Analysis and Design of Buildings with Added Energy Dissipation Systems

by Michael C. Constantinou, Gary F. Dargush, George C. Lee (Coordinating Author), Andrei M. Reinhorn and Andrew S. Whittaker

Research Objectives

This article is a summary of the progress made during 2000-2001 by MCEER researchers working in the subtask of facilitating technologies. These research progresses should be viewed from the context that the long term (3-4 year) objective is to complete an MCEER monograph on *Analysis and Design of Buildings with Added Energy Dissipation Systems*. Although each individual researcher is advancing the state-of-the-art knowledge with his respective graduate students and research collaborators, it is the total systems integrated effort directed toward the practicing professional that underpins the projects within this group. This undertaking is possible by using the "Center Approach" in earthquake engineering research.

MCEER's research program 2 on the seismic retrofit of hospitals concentrates on developing cost-effective retrofit strategies for critical facilities using new and emerging materials and enabling technologies. Current emphasis is given to hospitals that should remain functional during and immediately after damaging and/or destructive earthquakes.

The major disciplinary components of this program are geotechnical, structural, nonstructural, advanced technologies and high performance materials, socio-economic issues and systems integration. One important research task concerning the methods of analysis and design of buildings with added emerging materials (e.g., composite infill walls) and/or enabling technologies (e.g., damping devices) is carried out by a group of research investigators under the title "Facilitating Technologies." This task is the heart of the systems integrated approach concerning the performance of a system (i.e., the performance of hospital buildings and contents with added earthquake protective systems so that the medical functions can be carried out). To develop retrofit strategies for buildings by using added materials and/or enabling devices, practicing engineers need to know how to choose appropriate technologies to satisfy building performance indices and/or objectives cost-effectively for given earthquake risk. In view of FEMA 273/274 and NEHRP 2000, which encourage the

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use of emerging technologies to achieve building performance objectives, there is a need to develop principles and design guidelines for these engineers. This is the fundamental rationale of the research task on facilitating technologies.

MCEER investigators have made many key contributions to the two most advanced codes and guidelines related to the implementation of passive energy dissipation systems: *FEMA 273/274 Guidelines for the Seismic Rehabilitation of Buildings*, published in 1998, and the *NEHRP 2000 Guidelines for Seismic Regulations for New Buildings and Other Structures*, that will be published in the next few months.

The *FEMA 273 Guidelines* and *274 Commentary* represented the culmination of more than a decade of work funded by the Federal Emergency Management Agency, the National Science Foundation and other agencies. These documents provide structural engineers with new information on procedures for the analysis, evaluation, and design of existing and retrofit construction. Information is also presented on performance-based earthquake engineering, modeling and analysis, steel, concrete, and timber structures, foundations, and nonstructural components. MCEER researchers have contributed to FEMA 273/274 in two areas: modeling and analysis, and seismic isolation and damping systems (see Constantinou et al., 1998 and Tsopelas et al., 1997).

The *2000 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* includes robust procedures for the analysis and design of passive energy dissipation systems (Appendix to Chapter 13) using force-based methods of analysis that are consistent with those methods used for the analysis and design of conventional construction. The development of force-based analysis and component-checking methods for highly nonlinear or velocity-dependent energy dissipation devices proved to be a most demanding task. MCEER researchers have developed the technical underpinnings of the methods presented in NEHRP 2000 (see Ramirez et al., 2000).

Since the publication of FEMA 273/274 in 1998, many practicing engineers have been interested in using these guidelines to retrofit existing buildings with base isolation and/or energy dissipation devices. As a result, several major retrofit projects have been completed and their results publicized,

Structural engineers who develop cost-effective retrofit designs for existing buildings will find information regarding how to select the best passive energy dissipation device system for a given type of building (e.g., high rise, low-medium height, steel, reinforced concrete, masonry, timber, relatively symmetrical, irregularly-shaped, etc.) and for given earthquake risk very useful. Other procedures, such as how to optimally distribute damping devices throughout a structure and how to consider multi-performance indices are also of critical importance.

particularly in the area of base isolation systems, in which MCEER researchers (most notably, M. Constantinou and A. Whittaker) have acted as consultants. Because base isolation technology has a longer history of practical implementation for buildings and bridges, more projects have been successfully completed. However, only limited reports are available in the open literature on passive energy dissipation devices applied to buildings. This is primarily due to the relatively short history in experience of practical applications and the fact that many available devices/approaches are reported in research publications, many developed and/or improved by MCEER researchers.

During the past two decades, many advances have been reported on the performance and vibration reduction properties of passive energy devices. As noted earlier, MCEER researchers have played a significant role in the development of a variety of devices. This "device-based" line of pursuit will be continued as new ideas, materials and/or devices become available.

A new systems-based approach is now being undertaken to provide answers to the many questions on choosing appropriate devices. Regarded as the "building-device system based" consideration, these studies emphasize the performance of the building with added passive energy dissipation devices. This new systems-based approach is the central theme of the research task on facilitating technologies, and this paper focuses on these new approaches.

To develop analytical models or to carry out experimental observations for the systems-based study is considerably more complicated than to model or to test the behavior of a single device.

First, existing buildings themselves have different dynamic characteristics and are complicated to model. The performance of the devices cannot be generalized based on one simple structure. Many multiple degree of freedom (MDOF) systems cannot be treated as single DOF systems (decoupling assumption) with sufficient accuracy. To develop simplified finite element (FE) analysis models for complicated MDOF systems is itself a challenge.

When energy dissipation devices are implemented in these MDOF structures, the total building-device systems are generally nonlinear systems. Much creativity and fundamental research in structural dynamics principles have to be pursued to develop a reasonably simple and accurate analysis and design procedure. The current, MCEER studies may be grouped into three separate categories.

Type I Projects: New Devices and Systems —continued development of new ideas in passive energy dissipation devices and semi-active systems. The semi-active systems can extend the range of traditional passive energy dissipation systems and can be combined to provide an added fail-safe feature to these systems.

Type II Projects: MDOF Modeling of Building-Device Systems—This category of studies is concerned with the behavior and design of the building-device system that must be studied by using multiple DOF models, including when the systems are nonproportionally damped. These studies provide quantitative information on the er-

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Links to Current Research

Program 2: Seismic Retrofit of Hospitals

- *Task 2.4a Technology Portfolio – Structural*

rors when such buildings are approximated by decoupled single DOF systems.

Type III Projects: Analysis and Design Software—MCEER will continue its development of analysis and design software for buildings with added energy dissipation systems. Some projects are fundamental in nature to establish new approaches while others emphasize the development of user-friendly simplified procedures for design professionals with acceptable accuracy.

The findings from research in these three categories will culminate in a monograph on *Analysis and Design of Buildings with Added Energy Dissipation System* for the design professional. The following sections provide brief descriptions of the progress made in current projects.

Scissor-Jack Seismic Energy Dissipation System (Type I Project)

Energy dissipation systems are being employed in the United States to provide enhanced protection for new and retrofit building and bridge construction. The hardware utilized includes yielding steel devices, friction devices, viscoelastic solid devices and mostly, so far, viscous fluid devices.

Engineers are familiar with and have extensively used diagonal and chevron brace configurations for the delivery of forces from energy dissipation devices to the structural frame (Soong and Dargush, 1997; Constantinou et al., 1998). New configurations have been developed which offer certain advantages, either in terms of cost of the energy dissipation devices, or in terms of architectural considerations such as open space requirements. Particularly, stiff structural systems under seismic load or structural systems under wind load undergo small drift and the required damping forces are large. This typically results in larger damping devices and accordingly, greater cost. In other cases, energy dissipation devices cannot be used in certain areas due to open space requirements and the ineffectiveness of damping systems when installed at near-vertical configurations.

Two recently developed configurations, the toggle-brace and the scissor-jack energy dissipation system configurations, offer advantages that overcome these limitations. Both utilize innovative mechanisms to amplify displacement and accordingly lower force demand in the energy dissipation devices. However, they are more complex in their application since they require more care in their analysis and detailing. The theory and development of these systems has been described in Constantinou et al. (2001) and Constantinou and Sigaher (2000). This section briefly presents these new configurations and compares them with the familiar chevron brace and diagonal configurations.

The toggle-brace and scissor-jack systems are configurations for magnifying the damper displacement so that sufficient energy is dissipated with a reduced requirement for damper force. Conversely, they may be viewed as systems for magnifying the damper force through shallow truss configurations and then delivery of the magnified force to the structural frame.

Figure 1 illustrates various damper configurations in a framing system. Let the interstory drift be u, the damper relative displacement be u_D, the force along the axis of the damper be F_D and the damping force exerted on the frame be F. It may be shown that

$$u_D = f\,u \qquad (1)$$

$$F = f\,F_D \qquad (2)$$

where f = magnification factor. Expressions for the magnification factor of various configurations are shown in Figure 1. The significance of the magnification factor may be best demonstrated in the case of linear viscous dampers, for which

$$F_D = C_o \dot{u}_D \qquad (3)$$

where $\dot{u}_D$ = relative velocity between the ends of the damper along the axis of the damper. The damping ratio under elastic conditions for a single-story frame (as shown in Figure 1) with weight, W, and fundamental period, T, is:

$$\beta = \frac{C_o f^2 g T}{4\pi W} \qquad (4)$$

That is, the damping ratio is proportional to the square of the magnification factor. The toggle-brace and scissor-jack systems can achieve magnification factors larger than unity. The systems can be typically configured to have values f = 2 to 3 without any significant sensitivity to changes in the geometry of the system. By contrast, the familiar chevron-brace and diagonal configurations have f less than or equal to unity.

For the purpose of comparison, consider the case of the use of a linear viscous damper with C_o=160 kN-s/m (= 0.9 kip-s/in) in the framing systems of Figure 1 with weight W = 1370 kN (= 308 kip) and T = 0.3 second. The resulting damping ratios are shown in Figure 1. The effectiveness of the toggle-brace and scissor-jack systems is clearly

Web Sites

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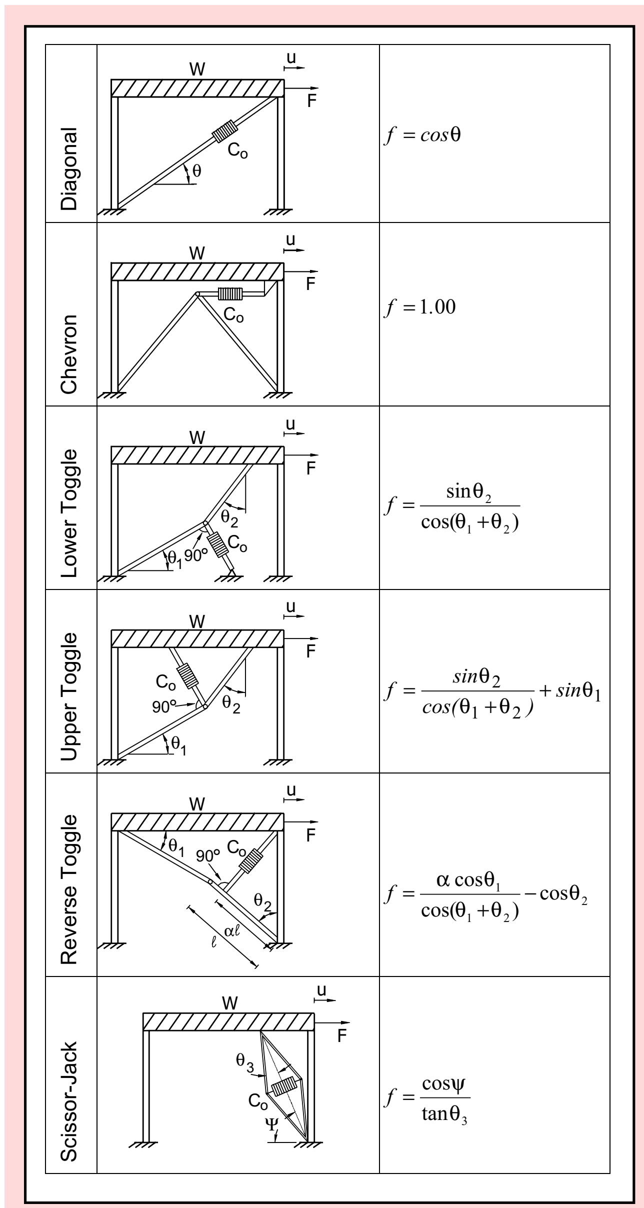


■ Figure 1. Effectiveness of Damper Configurations in Framing Systems

■ Figure 2. Tested Scissor-Jack Damper Configuration

demonstrated. It should be noted that the configurations for these two systems are identical to those tested at the University at Buffalo.

It is clear in the results of Figure 1 and in equations (1), (2) and (4) that the toggle-brace and scissor-jack configurations may provide substantial energy dissipation capability with the use of low output force devices. This may result in an important cost advantage in systems that undergo small drifts such as stiff structural systems under seismic load and most structural systems under wind load. Such cases of small drift lead to a requirement for increased volume of fluid viscous devices and accordingly increased cost. The use of the new configurations eliminates the necessity for large volume damping devices and may result in reduced cost.

Moreover, the scissor-jack system may be configured to allow for open space, minimal obstruction of view and slender configuration, which are often desired by architects. As an example, Figure 2 illustrates the scissor-jack system tested at the University at Buffalo. The open bay configuration, the slenderness of the system and the small size of the damper are apparent.

Damping Ratio as a Seismic Response Reduction Measure of Non-Proportionally Damped Structures (Type II Project)

In FEMA 273/274 (1997), an important design parameter for added devices is the effective damping ratio. As suggested in FEMA 273/274, displacements are reduced as the effective damping ratio is increased. Some believe that placing more dampers at the level of maximum inter-story drift will achieve optimized damping effects. This is true for proportionally damped or single degree of freedom (SDOF) systems. It has been shown by Lee et al., (2001) that for multiple degree of freedom (MDOF) systems, higher damping ratios could, in some cases, increase the seismic response. For structures with added passive energy dissipation or seismic isolation devices, the damping is no longer proportional nor negligibly small. To study the damping effects on MDOF building structures, the analysis method should consider the effects of non-proportional damping.

For non-proportionally damped MDOF systems, the damped mode shape is not orthogonal to the damping matrix in the n-dimensional physical domain. The complex mode shapes are orthogonal in the state-space domain, where real valued modal superposition methods cannot be directly applied. The "double modal superposition" approach developed by Gupta and Law (1986) is used in this analysis, where the response is the superposition of "modal displacement" and "modal velocity." These modes are not the un-damped system modes, nor the complex system modes. The conventional modal analysis routine of fast calculation can be used in this approach and the damping effects can be more readily explained by using structural dynamic parameters.

Theoretical Background

In a proportionally damped system, the damping ratio is used to describe damping effects. However, damping can affect the response of an MDOF non-proportionally damped system in many ways, including modal response, modal shape and natural frequencies, and damping ratio.

For an MDOF system subjected to earthquake excitation, the equation of motion can be written as:

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} = -\mathbf{M}\mathbf{U}_b \ddot{u}_g \qquad (5)$$

where **M**, **C** and **K** denote mass, damping and stiffness matrices, respectively; **U** is the relative displacement vector; $\mathbf{U}_b$ is a displacement vector obtained by statistically displacing the support by unity in the direction of the input motion; and u_g is the ground displacement.

The double modal superposition method obtains the response by equation (6):

$$\mathbf{U} = \sum_i^N \mathbf{U}_i, \quad \mathbf{U}_i = \mathbf{U}_i^d - \mathbf{U}_i^v \qquad (6)$$

$$\mathbf{U}_i^d = \psi_i^d X_i, \quad \mathbf{U}_i^v = \psi_i^v \dot{X}_i \qquad (7)$$

where U_i^d and U_i^v are real value response associated with the modal shape, as defined by equation (8), and ψ_i^d and ψ_i^v are displacement and velocity mode shapes, respectively. They are real value mode shapes and are calculated by the state vector eigen-equation. These mode shapes are determined not only by the system mass and stiffness but also by the added damping matrix. In some cases, the added damping will dominate the mode shapes (as when the fundamental modal shape collapse due to added damping.). X_i is the modal response of the following "modal" equation.

In equation (8), ζ_i and ω_i are the "modal damping ratio and circular frequency of mode i", and u_g is the ground motion.

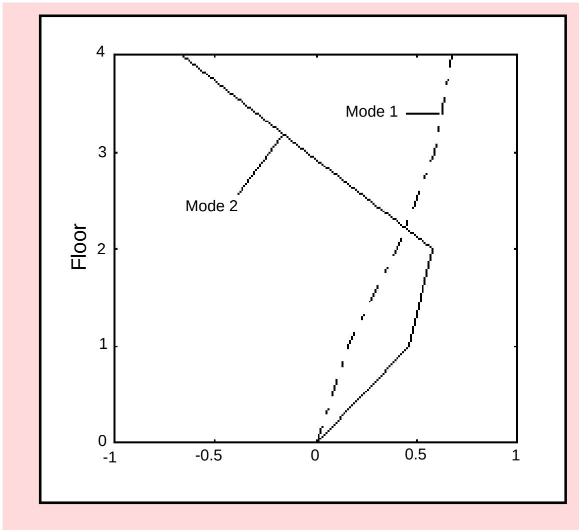
$$\ddot{X}_i + 2\zeta_i\omega_i\dot{X}_i + \omega_i^2 X_i = -\ddot{u}_g \qquad (8)$$

The damping ratio and natural circular frequency ζ_i, ω_i in the above equation are determined by the complex state vector eigenvalue solution, like the mode shape. Because the state vector will vary for different damping devices added, the modal shape, circular frequency and damping ratio will not be constant. Thus, the system response defined by equation (6) cannot be always reduced by increasing the damping ratio.

Case Studies

To illustrate how system characteristics change and their impact on seismic response due to added damping, a four DOF frame structure was analyzed. The first two vi-

"The results from modeling and analysis of a California hospital building will provide the engineering community with a three-dimensional nonlinear analysis platform that currently does not exist."



■ Figure 3. First Two Modal Shapes

bration modes of the frame are shown in Figure 3.

The added damping was limited to a maximum of 30% of the effective damping ratio (defined in FEMA 273 as a proportional ratio). Fifty-two linear viscous damper configurations were examined.The 52 configurations were arranged by considering all possible damper locations and their combinations, then changing the damping parameters to make the first modal effective damping ratio 5%, 10%, 20% and 30% (damping ratio by the added device plus 2%). As listed in Table 1, dampers were installed on every floor independently, every two floors, every three floors or on all four floors. There were 13 different damper configurations, with four damping ratios.

As noted above, the first mode of the complex damping ratio may be different from the first mode of the controlling effective damping ratio. The first complex modal damping ratio for all 52 cases is listed in Table 2. For small damping ratios (5%), the complex damping ratio is almost the same, however, when the damping ratio is increased to 10%, case 4 shows a dramatic change, while the other cases stay the same. Cases 3, 4, 7, 10, and 12 have very different values when the controlling ratio increases to 20%. Finally, the first complex damping ratio for cases 1, 3, 4, 7 and 12 becomes 99% when the ratio is increased to 30%.

The change in natural frequency in the first mode is given in Table 3. Both damping ratio and frequency changes are related to the modal change for different damper configurations.

To illustrate the non-proportional mode shape change, the first dis-

■ Table 1. Damper Location

Case	1	2	3	4	5	6	7	8	9	10	11	12	13
1st story	X				X			X		X		X	X
2nd story		X			X	X		X	X		X		X
3rd story			X			X	X	X	X	X			X
4th story				X			X		X		X	X	X

■ Table 2. Damping Ratio Comparison (First mode)

Case	1	2	3	4	5	6	7	8	9	10	11	12	13
5%	0.05	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
10%	0.10	0.10	0.10	0.99	0.10	0.10	0.09	0.10	0.10	0.10	0.10	0.10	0.10
20%	0.16	0.20	0.13	0.99	0.20	0.20	0.13	0.20	0.20	0.20	0.20	0.99	0.20
30%	0.99	0.28	0.99	0.99	0.31	0.31	0.99	0.30.	0.30	0.30	0.30	0.99	0.30

Table 3. Natural Frequency Comparison (First mode) (in Hz)

Case	1	2	3	4	5	6	7	8	9	10	11	12	13
5%	2.03	2.02	2.03	2.05	2.02	2.02	2.03	2.02	2.02	2.02	2.02	2.03	2.02
10%	2.06	2.04	2.07	1.17	2.03	2.07	2.02	2.03	2.03	2.03	2.03	2.05	2.02
20%	2.22	2.12	2.24	0.50	2.06	2.07	2.23	2.03	2.07	2.08	2.09	2.14	2.03
30%	1.96	2.29	1.50	0.32	2.12	2.15	1.41	2.04	2.14	2.17	2.20	1.30	2.04

placement mode shape at the controlling effective damping ratios of 5%, 10%, 20% and 30% are shown in Figure 4. The figure shows that, as the damping ratio becomes higher, dramatic changes can result in cases 1, 3, 4, 7 and 12 (the fundamental mode collapsed). When the fundamental mode shape collapses, the second mode shape becomes dominant in the system response, as shown in Figure 5.

The relationship between the maximum displacement response and the controlling effective damping is shown in Figure 6. Except for case 4, the response decreases as the damping ratio increases. When the controlling damping ratio is higher than 15%, different damper configurations will result in different response reductions even though they may achieve the same effective damping ratio value. It may also be seen from the figure that the maximum responses with a 30% effective controlling damping ratio for some cases are higher than those with 20%. Table 4 lists the maximum displacement re-

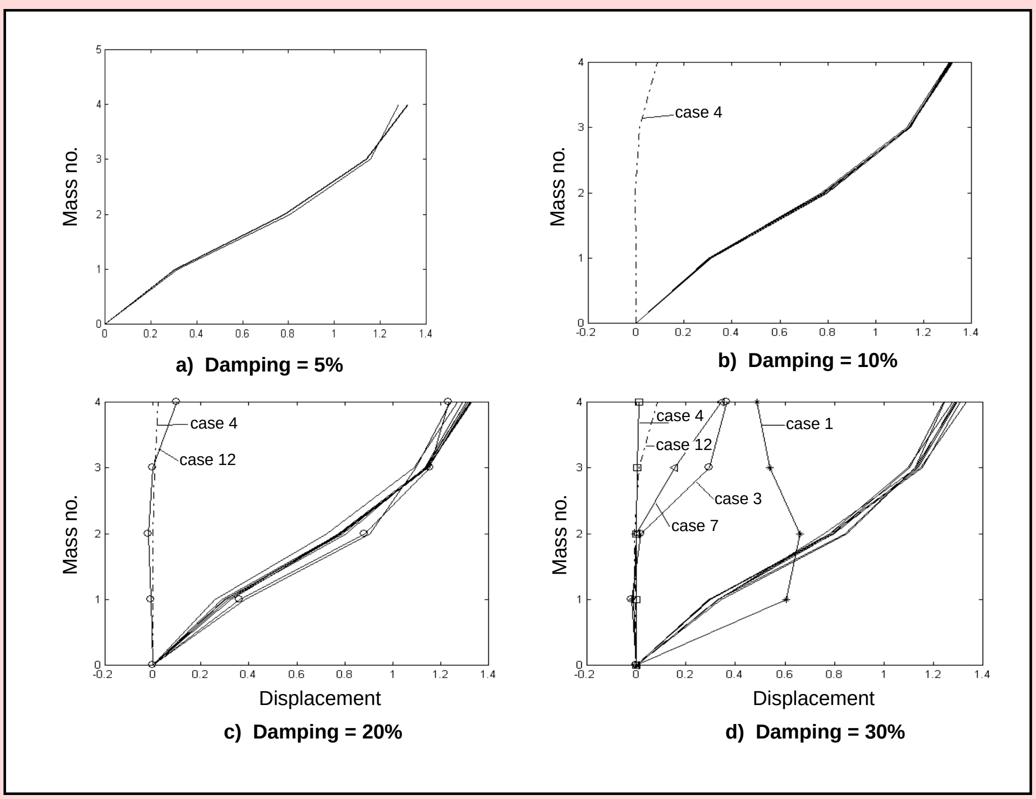
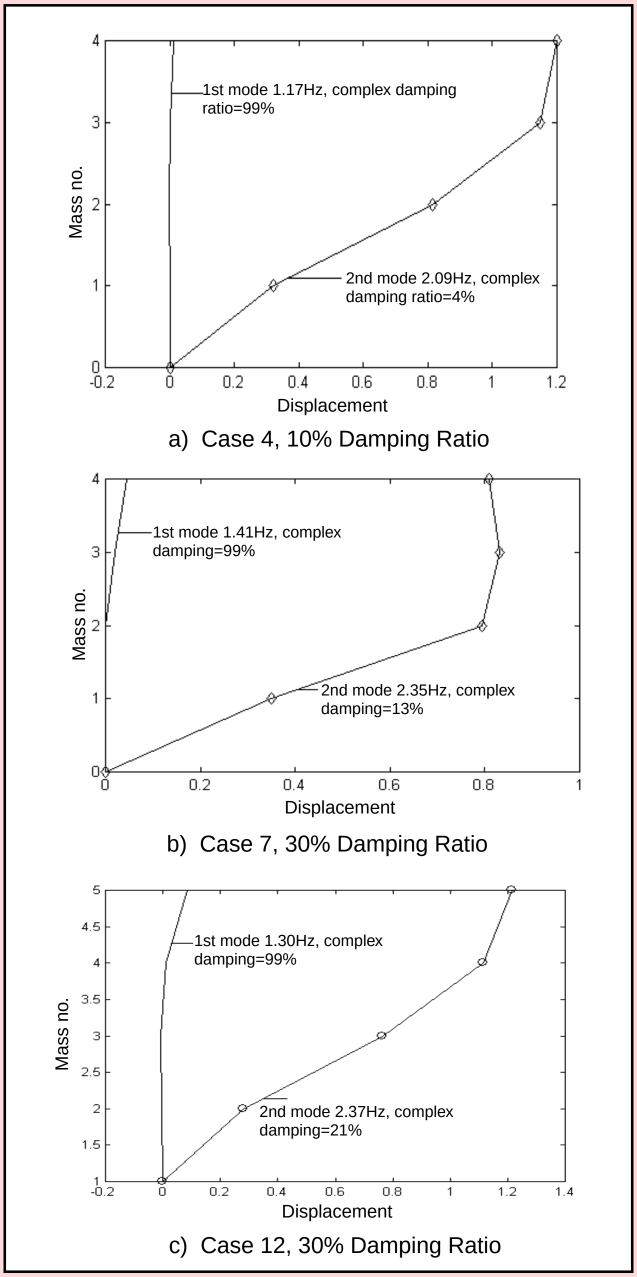


Figure 4. Displacement Modal Shapes



a) Case 4, 10% Damping Ratio

b) Case 7, 30% Damping Ratio

c) Case 12, 30% Damping Ratio

■ Figure 5. Mode Collapse

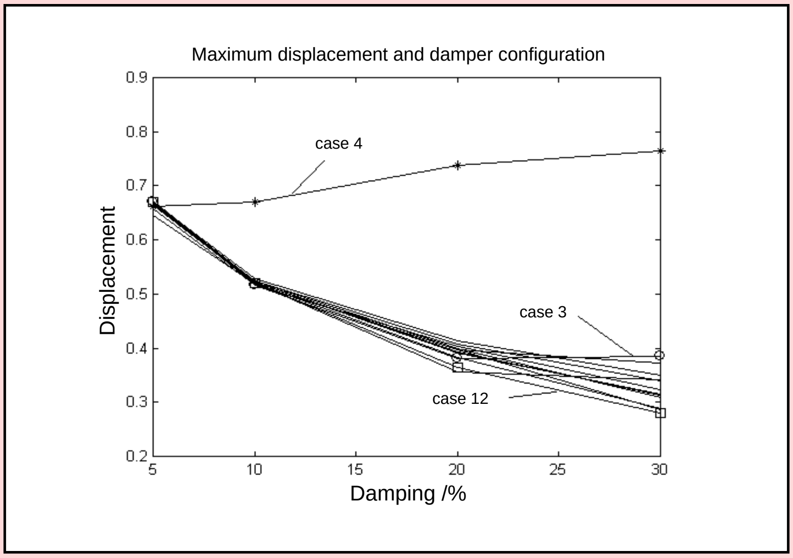
sponses for these two damping ratio values, calculated for the El Centro earthquake. As seen in the table, the damping increases in two ways: the first is where the response increased after more dampers were added and the configuration was unchanged (cases 3 and 4). The second case is when more dampers are added in different locations and configurations, as shown in case 1 at 20%, case 3 at 30%, case 4 at 30% and the rest of the cases are at 20%.This conclusion has also been obtained using other earthquake records, such as from the Northridge earthquake.

Continuing Effort

It is important to understand the limitations of using the damping ratio as the key seismic response reduction measurement. For many non-proportionally damped structures, the evaluation of performance should be based on response history analysis. In this regard, a simple method to cope with the various non-proportional damping effects will be valuable for engineering applications. This team is currently attempting to develop such a method.

■ Table 4. Maximum Displacement Response at the Top Level of the Frame Using Standard El Centro Earthquake Record

Case	1	2	3	4	5	6	7	8	9	10	11	12	13
20%	0.357	0.398	0.381	0.738	0.403	0.392	0.397	0.409	0.399	0.392	0.383	0.365	0.414
30%	0.343	0.287	0.384	0.765	0.324	0.315	0.374	0.339	0.309	0.313	0.289	0.280	0.350



■ Figure 6. Maximum Displacement Response

Optimal Design of Damping Devices for Multi-story Steel Frames Based on Multi-performance Indices (Type III Project)

FEMA 273, NEHRP 2000 and the Blue Book 1999 provide primary design guidelines for buildings with supplemental damping devices. These procedures can address building design for different performance objectives using linear or nonlinear methods after the damping device configuration has been determined. However, the rule or procedure of how to optimally distribute these damping devices throughout the building and how to consider multi-performance indexes is still not available. These procedures are very critical for practicing engineers. Since adding damping devices causes the structure to be non-proportionally damped, a "systems approach" considering the change in characteristics is necessary.

The earthquake ground acceleration can be approximated as a finite Fourier series expansion, and the seismic response as the linear combination of all responses to the single frequency excitation. Thus, to find the effective configuration, it is necessary to know the dominant frequency response (or dominant mode), the modal composition, and its mass participating factors. The selection of the response will follow the performance index. With this knowledge, an optimization scheme for damping devices can be developed.

Analysis and Design Procedure

The design procedure is outlined as follows:

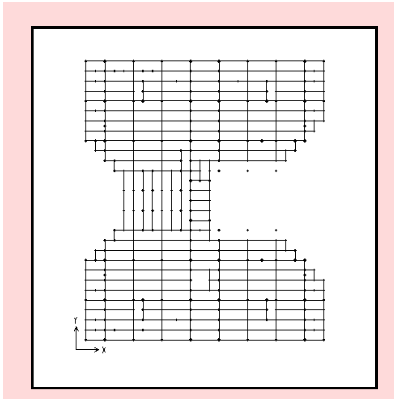
1. Calculate the characteristics of each potential configuration

2. Compare these with the original structural system's characteristics, and identify for each configuration:
   a. Natural frequencies (Some modes may collapse into each other due to added damping. This is particularly critical when damping becomes non-proportional. It follows that the natural frequencies may change significantly.)
   b. Modal damping ratio (100% critical damping usually implies a mode collapsed, which may be a problem for modal response reduction)
   c. Mode shapes
   d. Modal loading factors (variation in this characteristics may strongly influence the absolute acceleration response)
   e. Phase differences between the modes.
3. For a mass point of interest, check which natural frequencies will contribute most in the response, by using sinusoidal excitations of different amplitudes. Examine each corresponding steady state response vector to identify the largest contribution vector. A general excitation can be simplified as a sum of this sinusoidal excitation of various amplitudes, multiplied by certain envelopes. Thus, the response will be dominated by the combination of n basic vectors.
4. The vectors computed above can be further split into modal contributions. In this regard, comparisons can be made among modal shapes, loading factors, natural frequencies (which provides information on relative phase lags) and damping ratios (which provide information on dynamic amplification factors). This information illustrates the modes that are important in the response of a given mass point.
5. The damping distribution may be very different if the optimization target is selected as the story drift or acceleration. The drift response is dominated by the major modes. Thus, with a higher modal participation factor and a higher damping ratio, the drift responses will be further reduced.This is not the case for acceleration response, which includes more higher mode contributions.
6. For acceleration response, if a damper is placed between the i^{th} and $i+1^{th}$ floors, then the $i+1^{th}$ floor acceleration is usually lower than the i^{th} floor. In addition, $i-1^{th}$ floor acceleration will be lower than that of i^{th} floor.

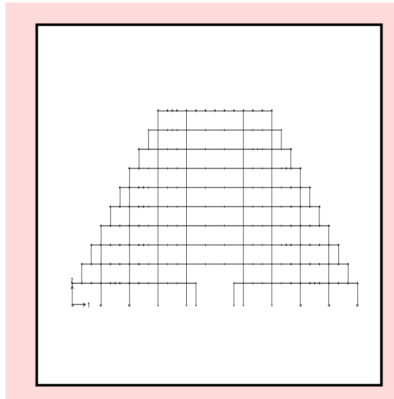
Case Study

An 11-story steel frame building structure was used as an optimal design example. The building's typical plan and north-south elevation are shown in Figures 7 and 8. This building had been designed with supplemental damping devices. The typical device configuration in the frame is shown in Figure 9. A total of 120 dampers were added to the building, with 24 dampers on the first story, and gradually decreasing as the story height increases.

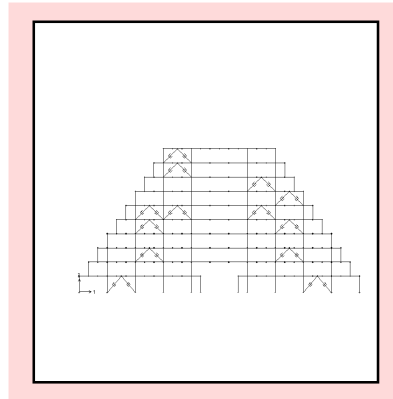
If the performance index is selected as optimal story drift, the first story mass contributes less to the dominant mode of the system response. Better results may be obtained if the dampers in this story are redistributed. The optimized distribution removes most of the devices from the first story, and



■ Figure 7. Floor Frame Plan



■ Figure 8. Elevation Frame Plan



■ Figure 9. Damper Distribution

adds them to the 6^{th} to 11^{th} stories. The same total number of dampers is used as in the original damper distribution. With this optimized distribution, the total system damping is increased by 4%. More importantly, the damping ratio of the dominant mode is increased by 19%, and the largest story drift, which occurred in the 6th floor, is reduced by an average of 11% for a series of spectra-compatible earthquake. If the performance index is selected as acceleration, the optimal distribution will be different.

Current Efforts

The design and analysis procedure proposed here is based on frequency domain analysis and time domain verification. Since response spectrum or time history analysis are preferred in structural design, the method is currently being improved and optimized using response spectrum-based objective functions.

Computational Aseismic Design and Retrofit for Passively Damped Structures (Type III Project)

Over the past two decades, considerable effort has been directed toward the development and enhancement of protective systems for the control of structures under seismic excitation. In the area of passive energy dissipation systems, applications typically involve metallic yielding dampers, friction dampers, viscous fluid dampers or viscoelastic dampers (e.g., Soong and Dargush, 1997; Constantinou et. al., 1998). Although the introduction of these new concepts and systems presents the structural engineer with additional freedom in the design process, many questions also naturally arise. In the case of passive energy dissipation systems, these questions range from performance and durability issues to concerns related to the sizing and placement of damping elements.

One promising direction for future research involves the further development of the FEMA 273/274 and NEHRP 2000 design guidelines based upon additional numerical simulations and practical experience. Alternatively, one may envision a dramatically different design process for passively damped structures by adopting a computational approach. Such an approach should incorporate the dynamics of the problem, the uncertainty of the seismic environment, the reliability of the passive elements and perhaps also some key socioeconomic factors. With these requirements in mind, one can conceptualize aseismic design as a complex adaptive system and begin to develop a general computational framework that promotes the evolution of robust, and possibly innovative, designs.

Complex Adaptive Systems

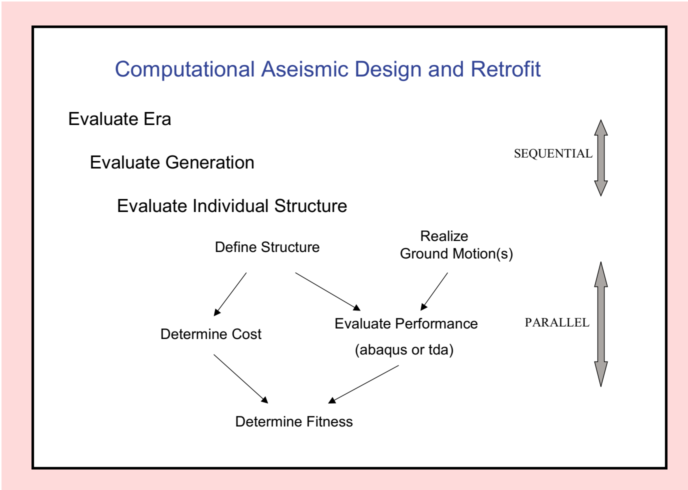
There is a broad class of systems in nature and in human affairs that involve the complicated interaction of many components or agents. These may be classified as complex systems, particularly when the interactions are predominantly nonlinear. Within this class are systems whose agents tend to aggregate in a hierarchical manner in response to an uncertain or changing environment. These systems have the ability to evolve over time and to self-organize. In some cases, the system may acquire collective properties through adaptation that cannot be exhibited by individual agents acting alone. Key characteristics of these complex adaptive systems are nonlinearity, aggregation, flows and diversity (Holland, 1995). Examples include the human central nervous system, the local economy, a rain forest or a multidisciplinary research center.

Holland (1962, 1992) also developed a unified theory of adaptation in both natural and artificial systems. In particular, Holland brought ideas from biological evolution to bear on the problem. Besides providing a general formalism for studying adaptive systems, this led to the development of *genetic algorithms.*

Computational Framework for Aseismic Design

With these ideas, one can now envision a new aseismic design approach based upon the creation of an artificial complex adaptive system. The primary research objective is to develop an automated system that can evolve robust designs under uncertain seismic environments. With continued development, the system may also be able to provide some novel solutions to a range of complex aseismic design problems.

Figure 10 depicts the overall approach for computational aseismic design and retrofit (CADR), borrowing terminology from biological evolution. Design involves a sequence of generations within a sequence of eras. In each generation, a population of individual structures is defined and evaluated in response to ground motion realizations. Cost and performance are used to evaluate the fitness, which in turn determines the makeup of the next generation of structures. Performance is judged by performing nonlinear transient dynamic analysis. Presently, this analysis utilizes either ABAQUS (2000) or an explicit state-space transient dynamics code (tda). The implementation of the genetic algorithm



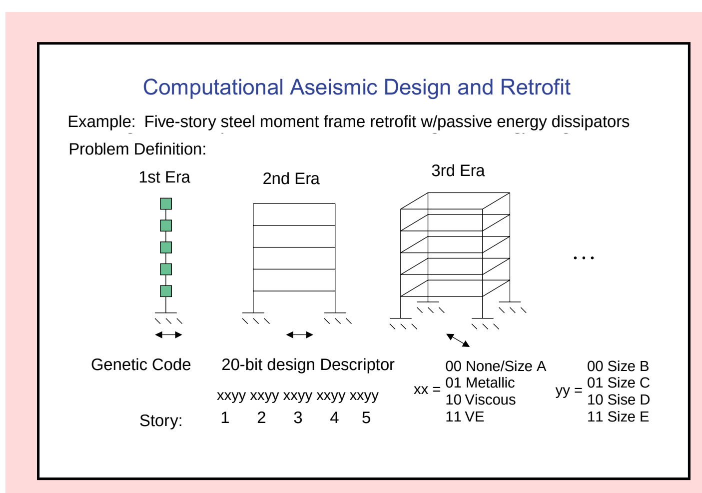
■ Figure 10. Overall Framework for Computational Aseismic Design and Retrofit

controlling the design evolution is accomplished within the public-domain code Sugal (Hunter, 1995).

Model Problem: Five-Story Steel Moment Frame

Consider an example of a five-story steel moment frame retrofit with passive energy dissipators as shown in Figure 11. Three different types of dampers are available: metallic plate dampers, linear viscous dampers, and viscoelastic dampers. For each type, five different sizes are possible. Consequently, a 20-bit genetic code is employed to completely specify the dampers used in each story of any particular structure $A \in \alpha$. Thus, for this problem, the set α contains 2^{20} (i.e., more than one million) possible structures. Figure 11 also defines a hierarchical approach in which different structural models with varying levels of complexity are utilized in each era. The idea is to first use simple models to widely explore the design space and then to employ more complicated and computationally expensive models later in the design process. Currently, a two-surface cyclic plasticity model is applied for the primary structural system and metallic plate dampers, while a coupled thermoviscoelastic model with inelastic heat generation is used for the viscoelastic dampers. Both interstory drift and story acceleration limits are set in order to establish acceptable performance.

As a specific example, consider the application of the CADR strategy to a typical five-story steel moment frame based upon Era 1 (i.e.,



■ Figure 11. Problem Definition for Five-story Steel Moment Frame lumped parameter) simulations. Let k_i and W_i represent the i^{th} story elastic stiffness and story weight, respectively. The baseline frame model has uniform story weights $W_i = W = 125$ kips for i =1,2,...5 and story stiffness $k_1=k_2=k_3=193$ kip/in, $k_4=147$kip/in,$k_5=87$ kip/in. The first two natural frequencies are 1.07 Hz and 2.72 Hz. A two-surface cyclic plasticity model is employed to represent the hysteretic behavior of the primary structure.

A retrofit strategy is now developed to protect this structure situated on firm soil in a simplified hypothetical seismic environment that can be represented by a uniform distribution of earthquakes with magnitude $7.2 \le M_w \le 7.8$ and epicentral distance $20 \text{ km} \le r \le 30\text{km}$. Each ground motion realization is generated according to the model of Papageorgiou (2000) for eastern U.S. earthquakes. For the retrofit, it is assumed that linear viscous (visc) dampers, metallic yielding (tpea) dampers and viscoelastic (ve) dampers are available and the 20-bit genetic code defined in Figure 11 is applied. Hypothetical device cost data for various size dampers were set as indicated in Table 5. Each increment in damper size corresponds roughly to a doubling of the damping capacity.

For the automated design, a population of $N_p = 40$ individual structures was evolved for a total of $N_g = 40$ generations. Within each generation, each structure was subjected to a total of $N_s = 10$ seismic events. Crossover and mutation operators were used to evolve new structures from an initially random pool. At the end of each generation, one-half of the structures were replaced with potentially new individuals. As generations pass, generally speaking, the average fitness increases, indicating that the population becomes enriched with more robust structures. However, the evolution of average fitness is not monotonic, because the genetic algorithm continues to explore the design space for better structures. Table 5 also presents the five structures that have appeared most frequently in the population. These are high fitness designs that have survived over many generations. The table data includes the total number of earthquakes that each of the five structures has experienced and the success (or survival) rate. Notice, according to Table 5, that the high fitness designs most often utilize viscous dampers and that the largest dampers are placed on the first story. In four of the high fitness designs, size C dampers appear in the fourth story, suggesting perhaps that the second mode response also requires damping.

Table 5. Five-Story Steel Moment Frame –Baseline (Case 1)

Allowable Drift =1.500 in. Allowable Acceleration =193.200 in/s^2					
Device Cost:					
	A	B	C	D	E
visc	2.00	4.00	6.00	8.00	10.00
tpea	2.00	4.00	6.00	8.00	10.00
ve	2.00	4.00	6.00	8.00	10.00
High Fitness Designs:					
No. Trials:	2350	1900	570	410	320
Damper Cost:	26.00	26.00	26.00	28.00	26.00
Success Rate:	0.9655	0.9611	0.9614	0.9561	0.9625
Story 5	visc A	visc A	visc A	visc A	visc A
Story 4	ve C	ve C	visc C	ve C	tpea B
Story 3	visc B	ve B	ve B	ve C	tpea C
Story 2	visc C	visc C	visc C	visc C	visc C
Story 1	visc D	visc D	visc D	visc D	visc D

Concluding Remarks

In this research, a new computational aseismic design and retrofit (CADR) approach is advocated. This approach centers on the development of an artificial complex adaptive system within which robust aseismic designs may evolve. As a first phase of this research program, a genetic algorithm is applied for the discrete optimization of a passively damped structural system, subjected to an uncertain seismic environment. The results of preliminary applications, involving the seismic retrofit of multi-story steel moment frames, suggest that continued development of the approach may prove beneficial to the engineering community. Current efforts are underway to work with several MCEER Industry Partners to enhance the CADR software and to develop applications associated with critical facilities.

Development of Analysis Tools for Engineering Community (Type III Project)

Any implementation of protective systems in design of new buildings or bridges, or in their retrofit, requires modeling and analysis of integral systems including the structures and the devices. When these multiple-DOF systems are implemented with energy dissipation devices, the total building-device system in general is nonlinear. Much creativity and fundamental research in structural dynamics principles have to be pursued in order to develop a reasonably simple and accurate analysis and design procedure for use by the practicing professionals. Two ongoing MCEER projects are described in the following sections. One is fundamental in nature to establish new approaches while the other emphasizes the development of user-friendly simplified procedures for the design professionals.

Nonlinear Structural Analysis by the State Space Approach

The State Space Approach (SSA) is an alternative approach to the formulation and solution of initial-boundary-value problems involving nonlinear distributed-parameter structural systems. The response of the structure, which is spatially discretized following a weak formulation, is completely characterized by a set of state variables. These include global quantities such as nodal displacements and velocities and element (or local) quantities such as nodal forces and strains at the integration points. The nonlinear evolution of the global state variables during the response of structures is governed by physical principles, such as momentum balance, and the nonlinear inelastic evolution of the local variables is governed by constitutive behavior. The essence of the SSA is to solve the two sets of evolution equations simultaneously in time using direct numerical methods, in general as a system of differential-algebraic equations. The proposed methodology results in a more consistent formulation with a clear distinction between spatial and temporal discretization.

"Much creativity and fundamental research in structural dynamics principles have to be pursued to develop a simple and accurate analysis and design procedure for practicing professionals."

Objectives and results

A material nonlinear three-dimensional beam column element and a fully geometric (equilibrium and nonlinear strain-deformation relations) and material nonlinear two-dimensional beam-column element have been developed in this framework based on a flexibility formulation. A general three-dimensional interactive constitutive macro-model has been developed. In this model, hysteretic degradation can also be modeled using suitable constitutive equations (Sivaselvan and Reinhorn, 2000). The resulting platform can study structures near collapse. The basic approach has been used to model a structure, which collapsed in shake table under severe lateral buckling (see Vian et al., in this volume).

The above models and solution procedure have been implemented in an object-oriented computer program that uses the graphical user interface (GUI) of the commercial structural analysis program, LARSA. Figure 12 shows the response of a three-dimensional frame with hysteretic behavior to bi-axial non-proportional loading. Figure 13 shows results of analysis of extremely large deformations, which allows an elastic beam to be bent into a circle. Figure 14 shows the collapse pattern of a simple structure while Figure 15 shows that all the models are developed using the macro model approach in which structures are represented by beam-column elements with hysteretic degradation.

Three Dimensional Inelastic Dynamic Analysis of Structures with Protective Systems: IDARC3D Version 2.0

The nonlinear analysis of inelastic structures with energy dissipation systems and base isolations was the subject of research and development throughout the existence of the Center's activities. The research work, both analytical and experimental, resulted in a series computer platforms, IDARC and 3DBASIS, now available nationally and internationally to the public at large through a dedicated Users Group (*http://civil.eng.buffalo.edu*). (See also Park et. al., 1987, Reinhorn et. al., 1988, Kunnath et. al., 1989, Nagarajaiah et. al., 1989, Nagarajaiah et. al., 1991, Tsopelas et. al., 1991, Kunnath et. al., 1992, Nagarajaiah et. al., 1993, Tsopelas et. al., 1994,

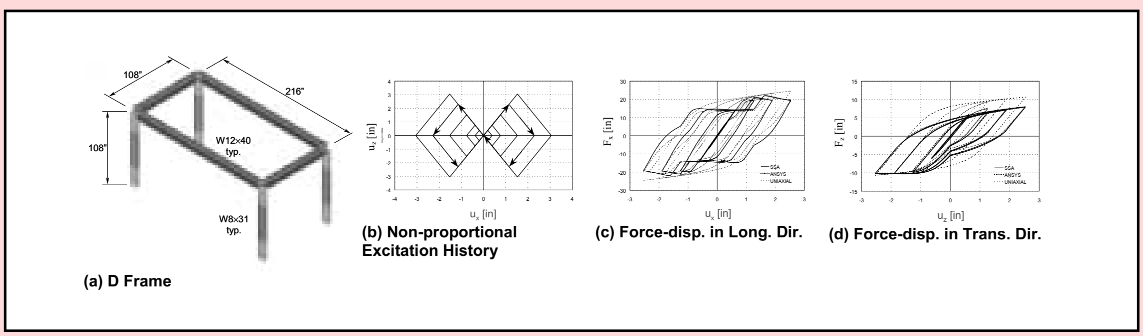
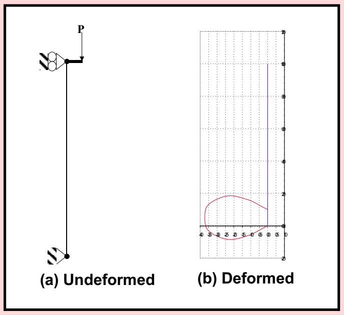
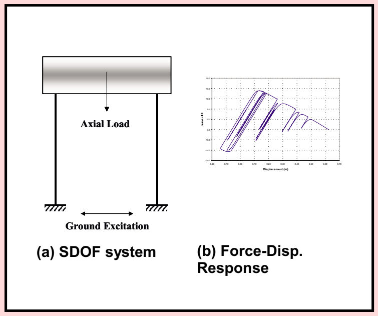


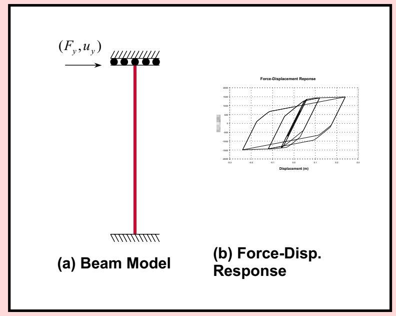
Figure 12. Inelastic Response of Frame Using 3D Interaction Elements



■ Figure 13. Eccentric Axially Loaded Elements



■ Figure 14. Dynamic Collapse using Geometric Nonlinear Beam



■ Figure 15. Hysteretic Degradation

Reinhorn et. al., 1994, Valles et. al., 1996, and Reinhorn et. al., 1998.)

The authors undertook an expansion to the three-dimensional systems of the code of IDARC in a redevelopment effort using an object-oriented approach. The resulting software architecture will enable progressive growth by easy addition of new models from other research tasks and provides the outcome to the engineering community at large. The current focus of work is to provide the tools for modeling damping and other advanced systems using a unified approach to nonlinear systems. The work done in cooperation with LARSA, Inc., a software developer, enables creation of a user friendly and acceptable analysis platform.

Objectives and results

The redevelopment includes three main steps. The first step is to create a flexible and extendable setup for the platform using an object-oriented finite element programming approach. This modular framework clearly separates the different elements of the program by encapsulating data in classes. Classes are black boxes, which provide easy to use interfaces throughout the program. Thus if a new class is added, the developer has to deal only with the data and routines of the new class itself. Also, changes to one class will not affect the rest of the program because of the encapsulation. This simplifies the integration of new parts.

In the second step, components are incorporated in the new platform IDARC3D Version 2.0: (i) energy dissipation systems / dampers and (ii) a computing core capable of nonlinear analysis. The new program structure provides possibilities to easily add new elements such as base isolators, adapted from the platform 3D-BASIS also developed by Reinhorn and Constantinou in multi-annual projects. To ensure convenience, IDARC3D Version 2.0 operates on a PC and has a graphical user interface for input and output (I/O). The I/O is decoupled from the core of the program so that it can be changed without interfering with the actual program.

The third step is to model and evaluate a structure with protective systems and to verify the results of the nonlinear analysis with IDARC3D 2.0 against results from other standard analysis programs or experiments.

The implementation of the new design is realized using FORTRAN 90 to be consistent with the previous and existing IDARC programs. Much of the existing code is reused in the new platform to minimize programming new code. Although FORTRAN 90 is not an object-oriented programming language, object-oriented features can be simulated with a reasonable effort. Also, source code written in FORTRAN 90 and C++ (as an example for an object-oriented programming language) can be used to form one platform together.

The documentation developed for the new platform includes guidelines to further develop the system, a users manual and installation examples. The developer's manual, which describes the modular setup and provides the reader with the necessary information to change or extend the program, will be published through the MCEER Networking activities.

A California hospital building is being modeled for research by other center investigators, and a benchmark physical model tested on the shake table at University at Buffalo is being analyzed to provide the first example cases. The result of this development will provide the engineering community with a three-dimensional nonlinear analysis platform that currently does not exist.

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