

Market-Focused and Open-Systems Approaches to Earthquake Loss-Reduction: Contextualizing Role of Engineering Research

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Abstract: To achieve loss-reduction objectives and to enhance community and societal resilience in the event of earthquakes and other disasters, researchers and practitioners must take into account the broader societal environment in which loss-reduction solutions are applied. For that purpose, researchers at the Multidisciplinary Center for Earthquake Engineering Research (MCEER) have developed two conceptual frameworks that clarify the linkages that need to be made between earthquake research and the application of loss-reduction solutions: an open-systems approach as a strategy for organizing a large-scale coordinated research agenda applied to a significant public problem, and market-based metaphors to introduce a new way of conceptualizing the loss-reduction process. This paper presents these proposed conceptual frameworks, which have been used by MCEER to formulate its research agenda, for consideration as potentially helpful tools for researchers and for the management of large multidisciplinary research endeavors in earthquake engineering, as well as for discussion and possible enhancements by others within the research community.

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Introduction

During the last two decades of the 20th century, earthquakes killed more than a million people worldwide (Noji 1997). Although earthquakes in the United States are not as deadly as they are in less-developed countries, they still pose major life-safety and health hazards and exact an enormous price in terms of property damage and economic losses. Major earthquakes in the United States and its territories killed approximately 1,400 people during the last century; nearly half of those deaths occurred in the 1906 San Francisco earthquake and fire (Noji 1997). Between 1975 and 1994, more than 14,000 people were injured in U.S. earthquakes (Mileti 1999).

Economic losses from urban earthquakes have risen dramatically in recent years. For example, although the 1994 Northridge earthquake was a moderate-sized seismic event, it proved to be the most costly disaster in U.S. history. A 1998 report that synthesized data from a range of sources estimated the direct costs of that earthquake to be at least \$24 billion and provided credible projections indicating that total *direct* economic losses could climb as high as \$44 billion (Eguchi et al. 1998).

The 1995 Kobe earthquake demonstrated that seismic events have the potential for producing enormous losses and extensive social disruption, particularly when they strike vulnerable urban areas. That potential clearly exists in the United States. In the San Francisco Bay area, for example, a 1996 planning scenario released by the Earthquake Engineering Research Institute (EERI) projected that following a magnitude 7 earthquake on the Hayward Fault, the occupants of 150,000 to 200,000 housing units will need emergency and temporary housing, natural gas service will be extensively disrupted, and about 60% of East Bay households and businesses will lose water for periods ranging from days to months (EERI 1996). Economic losses from such an event would easily double or even triple those experienced after Northridge. Some researchers have estimated these losses to exceed \$200 billion (Risk Management 1995).

Earthquake losses will rise at an escalating rate in future years unless new loss-reduction strategies are undertaken and existing approaches are strengthened. Research clearly plays an integral role in this process. Particularly important are efforts that focus on comprehensive multidisciplinary approaches that analyze the earthquake problem holistically—that is, from the perspective of various engineering fields as well as other disciplines that can provide the knowledge needed to reduce earthquake losses.

To ensure that such efforts are undertaken, the National Science Foundation has funded research centers that are intended to serve as vehicles for organizing the kinds of multidisciplinary teams required to address the earthquake problem in a comprehensive fashion. The strategy developed by the Multidisciplinary Center for Earthquake Engineering Research (MCEER) places considerable emphasis on the role that new technologies can play in earthquake loss reduction. However, it also proceeds from the assumption that the successful implementation of loss-reduction measures can only be achieved if researchers and practitioners understand the societal context in which research, application, and implementation efforts are undertaken. MCEER researchers

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have developed two conceptual frameworks that clarify the linkages that need to be made between earthquake research and the application of loss-reduction solutions. The first is the concept of the loss-reduction market (LRM), which provides a useful metaphor for understanding loss-reduction challenges. The second is an open-system model that characterizes the manner in which the larger societal environment affects implementation efforts. A key element in this model is the concept of the diversified loss-reduction portfolio, consisting of a variety of strategies, technologies, and techniques that can be employed to contain earthquake losses.

The objectives of this paper are to provide a brief overview of the LRM concept and to present a systems approach that illustrates how the broader societal environment affects the selection of loss-reduction measures, as well as how research, the development of loss-reduction strategies and techniques, and the application of those measures are related. The writers do not pretend to have formulated a rigorously exact, economics-based model for the earthquake loss-mitigation problem. Rather, this paper introduces, through this analogy, a new way to frame earthquake loss-reduction research in terms that can be used to develop a sensible strategy for organizing a large-scale, comprehensive, coordinated research agenda applied to a significant public problem. Likewise, the writers do not claim that such a research agenda can (or needs to) approximate a system, but that this research can be systematic and deemed to be based on an open-systems approach because it is aimed at affecting the inputs, processes, and outcomes of an open system.

Although this paper does not present new theories or research results, it does outline a potentially useful conceptual framework for characterizing the relationship between research activities and the broader societal environment in which research findings are implemented, recognizing that the proposed framework could be enhanced through further development and refinement by others. The market-based analogies and open-systems concepts presented here have been used by MCEER to better understand those relationships and to shape its own research agenda.

Beneficiaries and Users of Earthquake Engineering Research

Although research in earthquake engineering is aimed at protecting life safety and mitigating damage and losses, it can only provide these benefits if seismic safety measures are actually adopted and implemented. The implementation of these measures will ultimately be realized through the efforts of numerous and diverse users of research results. These users include the various decision makers, knowledge providers, and groups and individuals who undertake actions to increase the earthquake resistance of the built environment while containing direct and indirect earthquake losses. This group of societal actors includes (but is not limited to) practicing engineers and other design professionals, policymakers, regulators and code officials, facility and building owners, governmental entities, and other stakeholders who are responsible for loss-reduction decisions. These decisions can encompass a range of actions, including the adoption of various new technologies, the retrofitting of structures using improved techniques and approaches, and response- and recovery-related activities. This “loss-reduction market (LRM),” or set of entities that can potentially adopt and apply research-based solutions to the earthquake problem, has a number of significant characteristics that should be taken into account in efforts to implement loss-reduction measures. The section that follows discusses the features of the LRM.

Attributes of Loss-Reduction Market

First, the LRM is both diffuse and diverse, consisting of actors with multiple and often conflicting values and interests. It includes numerous public- and private-sector entities and individuals as well as organizations. The market spans geographic areas of high, moderate, and relatively low earthquake risk. It is also diverse with respect to the amount of earthquake-related knowledge actors possess and the priority they place on loss reduction. Additionally, it includes actors that are required to undertake loss-reduction activities as well as entities for which such actions are voluntary.

Second, while earthquake researchers and developers of seismic safety measures make a number of alternative solutions available for reducing earthquake losses, ranging from preearthquake mitigation to postearthquake response and recovery, LRM participants vary considerably in their receptivity to these alternative solutions. Measures that are deemed acceptable and even highly desirable by some entities may be considered unacceptable by others. A multiplicity of alternative approaches is needed to satisfy the preferences of LRM decision makers. For example, retrofit solutions applicable in one particular building may not be acceptable for another identical building due to factors such as differences in owner resources, location and importance of the facility, exposure to risk, and owners' tolerance for damage, loss of functionality, and overall costs.

Third, like other types of markets, the LRM is generally uncomfortable with uncertainty. Actors prefer clear, accurate, and valid information on the risks, potential losses, and costs associated with implementing loss-reduction measures because this information provides a sound justification for their decisions. One implication of this market characteristic is that researchers, and those who are advocates of new loss-reduction solutions, must find ways to communicate with market actors to address and clarify the uncertainties that inevitably arise in the course of seismic research.

Fourth, LRM is highly sensitive to the costs associated with the adoption of alternative loss-reduction solutions. Although this is especially true of private-sector market participants, public-sector agencies are also increasingly required to justify their loss-reduction decisions on cost-effectiveness grounds.

Finally, for many actors, involvement with the earthquake LRM competes with other activities in which they may feel more pressure to invest, including loss-reduction activity for other hazards and investments to address other social problems, such as crime. LRM activity may actually be quite low on many key actors' agendas. One implication of this market characteristic is that loss-reduction solutions can often be made more attractive if they can be shown to serve multiple purposes or provide actors with other benefits in addition to earthquake safety.

Because of these market characteristics, the LRM does not adopt loss-reduction measures readily or rapidly. The market's diversity and the voluntary nature of much loss-reduction activity militate against blanket or mandatory solutions, requiring instead an array of technologies, techniques, and strategies that meet decision makers' needs. Change tends to be gradual and incremental and is often brought about by dramatic earthquake events that increase the actors' willingness to undertake seismic safety programs.

Just as efforts to influence and change consumer behavior depend on an understanding of the market for different types of goods and services, activities aimed at achieving higher levels of seismic safety must be based on an understanding of LRM characteristics, behavior, and preferences. As is pointed out in the

section that follows, approaches are needed that recognize these distinctive market features, and research must be geared toward meeting the needs of the LRM and increasing market receptivity to loss-reduction measures.

Market-Oriented Research and Development Strategies

Before they can have an impact on the broader society, research products must be adopted and implemented by LRM participants. These processes will not occur unless market needs and preferences are addressed. For example, because of market sensitivity to both uncertainty and the cost of reducing earthquake losses, studies are needed to improve loss-estimation techniques and to bring about a better understanding of component and system fragilities. Such studies will reduce the uncertainties associated with loss projections and serve as the basis for determining the cost-effectiveness of alternative loss-reduction strategies. Similarly, to address the market's need for valid information as well as its sensitivity to cost, more rapid, reliable, and less expensive techniques are needed for estimating both potential losses and actual earthquake damage. New technologies may well offer the promise of enhanced levels of seismic safety, but unless those technologies are well aligned with the concerns of market participants, they will not be used. Put another way, unless research can demonstrate that tools, techniques, and technologies are effective in reducing direct and indirect earthquake losses, market participants will be reluctant to take on the risks associated with the adoption of those tools, thus impeding implementation.

Diverse markets require diverse products. Diversity shapes the loss-reduction preferences of different actors in the LRM, and research must recognize that for many of those actors, particularly in areas of lower seismic risk, extensive mitigation programs may not be feasible. Additionally, even in high-risk areas, decision makers will likely seek ways of containing losses that attempt to skirt the difficult issues associated with the adoption of mitigation measures. There is therefore a need for research that can lead to the development of solutions that address the entire disaster cycle, from mitigation through post-event response and recovery.

In all types of markets, product developers typically spend a great deal of time trying to understand what will make their goods and services attractive to potential customers and what barriers may stand in the way of higher sales and greater market share. In the earthquake hazards area, there is a parallel need for research on the impediments and incentives associated with the adoption of loss-reduction measures and on the entire implementation process because such research will lead to a better understanding of how to increase the LRM's receptivity to various loss-reduction measures.

Research activities can advance the state of the art without necessarily improving the state of practice or having other tangible effects beyond the research community. To have an impact, research activities must be linked to trends and events in the broader society and, more specifically, to fluctuations in LRM receptivity and resistance. In the section that follows, this interaction between the research community, the LRM, and society is conceptualized more generally in open-system terms.

Specifying Relationship between Research and Adoption and Implementation of Loss-Reduction Strategies: Open Systems Approach

Closely related to the concept of the LRM is an open-systems approach to research and development and the adoption and

implementation of loss-reduction measures that recognize and respond to market conditions. Fundamental to this perspective is the notion that in order to be effective, earthquake engineering research must be conducted with an understanding of the characteristics, needs, and requirements of both the LRM and the broader society. Rather than creating knowledge for its own sake, researchers must be able to produce solutions that can be applied in the wider societal environment. As previously noted, that societal environment consists of various stakeholder groups that have multiple and often conflicting values and interests.

There is a wide range of possible approaches to managing the earthquake threat, from investment in preevent mitigation through reliance on postevent response and the provision of postdisaster aid as strategies for containing losses. Market participants in different organizations, communities, and regions of the country vary in the emphasis they place on these alternative solutions. Key actors also differ in the extent to which they are willing to tolerate the uncertainties associated with research findings and recommended solutions. Equally important, they are likely to differ considerably in their expectations concerning acceptable levels of seismic performance for elements in the built environment and in the levels of risk and vulnerability they consider acceptable. Overall, however, the market is very sensitive to the costs associated with different loss-reduction approaches, which creates pressure for demonstrating that potential solutions to earthquake-related problems are cost-effective.

In addition to accurately gauging market preferences, needs, and expectations, it is also important to recognize that efforts to achieve higher levels of earthquake resistance are constrained by numerous barriers, including the sheer complexity of the earthquake problem and the difficulties inherent in developing reliable research findings and credible policy recommendations; the low priority assigned to earthquake loss reduction in many areas of the country and many market sectors; financial barriers associated with adopting and implementing loss-reduction solutions and, relatedly, the difficulties inherent in demonstrating the cost-effectiveness of loss-reduction measures; lack of clarity with respect to legal and regulatory authorities; and various other knowledge, political, perceptual, and economic barriers. If loss-reduction efforts are to be successful, a wide array of alternative products, technologies, and strategies is needed to allow market participants the latitude and flexibility to select among an array of different loss-reduction options.

A strategy to provide the new knowledge that can help overcome barriers to implementation is illustrated in Figs. 1 and 2. Fig. 1 illustrates how the loss-reduction market influences both research activities and the long-term process through which research findings are implemented. Fig. 2 provides more detail on the solution development process—that is, the activities that researchers undertake within the “control box” component of Fig. 1.

As shown in Figs. 1 and 2, the technologies, tools, and strategies developed by researchers must be appropriate for the societal environment in several respects. First, as illustrated in Fig. 2, they must take into account a number of market characteristics, such as the fact that communities and regions differ in the severity of the hazards they face and in their vulnerability, as well as in stakeholders' awareness of and receptiveness to loss-reduction measures. In order for earthquake solutions to be acceptable to a community, for example, they must be consistent with that community's conception of the earthquake hazard, as well as its views on different techniques that can be applied to reduce vulnerability.

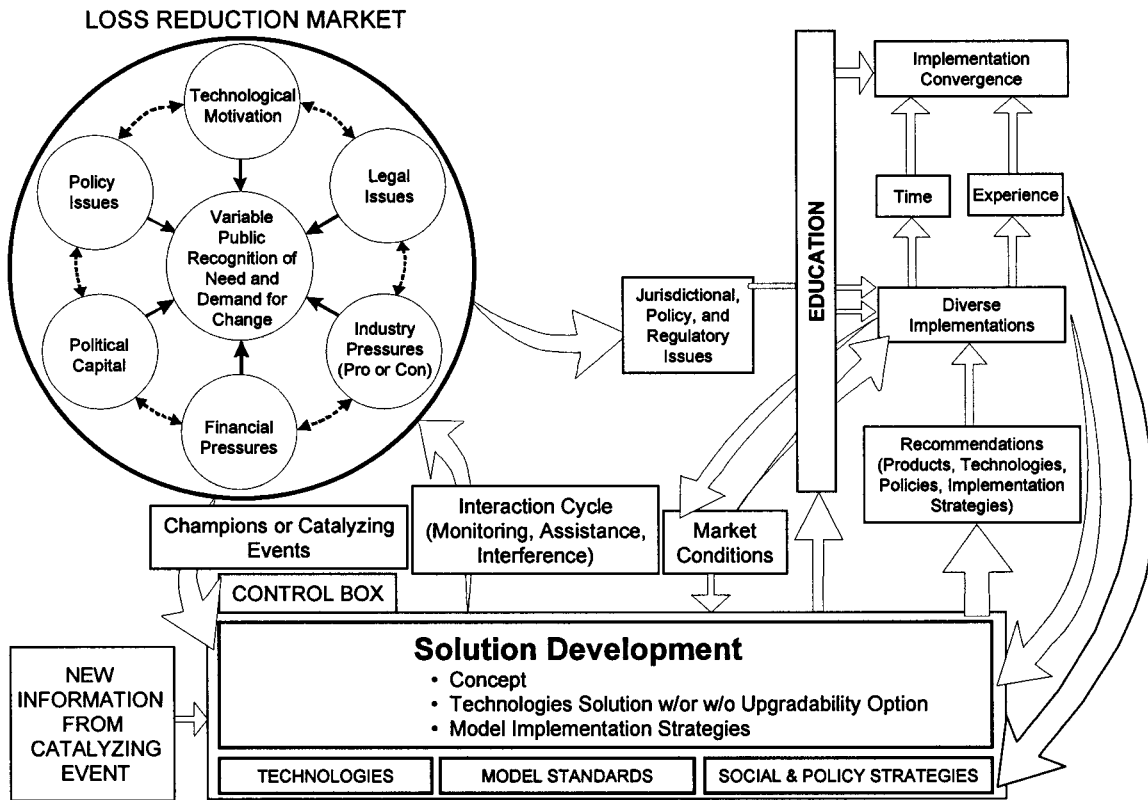


Fig. 1. Open-system framework

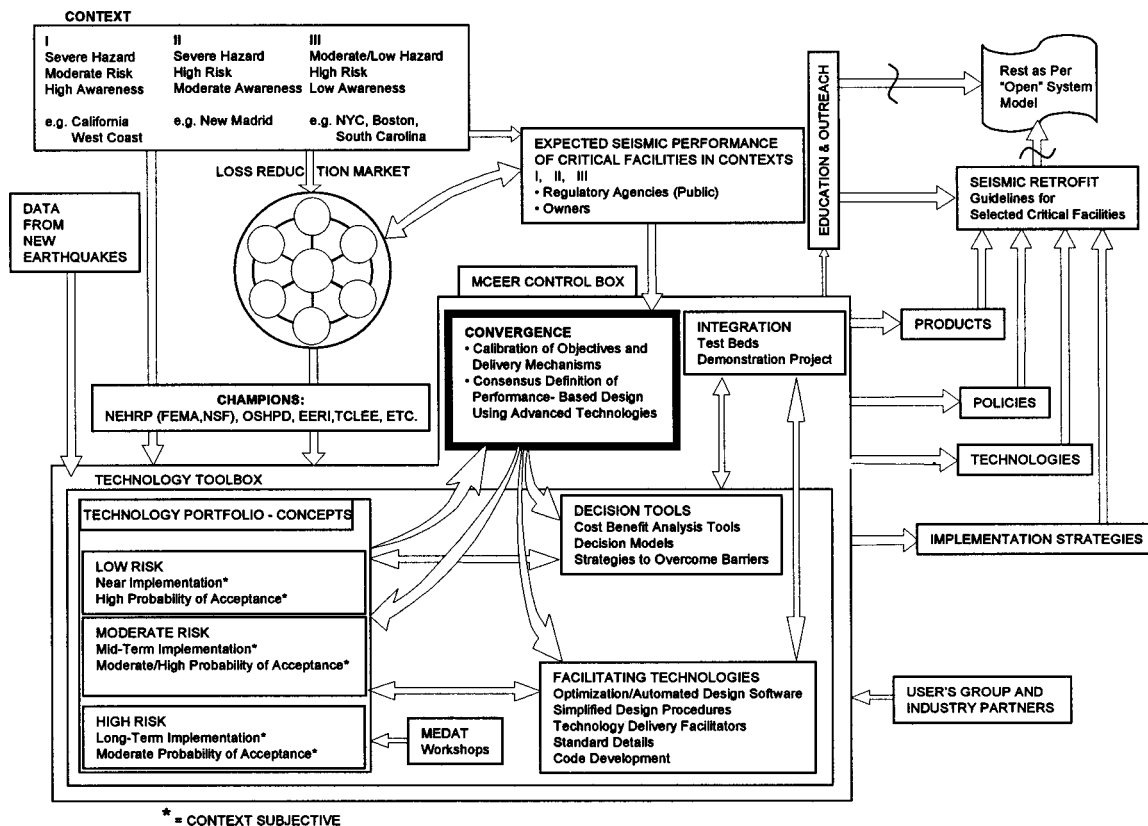


Fig. 2. Research strategy

Second, solutions must take into account the complexity of the loss-reduction market in terms of needs, economic and political interests, priorities, conceptions of acceptable risk, and familiarity with the earthquake problem. Third, they must be geared toward taking advantage of both research and implementation opportunities presented by earthquake events, since earthquakes and other disasters often serve as catalysts for change, particularly when they stimulate champions or policy entrepreneurs to place loss reduction on the policy agenda (Alesch and Petak 1986; Olson et al. 1998a, 1998b; Birkland 1998; Prater and Lindell 2000). Other changes in the societal environment, such as the passage of new laws or the adoption of new codes and standards, can also encourage stakeholders to adopt and implement loss-reduction measures.

As illustrated in Fig. 1, the research community develops various candidate solutions designed to reduce earthquake losses. These research and development activities are characterized here as taking place inside a “control box” because this is the part of the system over which the research community has the greatest amount of direct influence. However, in the final analysis, it is the LRM and the societal environment that influence which solutions are defined as significant enough to pursue and which are adopted and implemented. For example, as illustrated in Fig. 1, researchers may develop and recommend a variety of seismic safety techniques and technologies, but the process of selecting, adopting, and implementing solutions is ultimately driven by societal forces, as well as by actors who champion particular solutions and events that serve as catalysts for new research.

Fig. 2 focuses in more detail on activities that take place within the system’s control box, or the part of the system over which researchers have the most direct influence. It also outlines what the research community needs to take into account in making solutions “marketable” in the larger society and further elaborates on the relationship between societal and community settings, research activities, and the implementation process. Key elements in this part of the model are addressed in the following sections.

Technology Portfolio

One key component of the system’s internal control box is a “technology portfolio” consisting of a range of candidate approaches designed to achieve a specified loss-reduction objective—structural and nonstructural seismic retrofit strategies, for example. The term “portfolio” is used here to suggest that some of the technologies being investigated will always be riskier than others from the point of view of effectiveness and implementation potential. At the outset, researchers must recognize that some of the technologies they investigate may eventually prove not to be cost-effective (at a given time), or that they will encounter too much societal resistance to be implemented in the near term. This portfolio is, in other words, diversified in terms of both potential risks (for example, failure to demonstrate proof-of-concept or cost-effectiveness, or failure to demonstrate implementation potential) and potential payoffs.

The logic behind the development of the technology portfolio is that, among all the technologies that are investigated, many will prove cost-effective and will be adopted and implemented. However, it is important to emphasize that all technologies considered, even when assessed as high-risk, have a reasonable potential of being implemented—the higher risk rating should not be construed as negative, but rather as a recognition that research on that technology is still in the early stages and that relatively more work is required before full assessment of its effectiveness is possible. For example, in the early 1990s, although some re-

searchers had the foresight that dampers could be implemented in buildings to control seismic response (as is frequently done today), in accordance with the technology portfolio model proposed here, that research on dampers undoubtedly would have been rated as a higher-risk technology at the time.

The main challenge is that as a group, the technologies in the portfolio must provide the necessary diversity to tackle complex loss-reduction challenges. They must also offer the flexibility to adjust research directions rapidly when earthquake events or other changes in the societal environment alter stakeholder receptivity or attitudes about what constitutes acceptable solutions to various aspects of the earthquake problem. To ensure that candidate technologies are continually added to the portfolio, the earthquake engineering community must find ways to foster interaction with experts from various other disciplines. This can be achieved formally or informally in many different ways. For example, MCEER is in the process of conducting a series of workshops on the theme of “Mitigating Earthquake Disasters through Advanced Technologies,” which are designed to identify technologies that have been developed for other applications that can be usefully applied to enhancing levels of seismic safety.

Facilitating Technologies

Also included in the control box is a range of facilitating technologies that appear to offer the greatest promise for addressing key loss-reduction challenges. Examples of facilitating technologies include optimization and automated design software, simplified design procedures, other technology delivery facilitators, standard details, and seismic codes. The mix of technologies that are ultimately adopted and implemented, as well as the speed with which implementation takes place, will depend in large part on community context and on the operation of the LRM. In some localities, the market may support the adoption of measures that span the entire hazards cycle, from preevent mitigation and preparedness through postevent response and recovery. In others, postevent loss-reduction measures will be favored over preevent mitigation programs. Some decision makers may elect to adopt new, innovative, and perhaps more expensive solutions, while others may be more conservative.

Support Tools

A range of tools that provide support for rehabilitation, response, and recovery decision making constitutes a third set of marketable solutions to earthquake-related problems. These decision tools and their associated technologies include advanced methods for earthquake loss estimation and postevent damage assessment; cost-benefit methodologies that can be used to support mitigation decision making, response and recovery decision-support systems; and strategies for overcoming barriers to the adoption and implementation of loss-reduction techniques.

Testbeds and Demonstration Projects

Another component of this part of the model is project activities that focus on bringing about a convergence between engineering and societal perspectives on ways of improving loss-reduction efforts. Decision tools and facilitating technologies can be combined in testbeds and demonstration projects that provide a focus for the work of multidisciplinary teams. To facilitate and accelerate implementation in earthquake engineering, it is necessary to conduct full-scale multidisciplinary demonstration projects, as

well as to develop a range of products for end-users, such as comprehensive retrofit manuals that summarize, in a practical format, the expert opinion built and validated through the research activities.

Such demonstration projects and outreach efforts enable researchers and partners in industry and government to examine the promise of advanced technologies in real-world situations, while the products such as retrofit manuals provide the guidance required to make users comfortable with innovative approaches that depart from conventional practice. Additionally, activities that seek to bring about a convergence of disciplinary perspectives on earthquake hazards are needed because it has historically been very difficult to bridge gaps between the results of engineering analyses (which attempt to predict the performance of structures and systems) and the ways in which stakeholders (such as regulatory agencies, facility owners, and the general public) define acceptable performance levels. Multidisciplinary research activities must therefore be aimed at reconciling these often divergent views.

Research Outcomes

These multidisciplinary investigations lead to a diverse set of research outputs that include products and devices, policies and guidelines (for example, seismic retrofit guidelines for critical facilities), new methodological approaches, technologies whose effectiveness has been demonstrated, and implementation strategies. Research outputs lead to loss-reduction outcomes when research findings and new loss-reduction strategies are adopted and implemented. Successful implementation depends on market receptivity and on overcoming barriers to implementation; it also requires coordinated education and outreach efforts. Ultimately, given variations in earthquake vulnerability, commitment to earthquake loss reduction, and the costs associated with adoption relative to benefits, there will also be variation in which loss-reduction measures are judged most appropriate for different societal settings.

Other Interactions and Activities

Throughout this process, as shown in Figs. 1 and 2, continual monitoring and interaction take place among the entities represented in the various model components, which include stakeholders and champions, researchers, and those responsible for policy formulation and adoption. This ensures responsiveness and resource reallocation to capitalize on opportunities created by positive changes in the receptiveness of actors in the LRM to proposed solutions. Likewise, assessments of the effectiveness of pioneering implementations made as a result of early research outcomes, combined with the benefit of time and experience, make it possible to identify previously unrecognized shortcomings in knowledge, new needs, and better potential solutions and to use these findings to recommend new research activities.

As noted earlier, education and outreach activities clearly play a role in moving loss-reduction measures from the stage of pure research through the process of adoption, application, and implementation. However, to be optimally effective, education and outreach activities must be part of a well-coordinated implementation strategy that can provide important linkages between the earthquake engineering research community and all interested parties (public agencies, code committees, users of the technology, and so forth). While organizations such as the earthquake engineering research centers can provide integration and coordi-

nation on a small scale, only government agencies, working with all parties, can successfully orchestrate such an implementation plan at the national scale. Possible multistakeholder strategies and incentives toward implementation have been proposed in the past (EERI 1998) and are beyond the scope of this paper.

Evolving Challenges

Finally, it must be recognized that earthquake engineering research, application, and implementation activities are not part of a linear process. While it is important for researchers to identify, address, and ultimately overcome barriers associated with developing knowledge and encouraging the use of loss-reduction measures, it must be recognized that many barriers to knowledge development and transfer cannot be identified *a priori*. Rather, it is frequently the case that, as research and implementation efforts proceed, new and unanticipated barriers and challenges are recognized. Similarly, the research process typically uncovers new opportunities. The process is one in which an understanding of both barriers and chances for speeding knowledge development and application emerge out of the research itself.

This quality of openness, which characterizes all research endeavors, is especially prominent in earthquake engineering, for two reasons. First, the rapid pace at which technology is developing can be expected to lead to new research and application opportunities. Second, significant earthquakes (and other disasters) provide major opportunities for research as they raise new problems, often calling into question long-held beliefs in the research community. They also have the potential to cause shifts in governmental and organizational priorities, eliminating barriers that had existed earlier and opening “windows of opportunity” for change. Consequently, an effective earthquake engineering research, application, and implementation strategy is one that is sufficiently flexible to recognize that new barriers will be encountered and to be able to take advantage of research opportunities that technological developments and earthquake events may present.

Conclusion

One of the most important steps in the evolution of earthquake engineering research is the understanding that a unitary system approach to programmatic research is insufficient to achieve the objective of providing the tools to create a disaster-resistant or resilient community. Instead, a systems approach is needed that brings about the integration of multiple systems—social, political, economic, natural, and structural—before a set of solutions can be identified. This type of approach, which requires intensive collaboration across disciplines, must also be conceptualized as a set of interacting systems that may have contradictory goals, competing value systems, and participants who potentially have little in common with each other. This approach requires investigators to look more broadly at these various systems and to begin to think about where they are synergistic—that is, how the analysis of these different systems can be used to integrate our research efforts to achieve a more complex approach to identify potential solutions and to enhance their implementation.

The systems approach and market analogies described in this paper are initial outcomes of this rethinking. The models presented here represent an attempt to show how both the development of loss-reduction technologies and their ultimate implementation are influenced by conditions, groups, decisions, and events in the larger environment. They also take into account the fact

that when significant earthquakes occur, they require immediate attention and create new opportunities for research, policy changes, and implementation. Such sudden challenges are typical in earthquake engineering research and other research on hazards, and flexibility is required to rapidly adapt and refocus research efforts accordingly.

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