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ON PASSIVE AND SEMI-ACTIVE FRICTION DAMPING FOR SEISMIC RESPONSE CONTROL OF STRUCTURES

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ABSTRACT

Friction damping and other passive means of energy dissipation are effective methods of improving structural performance in the event of an earthquake. Two novel, semi-active schemes which can significantly enhance the performance of a passive friction damped structure are described in this paper. The semi-active systems proposed herein are referred to as the "Off-On" friction damper and the continuously variable "Semi-Active Friction Damper" (SAFD). In the Off-On system, the slip force is switched between a pre-determined constant slip force and zero at times which maximize the amount of energy dissipated in a response cycle. In the SAFD system, the slip force is adjusted continuously in response to the deformation state of the structure.

A preliminary design method for establishing the optimum slip load of multi degree of freedom passive friction damped structures based on transfer function concepts is examined. The results are illustrated by a design example and compared with the results of a "Level Set Programming" optimization procedure.

KEY WORDS:

structural control; semi-active; friction damping; hysteresis; energy dissipation; optimization

INTRODUCTION:

The following paper summarizes preliminary research into the performance of passive and semi-active friction dampers and compares the capability of each system. The design of such systems is considered for the case of both single and multi-DOF structures. Results are compared to those determined using an exact "Level Set Programming" (LSP) optimization process for a uniform 4-storey structure.

Research by numerous investigators has verified that energy dissipating devices, such as friction dampers, are viable and inexpensive methods of improving the performance of structures during major earthquakes. Semi-active systems have been proposed as a means of implementing a control algorithm without requiring the input of a large amount of energy from an external source. The use of semi-active friction damped base isolated structures has been investigated by Fujita *et al* (1989), who constructed and tested an optimal linear feedback friction damped isolation system that was capable of attenuating the large drifts that may be induced by seismic loads in base isolated structures.

Akbay and Aktan (1990, 1991) have developed and tested a variable amplitude friction damping system, which operates by slowly varying the slip force in response to the stick or slip state of the damper. Their control algorithm was relatively simple to implement. It allowed the damper to operate effectively at low as well as high levels of excitation. They determined that the performance ordinarily associated with an optimal passive friction damped system could be significantly improved by following their approach.

The authors have previously proposed two semi-active control algorithms, which are intended to improve the performance obtained from Constant Slip Force Friction Dampers (CSFD) by varying the slip force as a function of the response state of the structure as it deforms in time during the external excitation (Dowdell and Cherry, 1994(a) and (b)). The simplest algorithm proposed was the "Off-On" friction damper. The intent of the Off-On damper is to maximize the energy dissipated while utilizing a limited slip force. The second algorithm proposed was the continuously variable amplitude Semi-Active Friction Damper (SAFD). The SAFD system is intended to operate on the structure globally and attempts to minimize the dynamic response.

In this paper, the ability of the CSFD and the Off-On systems to minimize the RMS inter-storey drift is investigated. A design procedure for CSFD and Off-On friction damped structures, based on minimizing the RMS inter-storey drift, has been proposed for Single Degree of Freedom (SDOF) structures (Dowdell and Cherry, 1995). A preliminary attempt is made here to expand this procedure to Multi Degree of Freedom (MDOF) structures. This process is described and illustrated with an example and the results obtained are compared with results determined from an optimization procedure utilizing the LSP technique.

PASSIVE AND SEMI-ACTIVE FRICTION DAMPED STRUCTURES:

The form of the SDOF structure with which this paper is concerned is illustrated in Figure 1(a). The uncontrolled structure has mass, m, damping, c, and stiffness, k. The control is implemented by means of an added brace containing a friction damper in series with a spring. The spring and friction slider are shown in the horizontal direction to emphasize that the brace stiffness and slip force values to be used are those that have been transformed into the horizontal direction. The stiffness of the device (in the horizontal direction) when the friction damper is not slipping is given by the value K. The horizontal force which just causes the brace to slip is given by the value U: U_c in the case of a constant slip force, and $U(t)$ in the case when the slip force is varied as a function of time. The structure is subjected to a base excitation $a_g(t)$ having peak acceleration a_0, and RMS acceleration a_{rms}. During an earthquake, the deformation response of the structure is described by the inter-storey drift, $d(t)$.

Figure 1(b) illustrates an associated MDOF structure having 4 stories. With the MDOF structure, the mass, damping and stiffness quantities are interpreted as appropriate matrix quantities. The inter-storey drifts, $d_i(t)$, are compiled in vector form. The equation of motion (Dowdell and Cherry, 1994a) is formulated as follows:

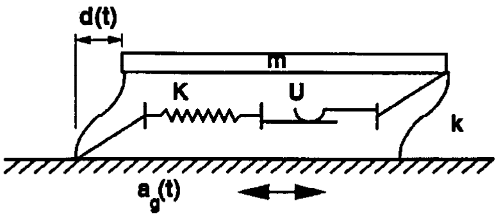
$$\begin{Bmatrix} \dot{d} \\ \ddot{d} \end{Bmatrix} = \begin{bmatrix} 0 & I \\ -m^{-1}k & -m^{-1}c \end{bmatrix} \begin{Bmatrix} d \\ \dot{d} \end{Bmatrix} + \begin{bmatrix} 0 \\ -m^{-1}b \end{bmatrix} U(t) + \begin{bmatrix} 0 \\ -l \end{bmatrix} a_g(t) \tag{1}$$

where the matrix b describes the locations of damper forces and the influence coefficient vector l represents the displacements of the structure resulting from a unit support displacement.

SEMI-ACTIVE CONTROL ALGORITHMS:

The character of the hysteresis loop for each damper type is illustrated in Figure 2. Figure 2(a) shows the hysteresis for a CSFD. The area enclosed by the loops is a measure of the energy dissipated.

The Off-On friction damper utilizes a simple algorithm that requires feedback of only the inter-storey drift velocity of the storey in which the damper is present. Ideally, the i^{th} damper slip force, $U^i(t)$, is given by



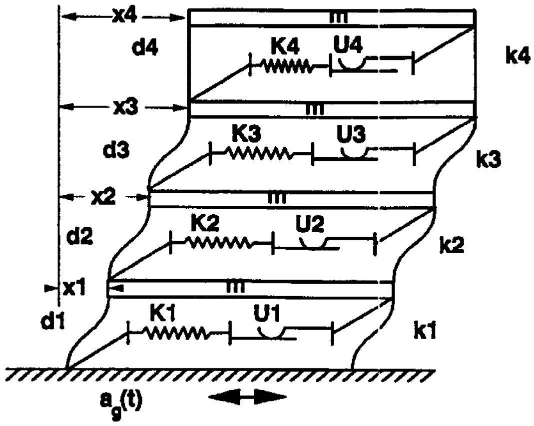


Figure 1: (a) SDOF Structure. (b) MDOF Structure.

$$U^i(t) = \begin{cases} U_c^i; & |\dot{d}_i| > 0 \\ 0; & |\dot{d}_i| = 0 \end{cases} \tag{2}$$

At the moment a reversal of direction in the inter-storey drift is detected $(\dot{d}_i = 0)$, the slip force is momentarily reduced from its preset level, U_c (the "On" state), to near zero (the "Off" state). This is accomplished through the reduction of the clamping force on the friction surfaces of the damper. When the brace slip force is released, the brace slips quickly to a new position resulting in the vertical branches shown on the hysteresis loop of Figure 2(b). After this has occurred, the clamping force on the friction surface is returned to its normal value (the "On" state) as the structure begins to deform in the opposite direction. Figure 2(b) shows the hysteresis loop characteristic of an Off-On friction damper. The hatched and double hatched areas taken together indicate the hysteretic energy dissipated in one cycle. The single hatched area indicates the energy dissipated by a CSFD. The double hatched area represents the energy dissipated in addition to that of the CSFD. It is this additional energy that enables the Off-On damper to provide a greater level of damping than that developed by a CSFD, while utilizing the same maximum slip force, U_c. It is noted that at excitation levels which do not generate brace forces in excess of the CSFD slip force, the Off-On damper is able to dissipate energy, whereas the CSFD does not have this capability.

The SAFD algorithm proposed is more complicated than the Off-On algorithm, in that state feedback from the entire structure is required to determine the slip force at each damper. The slip force is determined as:

$$U(t) = |G\tilde{d}(t)| = \left| G \begin{bmatrix} d(t) \\ \dot{d}(t) \end{bmatrix} \right| \tag{3}$$

where $\tilde{d}(t)$ is the state vector defined in terms of inter-storey drift and inter-storey drift velocity as shown. The matrix, G, is a pre-determined constant gain matrix. (see Dowdell and Cherry 1994a)

Figure 2(c) illustrates the hysteresis loop of a variable amplitude SAFD. The hysteresis loop appears to be a combination of an elliptical shape, as one would expect with a viscous damper, and a linear shape. The elliptical shape is produced through continuous variation of the slip force of the damper as the damper is slipping, while the linear segments result when the damper does not slip.

Non Dimensionalized Properties

To generalize the behaviour of the SDOF structure, it is useful to non-dimensionalize the characteristic properties as follows:

$$\alpha = \frac{K}{k}; \qquad \beta = \frac{\omega}{\omega_0}; \tag{4a}$$

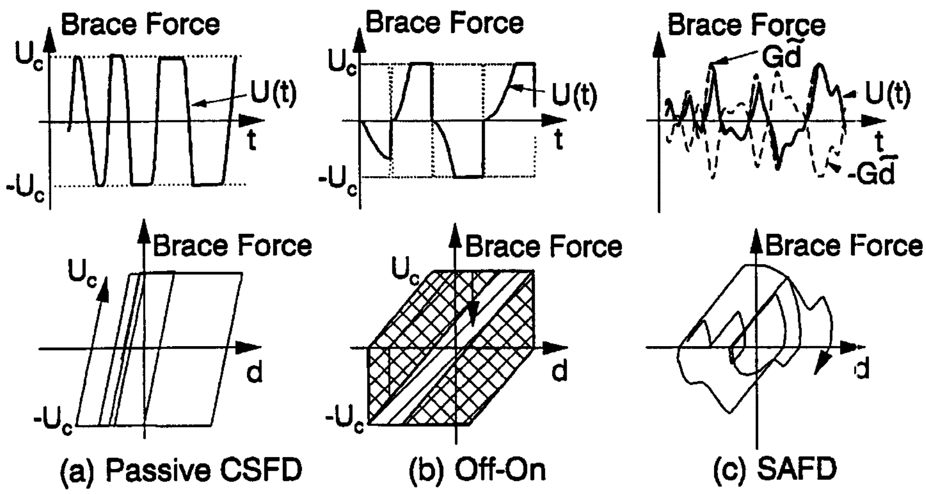


Figure 2: Time histories and corresponding brace hysteresis loops for (a) CSFD; (b) Off-On; (c) SAFD.

$$\gamma = \frac{U_c}{ma_{rms}}; \quad \delta(t) = d(t)\frac{k}{ma_{rms}}; \tag{4b}$$

where ω is a frequency and $\omega_0 = \sqrt{k/m}$ is the undamped natural frequency of the structure. The variables α, β, γ and δ are referred to as the stiffness, frequency, slip load and inter-storey drift ratios, respectively.

Frequency Response Characteristics:

The frequency response characteristics of the passive and semi-active friction damped structures have been established. Because the response of a friction damped system is non-linear in nature, response is dependent on the magnitude and the characteristics of the load. Figures 3(a) and (b) compare the transfer functions of CSFD and Off-On damped SDOF structures determined by taking the Fourier transform of response functions for structures subjected to white noise excitation. The plots shown have been non-dimensionalized using the relationships given in Equation (4). Particularly for values of $\beta > 1$, it is apparent that the Off-On damped structure has a superior performance since a peak in the transfer functions at the braced frequency ratio does not occur in this system at the higher values of γ. This indicates that for a structure which is excited by ground motions whose predominant frequencies are at or above the structure's natural frequency, the Off-On friction damped structure will perform better than the passive CSFD system.

DESIGN OF SDOF PASSIVE AND SEMI-ACTIVE HYSTERETIC SYSTEMS :

A design method, based on transfer function concepts, with the ability to take into consideration the frequency content of the excitation has been proposed for SDOF structures (Dowdell and Cherry, 1995). The methodology is based on minimizing the steady state RMS inter-storey drift response of a structure to a stationary random process. Earthquake ground motions, admittedly, are neither stationary nor of infinite duration. However, they are random processes, and design events such as large subduction earthquakes are expected to have long enough duration that many ordinary structures can potentially reach a steady state response. The proposed method is primarily suited to these conditions. RMS inter-storey drift is chosen as a matter of convenience since RMS drift response of a linear viscous damped structure to a stationary random process can be described in the frequency domain by the equation:

$$\delta^2_{rms} = \omega_0 \int_{-\infty}^{\infty} \phi(\beta) T_{\alpha,\gamma}(\beta) d\beta \tag{5}$$

where $T_{\alpha,\gamma}(\beta)$ is a transfer function describing the inter-storey drift response of the structure having stiffness ratio α, and slip force ratio γ, to a base acceleration input. The function $\phi(\beta)$ describes the power spectral

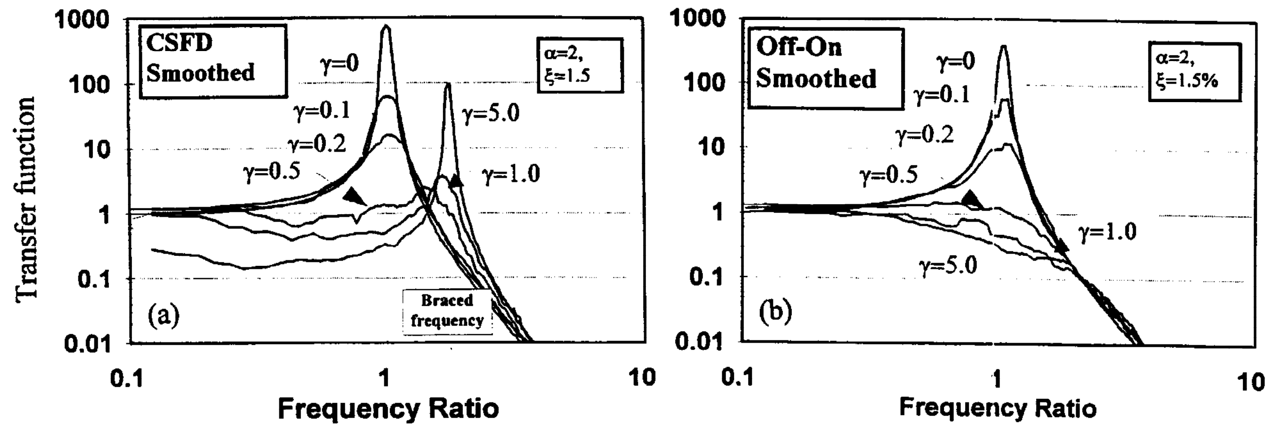


Figure 3: Transfer functions of (a) CSFD; (b) Off-On.

density function which represents the character of the ground motions. The design of a SDOF system requires the following steps: (1) Determine the Power Spectral Density function of the input ground motion together with the characteristic RMS base acceleration. This data should be determined for the strong motion segment of the earthquake (see definition following Equation (8).) (2) Using transfer function data for the SDOF structure and Equation (5), generate a plot of the inter-storey drift, δ, versus non-dimensionalized slip load, γ. (3) From the inter-storey drift vs. slip load plot, select the slip load ratio, γ, that yields the minimum inter-storey drift. (4) Finally, calculate the slip load, U_c, using the relationship $U_c = ma_{rms}\gamma$, (see Equation (4b).)

Figure 4 compares the drift ratio vs. the slip load ratio of a CSFD and an Off-On controlled structure for the case of a white noise input. It is seen that with the CSFD a definite minimum occurs on the curve at a slip load ratio of about $\gamma = 0.75$. With the Off-On friction damper, however, the shape of the curve does not exhibit a unique minimum. This indicates that with the implementation of the Off-On controlled SDOF structure, an optimization procedure need not be undertaken. It is only necessary for the designer to provide the highest possible brace force consistent with economic, structural and non-structural considerations.

DESIGN OF MDOF STRUCTURES:

The proposed SDOF design methodology is not easily extrapolated to MDOF systems. However, assuming that the structure responds primarily in its fundamental mode, the following approach was examined in an exploratory sense for the first design of such a system: (1) Assume an appropriate slip load distribution for the structure. (2) Consider the design of an equivalent SDOF structure. For this purpose it is suggested that the mass of the equivalent structure be equal to the total mass, m_t, of the MDOF structure, and the frequency be taken as that of the fundamental mode of the MDOF structure. (3) Follow steps (1) through (4), above, to select the optimal slip load, U_c, of the SDOF structure. (4) Equate the first storey slip load, U_c^1 in the MDOF system to U_c determined for the equivalent SDOF structure. (5) Proportion the slip loads of the remaining stories, $U_c^2 \cdots U_c^n$, based on the assumed slip load distribution.

Distribution of slip load:

The distribution of slip load in a MDOF structure is an important issue which must be resolved. Filiatrault and Cherry (1990) suggested that a reasonable approach to the problem would be to provide a uniform distribution - equal slip loads at each storey. Some analyses have shown that this is not necessarily the best choice. One plausible distribution suggested here is described by the equation

$$U_c^i = \lambda d_0^i \sum_{j=i}^{n} m_j \qquad (6)$$

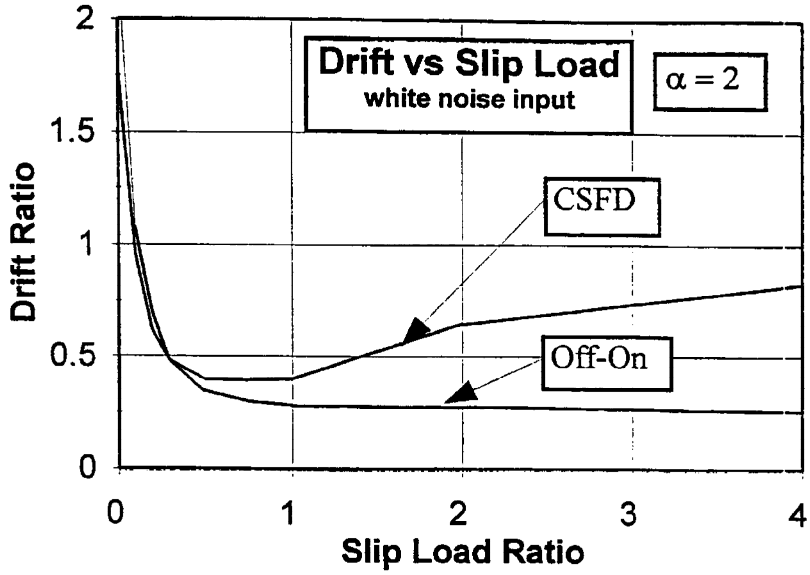


Figure 4: Drift vs. slip load ratio for SDOF structure subjected to white noise: CSFD and Off-On control.

where d_0^i is the inter-storey displacement of the fundamental mode at storey i, λ is a proportionality constant, and the remainder of the expression is the sum of the mass above and including storey i.

DESIGN EXAMPLE:

The design example presented here is for the case of the uniform structure shown in Figure 1(b), subjected to El Centro 1940 and San Fernando 1971 earthquakes. The mass at each storey is given as 1 (kN) and the stiffness at each storey is given as 1200 (kN/m). The fundamental frequency of vibration for this system is 12.0 rad/sec (1.91Hz) and the associated first mode shape, in terms of inter-storey drift, is given by the vector

$$d_0 = [0.657 \quad 0.577 \quad 0.429 \quad 0.228]^T \tag{7}$$

From Equation (6), the distribution of slip force, normalized with respect to the base, is given by

$$U_c = U_c^1[1 \quad 0.658 \quad 0.326 \quad 0.087]^T; \tag{8}$$

The strong motion segments of each earthquake is here defined as the time interval which takes place between the 5% and 95% contributions to the integral of the square of the accelerations, $\int_{\tau=0}^{\tau=t} a_g^2(\tau)d\tau$, following the method proposed by Trifunac and Brady (1975). It was found that the RMS base excitation for these strong motion portions of the records were $a_{rms} = 0.65\,\text{m/s}^2$ for El Centro and $a_{rms} = 0.68\,\text{m/s}^2$ for San Fernando. Both earthquake records have a broad band PSD and have peak ground accelerations of approximately 0.35g. El Centro has a strong motion duration of 24 seconds compared to 10 seconds for San Fernando. For the given structure, the El Centro input excitation is centered around $\beta = 0.8$, and the San Fernando input excitation is centered around $\beta = 2.9$. Using the transfer functions of Figure 3(a) together with Equation (5), the plots of RMS inter-storey drift versus slip load ratio shown in Figure 5 were computed. It was found that minimum RMS drift occurred at $\gamma \cong 1.0$ for El Centro, and $\gamma \cong 0.5$ for San Fernando. The first storey slip load was therefore found to be $U_c^1 = 2.6\,\text{kN}$ for El Centro, and $U_c^1 = 1.3\,\text{kN}$ for San Fernando. The distributions based on Equation (8) then becomes:

$$\text{El Centro: } U_c = \begin{bmatrix} 2.6 \\ 1.71 \\ 0.85 \\ 0.23 \end{bmatrix}; \qquad \text{San Fernando: } U_c = \begin{bmatrix} 1.3 \\ 0.86 \\ 0.42 \\ 0.11 \end{bmatrix}; \tag{9}$$

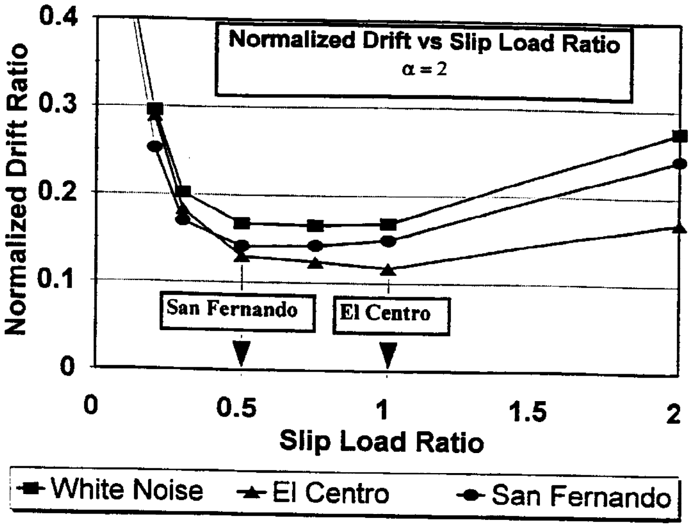


Figure 5: Optimal slip load ratio for structures subjected to El Centro and San Fernando base excitations.

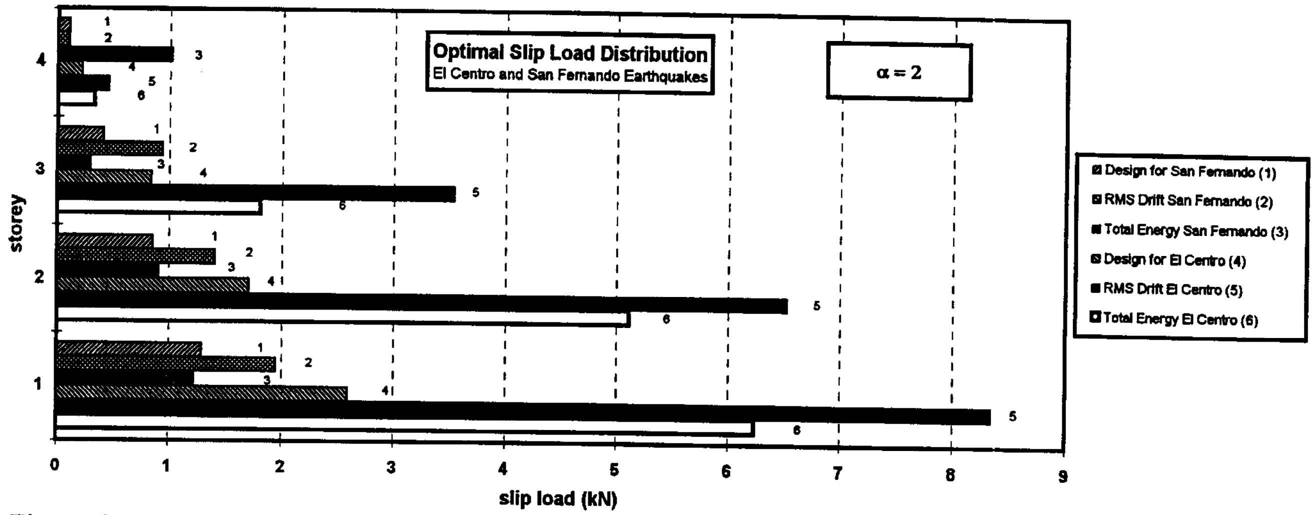


Figure 6: Optimal slip load distributions determined using LSP compared with proposed design method

Verification by LSP technique

Utilizing a "Level Set Programming" (LSP) procedure, the authors were able to establish directly the optimal slip load distributions for the given uniform 4-storey structure. The LSP technique, developed recently by Yassien (1994), is a computationally intensive method of searching for parameter values which yield the global minimum of a given objective function. It is particularly suited to processes which have rough, discontinuous or stochastic objective functions. The LSP technique utilizes the concept of a level set - a set of realizations of the objective function for which the value is less than or equal to a given value. This value is referred to as the level set value. The search for the minimum value of the objective function proceeds by generating values of input parameters at random. Those input parameters for which the objective function value is found to lie above the current level set value are discarded, while those that yield a value on or below the level set are retained. When a sufficiently large set of input parameters are found, the search algorithm simultaneously lowers the level set value, and, if possible, narrows the search space. The search continues in this manner until, after several iterations, assuming that the objective function is well behaved, the level set value approaches the global minimum and all of the input parameters which satisfy this level set lie in a narrow region of the search space.

The LSP technique was applied to the given 4-storey structure with El Centro and San Fernando earthquakes as input excitations. Two objective functions were chosen: strain energy area and maximum inter-storey drift. Strain energy area was utilized because its definition is similar to both the linear quadratic performance index used in optimal control theory and the performance index chosen by Filiatrault and Cherry (1990). Maximum inter-storey drift was chosen because it represents an extension of the inter-storey drift objective function used with SDOF structures.

Figure 6 summarizes the search results and also compares the LSP slip load distribution with the distribution established by the simplified design procedure proposed for MDOF structures. The results indicate that the distribution of slip load strongly favours relatively high slip loads in the lower stories of the structure. Using the maximum RMS drift as the LSP objective function generally leads to higher optimal slip loads than those obtained when using strain energy as the objective function. The LSP optimal slip loads associated with the El Centro earthquake were between 2-4 times the corresponding values for the San Fernando earthquake. The optimal slip loads estimated by the proposed design method are in reasonable agreement with the values derived using the LSP approach in the case of the San Fernando earthquake, but significantly underestimate LSP values in the case of the El Centro earthquake.

SUMMARY AND CONCLUIONS

Passive and semi-active friction dampers were considered for minimizing RMS inter-storey drift in SDOF and MDOF structures. Frequency response characteristics indicate that no optimization is required for Off-On friction damped SDOF structures. A simplified approach for the optimal design of MDOF structures controlled by CSFD was explored: this involved applying transfer function concepts to equivalent SDOF systems. For the case of a uniform 4 storey structure, an example slip load design was carried out and the results were compared with optimal slip loads determined using the "exact" LSP technique. The slip loads determined by the suggested simplified approach for the given structure matched the LSP results reasonably well for the case of the San Fernando earthquake; however, the results did not agree with the LSP derived optimal values for El Centro. More intensive studies are required to improve and validate the proposed design method.

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