**Decision Models:**

**Approaches for Achieving Seismic Resilience**

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**Research Objectives**

Decisions about enhancing seismic safety in critical facilities requires more than engineering choices about which technology is most appropriate. Such decisions are made in the context of organizational goals and strategy, financial capacity, choices about how safe is safe enough, and driving forces in the social, economic, and political environment. This project is aimed at devising integrated decision-assisting models for helping executives and engineers make informed choices about alternatives approaches to improving seismic safety. The platforms integrate state of the art understanding of structural response, alternative means for mitigating the risk, normative decision-assisting models, and behavioral models of organizational choice and decision processes.

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**The Challenge**

One of the fundamental long-term goals of earthquake engineering research in general and MCEER in particular is to enable the development of disaster-resilient communities. The development of innovative engineering technologies, and the associated design guidelines, is certainly beneficial in this regard. However, to prove effective, the new technologies must be implemented and corresponding enhancements to engineering design codes must be adopted. The processes involved in technology implementation and code adoption go far beyond strictly engineering concerns. It is essential to also give simultaneous consideration to the organizational, economic, social, political and legal aspects of the problem.

This multidisciplinary coupling significantly complicates the situation and necessitates the development of a new generation of decision support methodologies that can help organizations cope with the complexity of the decision-making process. These organizations may include companies interested in developing markets for new technologies, critical care facility owners required to meet legislated levels of seismic performance, local communities faced with prioritizing rehabilitation projects and federal agencies responsible for resource allocation. In all of these cases, the organizations are confronted with a myriad of decisions that must be made...
in the presence of a broad range of physical and sociotechnical uncertainties.

Consider, for example, the owner of a single acute care facility in California required to comply with the provisions of legislation known throughout California as Senate Bill 1953. The facility may consist of a stand-alone building constructed all at one time. More likely, however, it consists of multiple loosely-coupled buildings or one old, original structure that has had a series of additions built onto it. Major options include the decision to: (a) not retrofit and face the consequences; (b) not retrofit, but lobby to change the legislation; (c) tear down the facility and rebuild; (d) convert the facility from acute care to an alternative use; (e) retrofit the facility to meet minimum requirements; (f) retrofit to a higher level of performance; and/or (g) request extensions for compliance. Then, within each of these global options, many lower level decisions must be made. For example, within the retrofit options (e) and (f), many possibilities exist for the primary structure, including traditional and non-traditional (i.e., base isolation, passive energy dissipation, semi-active control) retrofit strategies. For option (f), consideration to upgrade the performance of secondary systems may also be relevant. Due to the current state of critical health care in California, there are important financial implications associated with all of these options. Beyond this, there is also a temporal dimension that further complicates the decision-making process.

What is a proper course of action for this owner? Clearly, some systematic analysis is needed. One possibility is to construct computational models in order to study the situation. These models may range from structural dynamics models for assessing the behavior of various retrofit options to organizational models that characterize the performance of health care delivery and financial viability of the healthcare organization. A collection of models could then be used for the analysis of a selected number of alternatives. Perhaps sensitivity studies could also be

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**Previous Summaries**

**2000-2001:**
- Alesch and Petak
- Constantinou et al.,

**1999-2000:**
- Shinozuka et al.,
  - [http://mceer.buffalo.edu/publications/resaccom/9900/Chapter2.pdf](http://mceer.buffalo.edu/publications/resaccom/9900/Chapter2.pdf)

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**The decision-assisting platforms are intended to help illuminate the consequences of choice for both engineering consultants and their clients.** Since clients must consider a wider range of variables than their engineers when making choices about seismic safety, the models are intended to couple organizational and engineering concerns into one or more models to help create recommendations for seismic safety that meet the needs of all the critical stakeholders. Stakeholders may include companies interested in developing markets for new technologies, critical care facility owners required to meet legislated levels of seismic performance, local communities faced with prioritizing rehabilitation projects and/or federal agencies responsible for resource allocation.
conducted. The difficulty with this approach relates to the combinatorial nature of the decision space. The associated computational complexity of this problem effectively prohibits full exploration. Alternative methodologies are needed to find good solutions; the effort to develop such methodologies drives this part of this research effort.

Goals and Approach

MCEER investigators working on this effort are focused on helping to meet the need for effective methodologies to assist organizational decision makers and those who advise them. The investigators' activities are aimed at remedying the fact that no integrated decision-assisting tool exists that can be used by hospital owners and consulting engineers to address complex issues and problems associated with seismic retrofit of acute care facilities within today's complex healthcare decision environment. The investigators' goal is to devise one or more decision-assisting platforms that will help to illuminate the consequences of choices in complex, multi-dimensional environments.

We have adopted a multidisciplinary approach to address a multidisciplinary problem. The team includes two structural engineers, one decision scientist, two specialists in organizational behavior and decision-making, a research assistant professor and a significant number of graduate students. Team members are working simultaneously on two approaches to decision-assisting platforms, each of which is fundamentally different from the other. One approach is based on decision analysis models, but goes beyond them to integrate information on earthquakes and their effects. The other approach is based on conceptually new models employing methods that allow for simulating the robustness, through time, of each of a very large number of alternative mitigations for a specific simulated structure. That model will work toward integrating organizational decision criteria, whereas the former works from decision criteria toward an integration of earthquakes and structural response. At the same time, two groups of researchers are collecting data for their respective decision-assisting platforms and further developing their models, while other researchers are focused directly on the question of how hospital owners and administrators make choices about enhancing seismic safety in a turbulent decision environment. Based on information obtained from interviews with administrators in a diverse set of acute care hospitals in California, these researchers are working to characterize the decision environments within which hospital owners and managers must make difficult choices about how to comply with SB 1953 regulations. They are identifying variables that affect the choices made by the owners and managers. They are attempting to integrate, or otherwise link, actual decision criteria employed by real-world managers with the two fundamental decision-assisting platforms being developed by the other research teams in this project. Investigators and their graduate students face significant obstacles in their attempts to link the various models to create a powerful set of decision-assisting tools. No precedents exist as guides. By the end
of summer 2003, the investigators expect to have completed a “proof of concept” test for linking the behavioral and engineering models being developed as a basis for the two fundamental platforms. Should the proofs of concept show that direct linkages can be made between the behavioral decision-making model and the engineering aspects of the platforms, work will progress in the coming year to advance those linkages. Should the tests prove less than encouraging, efforts will be made in the coming year to create more loosely-coupled linkages between the models. In that case, the behavioral model may simply provide constraints that preclude some seismic retrofitting approaches from being employed in some specific instances, while indicating which other approaches might work well.

The approach being taken by this research team reflects the three-level MCEER approach. It links basic research to tools for application and it embraces the multidisciplinary approach deemed essential to addressing complex socio-technical problems. Initial work focused on research in modeling both normative and behavioral decision-making, developing appropriate understanding of critical facility structural demands and response, and on means for evaluating the effectiveness of a wide range of alternative means for mitigation. In the past year, work has begun on integrating the component parts to create the desired decision-assisting platforms. Coordination meetings provide a checkpoint for addressing technical and communication issues and for assessing the effectiveness of team communication processes.

The team’s strategy is to work on two decision-assisting platforms simultaneously. The approach is intended to generate timely practical payoffs while, at the same time, providing for basic research that, if it proves out as expected, will lead to cutting edge methods for evaluating alternative means for mitigating earthquake forces on structures. The “sure-fire” approach is based on approaches to decision science, behavioral models of organizational decision-making, and structural analysis that are advanced, but that are lodged primarily in the mainstream of practice. The parallel approach is based on emergent models integrating evolutionary modeling with the contemporary computing power to test the robustness of many structural mitigations against many seismic forces. By simultaneously working on two approaches, the research team ensures that at least one practical, timely decision-assisting platform will be generated, with the likely probability of generating two extremely useful platforms, each with its own strengths and capabilities.

The following sections describe the four component parts of the decision platforms project.

Decision Analysis Approach Framework

This section describes one of two decision analysis frameworks currently being developed to support seismic rehabilitation decisions. This framework combines a probabilistic model of ground shaking, engineering fragility curves, statistical estimates of potential damage costs, and a financial model of the costs and benefits of rehabilitation.
Users of the analysis can choose among many important model parameters, including loan terms for financing the rehabilitation cost, the time horizon of ownership of the hospital building, the discount rate, and many more. The overall framework is shown in Figure 1.

The rectangles in Figure 1 are decision nodes, which include the alternatives under the decision maker’s control. For example, when considering whether to rehabilitate a building, the rehabilitation decision node would consist of the decision alternatives “No Rehabilitation,” “Life Safety Rehabilitation,” and “Limited Downtime Rehabilitation” (see Benthien and von Winterfeldt, 2002). In most real rehabilitation decisions, the decision maker also has financial options, which are described by the decision node “Financing Decision.” This node includes decision alternatives described by the time horizon considered, amount of the rehabilitation cost that the decision maker chooses to finance, the terms of the loan, and the discount rate.

The ellipses are chance nodes. They include events outside the decision maker’s control. The seismic event chance node includes the degree of ground shaking (measured as peak ground acceleration or spectral acceleration) at each of a series of specified time intervals (typically annually for up to 50 years or the useful lifetime of the building). Probability distributions are assessed over the degree of ground shaking using data from the USGS and the Southern California Earthquake Center (see Benthien and von Winterfeldt, 2002).

The second uncertainty concerns the damage states, given a specific degree of ground shaking. The decision analysis model considers five possible states: “No Damage,” “Green Tagged,” “Yellow Tagged,” “Red Tagged,” and “Total Loss.” Fragility curves are obtained for a particular structure, using fragility curves from the HAZUS Manual (Federal Emergency Management Agency, 1999). These fragility curves are only a starting point; they will usually be adapted based on engineer-
ing knowledge of the specific structure. The fragility curves are translated into conditional probabilities of damage states, given a level of ground shaking.

Given damage states, there still is some uncertainty about the consequences of the seismic event. The major uncertainties are the cost of repairs and the possible lives lost or injuries due to the damage. In some cases, e.g., acute care hospitals, there will also be uncertainty about the downtime during repairs and the resulting costs, e.g., lost revenue and reduced access to hospital care during the down time. The analysis also considers other, more certain consequences of the rehabilitation decision at this point. First, the analysis considers the cost of retrofitting (including financing costs). Furthermore, the analysis considers possible non-seismic benefits of rehabilitation. For example, acute care hospitals may be able to incorporate more contemporary service designs into hospital design during retrofit.

In the past year, the decision analysis approach was refined substantially by adding a module for decisions to finance rehabilitation projects. This module includes two major parameters: the percentage of the rehabilitation cost that is to be financed and the discount rate. These parameters have an important effect on the model results. With larger loans and larger discount rates, rehabilitation decisions become less attractive. In addition, the model has been expanded to include life loss and non-seismic benefits of rehabilitation.

To evaluate the retrofitting alternatives, the decision analysis approach includes a value model for possible consequences. This value model consists of two stages. In the first stage, all consequences are converted to a common unit (either utilities or economic cost equivalents). Next a multiattribute utility model is used to aggregate across consequences (see Keeney and Raiffa, 1976, Clemen and Reilly, 2001). In the simplest case, we use the sum of the equivalent economic costs and benefits to gauge the value of retrofitting. Since the consequences are time dependent, they are discounted at the rate specified by the decision maker.

Either of two generic decision analysis approaches can be used to combine the probabilistic information embodied in Figure 1 with cost and benefits information to help decision making. The first is a simulation approach in which the costs and benefits are estimated for each combination of peak ground accelerations, damage states and rehabilitation options. This approach results in probability distributions over net present value (NPV) for the different rehabilitation options. This approach is very useful for exploring the tails of the probability

![Figure 2. Typical Simulation Output](image-url)
Decision Models: Approaches for Achieving Seismic Resilience

The other approach is to translate the probabilistic information in Figure 1 into a decision tree, to assign costs and benefits at the end of the tree, and to calculate expected values or expected utilities. While this approach does not easily address extreme values, it lends itself to exploring the sensitivities of many of the probabilities, costs, and benefits.

We used both approaches in past applications. For the simulation approach, we used the software “Crystal Ball” by Decisioneering (2002). For the decision tree approach, we used the software package Decision Analysis by TreeAge (DATA), version 3.5 (TreeAge Software, 1998), to create the decision tree and run all analyses. Figure 2 shows a typical output of the simulation, in the form of exceedance probability curves over the total equivalent costs (retrofitting plus damage costs) for three retrofitting alternatives (low, medium and high). Figure 3 shows a segment of a typical decision tree. The real tree in this case is fairly large and cannot be displayed on a page. After running the analysis, the DATA program displays the expected costs at each node of the tree, so the decision maker can determine both the expected costs at the root decision node and anywhere else in the tree.

The decision tree approach was applied to homeowners’ decisions to rehabilitate hillside homes in the Los Angeles area (see von Winterfeldt, Roselund and Kitsuse, 2000) and both the decision tree and the simulation approach was applied to rehabilitating apartment buildings with tuck-under garages (Benthien and von Winterfeldt, 2002; von Winterfeldt, Gosh, and Gupta, in preparation).

Both applications led to similar conclusions. The results are very sensitive to the time horizon of ownership (favoring rehabilitation for longer time horizons, but not for shorter ones), the financial terms (favoring rehabilitation for low, subsidized interest rates, but not for normal market level interest rates), the ability to recover some of the rehabilitation cost with increases in property values or rent increases, and the degree of concern with losses of human lives.
Seismic Hazard, Fragility Surfaces, and Cost-Benefit Analysis

This component of the proposed framework is designed to be integrated with the other components of the model described in the previous section. It uses probabilistic models to characterize the seismic hazard for a community, describes the seismic performance of the critical systems in a community by fragility surfaces, and evaluates retrofit strategies for these systems using cost-benefit analysis.

During the past year, the work focused on (1) generating life cycle seismic hazard scenarios, (2) essentials of a methodology for generating seismic ground accelerations at a collection of sites, (3) methodology for generating fragility surfaces for structural/nonstructural components of an individual health care facility, and (4) preliminary cost-benefit analyses based on this and the decision approach framework. These developments will be used in the selection of an optimal strategy (apart from organizational constraints) for seismic rehabilitation of structural/nonstructural systems of the demonstration hospital project.

The essentials of the approach are outlined in the following sections.

Seismic Hazard

Suppose that the seismic hazard needs to be evaluated for a community over a time interval measured in years, for example, \( \tau = 10, 20, \) or 50 years. The definition of the seismic hazard for this community is based on the following models.

1. Seismic activity model. Tectonic considerations and/or seismic ground acceleration records can be used to identify all relevant seismic sources, that is, seismic sources causing damaging earthquakes, and calculate the annual rate of earthquake occurrence as a function of the seismic source to site distance \( r \) and the earthquake magnitude \( m \). Figure 4 shows this function for New York City (NYC).

A sample of the seismic hazard for New York City for \( \tau = 50 \) years is shown in Figure 5.

The sample provides the times of all seismic events in \( \tau \) and the magnitude \( m \) as well as the source to site distance \( r \) for each event.

![Figure 4. Seismic Activity for New York City](image)

![Figure 5. Sample of the Seismic Hazard in New York City for \( \tau = 50 \) years](image)
2. Seismic ground acceleration models. Two models are used to specify the probability law of the ground acceleration process at a collection of sites in a community. The specific barrier model characterizes the properties of the seismic ground acceleration at individual sites as a function of the earthquake magnitude $m$, seismic source to site distance $r$, soil conditions, and other parameters. The coherence function model describes the relationship between ground motions caused by a seismic event at various sites in a community.

The Monte Carlo algorithm for generating samples of the seismic ground motions at various sites in a community is based on the specific barrier and the coherence models, and involves two steps:

1. Generate samples of the seismic hazard for a community similar to the sample in Figure 5. The generation is based on the histogram in Figure 4 and properties of Poisson processes.
2. Generate $n$ ground motion samples at the system site, and calculate the system response to these simulated samples of the ground acceleration.

The generation is based on the definition of the ground motion process delivered by the specific barrier and the coherence function models, and Monte Carlo methods for generating samples of stochastic processes.

**Fragility Surfaces**

We have seen that for each $(m, r)$, soil condition, and some other parameters, it is possible to generate ground motion samples at all sites of interest in a community.

Consider a structural or non-structural system located at a site in a community for which one or more levels of performance criteria have been specified. Each level of performance can be associated with a damage state. The objective is to calculate the probability that the system reaches a damage state as a function of magnitude $m$ and source to site distance $r$, that is, the *fragility surfaces* for this system.

The calculation of these surfaces involves four steps:

1. Select a value for the pair $(m, r)$. Only values of these parameters that have a non-zero probability of occurrence need to be considered. These values result from the annual rate of earthquake occurrence (Figure 4).
2. Generate $n$ ground motion samples at the system site, and calculate the system response to these simulated samples of the ground acceleration.
3. Estimate the value of the fragility surface at $(m, r)$ by the ratio $n_f/n$, where $n_f$ denotes the number of response samples that do not meet a particular performance criterion.

![Figure 6. Ground Motion Samples for All Sites in a Community](image-url)
4. Repeat the calculations in the above steps for all relevant values of \((m, r)\) and a particular performance criterion. Match a surface, referred to as fragility surface, defined on the space of parameters \((m, r)\) to the estimates \(n_f/n\) in step 3. A family of fragility surfaces corresponding to various performance criteria can be developed following this algorithm.

**Cost-Benefit Analysis**

The input to cost-benefit analysis consists of (1) a time horizon \(t\), (2) seismic hazard at the site of interest (Figure 5), and (3) cost functions including, for example, retrofit and repair costs, loss of use, and loss of life, as well as some potential monetary benefits of retrofit such as increased efficiency in treatment, staffing, and logistics.

Suppose that a system experiences an earthquake with magnitude \(m\) occurring at a seismic source at distance \(r\) from the system site. Following the earthquake, the system enters a damage state \(d_s(m, r)\) with a probability \(p_s(m, r)\) given by the system fragility surfaces. Suppose also that the system is repaired so that it is brought to its initial state immediately following this earthquake. Denote by \(c_s\), the cost of bringing the system from damage state \(d_s(m, r)\) to its initial state. This elementary cost structure presented here for illustration can be augmented to include the components mentioned above.

Consider now samples of the seismic hazard at the system site, as shown in Figure 5. Let \((m_i, r_i)\) denote the values of \((m, r)\) corresponding to earthquake \(i\) in a sample of the seismic hazard. The corresponding damage states \(d_s(m_i, r_i)\) and their probabilities \(p_s(m_i, r_i)\) result from the system fragility surfaces. Denote by \(c_s\) the repair cost associated with the damage state \(d_s(m_i, r_i)\). Since damage state \(s\) has probability \(p_s(m_i, r_i)\), the repair cost for the seismic event \(i\) is

\[
C_i = \sum c_s d_s(m_i, r_i).
\]

The total cost for this sample of the seismic hazard is

\[
C = \sum_i C_i.
\]

The cost \(C\) is a random variable, whose properties can be estimated from a collection of seismic hazard samples. Figure 7 shows hypothetical histograms of \(C\) corresponding to various retrofit strategies.

These histograms have similar expectations but very different tails, suggesting that the use of expected cost as a decision tool for selecting an optimal retrofit strategy can yield unsatisfactory results.

![Figure 7. Histograms of Total Cost C](image)
Evolutionary Methodology as a Basis for a Decision Support Platform

Complex Adaptive Systems and Evolutionary 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 an excellent 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 structures with passive energy dissipation devices is considered.

Evolutionary Aseismic Design and Retrofit

This section includes 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. 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 opera-
tors modeling selection, crossover and mutation processes, define the makeup of the next generation of structures. In our system, performance is judged by conducting nonlinear transient dynamic analysis using an explicit state-space transient dynamics computer code (tda). The implementation of the genetic algorithm controlling the design evolution is accomplished within a modified version of the computer code Sugal (Hunter, 1995).

In the area of seismic passive energy dissipation systems, Singh and Moreschi (1999, 2000, 2002) developed the first genetic algorithm applications, while 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), Zhao (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. Three different types of dampers are available: metallic plate dampers, linear viscous dampers, and viscoelastic dampers (e.g., Soong and Dargush, 1997). For each type, four different sizes are possible. We utilize a four-bit genetic code to represent the devices in each floor. Consequently, 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 2^{48} 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 and all of the bracing elements associated with the passive dampers are assumed to be perfectly rigid. In order to establish acceptable performance for a structure, limits are imposed on interstory drift and story acceleration for each story.

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 $\log N = a - bM$. 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.

For this twelve-story structure, let $W_i$ and $k_i$ represent the $i$th story weight and story elastic stiffness, respectively. The baseline frame model has story weights $W_1 = \ldots = W_6 = W, W_7 = W_8 = 0.75W, W_9 = \ldots = W_{12}$.
= 0.5W and stiffnesses \( k_1 = \ldots = k_6 = k \), \( k_7 = \ldots k_{12} = 0.25k \). 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 in terms of the parameter \( W \) as follows:

\[
F^{yL}_1 = \ldots = F^{yL}_6 = 0.20W, \\
F^{yL}_7 = \ldots = F^{yL}_{12} = 0.05W
\]

We now assume that this steel structure is located on firm ground near Memphis, TN. The base structure without dampers survives only 29% 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 that utilize 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 only a model problem intended to illustrate the methodology.

Figure 8 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 9 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 10. Color indicates the damper type and the radius of the rings 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. Furthermore, beginning in Year 6, we are extending the methodology to examine proof-of-concept models for combined physical and sociotechnical decision support capabilities.

Behavioral Models of Organizational Decision Making about Enhancing Seismic Safety for Acute Care Hospitals

In another effort, researchers are focusing their attention on organizational and institutional impediments to implementing precautions for enhanced seismic safety and means for overcoming those im-
pediments, with a special focus on acute care hospitals. Their goal is to work with other investigators in this area to integrate what is known about organizational decision making and policy and program implementation into the decision-assisting frameworks being developed by other members of the team. Like the other members of the team, their work places special emphasis on mitigating seismic hazards in older acute care hospitals but is expected to have general application as well.

**The Approach**

Each of the team members working on decision-assisting models is coming at the problem from a different perspective, but each has the intent of coupling their work with that of other team members to create a truly effective tool. One approach stems from decision science. It is essentially based in normative theory; that is, it is based on how one “should” make choices. Another is empirically-based in engineering and earth science; it feeds directly into the decision science-based model. A third approach is also empirically-based on structural response and the effects of various kinds of damping systems, but employs a novel simulation approach that allows a large number of different mitigation strategies to be tested against a large array of ground-shaking events. The fourth approach is also empirically-based; it focuses on describing what happens in connection with policy implementation under various sets of circumstances. Those circumstances involve the design of policies and programs, the conditions within which implementing organizations find themselves when considering actions to improve seismic safety, and characteristics of the institutional arrangements within which programs are administered and decisions are made by those affected by policies and programs. At the same time, however, they must necessarily focus on characteristics of organizations that affect the decisions they make about how to respond to externally imposed policies and programs.

Initially, investigators worked to develop an understanding of obstacles to implementation, including characteristics of the policy itself and the dynamics of policy and program administration through various levels of government and agencies. For that initial work, they relied heavily on an extensive and intensive review of the literature. Following their initial work, they initiated an extensive case study of SB 1953 in California.

**Highlights from the Work**

The researchers talked extensively with professionals and have generated several very important propositions concerning enhancing seismic safety in older hospitals. First, individual healthcare organizations respond to SB 1953 very differently from one another. Some organizations are moving ahead in a timely fashion to comply. Others are doing as little as possible to comply. Still others apparently do not plan to comply. Some hospitals have been closed. Second, the response of individual healthcare organizations to the requirements of SB 1953 has less to do with their concern with seismic safety than it does with a myriad of other concerns, concerns that are in some cases contrasting.

“The goal of this effort is to provide significantly enhanced means for facilitating development of workable strategies to enhance the seismic safety of hospitals.”
cases unique to individual hospitals and, in others, common to most. The institutional and organizational decisions about what to do about SB 1953 are driven by the context within which the individual organizations must make their choices. Hindsight is not always 20-20, but, in retrospect, it has been possible to identify characteristics of the policies embodied in SB 1953 and its regulations that, had they been different, could have contributed to smoother and less painful implementation for the healthcare organizations and, perhaps, even the organization charged with administering the provisions of the Act. The lessons learned from the retrospective examination can be informative for subsequent policy development.

Finally, the research on organizational decision-making emphasizes the dynamics of policy and program implementation. Changing circumstances affect the solution set perceived by organizational decision makers. Rapidly changing, highly dynamic settings for critical systems, like acute healthcare, demand policy making that is temporally responsive to the needs of those delivering critical services. At the same time, the investigators are concerned that most traditional behavioral organizational decision making theory is based on static situations or on comparative statistics; the researchers are coming to believe that decision-assisting models, if they are to be most helpful, must be compatible with dynamic organizational processes and rapidly changing premises and perceived options.

Future Research

In summary, researchers are working on the basic problem of developing decision-assisting platforms from both ends—engineering and decision-making—while paying careful attention to how they might effectively merge their efforts in the middle. They are working as an multidisciplinary team to learn the extent to which they can integrate one or both of the basic platforms models with what is being learned about how acute care organizations actually make decisions about seismic retrofit. To the extent that it can be accomplished, it will provide significantly enhanced means for facilitating development of workable strategies for enhancing seismic safety in hospitals. Moreover, the array of potential applications of such a platform would make it a significant contribution to the field of decision-making under conditions of extreme complexity and uncertainty.

In the coming years, research on organizational decision making in older, acute care hospitals will be integrated into the two decision analysis systems being developed. A proof of concept test is being designed and conducted to learn the extent to which an organizational decision making component can be integrated into the respective models. Depending on the outcome of those tests, the team will work to integrate the models fully into the platforms. If the tests are not encouraging, the teams will seek other means for loosely-coupling the behavioral decision-making models to the current platforms so the information they have generated can be used as criteria for evaluating alternatives.
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