PERFORMANCE-BASED ENGINEERING FOR MULTIPLE HAZARDS: THE ROLE OF STRUCTURAL RELIABILITY AND RISK ASSESSMENT

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ABSTRACT

Buildings, bridges and other civil infrastructure facilities are designed by current codes and standards using provisions that invariably are prescriptive in nature. While facilities so designed usually possess adequate levels of safety under design-basis events, other environmental or man-made events may cause them to suffer damage or loss of function, leading to economic losses, with uncertain impacts on the building occupants, owners and the community that they serve. The new paradigm of performance-based engineering enables structural engineers to achieve more reliable and informative prediction of civil infrastructure behavior and control of performance across a range of hazards. When supported by a risk-informed decision framework founded on structural reliability principles, performance-based engineering provides stakeholders with a structured framework for thinking about performance objectives, uncertainty, and how public safety and socio-economic well-being may be threatened by the failure of civil infrastructure to perform under a spectrum of hazards.

KEYWORDS

Civil infrastructure, hazards, loads (forces), performance-based engineering, reliability, risk, structural engineering.

INTRODUCTION

Civil infrastructure facilities, including buildings, bridges and transportation networks, and public utilities, must be designed to withstand demands imposed by their service requirements and by environmental events such as extreme windstorms, floods and earthquakes. The design provisions found in current codes and standards governing structural design are prescriptive in nature, in that they provide unambiguous and easily interprete4d direction to the structural engineer. While buildings and other structures designed by such provisions usually possess adequate levels of safety under design-basis loads, the occurrence of other service, environmental or anthropogenic events may cause them to suffer various states of damage or loss of function, often under loads that are less than the design-basis loads, leading to substantial economic losses. These losses, in turn, may severely impact the facility owner or occupant and often have a substantial and highly uncertain ripple effect in the surrounding community and its social and economic institutions. Recent infrastructure failures have been widely publicized by ubiquitous media coverage, which has led to an increasing public awareness of infrastructure performance in the United States and in other modern societies. In this era of heightened public awareness of infrastructure performance and community resilience, the engineering profession is seeking improvements to building and construction practices to achieve levels of performance beyond what currently is provided by prescriptive code provisions.

At the root of ensuring safety, serviceability, functionality, durability and other infrastructure performance objectives is the fact that structural loads, strength and our ability to model their interactions through advanced analysis are uncertain. This uncertainty gives risk to risk, which must be managed by codes and standards at socially acceptable levels and at reasonable costs. In recent years, the advantages of structural reliability and risk analysis tools in providing the essential framework for modeling uncertainties associated with structural engineering practice and for trading off investments in infrastructure risk reduction against limited resources (Ellingwood 2001; Faber and Stewart 2003) have become apparent. Many countries have already adopted so-called probability-based limit states design (PBLSD) methods utilizing such tools (Ellingwood 1994, 2000).

First-generation PBLSD criteria, in their present form, are consistent in format and application with traditional engineering practice. They are prescriptive, quantitative, and detailed. They are applicable to a broad group of materials and building products. Component behavior is modeled accurately, for the most part. Supporting databases have developed remarkably over the past four decades. System behavior, on the other hand, is not reflected explicitly, other than in earthquake-resistant design,[1] and the relation between building performance and stakeholder expectations, while positively correlated, is still unpredictable. Current reliability benchmarks were established as part of the original code calibration and benchmarking process performed in the late 1970's (Ellingwood 1994, 2001). Performance in first-generation PBLSD was measured solely by the limit state probability, P_f (or its surrogate, the reliability index, β); consequences of failure were addressed only indirectly, by stipulating higher reliabilities for limit states that were perceived as having more severe consequences. In the intervening three decades, there has been a growing recognition that failure probability is only one of three essential components of risk; consequences and decision context (Who is the decision-maker? How broadly distributed are the consequences?) are equally important (Elms 1992). In first-generation PBLSD, increasingly severe consequences were reflected only indirectly by stipulating higher reliability indices for more "critical" limit states and decision context was not considered. Finally, at a fundamental level, prescriptive criteria (whether or not based on structural reliability) create the illusion that meeting the code minimums results in a satisfactory building. There is ample evidence from recent natural disasters that this is not the case. The devastating effects of recent natural and man-made hazards have prompted a search for design methods to limit the social and economic impacts of low-probability, high-consequence events, which are outside the traditional design envelope but are the source of many disastrous failures.

In short, current prescriptive design procedures have developed over many decades *ad hoc*, represent a collection of requirements that are difficult to follow and are sometimes contradictory in nature, are not directly tied to the performance they are intended to ensure, are not always reliable in achieving the desired protection for society, are sometimes excessively costly to implement, and may not be targeted at appropriate performance goals (Hamburger 1996). The new paradigm of performance-based engineering enables structural engineers to achieve more reliable prediction and control of civil infrastructure performance across a spectrum of hazards and offers society the opportunity to invest in avoid future losses in a more efficient manner.

PERFORMANCE-BASED ENGINEERING

Performance-based engineering replaces the traditional prescriptive design approach with a design process that is aimed at providing a connection between the building design and the owner and occupant-expected performance, which includes, but often exceeds, the traditional requirements for life safety that are embedded in current codes and standards. These expectations often extend to monetary loss and disruption or loss of function. Specifying a level of expected performance to a given hazard scenario and quantifying the consequences to the owner if such a hazard were to occur provides a basis for more informed decisions for achieving the desired performance. The basic premises of performance-based engineering are that performance levels can be quantified and tailored to stakeholder needs; that engineering computation has advanced to the point where performance can be predicted analytically with sufficient confidence; that uncertainties can be modeled; and that risk can be managed at an acceptable level. Perhaps most important, PBE provides a vehicle for implementing risk-based concepts into structural design and for communicating risk among stakeholders in the building process and to the client. Indeed, it may be said that modern probabilistic risk assessment methods are essential to the successful implementation of performance-based engineering: they provide a framework for managing the impact of uncertainties on performance and guide engineering decisions in an era of technological innovation, competition and financial constraints (Elms 1992; Corotis 2009).

In the United States, PBE has focused to date on two areas: fire engineering and earthquake engineering. In both areas, the motivation is clearly economic. Fire protection traditionally has relied on component qualification testing (according to *ASTM Standard E119* or *ISO Standard 834*), with acceptance criteria relying on survival to a "standard" fire for a prescribed rating period. Many of these test procedures have been in existence for nearly a century. They stipulate an unrealistic fire (one that presumes an inexhaustible fuel supply during the rating period), do not distinguish differences in compartment ventilation or composition, and do not account for realistic structural loads, thermal effects or conditions of structural restraint. Perhaps most importantly, they focus on fires that are localized in compartments and do not address the impact of the fire on a structural system. As a result, many structural components and systems that are known to perform acceptably under realistic fire exposures are penalized or proscribed (NISTIR 7563, 2009). The Society of Fire Protection Engineers is moving its standards program for fire-resistant design toward PBE (SFPE 2007), and the *AISC Specification* (2010) has an Appendix on structural design for fire conditions that first appeared in the 2005 edition. The European Convention for

[1] In ASCE Standard 7-10, the seismic design requirements purport to result in a structural system with an incipient collapse probability of 1% in 50 years.

Constructional Steelwork has developed a model performance-based fire engineering code (ECCS 2001). Such activities on the international scene will accelerate the development of improved quantitative methods for engineering structures for fire safety. In the earthquake engineering area, the recent push toward performance-based is typified by recent research on building seismic performance factors (FEMA 2009) and *ASCE Standard 41-13* (ASCE 2014), dealing with seismic retrofit of existing buildings. The motivation to adopt PBE for earthquake-resistant design is three-fold: to enhance building performance for clients who insist on a higher level of performance than is guaranteed by current code minimums; to better upgrade existing structures that are judged unsafe following an earthquake; and to limit the economic and social consequences of structural damage to communities following an earthquake. Implementation of PBE for both fire and earthquake-resistant design generally requires an explicit consideration of the behavior of specific structures, modeled as integrated systems, an obvious departure from traditional prescriptive structural design methods which focused on member and component behavior.

Several new initiatives for PBE in the United States are pending. The first is a proposed ASCE Standard for disproportionate collapse, scheduled to begin balloting in late 2015 or early 2016, in which the design requirements are based on the perceived hazard and the vulnerability of the building in the community (NISTIR 7396, 2007). The second is a new activity to develop performance-based provisions for wind engineering (NIST 2014), motivated by the damage to building construction and enormous economic losses suffered in Hurricanes Katrina (2005) and Sandy (2012) and the Tuscaloosa, AL and Joplin, MO tornados (2011). Although there are examples of limited uses of PBE for wind effects on a project-by-project basis, little information has found its way into practitioner usage, and performance requirements and acceptability criteria beyond the customary life safety objectives remain to be developed. Finally, in the area of hurricane storm surge and coastal inundation, current performance requirements are completely qualitative in nature; there are no performance-based design metrics for either individual buildings or communities, and the design premise has always been that evacuation is the primary mitigation strategy for life safety. In an era of climate change and its impact on coastal communities, this premise warrants re-examination.

Current performance-based criteria are risk-informed, to the extent that the risk can be measured by the probability of failure. Recent proposals for PBE often have included a matrix in which one axis describes increasing severity of hazard (e.g. moderate, very large) and the second axis identifies different performance level (maintenance of function or continued occupancy, life safety, collapse prevention). Buildings in categories where life safety or economic consequences differ [one such categorization is that in of *ASCE Standard 7-10*] are placed in appropriate bins in this table. The focus of current design practice is on life safety under severe events. The role played by probability and structural reliability principles in the development of such a matrix is evident.

RISK ASSESSMENT AND ENGINEERING DECISION ANALYSIS

Risk involves three components: hazard, consequences, and context (Elms 1992). The hazard is a threat or peril - earthquake, fire, terrorist attack - that has the potential for causing harm. In some instances, the hazardous event (or spectrum of such events) can be defined in terms of annual frequency. More often than not, however, it is necessary to envision a set of hazardous scenarios, without regard to their probability or frequency of occurrence (Garrick et al. 2004). The occurrence of the hazard has consequences – damage to or collapse of the constructed facility, personal injury, direct and indirect economic losses, damage to the environment – which must be measured by an appropriate metric reflective of the decision-maker's value system. Finally, there is the context – individuals or groups at risk and decision-makers concerned with managing risk may have different value systems and may take different views on how investments in risk reduction must be balanced against available resources.

Quantitative measures of risk are required to achieve ordinal rankings of decision preferences. The basic mathematical framework for risk assessment of a constructed facility is provided by the familiar theorem of total probability:

$$\lambda_{Loss > \vartheta} = \Sigma_H \Sigma_{LS} \Sigma_{DS} \; P[Loss > \vartheta | DS] \; P[DS|LS] \; P[LS|H] \; \lambda_H \qquad (1)$$

in which λ_H = annual mean rate of occurrence (for rare events, λ_H is numerically equivalent to event probability P[H]); P[LS|H] = conditional probability of a structural limit state (yielding, fracture, instability), given the occurrence of H; P[DS|LS] = conditional probability of damage state DS (e.g. negligible, minor, moderate, major, severe) arising from structural damage (this term provides the interface between structural engineering and economic loss), and $\lambda_{Loss > \vartheta}$ = annual frequency of loss exceeding ϑ, given a particular damage state. If the hazard is defined in terms of a scenario (or set of scenarios), the risk assessment equation becomes,

$$P[\text{Loss} > \vartheta|\text{Scenario}] = \Sigma_{LS}\Sigma_{DS} P[\text{Loss} > \vartheta|D] P[DS|LS] P[LS|\text{Scenario}] \tag{2}$$

The parameter ϑ is a loss metric: number of injuries or death, damage costs exceeding a fraction of overall replacement costs, loss of opportunity costs, etc. depending on the objectives of the assessment.

Eq. 1 and Eq. 2 deconstruct the risk analysis into its major constituents and, as an added feature, along disciplinary lines (Ellingwood 2007). Reading these equations from right to left conveys the order in which the risk assessment and mitigation process should be approached. An analysis of the frequencies of competing hazards allows trivial hazards to be screened and appropriate risk mitigation strategies to be devised for those hazards that lead to unacceptable increases in building failure rates above the de minimis level. It should be noted that the profession of structural engineering and its codes and standards impact the probabilities P[LS|H] in Eq (1) and P[LS|Scenario] in Eq. 2, and first-generation probability-based codes, such as LRFD, are aimed at reducing these probabilities to an acceptable level for life safety, which has been the historical performance goal for the structural engineering profession. Structural engineering has little impact on the other probabilities (frequencies) in these equations, and it is little wonder that when the control of economic or social losses is of importance, the practice of structural engineering, in and of itself, may be insufficient to ensure that the performance goals are met. At an advanced level of implementation, PBE would allow the design team to achieve the performance goals of the project (presumably encapsulated by a mutually agreed-upon set of values of $\lambda_{Loss > \vartheta}$ or $P[\text{Loss} > \vartheta|\text{Scenario}]$) by adjusting the terms within Eq. 1 and Eq. 2 by a combination of siting, architectural, structural, and other design strategies, provided that the overall loss metrics were not exceeded. There are already a few examples of such an approach in existing criteria for design against disproportionate collapse (NISTIR 7396 2007).

If the scenario approach is adopted because of a lack of data on hazard frequency, the loss (risk) estimate is conditional, and the risk estimate cannot be benchmarked against competing risks associated with other hazards. Moreover, the screening process is difficult when the hazard cannot be quantified. On the other hand, many decision-makers find the scenario approach more understandable than a fully coupled risk analysis. Whether a fully coupled risk analysis or a scenario analysis is used, cost-effective risk mitigation strategies require appropriate attention to all terms in Eq. 1 and Eq. 2 and thus a multi-disciplinary approach to risk mitigation. All sources of uncertainty, from the hazard occurrence to the response of the structural system, must be considered, propagated through the risk analysis, and displayed clearly to obtain an accurate picture of the risk.

RISK TOLERANCE, ACCEPTANCE AND COMMUNICATION

In first-generation probability-based design, the performance (risk) metric of choice has been the annual (or 50-year) failure probability (Ellingwood 1994, 2000, 2001). Situations identified as having progressively more severe consequences of failure are addressed indirectly by reducing their target probability. This approach, while useful for the narrow scope of probability-based code development, has some drawbacks for performance-based engineering and risk assessment of general civil infrastructure. For one, most stakeholders and public decision-makers are not trained in or comfortable with the tools of quantitative risk analysis, especially when the decision process involves rare events. Indeed, regulators often are skeptical of quantitative risk assessment, and may suspect that it might be used to justify socially or politically unacceptable decisions. For another, focusing solely on the probability without considering the consequences omits an important dimension of the assessment and decision process, noted previously. Low-probability events can be exceedingly risky; considering the diversity of civil infrastructure, it is difficult to see how it is possible to collapse all the consequences – mortality, direct and indirect economic losses – into a change of one to three orders of magnitude in the target probability. While it is difficult to quantify consequences in terms of loss, it is clear that this is what many building owners, engineers and regulatory officials in the civil arena want.[2] The "average annual loss" is sometimes cited as an appropriate risk measure but the distribution of loss determined from Eq. 1 (due to the epistemic uncertainties involved in loss estimation) can be very broad, and no central measure – mean, median or mode – represents loss adequately. So, while the average annual loss might be meaningful for an insurance provider underwriting a large portfolio, it is less useful for the individual attempting to measure risk to an individual facility, particularly an individual or decision-maker who is risk-averse. Other metrics must be sought.

Decisions regarding risk mitigation, once $\lambda_{Loss > \vartheta}$ or $P[\text{Loss} > \vartheta|\text{Scenario}]$ have been determined, depend on the decision-maker's view on the acceptability of risk and on how investments in risk reduction should be balanced

[2] Stakeholder workshops held in the aftermath of extreme natural hazards (e.g., Northridge Earthquake) have conveyed this message clearly.

against available resources. Most individuals are risk-averse, while governments and large corporations tend to be more risk-neutral (Slovic 2000). Recent studies, summarized by Corotis (2009), have indicated that *acceptance* of risk is based more on its *perception* than on the actual probability of occurrence and that biases in perception, whether or not they are well-founded, shape decisions. Reid (2000) has suggested that individuals view risks as negligible if they are comparable to mortality risk from natural hazards (on the order 10^{-6}/yr) and as unacceptable if comparable to mortality from disease (on the order 10^{-3}/yr in the 30 to 40 age group). Consideration of acceptable risk in quantitative terms for civil infrastructure facilities, the construction of which often has been regulated by public codes, is a relatively new development (Ellingwood 2001, 2007).

CONCLUSIONS

Performance-based engineering provides a vehicle for implementing risk-informed concepts into structural design and for communicating risk among stakeholders in the building process and to the client. PBE has already gained acceptance in earthquake engineering and fire-resistant structural design, where the incentives for its adoption as an alternative to traditional prescriptive methods are strongly economic in nature. Current research initiatives to extend the performance-based approach to other hazards, such as extreme wind, storm surge and coastal inundation, and tsunami effects, and to develop design procedures in which the risks due to competing hazards are properly balanced and investments in risk reduction can be targeted appropriately will bear fruit in the next decade. The worldwide interest in community resilience (McAllister 2014) will further motivate the development of performance-based engineering, because it is difficult to see how community performance goals regarding response/recovery from extreme hazards can be met without a performance-based approach. These initiatives will provide risk-based performance assessment tools for buildings and other structures that are accessible to a spectrum of stakeholders with different skills and talents. The benefits of such an approach are an improved ability to assess the effectiveness of various risk mitigation strategies in terms of risk reduction per dollar invested, and thus a better allocation of public and private resources for managing risk.

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