MCEER Advanced Technology Research for Next Generation Seismic Resilient Buildings

by

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ABSTRACT

Over the last two decades, significant research effort has been directed toward the application of advanced technologies to improve the seismic performance of civil infrastructure. MCEER has played a role in that development. In this paper, we present an overview of the integrated MCEER research program aimed at the development of a new generation of seismic resilient buildings. While MCEER research has a broad scope, here we concentrate specifically on aspects relating to the further development of structural control devices and systems. Three new passive elements are examined, including scissor jack dampers, light-gauge steel shear panels and polymer matrix composite infill walls, along with a novel hybrid control system. Although these research projects are at different stages of development, all four have significant application potential. Naturally, the MCEER research program must also address the overall system level performance. Along these lines, we examine a new retrofit strategy involving strength reduction combined with damping enhancement. With this approach, the resulting retrofit structure can exhibit reductions in both displacements and base shear forces. Two distinct automated design approaches, involving heuristic and evolutionary methodologies, also are presented in some detail. Initial investigations indicate that these approaches are quite promising. All of the work presented here leads us to the conclusion that the integrated MCEER research approach can contribute substantially to the development of next generation seismic resilient buildings.

KEYWORDS: earthquake engineering, seismic design, structural control

1.0 INTRODUCTION

One of the fundamental long-term goals of earthquake engineering research in general and the Multidisciplinary Center for Earthquake Engineering Research (MCEER) in particular is to enable the evolution of disaster resilient communities. The development of innovative engineering technologies is an important component in this overall program. In the present paper, we provide overviews of a few of the recent MCEER research projects that focus on the development of advanced technologies for application to a new generation of seismic resilient buildings.

Our presentation is organized as follows. Research relating to the development of three new types of passive control elements and one semi-active control system is discussed in Section 2. Then, in Section 3, we summarize some recent work on a novel structural control strategy that combines an intentional structural weakening along with the introduction of passive elements. Afterwards, two new approaches are presented in Sections 4 and 5 for automated design of next generation building structures that incorporate protective systems. Somewhat more detail is included for these two on-going projects since the coauthors are actively involved in this research. Finally, Section 5 provides some concluding remarks.

2.0 STRUCTURAL CONTROL ELEMENTS

MCEER, along with its predecessor NCEER, has a long history of research accomplishments associated

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with the development of protective systems. Much of the early work, supported under NCEER, is summarized in Constantinou et al. (1998) and Soong and Dargush (1997), where complete reference to the original literature is provided. Here we present brief overviews of some of the more recent control element development sponsored by MCEER. Initially, the emphasis is on passive energy dissipation components suitable for application to building structures. Included are scissor jack fluid dampers, metallic dissipating shear panels and polymer matrix composite infill wall systems. The final section describes a new combined RSPM and passive damping hybrid control system.

2.1 Scissor Jack Damper

In the usual arrangement, supplemental passive devices are incorporated into the structural system through the use of either diagonal or chevron bracing. With this configuration, the magnitude of the displacement across the passive device is at most equal to the interstory drift. Consequently, large dampers may be required, particularly for stiff structures. One remedy is to introduce a damping amplification. Kani et al. (1992) were perhaps the first to utilize the level principle to amplify the damping effect. Two fluid-filled dampers were employed in each frame bay along with an inverted T-shaped lever to achieve the amplification. More recently, Constantinou et al. (2001) developed toggle-brace-damper system configurations to significantly enhance the performance of high-energy dissipation density viscous fluid dampers. The analytical and experimental studies indicate that displacement magnification factors in the range from two to five are quite practical.

One difficulty that remains with all of these supplemental damper configurations pertains to the negative impact of bracing on the architectural aspects of design. Open bays are often much preferred. In order to address this issue, while achieving device amplification, Sigaher and Constantinou (2003) developed the scissor-jack-damper energy dissipation system, under support from MCEER.

A schematic of the scissor-jack-damper system is provided in Figure 1. Under the assumptions of small deformation theory with rigid frame and bracing elements, Sigaher and Constantinou (2003) characterize the performance of the system in terms of the two angles ? and ?, along with the viscous damping coefficient C_0 for the fluid dampers. As a result, the displacement magnification factor k can be written simply as $k = cos y / tan q$.

Sigaher and Constantinou (2003) conducted an experimental program involving half-scale steel frame structures with a variety of beam-column connections. Both sinusoidal strong floor tests and numerous earthquake simulator experiments were used to verify the performance of the scissor jack system and to validate the numerical models. Excellent performance and correlations were obtained indicating that practical scissor jack systems can be designed with magnification factors in the range $2 \le k \le 5$. Connection details must be given careful attention to ensure full magnification and proper load transfer.

2.2 Light-gauge Steel Shear Panels

Metallic passive devices, in the form of X-shaped or triangular plates and unbonded braces, have seen numerous applications for supplemental damping. Recent MCEER funded work has focused on the development of steel plate shear walls (SPSW). While significant effort since the mid-1980s has been directed toward the use of relatively thick hot rolled steel plates (Timler et al., 1998), the on-going MCEER research by Bruneau and co-workers employs light-gauge cold-formed steel infill panels. These new systems have the potential for a substantial increase in energy dissipation with minimal impact on exiting framing members. In order to examine the performance of these infill panels, Berman and Bruneau (2002) conducted a preliminary series of quasi-static, cyclic displacement-controlled loading tests. Both flat 1mm plate specimens and 0.75mm corrugated specimens were considered. For the experiments, the infill panel specimens were secured to the bounding frame with either welded or epoxy connections. Results from these preliminary tests indicate that the light-gauge cold-formed steel infill panels can enhance seismic performance through energy dissipation associated with tension field yielding. Further research is needed concerning connection details, modeling approaches and seismic testing.

2.3 Polymer Matrix Composite Panels

Besides steel infill panels, one may also consider the use of non-traditional structural engineering materials. Early examples include viscoelastic infill panels (Gasparini et al., 1981) and viscous damping walls (Arima et al., 1988). Within MCEER, work is underway toward the development of a polymer matrix composite (PMC) infill wall system for seismic applications.

A schematic of the initial PMC system proposed by Aref and Jung (2003) is provided in Figure 2. The system consists of an inner panel sandwich construction with a fiber-reinforced polymer (FRP) laminate shell and a vinyl foam core. FRP laminates are also used to form the outer shell. For the initial version of the infill walls, viscoelastic honeycomb interface layers are used to transfer the shear forces between the inner panel and outer shells. This is intended to provide stiffness and energy dissipation.

The development of these new infill panels is based upon a combined experimental and numerical modeling approach, as described in Aref and Jung (2003). In particular, finite element models of the composite panels were employed to help guide the design in terms of geometric configuration and FRP lay-up selection. For the physical experiments, both monotonic and cyclic testing of a large-scale steel frame was conducted with and without the PMC panels. Significant increases in both the stiffness and strength of the frame were observed when the PMC panels were included. Energy dissipation also increased substantially with the panels, suggesting that the concept has potential. Additional work is needed to reduce local damage to the panel at high drift ratios and to improve the energy dissipation. With regard to the latter issue, Jung and Aref (2003) have investigated the combined use of the polymeric honeycomb and a solid viscoelastic material for the interface layer. Small-scale material tests indicate that this approach ultimately may allow the designer to tune the stiffness and damping characteristics of the proposed PMC panels.

2.4 Combined RSPM and Passive Damping Hybrid Control System

Real-time Structural Parameter Modification (RSPM) system is a semi-active nonlinear control system for reducing structural seismic responses (Liang, et al., 1999a,b; Lee et al., 1997). This semi-active nonlinear system can effectively reduce seismic responses, especially when the objective is to reduce displacement or story drift. A combined RSPM and passive damping control approach can achieve better seismic reduction than the passive damping alone. The combined system can reduce the acceleration response very effectively because of the added damping. Figure 3 shows this hybrid system that consists of a passive damper and a controlled stiffness unit. The passive damper is always engaged to dissipate energy. The stiffness unit is engaged when the deformation reaches a threshold value—termed as the open distance. If the relative displacement magnitude is larger than the open distance, the stiffness unit will contribute to reduce the response. If, at any instant, the displacement magnitude is smaller than the threshold, the RSPM nonlinear stiffness is disengaged. The stiffness is engaged again only when the displacement exceeds the threshold, and the RSPM control mechanism is activated only when the stiffness is engaged. The devices are combined in pairs of tension and compression units working as a push-and-pull set.

This hybrid control system has been studied and designed for two adjacent existing buildings in LA, as described in Lee et al. (2002). The weaker building is a seven story steel structure with full moment resisting connections. The seismic retrofit problem is to avoid collision of this building with the much stiffer adjacent buildings. A combined RSPM and passive damping system is considered between the two buildings at the roof level. A secondary requirement of this retrofit project is to reduce the acceleration response level, for which pure damping device can be effectively used. The combined RSPM and damping approach therefore is developed to take advantage of their respective strengths.

3.0 RETROFIT STRATEGIES

Many non-traditional retrofit strategies have been proposed in recent years, including a number of approaches involving passive, semi-active, active and hybrid control. Passive dampers, for example, are often very effective for reducing the displacement response, but may tend to elevate base shears and accelerations due to the increase in strength and/or stiffness. This may be problematic, particularly when critical non-structural components must be protected.

An interesting new approach developed by Reinhorn, Whittaker and co-workers, within the MCEER Acute Care Facility research thrust, relies on an intentional structural weakening combined with added damping. The main ideas of this retrofit strategy can be found in Viti et al. (2002). The first step in this approach involves weakening of the existing structure, which may be accomplished, for example, by modifying connection details. The structural response is altered, as indicated by the schematic in Figure 4. This tends to reduce the base shear (and accelerations), but increase the deformations. Subsequently, in Step 2, supplemental dampers are introduced into this weakened structure. This has the potential to substantially reduce displacements, while causing modest increases in base shears. Consequently, the overall result may be quite good, depending of course on the specific details of the retrofit.

Viti et al. (2002) studied the application of this retrofit strategy to a five-story steel frame hospital in Los Angeles. The goal was to significantly reduce accelerations in order to better protect the non-structural components. In Step 1, hinges were introduced at the beam-column joints for a series of interior bays. Then viscous fluid dampers were added to those bays to increase the effective damping ratio to approximately 16% for a highly damped case. Both spectral analysis and nonlinear dynamic analysis indicated that base shears could be decreased significantly from the original structure, with only a slight increase in interstory drift. Consequently, this new approach provides interesting possibilities in the seismic retrofit of acute care facilities, as well as for more general building structures.

4.0 HEURISTIC DESIGN

Although passive energy dissipation has been used as a viable strategy for seismic protection of buildings for many years, the current design codes do not provide guidelines for optimizing damper configurations. However, a number of researchers have proposed computational design approaches to optimize passive device sizing and placement. Examples include the work by Zhang and Soong (1992) using a sequential placement strategy for rate-dependent dampers, by Gluck et al. (1996) with an optimal control theory approach, and by Singh and Moreschi (2001) via a gradient projection method.

Under sponsorship from MCEER, Liu et al. (2002) developed a heuristic approach to optimize the damper configuration based upon building performance objectives. This method combines the evolutionary approach and engineering knowledge to minimize different performance indices of response, such as interstory drift or acceleration.

The proposed optimization methodology combines the efficiency of a heuristic approach and the effectiveness of an evolutionary approach to search for the optimal solution based on improving through generations. The heuristic knowledge for improvement comes from modal analysis of the structure.

Since the added passive devices may contribute nonproportional damping to the structural system, the standard modal analysis approach cannot be used. However, the total response can be solved using the linear combination of contributions from all modes using a state-space technique. In general, each mode contributes to the total response. The relative magnitude of each modal contribution depends on its modal response, mode shape, and earthquake frequency content. It also depends on the performance requirement of the structure, since the high frequency modes generally contribute more to the acceleration response than to the displacement response.

Among all the modes that contribute to the total structural response, some modes will dominate and some will have negligible contribution. If we can capture the dominant modes and reduce their contribution, then the total response can be reduced. Consequently, the primary objective of the present heuristic approach is to reduce the contribution from the dominant modes by increasing their modal damping ratios.

Consider the case of linear viscous supplemental dampers added to a linear structural system. Then, the following heuristic approach is adopted. To increase the modal damping of the dominant modes, the contribution from each possible device location is ranked. The devices are moved from the least effective location to the most effective location. Since this heuristic is not guaranteed to reduce the structural response under earthquake conditions, the powerful evolutionary approach is also used. The optimization problem of device configuration iterates through generations, and each generation is an improvement from the previous generations. With the heuristic included in the search, the iteration is expected to converge faster. Thus, the optimization results can be expected in a reasonable amount of time.

The procedure can be summarized as follows:

1. Select a performance index according to the building performance objective
2. Select an initial damper configuration
3. Analyze the structural modal composition and find the dominant modes
4. Find the effectiveness of each device location
5. Redistribute the devices iteratively

Further details on the methodology can be found in Liu (2003). Here we present results from that work for an illustrative example concerning a uniform ten-story building.

Let k and m represent the stiffness and mass for each of the ten stories, with $k = 4.5\times 10^8$ N/m and $m = 2.5\times 10^5$ kg. Then the first two natural frequencies are 1Hz and 3Hz. We assume that 50 purely viscous dampers are available for the design, each having a damping coefficient $c = 3.5\times 10^6$ N-s/m. Meanwhile, the seismic environment is characterized by three ground motions. These represent frequency-adjusted versions of El Centro, Kobe and Northridge records.

Rows number one and two in Table 1 provide the maximum response quantities for the cases with no dampers and for a uniform damper distribution, respectively. The response is greatly reduced with the addition of dampers. Notice that the effective first mode damping-ratio is also provided in the table. This increases from 3% to more than 15% with the passive dampers.

The heuristic optimization algorithm is then used to more effectively distribute the supplemental dampers. Rows three and four in Table 1 present the results for cases in which the performance index is interstory drift and story acceleration, respectively. Notice that when interstory drift is optimized, an improvement of 24% from the maximum drifts of 13.92mm to 10.51mm is obtained. The corresponding optimal damper distribution is detailed in Table 2. Considerable damping is added to the lower stories.

On the other hand, when story acceleration is optimized, only modest reductions in maximum acceleration can be obtained in this example, as indicated in Table 1, and in fact the optimal damper distribution presented in Table 2 is nearly uniform.

As a final case, drift limits are set and damper cost is minimized. From Table 1, we find that drift levels comparable to the uniform design can be achieved with slightly less than half the number of dampers. Story accelerations are somewhat higher than with the uniform damper design configuration, but still well below the levels obtained in the bare frame. In conclusion, we find that for this and a series of additional examples (Liu, 2003), the heuristic algorithm provides a computationally efficient approach for optimal design of passively damped linear structures. The method can also be used to gain insight into the behavior of structures with supplemental damping.

5.0 EVOLUTIONARY DESIGN

Additional research is needed to extend the heuristic design approach of Section 4 to structural systems that respond in a nonlinear fashion under seismic excitation. As an alternative approach, purely evolutionary methodologies can be employed.

5.1 Complex Adaptive Systems and Methodologies

Over the past two decades, there has been increasing interest in the concept of complex adaptive systems, originally formulated by Holland (1975). These systems typically involve the complicated nonlinear interaction of many components or agents, which aggregate in a hierarchical manner in response to an uncertain or changing environment. As a result, complex adaptive systems evolve over time through self-organization and ultimately acquire collective properties not exhibited by the components or agents acting alone. Classical examples are the human central nervous system, the local economy or a rain forest. Notice, however, that many of these same characteristics are essential for the development of disaster-resilient communities. This suggests that computational approaches suitable for studying complex adaptive systems may be quite appropriate for use in multidisciplinary seismic decision support.

By bringing ideas from biological evolution to bear on the problem, Holland (1962, 1975) also developed a unified theory of adaptation in both natural and artificial systems. Besides providing a general formalism for studying adaptive systems, this led to the development of a variety of evolutionary methodologies, including genetic algorithms. These computational approaches have enjoyed considerable success in recent years over a wide range of applications in science and engineering (Goldberg, 1989; Mitchell, 1996). These are essentially naturally parallel non-calculus based optimization procedures that can readily accommodate a disparate collection of models. Genetic algorithms are particularly effective for finding robust solutions to combinatorial problems in the presence of environmental uncertainties. Consequently, evolutionary methods hold significant promise as a possible framework for the development of a new class of decision support tools toward earthquake hazard mitigation. In the following section, an initial application of this approach for seismic retrofit of building structures with passive energy dissipation devices is considered.

5.2 Evolutionary Aseismic Design and Retrofit

In this section, we provide a brief overview of the proposed computational framework for aseismic design and retrofit. The primary objective is to develop an automated system that can evolve robust designs under uncertain seismic environments. As indicated in Figure 5, this evolutionary design process involves a sequence of generations. In each generation, a population of individual structures is defined and evaluated in response to ground motions that are realized in association with the geophysical environment. Cost and performance are used to evaluate the fitness of each structure in the population. These fitness values, along with random genetic operators modeling selection, crossover and mutation processes, define the makeup of the next generation of structures. In the current work, performance is judged by conducting nonlinear transient dynamic analysis using an explicit state-space transient dynamics code (tda). Alternatively, the finite element code abaqus may be utilized. The implementation of the genetic algorithm controlling the design evolution is accomplished within a modified version of Sugal (Hunter, 1995).

In the area of seismic passive energy dissipation systems, Singh and Moreschi (1999, 2000, 2002) developed the first genetic algorithm applications. Meanwhile further information on several different aspects of the present evolutionary aseismic design approach can be found in Dargush and Sant (2000, 2002), Dargush et al. (2002) and Dargush and Green (2002).

For illustrative purposes, we will now consider an example of a twelve-story steel frame retrofit with passive energy dissipators (e.g., Soong and Dargush, 1997). Three different types of dampers are available: metallic plate dampers, linear viscous dampers, and viscoelastic dampers. For each type, four different sizes are possible. Consequently, a four-bit genetic code is used to represent the devices used in each floor and a 48-bit chromosome is employed to completely specify the dampers present in any particular structure. Then for this problem, the set of attainable structures contains roughly 10^{14} members. Exhaustive search of the decision space is clearly not possible.

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. The mathematical models employed for these elements are defined in Dargush and Soong (1995) and Dargush and Sant (2002). In addition, the viscous dampers are strictly linear Newtonian devices. All of the bracing elements associated with the passive dampers are assumed to be perfectly rigid. In order to establish acceptable performance, limits are imposed on both interstory drift and acceleration for each story.

For this twelve-story structure, let W_i and k_i represent the i th story weight and elastic stiffness, respectively. The frame model has story weights, $W_1 = \ldots = W_6 = W$, $W_7 = W_8 = 3W/4$, and $W_9 = \ldots = W_{12} = W/2$. Meanwhile, the story stiffnesses can be written as $k_1 = \ldots = k_6 = k$ and $k_7 = \ldots = k_{12} = k/4$. Notice that there is a strong discontinuity at the seventh story. After selecting the parameters W and k, the first two natural frequencies are 0.50Hz and 1.10Hz. Additionally, the story yield forces are also specified as follows: $F_1^{yL} = \ldots = F_6^{yL} = W/5, F_7^{yL} = \ldots = F_{12}^{yL} = W/20$.

We employ the USGS Gutenberg-Richter seismicity database for eastern North America (Frankel, 1995; Frankel et al., 1996) to model the seismic environment. The entire geographical region is subdivided into bins, with each bin representing 0.1 degrees of longitude and latitude. The USGS database then provides Gutenberg-Richter parameters a and b for each bin such that the number N of earthquakes per year of magnitude greater than or equal to M can be written as $\log N = a\text{-}bM$. We simulate the seismic environment by running Poisson processes in each bin to determine significant events that may occur during the intended life cycle of the structure. Whenever a significant event occurs, the ground motion generation algorithm defined by Papageorgiou (2000) is used to produce an appropriate synthetic accelerogram for the specified magnitude and epicentral distance.

Let us now assume that this steel structure is located on firm ground near Memphis, TN. The base structure without dampers survives less than 30% of the significant earthquakes. In our retrofit options, we permit all three damper types: triangular plate metallic dampers (tpea), viscous dampers (visc), as well as, viscoelastic dampers (ve). In order to restrict the search to more practical designs, we introduce a recessive gene concept in the genetic algorithm to prohibit structures with more than two different damper types. Hypothetical device cost data for various size dampers are set with each increment in damper size corresponding roughly to a doubling of the damping capacity. There is, of course, considerable subjectivity introduced in setting the relative cost-performance relations for the different damper types. However, we should emphasize that this is primarily a model problem intended to illustrate the methodology.

Figure 6 presents a snapshot of the overall graphical system. Included is a map that locates the generated seismic events, a database of candidate structures, and reliability plots of robust designs that have evolved through the automated design process. In particular, the upper left diagram provides a detailed view of the earthquakes generated throughout the New Madrid fault zone surrounding Memphis within a portion of one simulation. The variation of mean fitness of the population versus generation number is shown in Figure 7 for four separate simulations. As the system evolves, the population becomes enriched with robust structures. However, the mean fitness does not increase in a monotonic fashion due to the inherent uncertainty of the seismic environment and the continual search for better structures. Several robust designs that evolved over 256 generations are shown in Figure 8. Shading indicates the damper type, while the radius of the ring corresponds to damper size. Notice that each of these designs experienced over four hundred earthquakes with survival rates well above 90%. Interestingly, all three of these robust designs attempt to compensate for the structural discontinuity at the seventh story by introducing large viscoelastic dampers that provide increased damping and stiffness.

Results for this and a range of other structures suggest that the proposed evolutionary methodology is capable of identifying robust design alternatives while explicitly accounting for the uncertainty in the environment. Furthermore, this approach can be readily extended to other retrofit options, including those associated with secondary systems. Current work focuses on the development of efficient versions of the code for massively parallel computer architectures, on the incorporation of a knowledge base to help guide the evolutionary process and on the enhancement of the graphical user interface. Additionally, the evolutionary methodology is being extended to include macro-models for the newly developed passive elements described in Section 2 and to address problems of sociotechnical decision support.

6.0 CONCLUDING REMARKS

The long-term vision of MCEER is to assist in the development of seismically resilient communities. In the present paper, we have focused on the integrated research effort that specifically addresses enhanced structural performance of buildings through the development of advanced structural control technologies. Three promising new passive elements have been reviewed, including scissor jack dampers, light-gauge steel shear panels and polymer matrix composite infill walls. A novel combined RSPM and passive damping hybrid control system has also been presented. Furthermore, several new structural system level developments have been presented. These include a novel retrofit strategy involving the combination of intentional weakening and enhanced damping, along with two distinct automated design procedures. The latter developments, which were presented in some detail, can lead to the systematic design of efficient passively damped structures. Additionally, these computational approaches can provide new insight into overall structural system behavior under seismic excitation.

Finally, we should remark that the research developments summarized in this paper would not be possible within a traditional individual investigator environment. An integrated team approach is necessary to make substantial contributions toward the development of next generation seismic resilient buildings.

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Table 1: Heuristic Design – Ten Story Building (Liu, 2003)

	Number of Dampers	1st Mode Damping Ratio (%)	Drift (mm)	Acceleration (mm/s ^{2})	Velocity (mm/s)
No dampers	0	3.0	26.08	10207	1289
Uniform	50	15.3	13.92	4580	652
Optimal drift	50	22.8	10.51	5286	604
Optimal acceleration	50	17.5	12.69	4509	618
Optimal cost	24	13.3	13.56	6311	718

Table2: Heuristic Design – Ten Story Building Optimal Damper Configurations (Liu, 2003)

Story	Uniform	Optimal drift	Optimal acceleration	Optimal cost
10	5	0	2	0
9	5	0	3	0
8	5	0	4	0
7	5	0	4	0
6	5	2	5	0
5	5	5	6	0
4	5	8	6	3
3	5	10	6	6
2	5	12	6	7
1	5	13	8	8

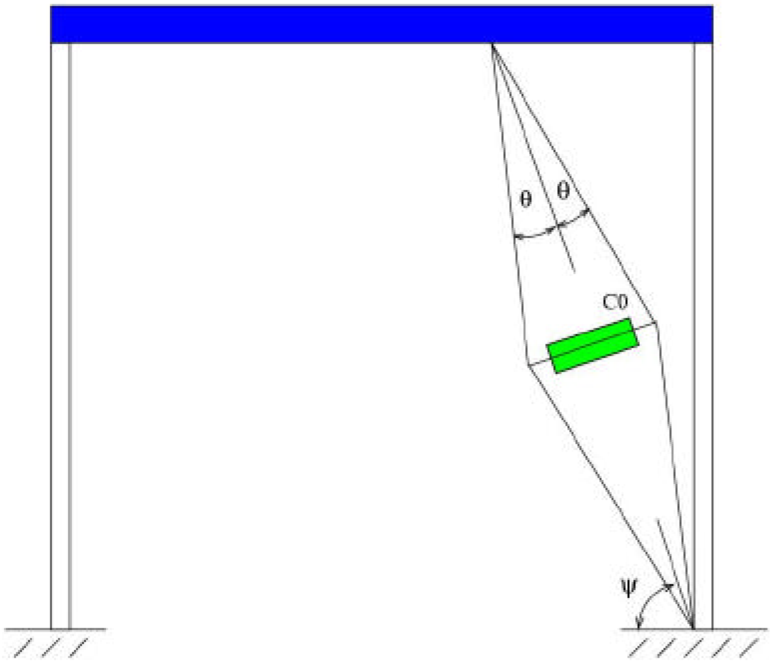


Figure 1: Scissor-Jack-Damper (Sigaher and Constantinou, 2003)

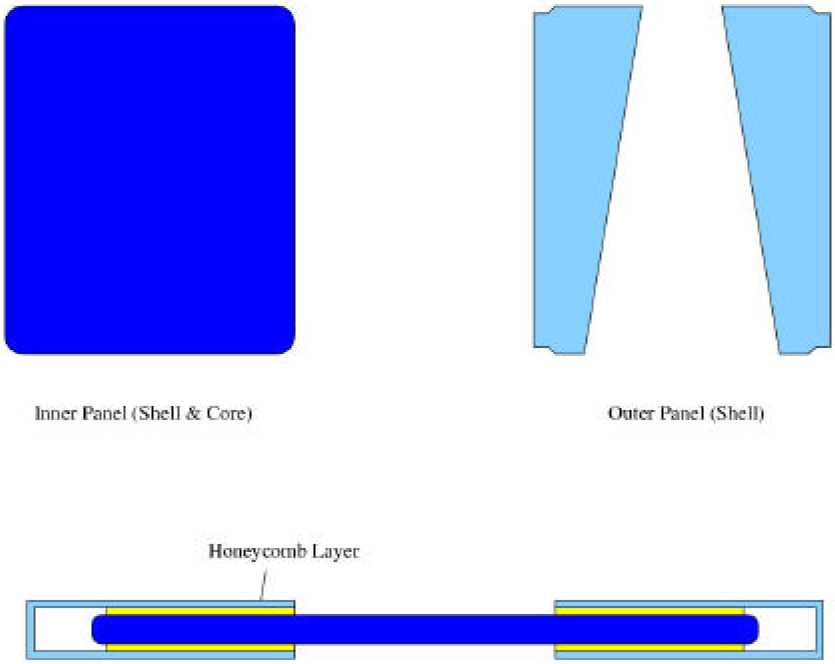


Figure 2: Polymer Matrix Composite Infill Panel (Aref and Jung, 2003)

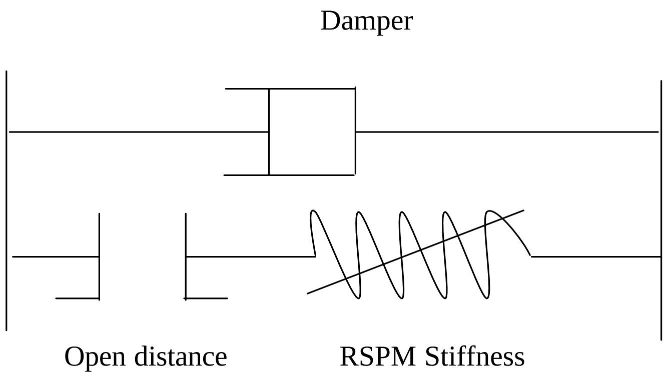


Figure 3: Combined RSPM and Passive Damping Hybrid Control System

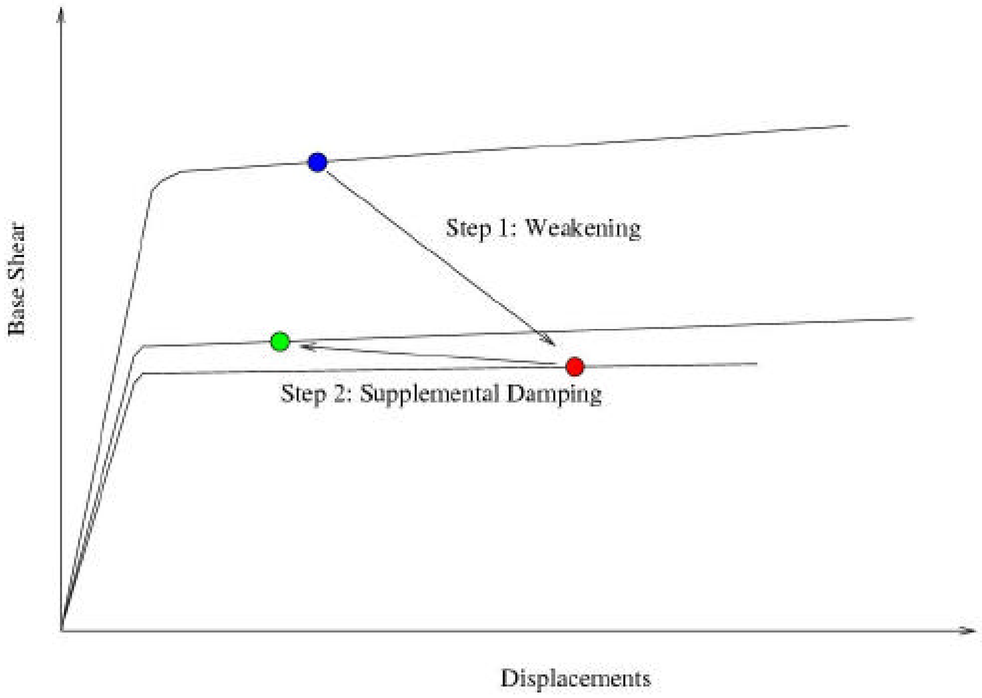


Figure 4: Strength Reduction with Damping Enhancement (Viti et al., 2002)

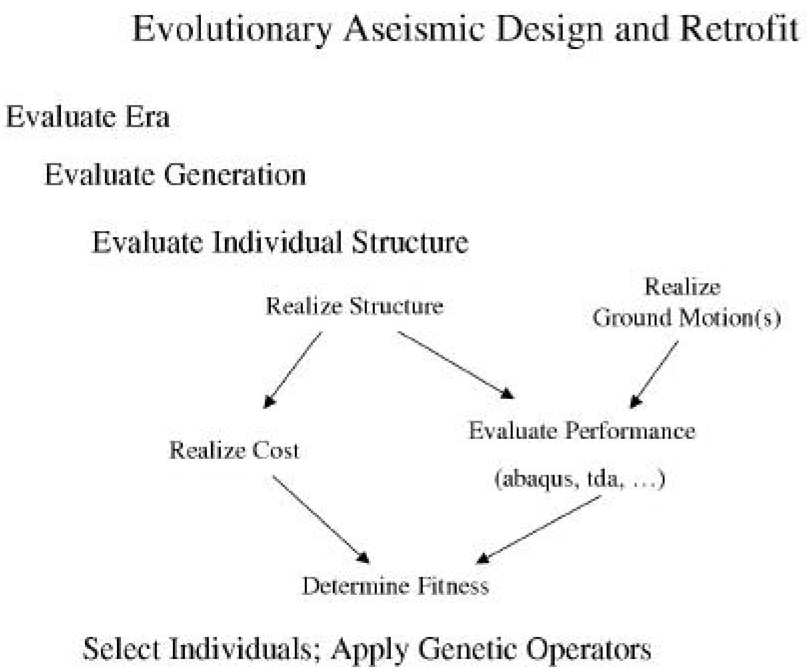


Figure 5: Evolutionary Aseismic Design and Retrofit - Overall Framework

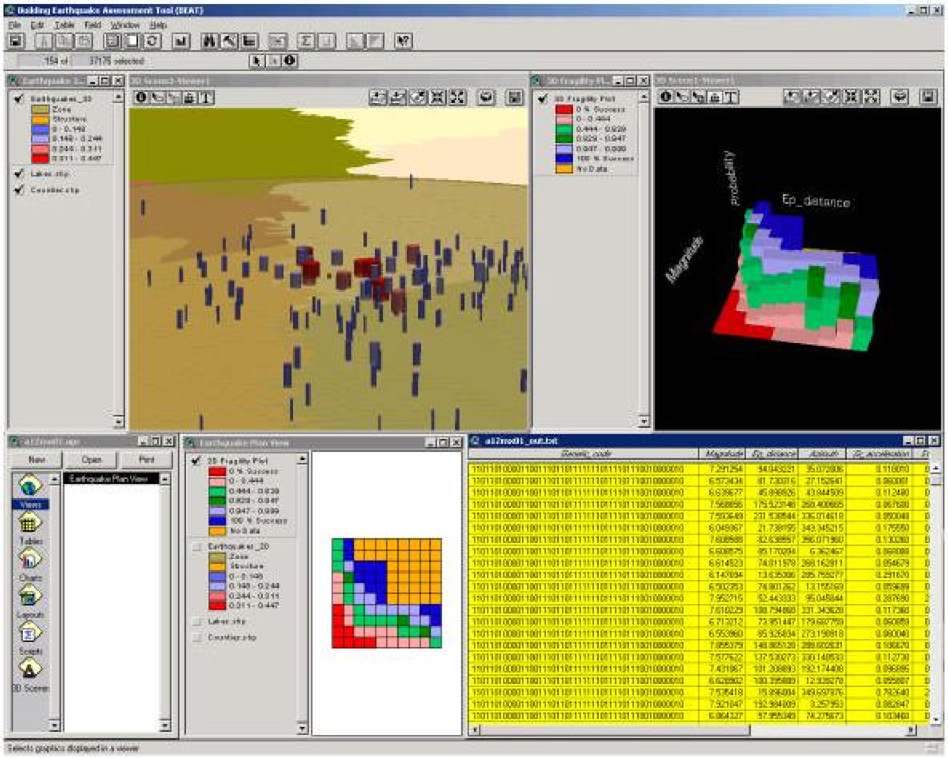


Figure 6: Evolutionary Aseismic Design and Retrofit - Graphical Interface

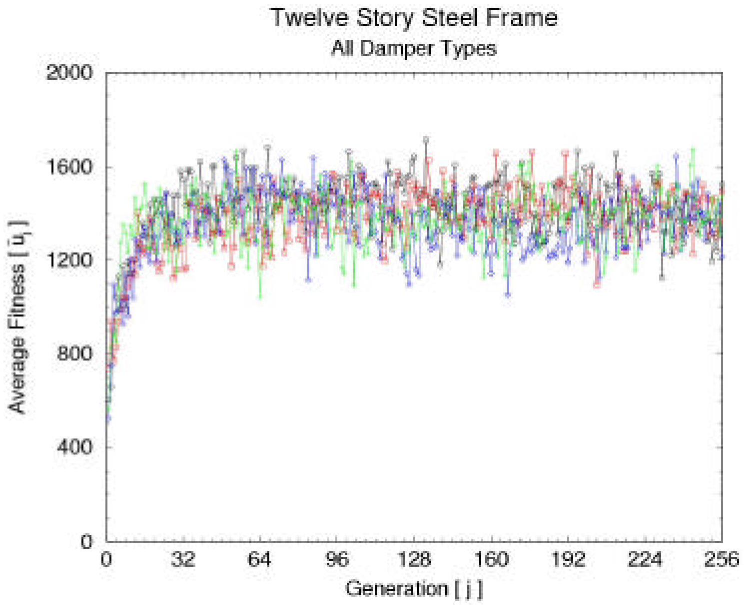
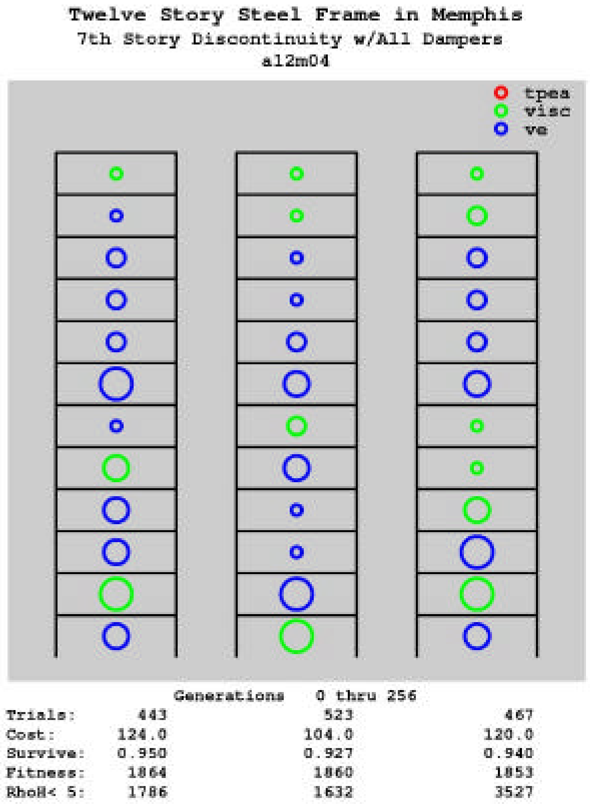


Figure 7: Evolutionary Aseismic Design and Retrofit – Average Fitness Variation for Twelve Story Steel Frame



```
                    Generations    0 thru 256
Trials:       443                     523                    467
Cost:       124.0                   104.0                  120.0
Survive:    0.950                   0.927                  0.940
Fitness:     1864                    1860                   1853
RhoH< 5:     1786                    1632                   3527
```

Figure 8: Evolutionary Aseismic Design and Retrofit – Robust Design Configurations for Twelve Story Steel Frame