A SIMPLIFIED DESIGN METHOD FOR RETROFIT OF GRAVITY LOAD DESIGN RC FRAMES WITH FRICTION DAMPERS

RAJESH S. RAO
(Simpson Gumpertz & Heger Inc., Arlington, Massachusetts, U.S.A.)
PROF. PETER GERGELY
(deceased, Professor of Civil and Environmental Engineering, Cornell University, Ithaca, New York, U.S.A.)
PROF. RICHARD N. WHITE
(James A. Friend Family Professor of Civil and Environmental Engineering, Cornell University, Ithaca, New York, U.S.A.)

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ABSTRACT

This paper has two primary thrusts: (a) the analysis of existing frame structures by the *inelastic demand spectrum method* for evaluation of their seismic resistance both before and after retrofittiing, and (b) the design of *friction damper systems* for use in retrofitting frame structures to better resist earthquake loadings. The methodologies are illustrated by means of a case study based on a three story gravity load design reinforced concrete frame with dimensions and details representative of existing structures in the central and eastern U.S.

Keywords: friction dampers; seismic retrofit; inelastic demand spectrum; masonry infill; passive damping; damper design, retrofit design.

INTRODUCTION

Many existing reinforced concrete (RC) structures, especially in the central and eastern U.S. were designed with no consideration for seismic loading and may be described as “gravity load design”. Retrofit of such structures to improve their seismic resistance is becoming a topic of increasing interest. Although several retrofit methods have been studied experimentally and analytically, there is no clear approach available for the designer to understand the effect of retrofitting on the structure’s seismic response and to evaluate the various available retrofit options.

Energy dissipating devices are becoming increasingly popular in the design of new structures as well as for retrofitting. Friction dampers have been shown to successfully improve the seismic resistance of flexible structures. In this paper a simplified design method is presented which will be used to understand the influence of retrofitting on the seismic demand on the structure and guide the designer in the selection of the appropriate retrofit scheme. The method may be used for designing friction dampers.

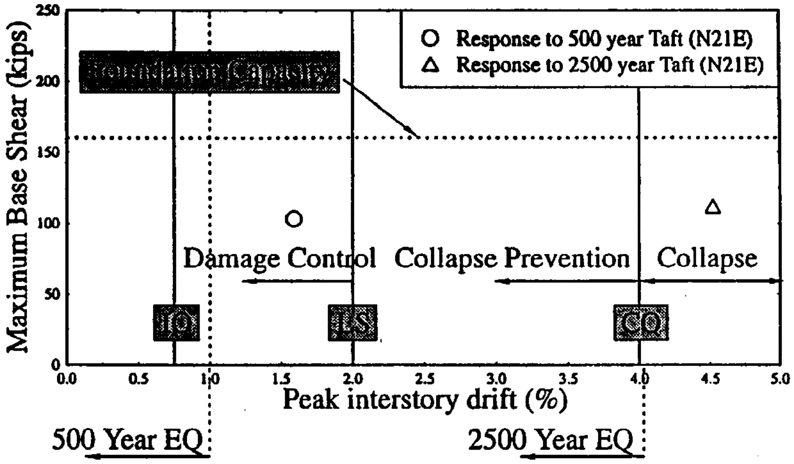
SELECTION OF CASE STUDY BUILDING

The majority of the existing buildings are three stories high or less. For the NCEER research program at Cornell and SUNY-Buffalo, a three story RC frame, designed for gravity loading alone, was considered as a typical seismically vulnerable low-rise structure. Details of the this structure are given in [2]. In this paper the same three story building is used for the case study. Full scale component tests, shake table tests, and analytical studies have shown that the three story frame is excessively flexible and undergoes large displacements under moderate seismic loading.

Seismic Loading and Performance Criteria:

The structure was assumed to be in zone 3 and situated at a site with stiff soil. The seismic loading for the three story building was defined by two levels of ground motions, with expected return periods of 500 years and 2500 years. For each return period, design spectra were constructed using the approach suggested in [1]. The Kern County Earthquake (1952) recorded ground motion time history was scaled such that the response spectrum matches the appropriate design spectrum in the period of interest. Using this approach results in PGA values of 0.262g and 0.485g for return periods of 500 years and 2500 years, respectively.

The performance criteria was defined in terms of maximum interstory drifts and maximum base shear. Fig. 1 shows the various ranges of performance levels. It was decided to aim for collapse prevention for a 2500 year earthquake and substantial damage control for a 500 year earthquake (Fig. 1). Also, since the existing building foundations are expected to have limited base shear capacity, the base shear demand on the frame must be limited (here assumed to be 150 kips/frame). Nonlinear time history analyses for the structure using the program IDARC [3] show that the structure would collapse under 2500 year Taft and drifts would exceed 1% for 500 year Taft. Hence the structure needs to be retrofitted in order to satisfy the performance criteria.



IO: Immediate Occupancy, LS: Life Safety, CO: Collapse

Figure 1. Target Responses for two earthquake levels

Retrofit Options:

Conventional seismic retrofit schemes that have been used in practice include jacketing of columns and beams, and adding infill walls and lateral bracing. Jacketing of the frame elements leads to an increase in component ductility and overall lateral stiffness and strength of the structure. Since it is uneconomical to jacket all columns, the maximum drift capacity is still controlled by the unjacketed columns. Infill walls and bracings provide large increases in stiffness and strength but reduce the ductility in the lateral system. More recently researchers have suggested the use of supplemental damping devices such friction, viscous or viscoelastic dampers. Damping devices provide additional energy dissipating capacity and can also increase overall lateral stiffness of the structure. Introduction of a retrofit scheme changes the displacement and shear demand on the structure depending on the frequency content of the ground motion. There is no simple method that quantitatively describes the change in response of the structure produced by retrofitting in terms of forces and displacements. In the next section a simplified method is presented for determining the influence of retrofitting on the dynamic response of the structure. The method is then used to show the superior performance of friction dampers as a retrofit scheme and to select the slip load setting for the friction dampers.

INELASTIC DEMAND SPECTRUM METHOD

The method consists of carrying out a pushover analysis of the frame to obtain the capacity curve. The force distribution used for the pushover analysis must incorporate the various modes of vibration. For low-rise structure, it is sufficient to use the first mode. At each stage of the analysis the displacements and shears in the structure are converted to spectral displacements (S_d) and spectral accelerations (S_a) using the following equations:

$$S_a = V\frac{\sum_{i=1}^{N} m_i\varphi_i^2}{(\sum_{i=1}^{N} m_i\varphi_i)^2} \quad (1); \qquad S_d = \left(\frac{\sum_{i=1}^{N} m_i\varphi_i^2}{\sum^{N} m_i\varphi_i}\right)\frac{v_{top}}{\varphi_{top}} \quad (2); \qquad T = 2\pi\sqrt{\frac{S_a}{S_d}} \quad (3);$$

where N = number of stories, $\{\varphi_i\}$ = mode shape of the structure, V = base shear, T = period of the structure and {v} = displacement vector of the frame during pushover. The mode shapes used in Eqs. (1) and (2) were obtained using the secant stiffness matrix. The structure is pushed to collapse, introducing inelastic hinges as they occur, and the resulting S_a vs S_d plot provides the capacity curve. S_a and S_d values give, respectively the measure of the force and displacement level in the frame as the pushover analysis progresses. The capacity curve can be seen as the envelope of secant responses of an equivalent SDOF system.

The demand on the system i.e. its response, can be calculated using equivalent damping methods. If the mass of the equivalent SDOF system is set to 1.0, the capacity curve would give the force-deformation curve for the equivalent non-linear SDOF system. It is proposed here to replace the non-linear force response with a bilinear curve. Time history analysis of the bilinear SDOF gives the demand on the structure. Hence the non-linear MDOF RC frame is reduced to an equivalent bilinear SDOF system. This method was used to predict the response of the 3 story RC frame to Taft (500 year) earthquake. Figure 2 shows the capacity curve obtained from pushover analysis and the equivalent bilinear curve. The comparison of story drifts and story shears (Fig. 3) shows good agreement between nonlinear MDOF analysis and equivalent SDOF analysis results.

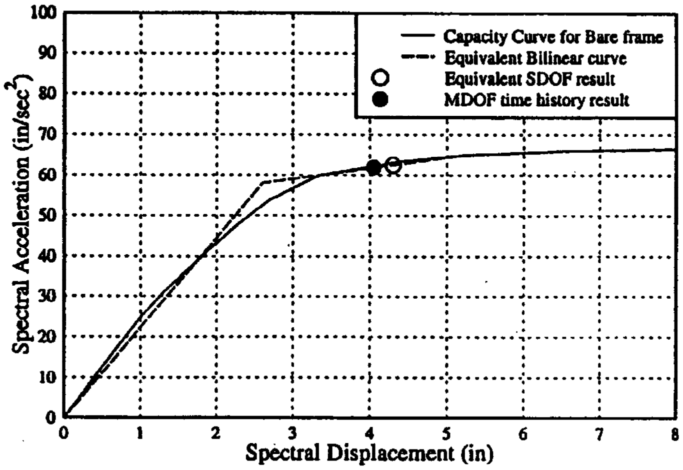


Figure 2. Obtaining an equivalent bilinear capacity curve

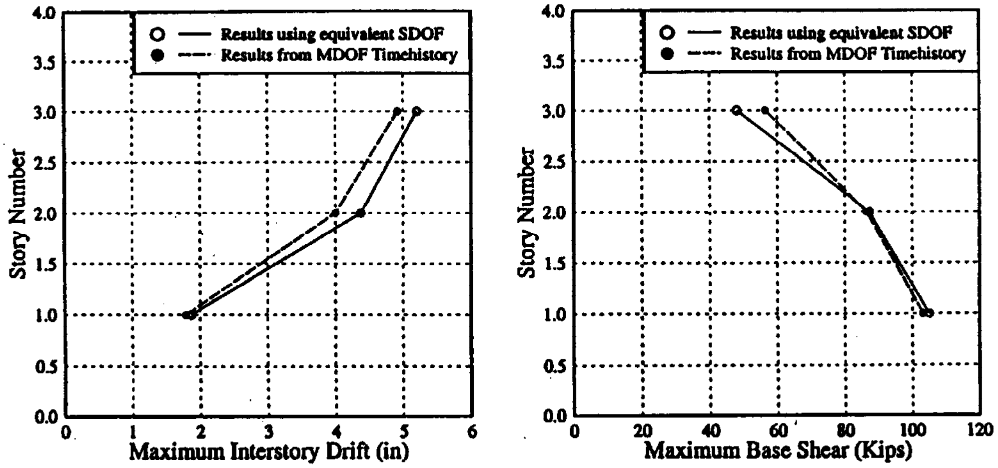


Figure 3. Comparison of results from MDOF time history and equivalent SDOF system

The capacity curve of the retrofitted frame also can be represented in the S_a-S_d plane by an equivalent bilinear curve. An increase in the lateral stiffness of the MDOF structure results in a corresponding increase in the stiffness of the bilinear SDOF system. The maximum response of the equivalent bilinear SDOF system provides the resulting demand. For a given increase in stiffness, time history analyses can be performed for the bilinear SDOF system at various yield levels. When the maximum responses are plotted on the S_a-S_d plane and connected, the "inelastic demand spectrum" curve is obtained. The inelastic demand spectra provides the envelope of the inelastic response of the various structures with the same initial stiffness and different strength levels.

Figure 4 shows the demand spectra for the 500 year Taft, for cases when the initial stiffs of the retrofitted structure is 2, 4 and 10 times that of the original structure. Fig. 4 also shows the drift limit and the base shear limit for 500 year Taft (obtained from the performance criterion), expressed in terms of S_d(lim) and S_a(lim). A clear picture is provided on the variation in displacement and shear demand on the structure as a result of the change in stiffness and strength of the structure produced by retrofitting. It can be inferred from the demand spectrum curves that for a given increase in stiffness, higher strength does not necessarily imply lower displacements. There is an optimum strength level for which the displacement levels are the lowest; hence the strength needs to be controlled. The strength also needs to be controlled in order to prevent exceeding the base shear capacity of the foundations. It also can be observed from Fig. 4 that the drifts can be reduced by increasing the stiffness.

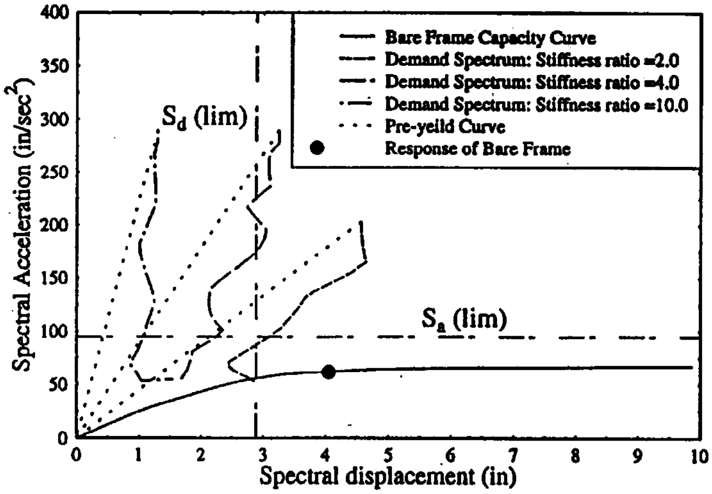


Figure 4. Inelastic Demand Spectrum curves for different stiffness ratios

RETROFITTING WITH FRICTION DAMPERS

Conventional retrofit schemes such as jacketing and adding bracings or shear walls increase the stiffness and strength of the structure. However there is minimum control over the extent of strength increase and hence the retrofitting may not necessarily improve structural response. Retrofitting the structural with friction dampers provide the strength control required to obtain the optimum structural response. Adding friction dampers would increase the stiffness of the structure until a certain shear level is reached, at which the dampers can be set to slip. Hence, the base shear demand on the foundations can be limited. Also, the appropriate slip level can be selected to give the optimum response for the earthquake loading. The energy dissipated by the friction damper reduces the energy demand on the structure and damps out the structural response.

A constructible Friction Damper Retrofit Scheme

A friction damper system consists of the friction unit (consisting here of cold rolled steel plates rubbing against clutch-lining pad material, "clamped" together by one or more bolts) and a structural system for integrating the friction unit with the structure. The force level at which the frictional surfaces slip is controlled by the tension in the bolt crossing the slip surfaces. In a frame, the structural system can be either steel braces bolted to corner region of the open bay space in the frame, or an infill wall with gaps around the edges to prevent stiffness interaction of the wall with the frame members.

The installation strategy adopted in this study [4] is to use a masonry infill wall with gaps around the sides and top of the wall, with the friction unit installed between the top of the wall and a beam spanning between columns at the top of the open bay of the frame (Fig. 5). This system has the advantage of needing only simple compression-type connections between the damper and the frame, with little or no drilling required (and hence no noise or dust problems) for anchorage of tension/shear connections required for normal steel bracing systems. The retrofit scheme proposed in Fig. 5 was installed in a 1/3 scale single story steel frame and then subjected to dynamic loading on a shake table. Results given in [4| indicate that the retrofit scheme is successful in providing moderate added stiffness and large energy dissipation.

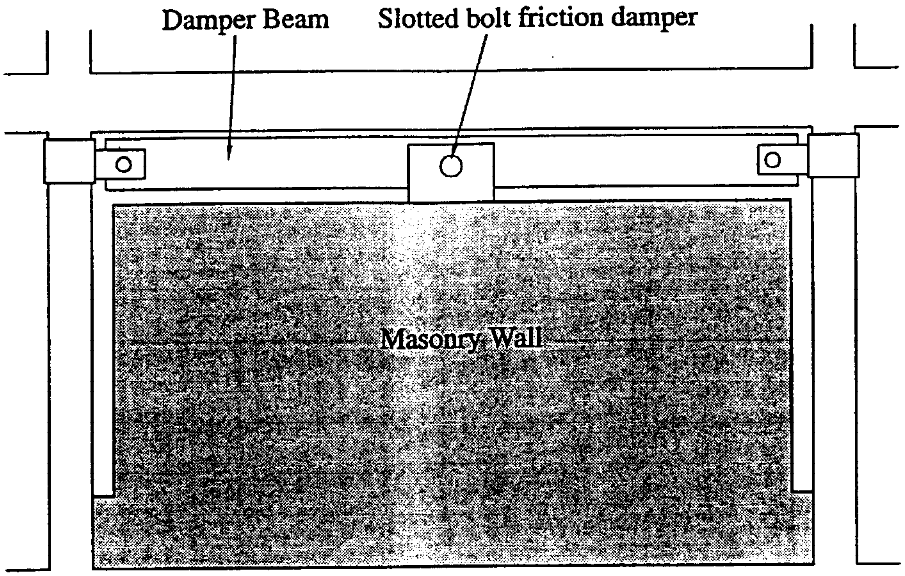


Figure 5. A constructible retrofit scheme using masonry infill with friction damper

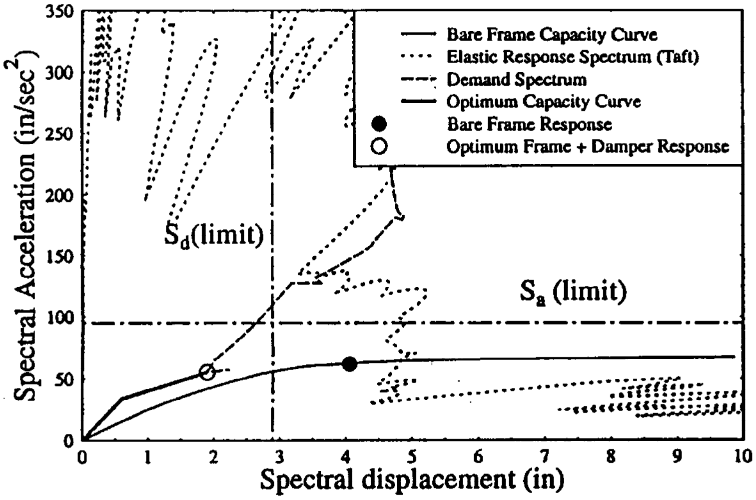


Figure 6. Selecting the optimum capacity curve

DESIGN OF FRICTION DAMPERS:

Design of the dampers requires selecting the initial stiffness of the damper system before the damper slips, and selecting the load at which the damper slips. The retrofit scheme proposed here for the three story building is to install the wall-damper scheme in the central bay of each story. The stiffness of the wall damper system was obtained from the shake table test results. To obtain the optimum slip load, a large number of nonlinear time history analyses would normally be required, but the inelastic demand spectrum method proposed here serves as a powerful tool to obtain the design slip loads in the friction dampers. For the three story building, the dampers are designed for the 500 year earthquake and then the performance for the 2500 year earthquake is checked. The capacity curve for the bare frame and the demand spectrum for the frame with dampers for various slip levels are shown in Fig. 6. The demand spectrum curve was constructed by carrying out time history analyses of a series of bilinear SDOF systems with different yield levels and initial stiffness corresponding to pre-slip stiffness of the retrofitted frame. Each point on the inelastic demand spectrum curve corresponds to the response of a bilinear capacity curve which represents the nonlinear response of the retrofitted frame with a certain slip load setting. From the demand spectrum, the bilinear capacity curve was obtained which gives the optimum response (Fig. 6), and which also satisfies the drift limits and the maximum base shear limits. For a bilinear SDOF having a different slip level, the displacement response would be higher. The slip load distribution corresponding to the optimum capacity spectrum was calculated from Eqs. 1 and 2, with results as follows: S_d (slip) = 0.6 in; S_a(slip) = 33.4 in/sec^2

Total base shear in the frame with damper at slip is given by:

$$V\,(at\ slip) = S_a(slip)\,\frac{\left(\sum_{i=1}^{N} m_i \varphi_i\right)^2}{\sum_{i=1}^{N} m_i \varphi_i^2}$$

The part of the base shear resisted by the dampers is calculated by subtracting the base shear in the frame from the total base shear. This is the shear level in the first story wall at which the dampers slip. The distribution of the slip forces in the stories is set proportional to the shears developed in each story due to a lateral load with triangular distribution. Hence the slip force distribution in the dampers, from the design procedure presented here, must be 15.0 kips (first story), 12.6 kips (second story) and 7.6 kips (third story). To confirm the efficacy of the proposed method, several time history analyses were performed on the three story frame, using different slip load levels. Fig. 7 shows that the design slip load distribution (15 kips for first story) obtained from the proposed method is indeed an optimum distribution, and leads to acceptable drift and shear levels for the 500 year earthquake loading. Time history analysis was performed on the retrofitted frame with the 2500 year Taft earthquake loading. Results in Fig. 8 show that for both levels of loading, the retrofitted structure satisfied the target performance criterion.

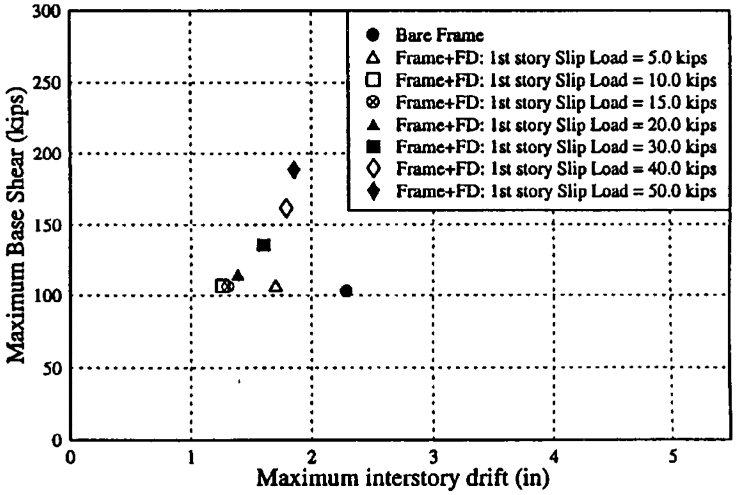
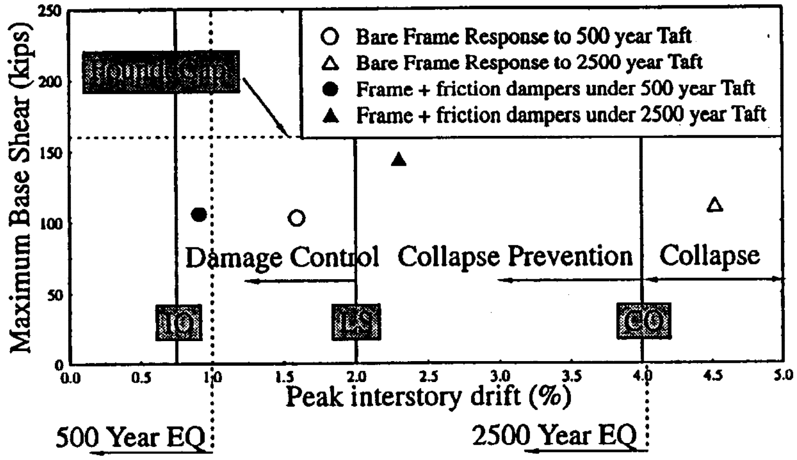


Figure 7. Response of structure with different damper settings



IO: Immediate Occupancy, LS: Life Safety, CO: Collapse

Figure 8. Target and achieved response levels for three story RC frame

SUMMARY AND CONCLUSIONS:

A gravity load designed three story structure was considered for evaluation and retrofitting. The structure was found to be inadequate under the two design loading levels. An inelastic demand spectrum method was presented and used to show that optimum structural response is obtained by increasing stiffness and a controlled increase in strength. Friction dampers can provide the necessary stiffness increase and strength control. A friction damper retrofit scheme installed in combination with masonry infill was described. The inelastic demand spectrum method was used to obtain the design slip load for the dampers, thereby avoiding the need to perform large number of inelastic time history analyses. Time history analyses confirmed that the simplified design method provides the optimum slip load distribution and that the retrofitted structure satisfies the target performance criterion.

The concepts and method presented here can be easily extended to any other frame structures and one can include several different design ground motions. When higher pre-slip stiffness is required, the masonry wall in Fig. 5 must be replaced with K-bracings and the bracing sizes adjusted to obtain the necessary story stiffness.

ACKNOWLEDGMENTS

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REFERENCES

[1] "Guidelines and Commentary for the Seismic Rehabilitation of Buildings", 50% submittal draft, 1995.
[2] Bracci J.M., "Experimental and Analytical Study of Seismic Damage and Retrofit of Lightly Reinforced Concrete Structures in Low Seismicity Zones", Ph.D. Thesis, SUNY Buffalo, 1992.
[3] Inelastic Damage Analysis of Reinforced Concrete (version 3.0), Kunnath S. and Reinhorn A., SUNY Buffalo, 1992.
[4] Rao, R.S., "Seismic Retrofit of Non-Ductile RC Structures using Friction Dampers", Ph.D. thesis, Cornell University, 1996.