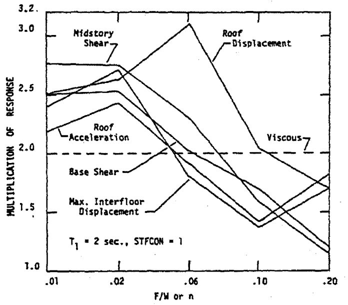

FIG. 6 - Multiplication of Response Due To Doubled El Centro Earthquake Intensity.

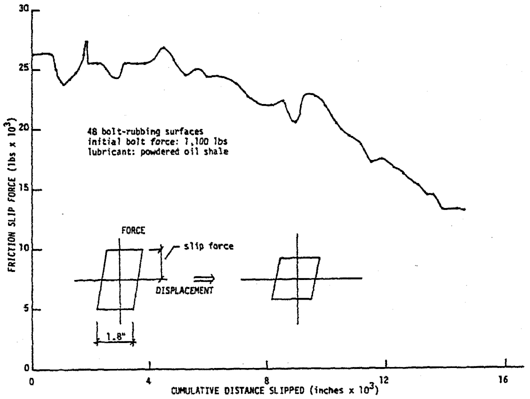

FIG. 8 - Variation of Friction Slip Force With Distance Slipped.