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SEISMIC DESIGN OF SIMPLE FRICTION DAMPED BRACED FRAMES

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SUMMARY

Presented in this paper is a new and efficient modelling approach for the seismic analysis and design of steel structures equipped with a novel friction damping system. The hysteretic properties of the friction devices are derived theoretically and included in a Friction Damped Braced Frame Analysis Program (FDBFAP), which is adaptable to a micro-computer environment. FDBFAP is then used in a parametric study of single-storey friction damped structures, which leads to the construction of a design slip load spectrum.

INTRODUCTION

Recently a novel structural system has been proposed (Ref. 1) for the seismic design of steel framed buildings. The system basically consists of a simple inexpensive mechanism containing friction brake lining pads introduced at the intersection of frame cross-braces. Fig. 1 shows the location of the friction devices in a typical steel frame. The general arrangement of an actual friction device is presented in Fig. 2.

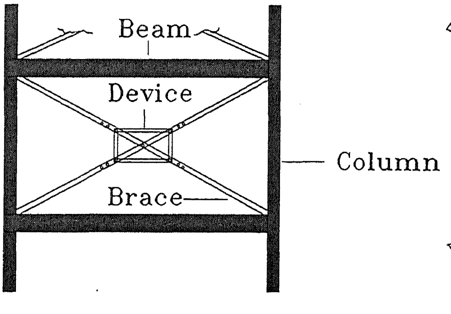

Fig. 1. Location of Friction Device.

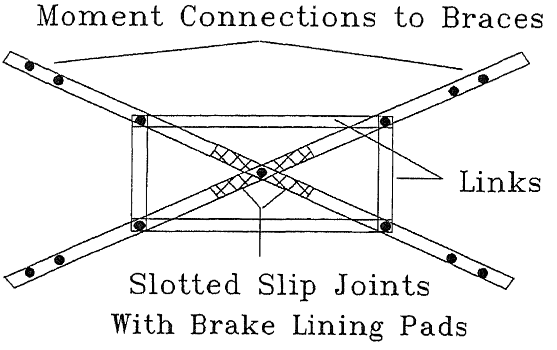

Fig. 2. Friction Device.

Each brace is provided with a connection which, during a severe earthquake, is designed to slip before the yield capacity of any member in the structure is exceeded. When the device slips, the four links (Fig. 2) are activated and energy is dissipated in both braces in each half cycle, even if the compression brace has buckled. Analytical and experimental investigations have clearly confirmed the superior performance of structures equipped with these friction devices compared to conventional building systems (Ref. 2).

The energy dissipation of a friction device is equal to the product of the slip load by the total slip travel. For very high slip loads the energy dissipation in friction will be zero, as there will be no slippage. If the slip load is very low, large slip travels will occur but the amount of energy dissipation again will be negligible. Between these extremes, there is an intermediate value of the slip load which results in the optimum energy dissipation. This intermediate value is defined as the "Optimum Slip Load". At the present stage of knowledge, the optimum slip load of a given structure is determined by performing a series of inelastic time-history dynamic analyses for different values of the slip load, using the general purpose computer program DRAIN-2D (Ref. 3). Such analyses are very expensive and tedious. From the practical point of view, it is essential to develop a simplified design method for evaluating the optimum slip load of the friction devices. This paper provides a procedure for optimizing the slip load, thereby leading to a simple and direct approach for the design of Friction Damped Braced Steel Frames (FDBF).

NUMERICAL FORMULATION

A specialized computer program for the analysis and design of friction damped braced frames (FDBFAP), which is adaptable to a microcomputer environment, was created. Using a step-by-step integration procedure, FDBFAP automatically performs a series of dynamic response analyses of FDBF of arbitrary configurations for specified distributions of slip load. Energy calculations are made at the end of each time step and a Relative Performance Index (RPI) is calculated after each analysis. The optimum slip load distribution of the structure is the distribution which minimizes this RPI.

Friction Device Finite Elements Discretization The direct stiffness method is used at the end of each time-step to form the global nonlinear tangent stiffness matrix of the structure ($[K_{NL}(t)]$) from an assemblage of friction device element stiffness matrices.

The assemblage of members contained within the dashed lines in Fig. 3 forms a "friction device element", which includes the friction mechanism itself along with the four external diagonal braces.

The tangent stiffness matrix of a friction device element depends on the deformed configuration of the friction device at the end of the time-step. To save computing time, all possible deformation states of a friction device are considered; the tangent stiffness matrix for each state is derived theoretically

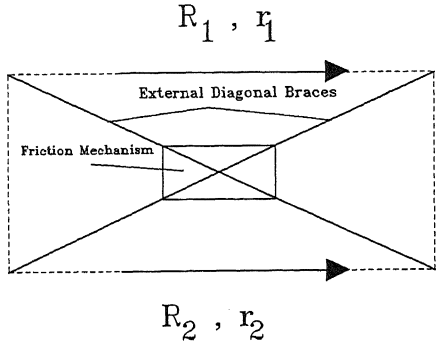

Fig. 3. Friction Device Finite Element.

and stored in FDBFAP. The results can be expressed as a relation between incremental forces ($\Delta R_1, \Delta R_2$) and the associated incremental displacements ($\Delta r_1, \Delta r_2$) for a friction device element:

$$\begin{Bmatrix} \Delta R_1 \\ \Delta R_2 \end{Bmatrix} = \frac{E A_b A_p \cos^2\alpha}{(C_1 A_p L_b + C_2 A_b L_p)} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} \Delta r_1 \\ \Delta r_2 \end{Bmatrix} \qquad (1)$$

where E is Young's modulus, A_b is the cross-sectional area of the diagonal cross-braces, A_p is the cross-sectional area of the friction pads and the links, α is the angle of inclination of the diagonal braces from the horizontal, L_b and L_p are the lengths of the diagonal braces and the diagonal pads, respectively. The values of C_1 and C_2 depend on the deformation of the friction device element at the end of the previous time-step (Ref. 4).

FDBFAP determines the displacement of each friction device element (r_1-r_2) at the end of each time-step, and then assembles the proper nonlinear tangent global stiffness matrix needed in the incremental equations of motion for the following time-step. The Newmark-Beta method with a constant acceleration algorithm is used to integrate the equations of motion.

Slip Load Optimization For each slip load distribution, the time-history of the strain energy in the structure is calculated and a Relative Performance Index (RPI) is defined as:

$$RPI = \frac{1}{2}\left[\frac{SEA}{SEA_{(o)}} + \frac{U_{max}}{U_{max(o)}}\right] \qquad (2)$$

where

- SEA = Strain energy area = Area under the strain energy time-history for a friction damped structure.
- $SEA_{(o)}$ = Strain energy area for the identical structure, but without bracing (slip load = 0)
- U_{max} = Maximum strain energy for a friction damped structure
- $U_{max(o)}$ = Maximum strain energy for the identical structure, but without bracing (slip load = 0)

FDBFAP calculates the value of RPI for each slip load distribution. The optimum slip load distribution of the structure is defined to be the slip load distribution for which RPI is minimum.

PARAMETRIC STUDY

Using FDBFAP as a tool, a parametric study was performed on a series of one storey structures in order to develop a simplified design equation for the optimum slip load.

Ground Motion Representation The steady-state response of a single storey structure equipped with the new friction damping system and subjected to sinusoidal ground motion has been investigated analytically (Ref. 5). The results show that the optimum slip load depends on the frequency and amplitude of the ground motion and is not strictly a structural property. Therefore, it becomes necessary to consider a variety of ground motions in the parametric study involving the optimum slip load.

A stochastic representation of earthquake ground motion was used in the parametric study. In this model, proposed by Vanmarcke and Lai (Refs. 6 and 7), the strong motion duration captures the essential transient character of the earthquake ground motion while the Kanai-Tajimi power spectral density function (Ref. 8) represents its equivalent frequency content. This representation offers the advantage of completely describing the ground motion by seismic parameters that can be estimated at a given site: the peak ground acceleration a_g, the ground predominant period T_g and the ground damping h_g.

Dimensional Analysis A sensitivity study was performed with FDBFAP in order to determine the parameters influencing substantially the optimum slip load. These governing parameters were used subsequently in a dimensional analysis leading to the nondimensional design equation:

$$\frac{2P_0 \cos\alpha}{W} = F\left[\frac{T_b}{T_u}, \frac{T_g}{T_u}, \frac{a_g}{g}\right] \tag{3}$$

where P_0 is the optimum slip load, W is the weight of the structure, T_b is the fundamental period of the fully braced structure without slipping, T_u is the fundamental period of the unbraced structure, g is the acceleration of gravity and F is an unknown function to be estimated in the parametric study.

Among the ratios in (3), a_g/g is the one for which the optimum slip load is the most sensitive. The sensitivity study showed that the relationship between $2P_0\cos\alpha/W$ and a_g/g is practically linear with zero ordinate at the origin. This result agrees with some analytical and experimental studies reported in the literature (Refs. 5 and 9). Therefore, the unknown function F in (3) can be approximated by:

$$\frac{2P_0 \cos\alpha}{W} = \frac{a_g}{g} G\left(\frac{T_b}{T_u}, \frac{T_g}{T_u}\right) \tag{4}$$

where G is an unknown function to be estimated.

Design Slip Load Spectrum Table 1 presents the values of the parameters used in the parametric study with FDBFAP.

Table 1 Values of Parameters Used in Parametric Study

Parameter	Values
T_u (s)	0.1243, 0.3764, 1.0016, 1.9525
T_b/T_u	0.20, 0.40, 0.60, 0.80
T_g/T_u	$0.1/T_u$, $0.7/T_u$, $1.4/T_u$, $2.0/T_u$
a_g/g	0.005, 0.05, 0.10, 0.15, 0.20, 0.30, 0.40

Five different sample accelerograms were simulated for each combination of the parametric values given in Table 1. The total number of FDBFAP analyses was 2240; a microcomputer version of FDBFAP was used on an IBM-PC microcomputer to perform these analyses.

The results were analyzed by the least square method and the following design equation was constructed:

$$\frac{V_0}{ma_g} = \frac{2P_0\cos\alpha}{ma_g} = (K_1 \frac{T_b}{T_u} + K_3) \frac{T_g}{T_u} + (K_2 \frac{T_b}{T_u} + K_4) \qquad (6)$$

where m is the mass of the structure and:

$$\left.\begin{array}{l} K_1 = -1.47 \\ K_2 = 0 \\ K_3 = 1.46 \\ K_4 = 0 \end{array}\right] \text{ if } 0 < T_g/T_u \leq 1 \qquad \left.\begin{array}{l} K_1 = 0.02 \\ K_2 = -1.49 \\ K_3 = -0.01 \\ K_4 = 1.47 \end{array}\right] \text{ if } T_g/T_u > 1$$

Figure 4 presents a design slip load spectrum constructed from (6), by plotting curves of V_0/ma_g vs T_g/T_u for particular values of T_b/T_u.

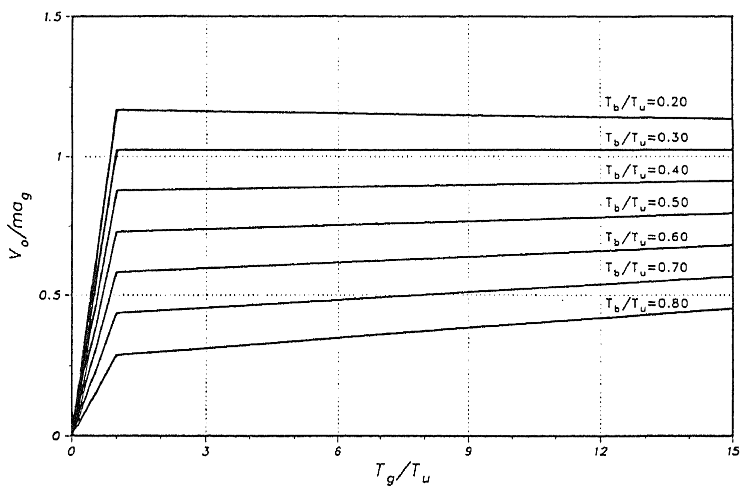

Fig. 4. Design Slip Load Spectrum for Single Storey FDBF.

DESIGN EXAMPLE

Consider a one storey friction damped braced frame which is to be retro-fitted with the friction damping system. Assume that the calculated fundamental period of the unbraced structure T_u is equal to 1.09 second, and the fundamental braced period T_b is equal to 0.37 second. Assume also that the specified design earthquake for the construction site can be represented by the December 21, 1954 Eureka Earthquake, N46W component. The parameters of this seismic event have been determined by Vanmarcke and Lai (Ref. 6): a_g = 0.201 g, T_g= 0.69 second. The nondimensional ratios can then be calculated: T_b/T_u = 0.34, T_g/T_u = 0.64, a_g/g = 0.201. Using the design slip load spectrum we obtain: $2P_0\cos\alpha/ma_g$ = 0.62 or P_0 = 65 kN for α = 30° and m = 90 kN-s²/m.

CONCLUSION

A simple and efficient numerical modelling procedure for structures equipped with a new friction damping system has been presented. Using this model in a parametric study, a simple design equation along with a design slip load spectrum has been constructed for a rapid and direct evaluation of the optimum slip load of single storey friction damped structures. The design equation takes into account the properties of the structure and ground motion anticipated at the construction site. It is believed that the availability of this design slip load spectrum will lead to a greater acceptance by the engineering profession of this new and innovative structural concept. The authors are now examining the possibility of extending the slip load spectrum approach to the design of multi-storey friction damped structures.

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