Chapter 6

Methodology for Assessing the Seismic Efficiency of Friction Dissipators

6.1 Introduction

This chapter presents a methodology to evaluate numerically the usefulness of friction dissipators to reduce the lateral vibrations of buildings undergoing seismic motions. To quantify the efficiency of the dissipators, four dimensionless performance indices are defined. A numerical parametric analysis using the ALMA program (see Chapter 4) is performed. The proposed procedure allows to select the optimal design parameters of the dissipators in terms of the considered parameters of the input (even accounting for the local soil conditions) and of the building. Some example design plots are presented to highlight the capacities of the proposed methodology and to derive initial conclusions.

This methodology could also be applied —with minor modifications— to other types of dissipators.

6.2 Parametric Analysis

The methodology proposed in this chapter is based on performing a numerical parametric analysis of building structures protected with friction dissipators, using the ALMA program (see Chapter 4). The parameters of the analysis are selected to span the most common situations dealing with the building, the seismic input and the dissipators. To have generalizable conclusions, dimensionless parameters are selected whenever possible.

6.3 Performance Indices

6.3.1 Description

Four dimensionless performance indices are introduced to characterize the seismic efficiency of friction dissipators. All these indices are defined as the ratios between the maximum values of a certain response quantity (e.g., displacement, acceleration, dissipated energy, etc.) of the protected frame (frame with friction dissipators), and the same values of the bare frame (frame without dissipators). Consequently, these indices are always positive and their values range usually between 0 and 1; values close to 0 indicate good performance while values close to 1 mean poor performance. If any index is equal or bigger than 1, FDs are not useful to reduce the quantity included in such an index.

Most of the values considered in the indices are both maximum along time (i.e., during the seismic event) and along space (all the floors). For instance, the 'maximum displacement' means the maximum displacement at any instant and at any floor (maximum of the maxima). Other approach would consist in defining separate indices for each floor.

In spite of these indices have been formulated for seismic inputs, they could also be used to evaluate the efficiency of friction dissipators for other excitations (e.g., any driving forces $P_i(t)$).

No indices comparing the responses of the protected frame and of the braced one (in which the friction dissipators have been replaced by rigid connections) are considered explicitly. However, the braced frame corresponds to a protected frame with all $\mu_i N_i \to \infty$, thus this comparison can be also made within the four considered indices.

Other indices dealing with the introduction of high frequencies in the building response should be defined. However, as discussed next, some information about that issue could be given by the second index.

Each index is described and discussed in the following subsections.

6.3.2 Interstory drift index

The *interstory drift index* (IDI) can be expressed as

$$IDI = \frac{MID}{MID_0} \tag{6.1}$$

where MID is the maximum interstory drift (along time and along the height of the building) of the protected frame and MID_0 is the maximum interstory drift for the structure without bracing (bare frame, all $\mu_i N_i = 0$).

This index accounts for the reduction of the response that mostly characterizes the level of damage in the structural members and in the non-structural ones (partitioning walls, cladding).

Other authors have defined another similar index related to the maximum lateral displacement of the top floor [26]. Its meaning is similar to the IDI; in fact if the building deforms according to the first natural mode of vibration, the information given by these indices is equivalent; otherwise, conclusions derived from the IDI are more reliable as the displacements in all the floors are taken into account.

6.3.3 Absolute acceleration index

The *absolute acceleration index* (AAI) can be defined as

$$AAI = \frac{MAA}{MAA_0} \tag{6.2}$$

where MAA is the maximum absolute acceleration (along time and along the height of the building) of the protected frame and MAA_0 is the maximum absolute acceleration for the same structure without bracing nor dissipators (bare frame, all $\mu_i N_i = 0$).

This index accounts for the reduction of the response that mostly characterizes the level of damage in some non-structural members (e.g. pipes, glass cladding, etc.) and the human comfort conditions. This index yields information about the maximum base shear too. However, a more specific index could be defined for base shear; it could be the ratio between the maximum values of the sums of the absolute accelerations at each floor for the protected frame and the same quantities for the bare frame, respectively.

Values of MAA bigger than 1 could indicate the introduction of high frequencies in the response.

It is interesting to notice that IDI and AAI can not be simultaneously reduced. In fact, values of AAI bigger than 1 are frequent because the friction dissipators, in some way, add stiffness to the structure.

6.3.4 Relative performance index

The *relative performance index* (RPI) [26, 38] can be expressed as

$$RPI = \frac{1}{2}\left(\frac{ASE}{ASE_0} + \frac{MSE}{MSE_0}\right) \tag{6.3}$$

where ASE is the area under the strain energy time-history of the MSBFD, ASE_0 is the area under the strain energy time-history of the MSB without bracing (i.e., all $\mu_i N_i = 0$, bare frame); MSE is the maximum strain energy of the MSBFD and MSE_0 is the maximum strain energy of the MSB without bracing nor dissipators (all $\mu_i N_i = 0$, bare frame). The ratio $\frac{ASE}{ASE_0}$ can be considered as a norm of the relative displacements response while the meaning of $\frac{MSE}{MSE_0}$ is closer to the maximum values of such relative displacements.

This index behaves similarly to the IDI. It does not mean that their values are close but rather it means that the information obtained out of the RPI is roughly equivalent to the information given by the IDI.

6.3.5 Energy dissipated by friction index

The *energy dissipated by friction index* ($EDFI$) is defined as

$$EDFI = 1 - \frac{E_F}{E_I} \tag{6.4}$$

where E_F is the total energy dissipated by friction for the MSBFD and E_I is the total input energy.

This index does not provide relevant quantitative information about the performance of the dissipator but quantifies the energy dissipated by friction.

If $\mu_i N_i = 0$ (bare frame) $EDFI = 1$ and if $\mu_i N_i \to \infty$ (braced frame) $EDFI = 1$ too; for some set of intermediate values of $\mu_i N_i$, smaller values of the $EDFI$ are obtained.

6.4 Parameters of the Analysis

6.4.1 Description and classification

In this section the parameters of the analysis are presented grouped in three categories: those dealing with the seismic excitation, those concerning the dynamic properties of the building and those related to the friction dissipators and to their supporting system.

6.4.2 Seismic input

The main parameter characterizing the destruction capacity of the input is the Housner intensity $H(\xi)$ given by $H(\xi) = \int_{0.1}^{2.5} S_v(\xi, T)\, dT$ where ξ is the damping ratio, T is the natural period of the structure and S_v is the pseudo-spectral velocity spectrum [65]. This parameter should range at least between 10 cm and 100 cm, which corresponds to moderate and strong earthquakes, respectively.

Besides, local soil conditions should be considered; the coefficients associated to these conditions can be found usually in the design codes (e.g., Eurocode 8) and might be used. An interesting approach could be to use a number of seismic events (representative of different local soil conditions) normalized with respect to their Housner intensities. This approach was used in [52].

Other relevant but less meaningful parameters are the peak ground acceleration (PGA), the total duration or other parameters related to the response spectrum.

Near source effects (pulses) should also be accounted for.

6.4.3 Building

Friction dissipators are usually installed on moment resisting frames made of concrete or steel, which can be often considered as shear buildings. Hence, the most relevant parameter is the fundamental period T_F, which is closely related to the number of floors. This parameter should range at least between 0.1 and 2.5 s, as in the Housner intensity [65], which corresponds roughly to buildings with 1 and 25 floors, respectively.

Moreover, two main groups could be considered: symmetric and asymmetric buildings. In the first case the lateral dynamic behavior can be described by two independent 2D models (a single degree of freedom per floor) while in the second case a 3D model need to be considered (three degrees of freedom per floor: two horizontal displacements and one rotation angle).

6.4.4 Dissipators

Two main parameters have to be considered: the number of dissipators and the optimal sliding load, $OSL = (\mu_i\, N_i)_{\mathrm{opt}}$ of each of them.

Regarding the first parameter, one device is installed per floor (e.g., the number of dissipators is equal to the number of floors). Despite that some authors have proposed other distributions along the height of the building (e.g., some floors do not have dissipators) [56], it is considered that a uniform arrangement yields smoother distribution of stiffness and damping, as usually recommended in any earthquake-resistant design.

About the second parameter, the OSL, two possibilities are considered: equal values ($\mu_1\, N_1 = \ldots = \mu_N\, N_N$) or some variation along height (usually bigger values are in the lower floors and the smaller ones are in the upper floors).

These two parameters are the main quantities to be determined in the design process.

Other relevant parameters might be the values of the masses m_i' of the bracing-dissipators combination.

6.4.5 Summary

The most relevant parameters are:

- Housner intensity of the input signal: $H\,(\xi)$.
- Fundamental period of the building: T_F.
- Optimal sliding load (OSL) of each dissipator: $(\mu_i\, N_i)_{\mathrm{opt}}$.

It is remarkable that, with respect to design, the role of the two first parameters and that of the third one are different: the Housner intensity of the ground acceleration and the fundamental period of the building are the input parameters (data) while the sliding loads of the dissipators are the output parameters (results).

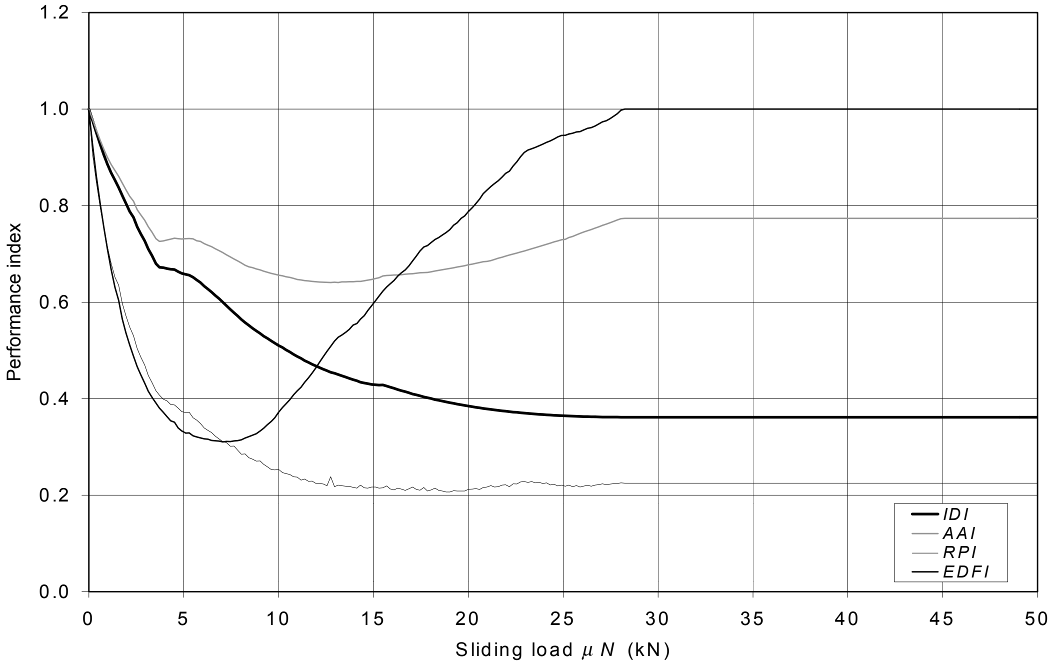

Figure 6.1 Performance indices of a SSBFD subjected to the Northridge earthquake

6.5 Design Plots

In this section some preliminary calculations are presented. Figs. 6.1, 6.2 and 6.3 contain plots of the four performance indices above defined versus the sliding loads $\mu_i N_i$ in the dissipators. Figs. 6.1 and 6.2 correspond to single-story buildings while Fig. 6.3 deals with the three-story benchmark building analyzed in Chapter 4.

Fig. 6.1 corresponds to the single-story building model depicted in Fig. 2.22. The input signal is the Northridge earthquake (see Fig. 3.13).

Plots from Fig. 6.1 show that if $\mu N > 28$ kN no sliding occurs in the dissipators and the protected frame behaves as the braced one as all the plots tend to stabilize (horizontal lines). Plots for IDI and RPI are equal to 1 for $\mu N = 0$ (bare frame) and decrease continuously until joining their horizontal branches; it means, in this case, that friction dissipators are not useful to reduce the seismic response when compared to the braced frame (e.g., for the IDI and the RPI the OSL is any force bigger than about 28 kN). This confirms the conclusions formulated by Foti, Bozzo and López-Almansa [52]. Plots for AAI and $EDFI$ are equal to 1 for $\mu N = 0$ but both reach minimum values before joining their horizontal branches; this means that friction dissipators are useful to reduce the absolute acceleration when compared to the braced frame (e.g., for the AAI the OSL is 12.4 kN). The comparison between the

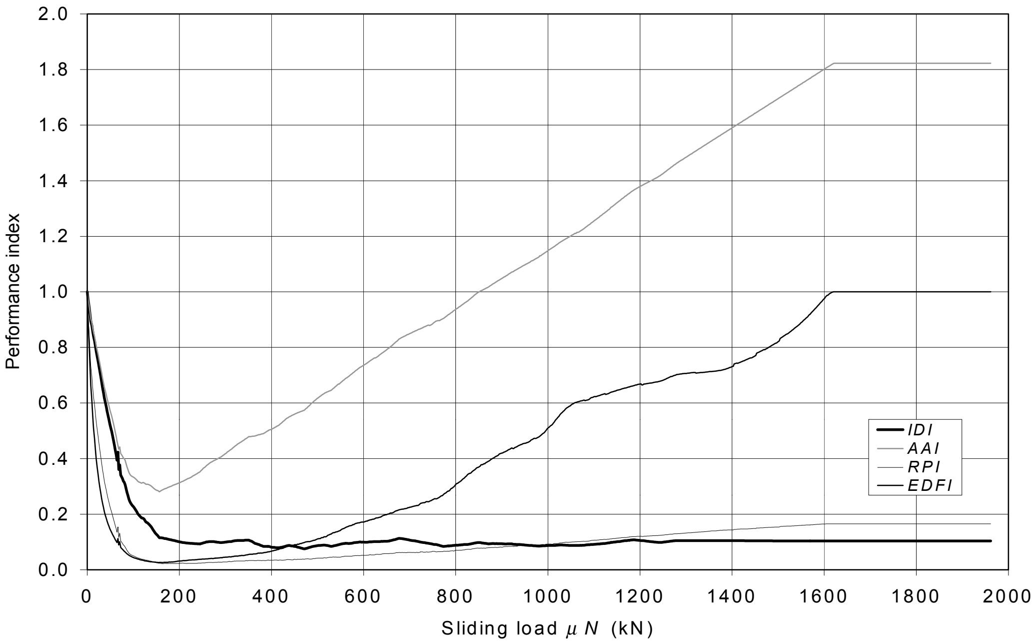

Figure 6.2 Performance indices of a SSBFD subjected to an artificial earthquake [67]

plots for AAI and $EDFI$ shows that there are generally different values of this optimum slip load, which depend precisely on the index to be minimized [66].

Fig. 6.2 corresponds to a similar single-story building as the one analyzed in Chapter 3. The input is the artificial Newmark earthquake (see Fig. E.23a) [67].

Plots in Fig. 6.2 allow to derive similar conclusions than those obtained from Fig. 6.1. The main difference is that the horizontal branch for the AAI corresponds to a value bigger than 1, which means that absolute accelerations are higher in the braced frame than in the bare (unprotected) one.

Fig. 6.3 corresponds to the three-story building (benchmark problem) analyzed in Chapter 4. The input is the Imperial Valley earthquake, El Centro register, 1941, N-S component. The same values of $\mu_i N_i$ are selected at all floors.

Plots in Fig. 6.3 allow to derive similar conclusions than those obtained from the two previous figures. The main difference is that the plots for IDI and RPI reach minimum values before joining their horizontal branches, which means, in this case, that friction dissipators are useful to reduce the interstory drifts if compared to the braced frame (e.g., according to Fig. 6.3, the optimum value of μN is 592 kN for the IDI and 494 kN for the RPI).

Plots in Fig. 6.4 were obtained taking again the benchmark structure (see Chapter 4) and using the Northridge earthquake as the ground acceleration ($PGA = 0.604g$). IEI accounts for the 'input energy index', which is equal to the ratio between the input energies for the

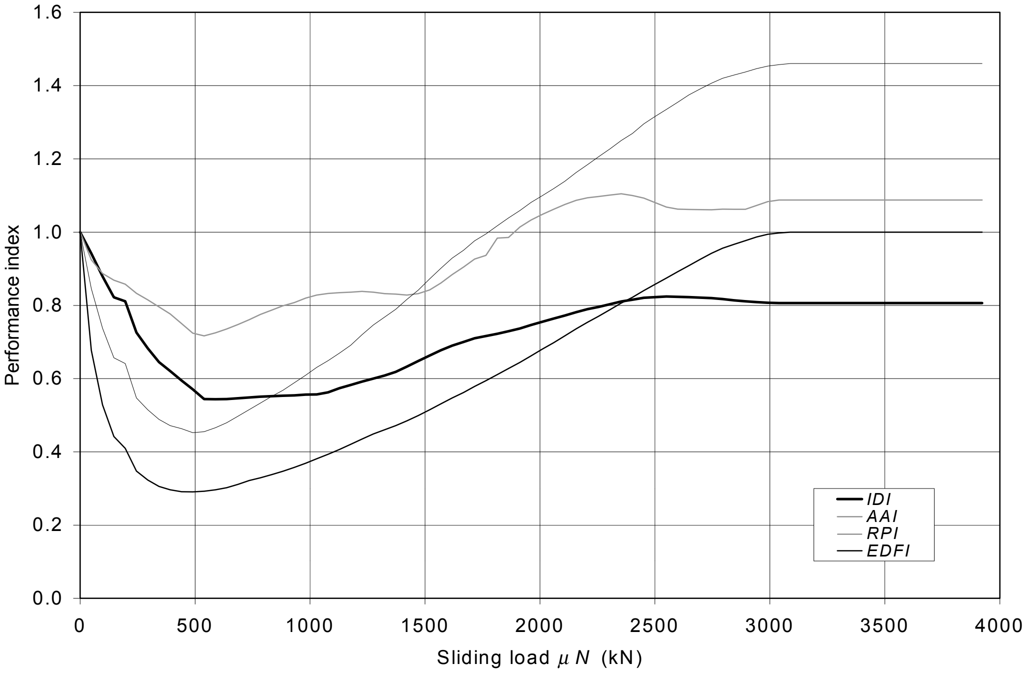

Figure 6.3 Performance indices of a the benchmark building subjected to El Centro earthquake

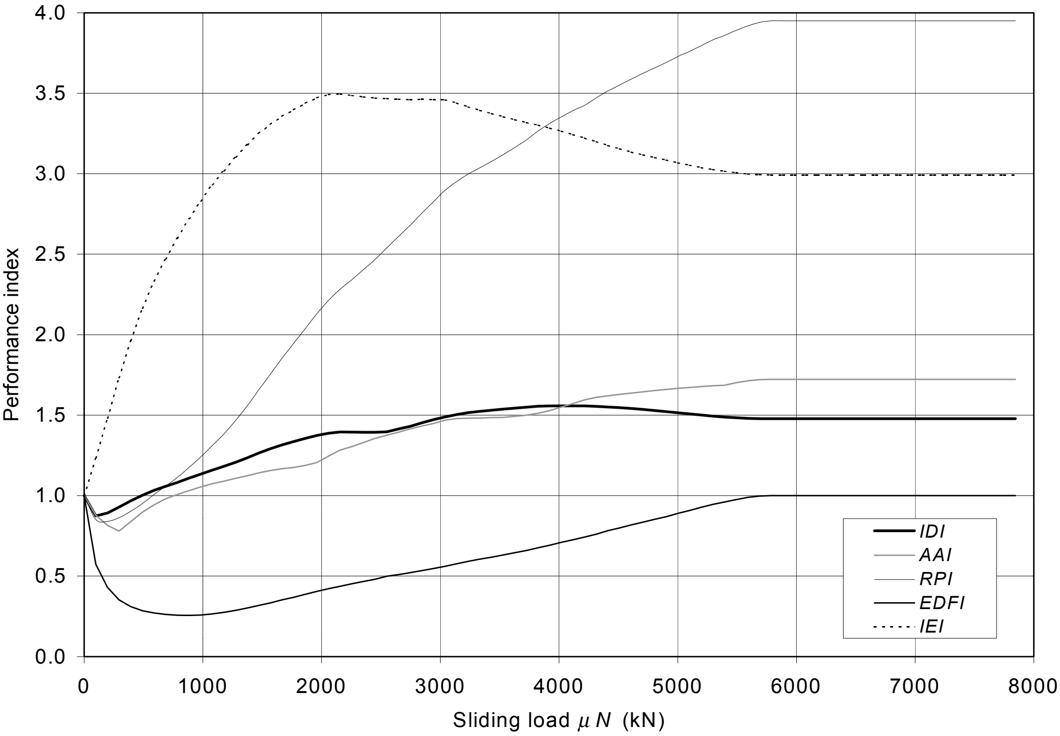

Figure 6.4 Performance indices of the benchmark building subjected to the Northridge earthquake

protected frame and the bare (unprotected) frame, respectively.

Fig. 6.4 shows a case where the braced brace apparently behaves badly with respect to the bare (unprotected) frame. However, this figure also indicates that, if FDs are used in each floor, the structure will reach its 'optimum' behavior for a sliding load of about 200 kN if the IDI or the RPI is going to be minimized. Finally, it is interesting to notice that the *IEI* changes when the sliding load does. This indicates that the input energy does not remain constant if the sliding load in the dissipators changes.

6.6 Robustness Assessment

To demonstrate the seismic efficiency of the energy dissipators, it is necessary to show that their performance is not significantly impaired if some unexpected situations arise. Three main problems will be considered:

- The input is stronger than the expected one. Since the energy dissipated by friction is proportional to the maximum amplitude (instead of to its square, as in viscous damping case), the consequences of an increment of this amplitude could be important. Moreover, stiffness degradation might be also relevant.
- Failure (total or partial) of some dissipators. It can be easily accounted for (i.e., simulated) by decreasing (softening of the friction surfaces) or increasing (blocking of the friction surfaces) the values of the sliding loads $\mu_i N_i$.
- Design errors, mainly when selecting the values of $\mu_i N_i$.

The sensitivity to these situations should be investigated.

Some preliminary calculations about failure in some dissipators were performed by Foti, Bozzo and López-Almansa [52].

6.7 Preliminary Conclusions

Some trends can be observed from the initial results shown in this chapter:

1. Friction dissipators are able to reduce the dynamic response when compared to the bare frames. This fact has been observed in virtually all the analyzed cases.
2. Compared to the response of braced frames, the dynamic response of buildings is not always reduced when friction dissipators are used; in fact, in some situations, the maximum reduction is obtained for rigid connections between the main structure and the braces (braced frames). As found in [52], initial results seem to indicate that this last situation arises usually in stiff buildings that have less than about 6 floors. No theoretical explanation for this behavior has been found.

3. In some cases, the response of the braced frame is even bigger that the one of the bare frame. However, the dissipators have demonstrated their capacity to reduce the seismic response.

4. Objective criteria for selecting the optimum values of the design parameters (OSL) for each performance index can be given.

5. The behavior of the dissipators is not very sensitive (i.e., it is robust) with respect to the considered irregular situations.

6. If friction dissipators are used for the retrofitting of existing structures, the increments in the axial forces in the columns due to the effect of bracing might be relevant. This issue deserves further attention.

Further research is required to confirm and to wide these preliminary conclusions.