Chapter 1
Challenges Towards Achieving Earthquake Resilience Through Performance-Based Earthquake Engineering

Helmut Krawinkler and Gregory G. Deierlein

Abstract Much has been accomplished in performance-based earthquake engineering over the past two decades. Processes have been established that facilitate probabilistic seismic hazard analysis, evaluation of relevant engineering demand parameters through advanced modeling and nonlinear response history analysis, quantification of damage measures and associated repair/replacement costs at the component level, and aggregation of losses for structural and nonstructural systems. The outcome is a probabilistic assessment of direct economic loss and collapse safety due to earthquakes. In contrast to assessment of structural collapse and direct losses, comparatively less has been accomplished in quantifying factors that affect downtime, business interruption, and community functions. These issues are critically important to bridge between performance of a single structure and the earthquake resilience of a community or region or country. A key aspect of resilience is looking beyond direct damage and losses to their implications on disaster response and recovery. From a societal perspective, resilience is the key challenge to mitigate the lasting effects of earthquakes. Drawing upon relevant research and recent initiatives in California to create more earthquake resilient communities, this paper explores challenges to improve performance-based engineering to address specific aspects of resilience.

(Helmut Krawinkler) Author was deceased at the time of publication.

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M. Fischinger (ed.), *Performance-Based Seismic Engineering: Vision for an Earthquake Resilient Society*, Geotechnical, Geological and Earthquake Engineering 32,
DOI 10.1007/978-94-017-8875-5_1,

Keywords Performance-based earthquake engineering • Resilience • Risk • Safety • Loss assessment

1.1 Introduction

Over the past 20 years, performance-based earthquake engineering (PBEE) has developed from the conceptual framework to a workable set of procedures and enabling technologies. As described in SEAOC's *Vision 2000* report (SEAOC 1995), "*the intent of performance-based earthquake engineering is to provide methods for siting, designing, constructing and maintaining buildings, such that they are capable of providing predictable performance when affected by earthquakes.*" Here the key distinction from traditional earthquake engineering is the emphasis on *predictable performance* – implying the need for methods to determine the expected response of structures and to relate this to meaningful performance metrics. In first generation implementations of PBEE, such as *FEMA 273* (1997), performance is quantified by approximate relationships between structural component deformations and qualitative performance measures of Immediate Occupancy, Life Safety and Collapse Performance. In contrast, the current second-generation procedures, most notably those embodied in *FEMA P-58 Seismic Performance Assessment of Buildings* (2012a), quantify performance in terms of direct economic losses and collapse risk. Other performance measures, including risks of building closure, repair times and casualties are also included in the *FEMA P-58* procedures, though admittedly with more reliance on judgment.

Whereas the primary developments in PBEE have focused on the performance of individual buildings and facilities, from a societal view, it is ultimately the aggregate performance of the built environment and resilience of communities that are most important. The United Nations International Strategy for Disaster Reduction defines resilience as follows: "*The capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures* (UNISDR 2004)." Implied in this statement is awareness, planning, improved protection, leadership, and resource allocation. PBEE can contribute to each of these aspects, but major contributions can be made to improved awareness, protection and planning. The paper discusses the role of PBEE in quantifying earthquake risks and facilitating better informed planning and design of the built environment. In taking a broader view of performance, a key challenge is to move beyond evaluation of direct losses from earthquakes to emphasize factors that are most important to recovery and rebuilding.

1.2 PBEE: Background and Status

1.2.1 PBEE Framework

The high level objectives of PBEE are to develop scientifically-based transparent engineering methods and tools that can:

1. Facilitate decision making of cost-effective risk management of the built environment in areas of high seismicity
2. Facilitate the implementation of performance-based design and evaluation by the engineering profession
3. Provide a foundation on which code writing bodies can base the development of transparent performance-based provisions
4. Facilitate the development and implementation of innovative systems (response modification devices, rocking/self-centering systems, etc.)

The underlying framework for the current generation of performance-based approaches is shown in Fig. 1.1. This framework was developed by the Pacific Earthquake Engineering Research (PEER) Center (Cornell and Krawinkler 2000; Moehle and Deierlein 2004; Krawinkler and Miranda 2004) and has since been implemented in the *FEMA P58* (2012a). The framework provides a clearly articulated procedure to relate quantitative measures of the earthquake hazard to system performance metrics. While this overall framework is well-established, details of

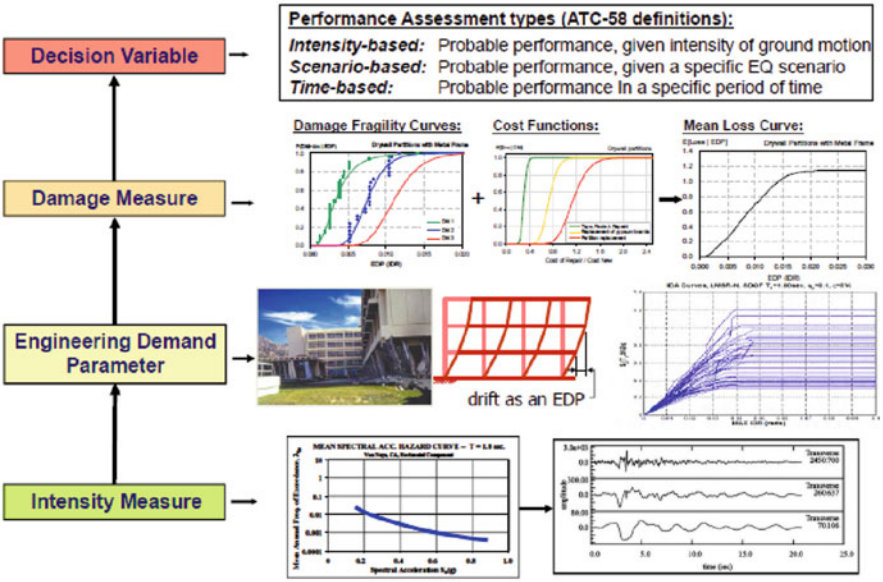

Fig. 1.1 Performance-based earthquake engineering framework

the procedures are still being further developed and refined. Brief highlights of methodology components and their current status are as follows:

Earthquake Hazard: For use in nonlinear dynamic analyses, the earthquake hazard is characterized by input ground motions, which may be obtained by scaling or spectrally matching recorded motions or through earthquake simulations. While it is generally accepted to characterize the ground motions based on their spectral acceleration intensity, there is continued exploration on ways to incorporate frequency content, duration, and other aspects of the earthquake hazard in the input ground motions. The concept of Conditional Spectra, which accounts for correlation of ground motion intensities at multiple periods, has been proposed as a more appropriate target than Uniform Hazard Spectra to characterize the spectral intensity (e.g., Baker 2011; Bradley 2010), and research is ongoing to address near-fault directivity pulses, duration, and other effects (e.g., Champion and Liel 2012; Chandramohan et al. 2013; Shahi and Baker 2011). For a comprehensive summary and recommendations on this topic the reader is referred to a recent report, *Selection and Scaling Earthquake Ground Motions for Performing Response-History Analyses* (NIST 2011).

Structural Analysis: Nonlinear dynamic (response history) analysis is arguably the most mature component of PBEE, but many challenges remain to validate and improve the reliably of technologies to simulate the response of realistic structures from the initiation of damage up to the onset of collapse. Commercially available analysis software with capabilities to simulate elastic and moderately nonlinear response of three-dimensional models are becoming used in practice (Deierlein et al. 2010); however, the ability of these to model large inelastic deformations is questionable. Even in research, where models have been developed to capture strength and stiffness degradation up to the onset of collapse (e.g., Ibarra et al. 2005; Haselton et al. 2010), the modeling capabilities are limited to certain behavioral effects and by calibration of phenomenological parameters. Moreover, the accuracy of models to determine demand parameters, such as local deformations, residual drifts, and floor accelerations has not been fully validated. As other components of the PBEE process mature, the limitations in nonlinear structural analysis will become more important to address.

Damage Assessment: Perhaps the most unique new feature of PBEE is the formalization of damage assessment models, where the damage states and demand parameter limits are defined in terms of repair thresholds that have specific costs and consequences. For example, the limiting drift criteria for partition walls correspond to repair states that increase from (1) patching and repainting, to (2) replacement of gypsum wallboards, to (3) complete replacement of the wall and its embedded electrical and mechanical components (Taghavi and Miranda 2003). These repair limits can then be related to the cost, duration and other implications of repair. The *FEMA P-58* (2012a) development effort created many new damage fragility curves for a wide range of structural and nonstructural components and facilitated the practical implementation of damage assessment. Nevertheless, to fully realize the full potential of PBEE, further work remains to validate and expand the library of damage data and fragility functions.

Performance Calculations: Translating damage into appropriate performance metrics is the most important stage of PBEE, though probably the least well-developed. Performance measures have been coined “death, dollars and downtime”, referring to risk of casualties, economic losses, and loss of function, but quantifying these seemingly straightforward metrics remains the most elusive. To date, most emphasis has been on calculating direct costs associated with repair of damage. *FEMA P58* provides repair costs, developed by professional cost estimators, for each component damage function. *FEMA P58* also includes consequence functions to calculate casualties, repair time, and building placard tagging (denoting safety for occupancy), though with relatively little data or hard science to determine these, their development relies heavily on judgment. As will be expanded on later, in addition to the need to validate and improve these existing performance models for individual facilities, more thought must be given to measures of communities (e.g., cities and urban regions comprised of large building inventories) and to relate building-specific measures to community-wide concerns.

1.2.2 Benchmarking Building Performance

Some of the first applications of the PBEE tools have been to evaluate the performance of buildings designed according to current building codes. The studies are intended to provide a basis against which to judge the performance of other new or existing buildings and to evaluate the effectiveness of building code provisions. In companion studies, Haselton et al. (2010) and Ramirez et al. (2012) evaluated the performance of a set of modern concrete-framed buildings, designed for a high-seismic region near Los Angeles. They reported rates of collapse risk that range from 0.4 to 3.6 % in 50 years and expected annual losses (direct costs) on the order of about 1 % of the building replacement cost. With such data, the more important question becomes whether this level of performance is appropriate or optimal (in a cost-benefit sense) for individual building owners or society at large.

In an extension to this study, Ramirez and Miranda (2012) examine the breakdown of losses associated with repair versus building replacement. As shown in Fig. 1.2, their results reveal that over half of the expected loss is from damage that is deemed non-repairable (residual drifts in excess of 1.5 %), leading to building demolition. Their results also confirm that building collapse is a small contributor to direct losses for modern building designs. However, whether building replacement arises from collapse or demolition, apart from the cost of replacement, the complete replacement of the building has important long-term consequences on displacement of occupants and loss of function. This is in contrast to direct losses associated with damage of non-structural components, which accrue rapidly under modest ground motion intensities, but could be repaired faster and, possibly, while the building

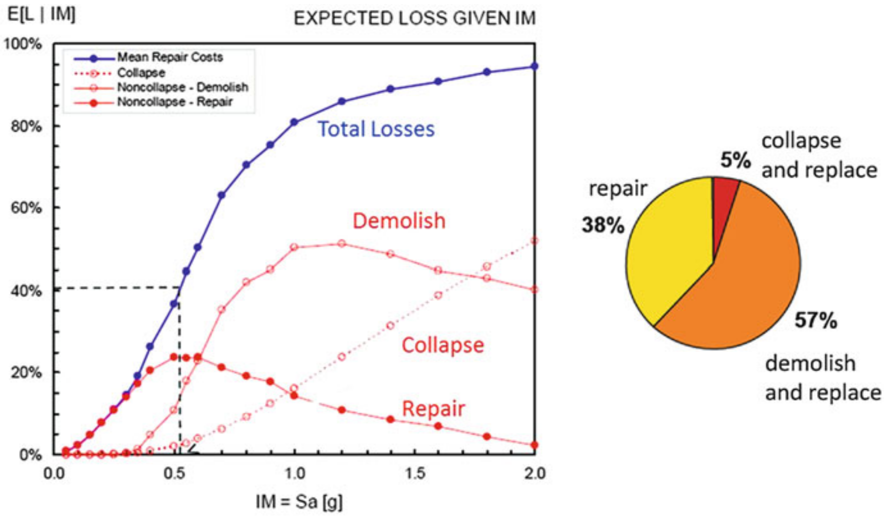

Fig. 1.2 Components of expected loss for a low-rise office building (Ramirez and Miranda 2012)

remains occupied. Thus, direct economic losses due to these repairs may have significantly less impact on indirect losses than direct losses associated with major structural repairs or building replacement.

In a related study, Liel et al. (2010) and Liel and Deierlein (2013) examine the collapse safety and losses of non-ductile concrete buildings, representative of buildings constructed before ductile detailing provisions were introduced to practice in the mid-1970s. The reported collapse risks for the non-ductile concrete buildings are on the order of 30 to 40 times higher than for modern code-conforming buildings, whereas direct economic losses (due to repair and replacement) are only twice those for modern buildings. This data helps confirm that it is the collapse and casualty risks, rather than direct economic losses, which are the primary consideration for existing non-ductile concrete buildings. Questions related to the safety of non-ductile concrete buildings and what, if any, government policies or other measures should be implemented to address the risk, are the focus of the Concrete Coalition (http://www.concretecoalition.org/) and related efforts in California.

1.2.3 Implementation of PBEE Framework

The PBEE framework described above is influencing the development of guidelines and standards in the United States. Three significant developments are briefly summarized below.

FEMA P58: The development of *FEMA P58 Seismic Performance Assessment of Buildings* (2012a) represents a comprehensive implementation of PBEE. The *FEMA P58* procedures allow for evaluating the risks of (1) collapse and casualties, (2) direct economic losses to repair damage or replacement of collapsed or demolished buildings, (3) repair time, which is indexed off of repair costs, and (4) building closure, which is defined in terms of criteria defined for an “unsafe” (red) post-earthquake building inspection placard. *FEMA P58* incorporates these performance measures in three approaches that are referred to as intensity-based, earthquake scenario-based, or time-based assessments. The intensity-based assessment, where performance is calculated for a specified spectral acceleration response spectrum, is the most basic of the approaches and a subset component of the other two. Results of the scenario-based assessment, defined by an earthquake fault rupture magnitude and distance to the building site, reflects both the expected value of ground motion spectral intensity and the dispersion of this intensity for the specified scenario. The time-based assessment is the most comprehensive of the approaches, considering all earthquakes affecting a site and their risk of occurrence over a specified period of time.

In addition to assessment procedures, *FEMA P58* provides a library of damage and consequence functions, to evaluate losses in common building systems. Software called PACT (Performance Assessment Toolkit) is also available to apply the procedures and facilitate their practical use by design professionals.

***FEMA P695* and new MCE Maps**: The *FEMA P695 Quantification of Building Seismic Performance Factors* (2009) outlines a procedure to determine seismic force reduction factors (e.g., R, Ω_o and C_d factors) that are used to define the minimum seismic base shear requirements in US building codes, such as the *ASCE 7* (ASCE 2010). The underlying approach of *FEMA P695* entails quantifying the collapse risk using nonlinear dynamic analysis, combined with judgment-based factors to account for uncertainties. Nonlinear dynamic analyses are used to assess the median value of notional collapse fragility curves, and the dispersion (uncertainty) in the collapse fragility is determined by variability in nonlinear response due to alternative ground motion records along with judgments of uncertainties arising due to the quality of (1) design and construction, (2) nonlinear analysis models, and (3) knowledge of structural behavior. While *FEMA P695* was conceived for the specific purpose of establishing response parameters for design, the collapse assessment procedures follow a performance-based approach that can be modified for more general use. Perhaps the most remarkable aspect of *FEMA P695* is to establish a minimum collapse risk, defined as a conditional collapse probability of 10 % under the Maximum Considered Earthquake (MCE) intensity. This collapse risk is based on judgments informed by benchmark studies of representative buildings designed according to current building code provisions.

In the United States, the MCE ground motion intensity has traditionally been defined in terms of ground motion exceedance rates, typically a 2 % chance of exceedance in 50 years. Building on the collapse fragilities defined in *FEMA P695*, the MCE seismic design maps for the United States have recently been revised to provide more consistent collapse safety over the entire United States (Luco et al. 2007). These new MCE design maps are targeted based on a maximum risk of collapse with a 1 % chance of exceedance in 50 years. This "risk targeted" approach is in contrast to previous MCE maps that were based on ground motion exceedance rates. Similar to the permissible collapse risk criteria of *FEMA P695*, the target risk of 1 % in 50 years is based on a combination of judgment and benchmark building studies. The new MCE design map intensities were obtained by integrating site ground motion hazard information with a generic collapse fragility curve that has an assumed lognormal dispersion of 0.6 and a 10 % probability of collapse at the MCE intensity (as specified in the *FEMA P695* procedures). Thus, given the default collapse fragility and the ground motion hazard for a specific location, the MCE intensity was determined for each map location so as to yield a target collapse risk of 1 % in 50 years. These uniform risk MCE maps have been adopted into the latest *ASCE 7* (2010) seismic design standard.

Tall Building Guidelines: As an alternative to traditional prescriptive design requirements for tall buildings, new guidelines have recently been developed to assess the adequacy of tall buildings based on nonlinear dynamic analysis (PEER 2010; LATBSDC 2011). The guidelines are intended to provide equivalent performance to that provided by prescriptive building code requirements, while providing a more transparent design basis that can be modified to provide enhanced performance. By focusing attention on the intended performance, they highlight important questions as to whether tall buildings, with high occupancies and potential consequences from earthquake damage, should be designed to higher performance targets than conventional low-rise buildings.

1.2.4 PBEE of Distributed Systems

Whereas the current implementations of PBEE are primarily geared towards evaluating the performance of individual facilities, there are obvious cases where PBEE approaches only make sense to apply at the system level. For example, in transportation systems the performance of the overall highway system must consider network interactions between individual bridges. Thus, except for bridge collapse safety, which has direct implications on the safety of drivers, the functional performance of individual bridges is only important as it relates to functionality of the overall highway system, whose performance is typically measured in terms of traffic delay time (e.g., Kiremidjian et al. 2007; Chang et al. 2000). The same sort of argument could be made for other utility systems, such as water distribution systems, where the water service level depends on the performance and interactions between various network components associated with water supply, storage, treatment, and pipeline transmission (e.g., Davis et al. 2012; Romero et al. 2010).

Conceptually, extension of the PBEE framework from component to system performance is straightforward, but, implementation of the framework presents several challenges. As most systems are geographically distributed, performance assessment requires earthquake scenario-based approaches, which consider earthquake damage and functionality of components across the distributed network. Thus, the ground motion hazard assessment requires consideration of spatial correlations between ground motion intensities for scenario earthquakes (e.g., Han and Davidson 2012). While the seismic demands and physical damage can generally be evaluated discretely for each component, the consequence of damage on system performance requires a comprehensive system analysis, considering network interactions between the components. Evaluation of the system performance itself may be further complicated by exogenous effects of the earthquake on the functional demands on the systems. For example, travel times and delays on a transportation system depend on both the physical condition of the highway network and on the demand for transportation. As the travel demand is a function of economic or other activity, it is likely to be impacted by earthquake damage to non-transportation facilities and systems. Similarly, service level demands for water and other utilities may be impacted by earthquake damage to other systems. Therefore, to the extent that the changes in demand and interdependencies between systems depend on socio-economic factors impacted by the earthquake, these factors should be considered in assessing their earthquake performance.

1.3 From PBEE to Earthquake Resilience

While the performance-based methods described previously are a major step forward towards quantifying and managing earthquake risks of individual buildings, a much broader interpretation of performance is needed to understand how communities will be impacted and recover from devastating earthquakes. Consideration of recovery, including its dependence on available resources and the human workforce, raises important new questions that go beyond the traditional PBEE metrics. As illustrated in Fig. 1.3, resilience relates to the loss in functionality in a community that depends on the amount of damage caused by the earthquake disaster and the rate at which the functionality is recovered. The total loss is represented by the "loss triangle" which is the integration of the reduced system function over time to recovery (NRC 2011). This loss can be reduced by (1) pre-disaster mitigation to reduce earthquake damage and its consequences, and (2) planning and taking appropriate measures to hasten recovery and rebuilding. Thus, a key component of resilience is to incorporate post-disaster recovery and rebuilding considerations into the pre-disaster evaluation and planning. There is a large body of published work on resilience to earthquakes and other natural hazards, ranging from theoretical to applied and from socio-economic and political aspects to engineering oriented (e.g., UNISDR 2004; NRC 2011; Bruneau et al. 2003; Cutter et al. 2010; Poland 2012). Common to most of these are four dimensions to resilience from earthquakes:

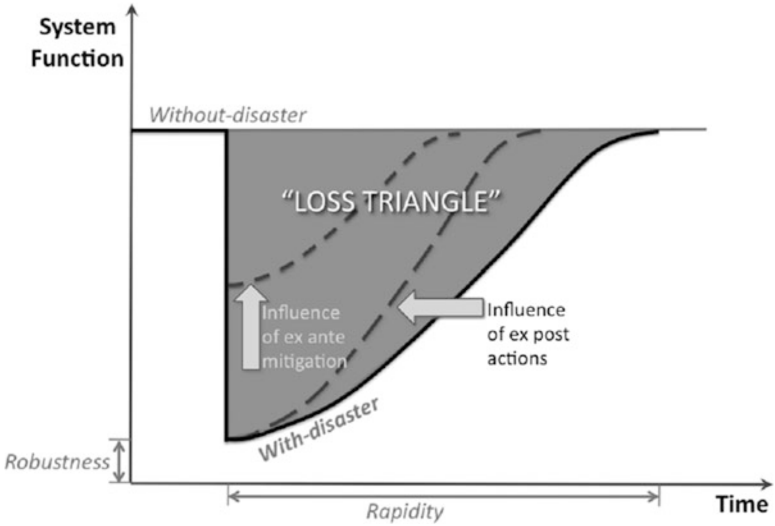

Fig. 1.3 Idealized concept of resilience (NRC 2011)

Technical – concerning the physical characteristics of the built environment including (1) evaluation of the expected seismic performance of buildings, lifeline systems, etc. and implications on post-earthquake functionality, and (2) planning and designing ways to improve performance through retrofit of existing facilities and enhancements to new facilities. As recovery and rebuilding is central to resilience, the technical engineering considerations must go beyond evaluation of expected damage to address post-earthquake functionality (e.g., safety to aftershocks) and repair of the buildings and infrastructure.

Organizational – concerning governance and organizations that have responsibility to plan and lead post-earthquake response, recovery and rebuilding. While the natural emphasis in organizations is on preparations for emergency response, resilience planning requires emphasis on longer-term considerations, such as natural hazards considerations in land use planning and development of streamlined post-earthquake decision-making procedures that can facilitate repair and rebuilding.

Social – concerning individual residents and non-governmental community organizations and (1) how these groups are likely to be impacted by the earthquake, (2) measures that can be taken to lessen these impacts on these groups, and (3) ways to enhance the capability of these groups to participate in recovery and rebuilding. One of the most important social factors concerns the availability of housing or shelters to help ensure that communities will not be displaced and can function after the earthquake. The social component also involves the effectiveness of civic and religious organizations to help coordinate local recovery and rebuilding.

Economic – relating to (1) the economic consequences of the earthquake, including direct economic losses and indirect losses associated with business interruption, lost jobs, etc. and (2) the availability of resources to rebuild after a disaster, including insurance, availability of financing, government grant programs, and savings of individuals or business. An important related factor affecting the earthquake impact and recovery is the economic profile of the community.

While there is general consensus as to the overall goals and definition of resilience, one of the major challenges is to measure resilience, since this is an essential step towards identifying and overcoming weaknesses. As one research group notes regarding resilience measures, "qualitative models tend to be more comprehensive than quantitative models, which are instead more discipline-oriented. This observation demonstrates the marked disconnect between what is thought to be an ideal understanding of resilience versus what is actually measurable" (Verrucci et al. 2012). Studies that attempt to comprehensively quantify resilience metrics in all four of its dimensions generally resort to indexed ratings across a broad range of topics, such as (1) population and building density in areas of high expected ground shaking, (2) typical age and quality of building stock, (3) availability of emergency response and shelter facilities, (4) prevalence of earthquake insurance and financial resources of communities, and (5) strength of community organizations, etc. (Verrucci et al. 2012; Cutter et al. 2010). Studies that are more quantitative, such as examination of restoration of water service following the Northridge earthquake (Davis et al. 2012) or critical lifeline and support systems (Bruneau et al. 2003), tend to be more case- and discipline-specific.

Notwithstanding the challenges in measuring resilience, there is no question that efforts to measure and improve resilience must consider its multiple dimensions. This is not to say that specific steps to improve resilience cannot be discipline-specific, since most improvements are usually developed and implemented within a discipline. But, in order to be effective, all individual efforts to improve resilience must be devised and integrated through a larger overarching plan that helps establish performance requirements for the individual components.

Experiences from large earthquakes and other natural disasters demonstrate that community resilience cannot be evaluated solely in terms of the performance of individual buildings or lifeline system components. The February 2011 earthquake in New Zealand is an obvious example where the damage to individual buildings has had a disproportionate effect in the social and economic devastation of the central business district of Christchurch. This situation is at odds with the fact that current building code requirements in New Zealand, and most other countries, do not distinguish between design requirements for buildings in a densely populated urban region, which can be impacted by a single earthquake, and buildings in outlying suburban areas (Liu 2012). The new "risk targeted" MCE maps in the *ASCE 7* (2010) are another example, where efforts to make building codes risk consistent across the United States may be at odds with risks to specific urban regions. Similar comparisons could be made to design requirements for levees and other flood protection, and whether components of a network that are essential to a city or region (such as levees around New Orleans) should be designed to higher standards than ones where the consequences of isolated failure are less.

1.4 San Francisco Resilient City Initiative

To mark the 2006 centennial of the 1906 San Francisco earthquake and fire, an earthquake scenario study was conducted to consider what would happen to modern day San Francisco if the 1906 M7.9 earthquake were to reoccur. The study predicted a disaster with up to 3,400 deaths, 10,000 buildings destroyed, 250,000 households displaced, and $120 billion in losses (Kircher et al. 2006). This study, together with increased awareness of risks from the 1989 Loma Prieta earthquake and other disasters, prompted the San Francisco Planning and Urban Research Association (SPUR) to undertake an initiative to evaluate ways to make San Francisco more resilient to earthquakes. Spearheaded by earthquake engineers, this "resilient city" initiative involves a broad range of design and emergency professionals, city government officials, and urban planners (Poland 2009; SPUR 2009). It provides a focused example to promote resilience through pre-earthquake mitigation and planning for post-earthquake recovery, and it illustrates ways that PBEE can help inform the process and for earthquake engineers to engage with a broader constituency. This resilient city initiative (Fig. 1.4) has been an integrating mechanism for other related efforts, including the CAPPS project (Community Action Plan for Seismic Safety, http://sfcapss.org/) to identify vulnerabilities in the San Francisco and ways to mitigate these so as to preserve the city's diverse communities. The CAPPS project identified comparable overall damage and losses as for the 1906 earthquake scenario study but with more specifics on the vulnerable building stock in San Francisco. It also makes recommendations on steps to mitigate

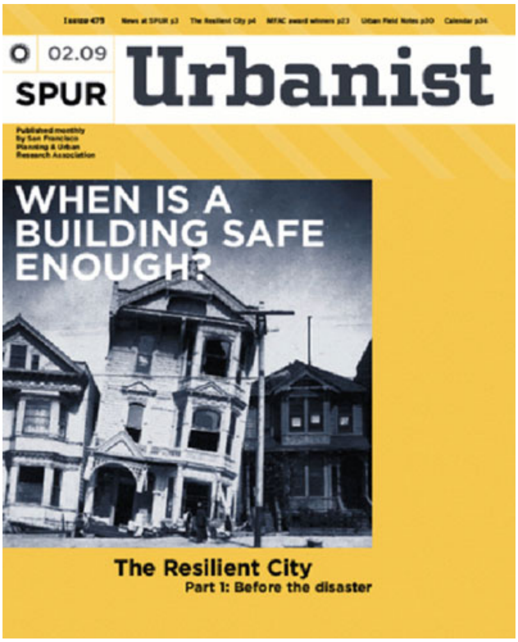

Fig. 1.4 San Francisco resilient city initiative (SPUR 2009)

damage risks through seismic retrofit and to facilitate post-earthquake recovery by establishing governance plans and repair standards for rebuilding.

The SPUR initiative embraces the goal that "Resilient communities have an ability to govern after a disaster has struck. The communities adhere to building standards that allow power, water and communication networks to begin operating again shortly after a disaster and allow people to stay in their homes, travel to where they need to be, and resume a fairly normal living routine within a few weeks. They are able to return to a *new* normal within a few years." (Poland 2009). The resilient city initiative is built around a realistic assessment of damage from an "expected earthquake" and its impact on response and rebuilding. Seismic mitigation and recovery strategies are then identified and evaluated to enable an appropriate timetable for recovery. The concept of an "expected earthquake" (scenario earthquake) is important to establish a common basis for evaluation and planning over geographically distributed facilities, systems and organizations. The "expected earthquake" is defined as a M7.2 event on a nearby portion of the San Andreas fault. This is not the most extreme earthquake that can affect San Francisco, but it is judged to be the most appropriate for overall assessment and planning purposes. Presumably, scenarios that are more or less severe could be evaluated in follow up studies to fine tune the planning. Resilience assessment is based on transparent performance measures of facilities and systems, considering direct earthquake damage and its implications on the city-wide recovery effort.

Seismic performance targets for facilities and systems are defined based on the implications of damage on post-earthquake functionality and repairs. Building performance is characterized by the following performance categories:

A – *Safe and operational*: Essential facilities such as hospitals and emergency operations centers
B – *Safe and usable during repair*: "shelter-in-place" residential buildings and buildings needed for emergency operations
C – *Safe and usable after repair*: current minimum design standard for new, non-essential buildings
D – *Safe but not repairable*: below standard for new, buildings; often used as a performance goal for existing buildings undergoing voluntary rehabilitation
E – *Unsafe* – partial or complete collapse: damage that will lead to casualties in the event of the "expected" earthquake

Targets for performance of utility and transportation systems are organized into the following three categories, depending on how quickly their level of service can be restored following the expected earthquake:

Category I – resume 100 % service within 4 h
Category II – resume 90 % service within 72 h, 95 % service within 30 days and service 100 % within 4 months
Category III – resume 90 % service within 72 h, 95 % service within 30 days, and 100 % service within 3 years

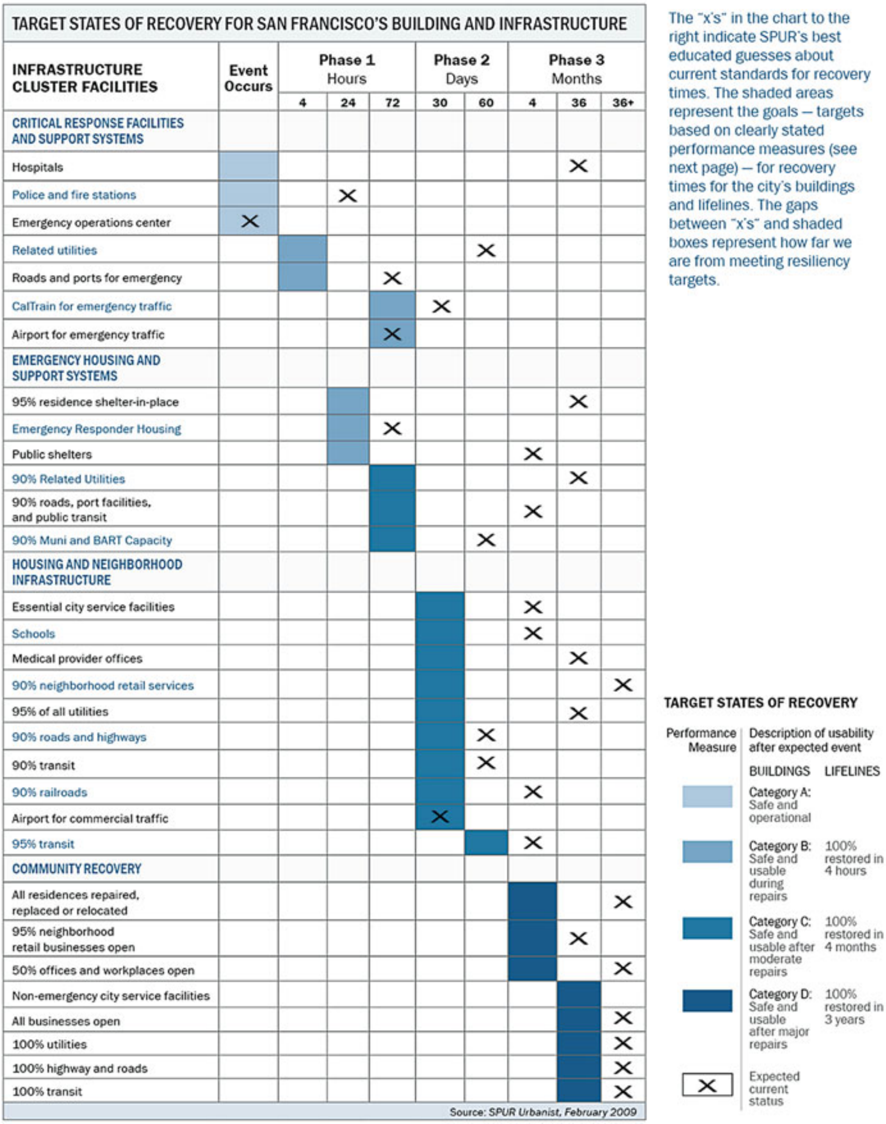

Fig. 1.5 Target recovery states for San Francisco's buildings and infrastructure (SPUR 2009)

Using these categories, specific target goals for building and infrastructure are established, considering city-wide needs. These are illustrated in Fig. 1.5, where specific performance goals are identified for buildings based on their occupancy type and usage and for lifeline systems (designated by shading corresponding to building categories A through D and systems categories I through III). The "X" markers in Fig. 1.5 are estimates of performance for the current inventory of facilities,

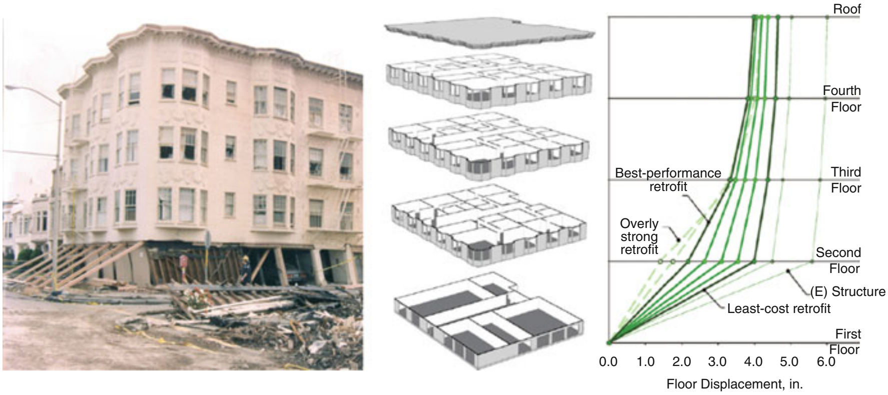

Fig. 1.6 Assessment and retrofit for soft-story wood-framed buildings (FEMA 2012b)

indicating where measures are needed to upgrade buildings and other facilities. It should be noted that while there is some data to support the performance targets and inventory estimates in Fig. 1.5, these are based largely on judgments from the professional participants of the SPUR resilient city initiative and related CAPSS project.

While buildings in category E, deemed to pose a significant life safety risk, are a primary concern, another important focus is to determine whether buildings can provide for post-earthquake occupancy, including "shelter-in-place" for residential buildings (SPUR 2011). This emphasis on post-earthquake performance is an important new consideration since performance-based research and developments have traditionally focused on collapse (life-safety risk) and repair cost (economic losses). Comparatively less attention has been paid to quantifying post-earthquake occupancy and function, in part due to the lack of specified performance targets. In this regard, the specific targets defined by the building performance categories (A through E) and specified in Fig. 1.5 are a major step forward to quantifying the performance targets for individual buildings to ensure community resilience.

In addition to outlining a framework for community resilience, the resilient city initiative has captured the attention of civic leaders and prompted earthquake mitigation legislation to address an important weakness that was brought to light. The CAPPS project identified soft-story wood-framed apartment buildings (see Fig. 1.6) as a significant weakness, where scenario earthquake damage posed a significant collapse risk (category E) and would displace a large number of residents. This prompted the development of performance-based guidelines to assess and retrofit soft-story wood-frame buildings (FEMA 2012b) and to recent legislation by City of San Francisco to require mandatory of these buildings (SFGate 2013). This is an excellent example where seismic mitigation policies resulted from (1) identifying the risks to both the building occupants and broader community, and (2) providing cost-effective engineering solutions to assess and mitigate the risks through retrofits designed by performance-based methods.

CoRE Rating	Safety	Reparability	Functionality
★★★★★	Life Safe	Loss <5%	Occupiable Immediately Functional < 72 hours
★★★★	Life Safe	Loss <10%	Occupiable Immediately Functional < 1 month
★★★	Life Safe	Loss <20%	Occupiable < 1 month Functional < 6 months
Certified	Life Safe	Not estimated	Not estimated
Not Certified	Life Safe Hazard	Not estimated	Not estimated

Fig. 1.7 Building seismic rating system of the US Resiliency Council (Reis et al. 2012)

Another noteworthy development catalyzed by the resilient city initiative involves the development and implementation of a seismic rating system for buildings. Seismic building ratings have long been suggested as a mechanism to raise awareness of the expected building performance by building owners, occupants, and other stakeholders, but previous efforts to develop rating systems have languished. Building on the momentum of the resilient city initiative, the existing buildings committee of the Structural Engineers Association of Northern California has proposed a seismic rating system that reflects performance metrics similar to the A to E categories identified previously (SEAONC 2012). More recently, this rating system has been embraced by the U.S. Resiliency Council (http://usrc.org/), which is a new nonprofit organization that has been created to institutionalize implementation of the rating system. The U.S. Resiliency Council follows an approach of voluntary ratings, similar to how the LEED program is applied to evaluate green building performance (http://new.usgbc.org/leed). Shown in Fig. 1.7 is the proposed building rating system metrics, which are defined based on performance during the "expected earthquake". The performance categories of safety, reparability, and functionality are defined along the lines of building performance targets identified in SPUR's resilient city plan.

1.5 PBEE as a Facilitator Towards Seismic Resilience

Performance-based methods and technologies clearly have an important role in assessing and designing for community resilience. However, to effectively serve this role, PBEE research and development needs to expand beyond the current emphasis on calculating direct losses (collapse risk and repair costs) and place greater attention on post-earthquake functionality and repair. Referring to Fig. 1.8, SPUR's five building performance categories (A through E) can be described in terms of the resilience loss triangle, introduced previously in Fig. 1.3. For comparison, characteristic values of direct losses due to repair are also shown in Fig. 1.8. The

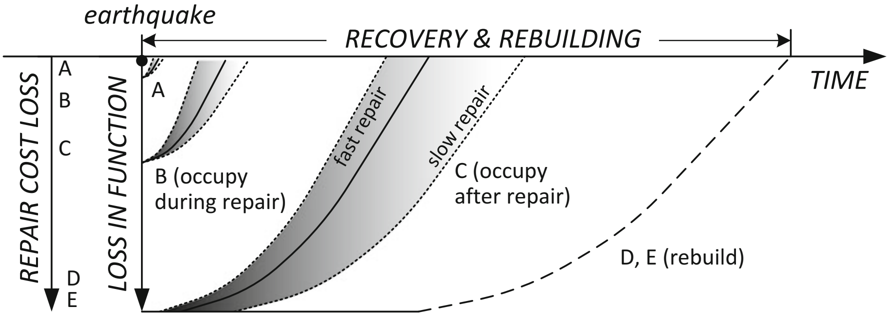

Fig. 1.8 Direct repair cost and loss of function for alternative building performance categories

figure highlights several important distinctions between the performance for each building category:

- Whereas the direct repair costs for building categories A, B and C are relatively close (5, 10 and 20 %, per Fig. 1.7), the difference in post-earthquake functionalities are dramatically different. In particular, buildings in category C, which requires repairs prior to reoccupancy, have essentially the same initial loss in function as buildings in categories D (damaged beyond repair) and E (collapsed). On the other hand, buildings in category B (safe to reoccupy during repairs) have a much smaller loss in functionality.
- Beyond the initial loss in functionality, the speed with which repairs can commence and be completed can have a major effect on the total functional loss. Repairs for category B buildings, which are safe to reoccupy immediately after an earthquake, are likely to begin and be completed much sooner than those in category C buildings. The duration of repairs for both categories B and C will, of course, depend upon the details of the repairs and whether the original building designs included provisions to facilitate repairs, e.g., by isolating inelastic action in structural elements that are easy to replace.
- Once buildings are damaged to the point to be technically or economically prohibitive to repair (category D), the buildings have essentially the same loss in functionality as collapsed buildings (category E). As illustrated previously by the example of Fig. 1.2 and as has been observed in damaged buildings in Christchurch (from the 2011 earthquake), existing buildings may be far more likely to experience losses in category D that is generally recognized.

These considerations from Fig. 1.8 highlight the critical importance of two damage thresholds to community resilience: (1) the threshold damage for building closure, which differentiates between building category B and C, and (2) the threshold of damage that makes repairs prohibitive and demolition inevitable, which differentiates between building category C and D. While these thresholds are generally related to the amount of damage and repair costs, more so than the cost of damage, they may depend heavily on the nature of the damage and implications on repair. Foremost of these considerations is whether there is significant structural damage that jeopardizes the building safety and triggers building closure. This point runs counter to observations that damage to non-structural elements is a major contributor to “expected losses”. While damage to nonstructural components is disruptive and can be expensive to repair, it is usually not the major driver to trigger building closure. A related consideration is whether there are significant residual story drifts, which are one of the primary triggers for building closure and, potentially, demolition. Data from the 1995 Kobe earthquake suggest a residual story drift threshold of $\sim$1.4 % for demolition of steel-framed buildings (Iwata et al. 2006), and values for other systems are likely to be lower.

Looking beyond the performance of individual buildings, the San Francisco resilient city study highlights the importance of evaluating potential damage to the overall community – taking into account the region’s inventory of buildings and the utility and transportation systems. As illustrated in Fig. 1.5, in addition to differentiating between building performance targets for critical versus non-critical facilities, the targets should also consider specific community needs for housing and commerce. While individual residential or office buildings are typically considered to be non-critical, it is critical to maintain functionality (occupancy) for a sufficient number of buildings in order to preserve community functions that are necessary for human welfare, recovery and rebuilding.

1.6 Concluding Remarks

While tremendous advancements have been made in PBEE methods and enabling technologies, many important challenges remain. Certainly, there is continuing need for improvements and refinements in all aspects of the methodology, from the characterization of ground motions through to evaluation of performance. However, from the standpoint of community resilience, the authors would venture that the most important research needs include the following:

- Improved analysis technologies to enable more reliable evaluations of residual drift and the collapse safety of structures. This is motivated by the need to (1) identify existing buildings that pose a significant life-safety risk (category E buildings), (2) differentiate between buildings that are safe or unsafe to occupy after an earthquake (category B versus C buildings), and (3) differentiate between buildings that are or are not likely to be demolished after an earthquake (category C versus D buildings).
- Improved evaluation of the economic loss and functional performance of large inventories (portfolio’s) of buildings and implications on socio-economic factors for communities. These data are important to establish appropriate performance targets for buildings to ensure that communities can survive, rebuild and flourish again after a large earthquake. The critical need is to provide quantitative

measures to substantiate and refine the judgment-based targets proposed by the SPUR project in Fig. 1.5.

- Improved technologies to enable comprehensive regional earthquake scenario studies that reliably simulate ground motions, damage and reduced function of facilities and systems, and the process of rebuilding and restoration of functions. Ideally, these technologies would be based on more scientific (fundamental) models of phenomena that would reduce reliance on empirical models and judgment to assess both the immediate damage and the rebuilding process. In addition to modeling the physical building and infrastructure systems, the simulations to assess the reduction and restoration of functions should, to the extent possible, consider socio-economic factors that connect the physical and human elements.
- Development of innovative structural systems, devices and materials for buildings and infrastructure that can improve resilience by (1) decreasing the damage potential on functional performance and (2) facilitating repair and rebuilding. Design innovations are needed for new facilities as well as retrofit and repair of existing facilities. The value and effectiveness of these innovations should be judged in the context of how they reduce direct losses and improve resilience.

Acknowledgments The concept for this paper was conceived of by Helmut Krawinkler as a collaborative effort with the second author. This collaboration was cut short by Helmut's unexpected death on April 16, 2012, leaving the second author to fulfill Helmut's vision for the paper. Apart from the specific references cited in the paper, the primary sources for this paper are the inspiration, knowledge and insights that Helmut shared over his career and at the Bled 4 workshop in June 2011.

The authors gratefully acknowledge the contributions of many colleagues and former students who have helped advance the state-of-art in PBEE and for financial support for their work by the National Science Foundation, the Pacific Earthquake Engineering Research (PEER) Center, the Applied Technology Council (funded by FEMA and NIST), and the John A. Blume Earthquake Engineering Center at Stanford University. They are also grateful to the organizers and sponsors of the Bled 4 workshop, and in particular the tremendous contribution of Matej Fischinger in planning and hosting the workshop and producing the conference proceedings.

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