Performance Indicators for Structural Systems and Infrastructure Networks

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Abstract: Establishing consistent criteria for assessing the performance of structural systems and infrastructure networks is a critical component of communities' efforts to optimize investment decisions for the upkeep and renewal of the built environment. Although member-level performance and reliability assessment procedures are currently well-established, it is widely recognized that a member-oriented approach does not necessarily lead to an efficient utilization of limited resources when making decisions related to the management of existing deteriorating structures or lifeline systems, especially those that may be exposed to extreme events. For this reason, researchers have renewed their interests in developing system-level assessment methods as a basis to modern structural and infrastructure performance evaluation and design processes. Specifically, system-level performance metrics and characteristics such as reliability, redundancy, robustness, resilience, and risk continue to be refined. The objective of this paper is to extend the content of the accompanying paper on reliability-based performance indicators for structural members by reviewing proposals for the development and implementation of performance-based criteria for structural systems and infrastructure networks. The paper reviews established concepts of reliability design along with emerging ideas of performance-based and resilience-based design that are especially relevant for assessing and managing system-level risk. The paper also studies structural redundancy and robustness concepts as well as network-level performance metrics along with ranking approaches. Insights from these analyses reveal the need for transitioning structural and infrastructure design processes from a traditional component-level reliability-based approach, to one that seeks uniform levels of risk across scales (from structural systems to interconnected infrastructure networks across communities). Implementation examples are drawn from experiences with buildings, bridges, offshore oil and gas platforms, and a variety of infrastructure systems. The paper also reflects on promising avenues for pursuing practical and calibrated system-level performance indicators that support life cycle performance, safety, reliability, and risk of structural and infrastructure systems as integral parts of resilient communities. **DOI: 10.1061/(ASCE)ST.1943-541X.0001542.**

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Introduction

Over the last decades, structural reliability methods have been widely employed to calibrate structural design codes and have also been used in engineering practice for the direct safety evaluation of existing structures and proposed new designs. Early on, most applications focused on evaluating the performance of individual structural members rather than entire structural systems or

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infrastructure networks. Member-based evaluation procedures generally followed the concepts described in the accompanying paper by Ghosn et al. (2016). Because the failure of individual members does not necessarily lead to structural collapse or the complete loss of system functionality, researchers are extending the member-level reliability concepts to evaluate the safety of entire structural systems, such as buildings and bridges, as well as infrastructure systems, such as highways and utility networks.

System safety assessment requires the availability of clear metrics to measure system performance and well-defined acceptability criteria. Ideally, decisions on performance acceptability should be made using risk-based cost-benefit analysis principles, which would compare risk to the costs of reducing it. This usually entails reliability analyses of complex structural systems and infrastructure networks with large numbers of random variables and low probabilities of failure and the appraisal of the consequences of their possible failures to the owners, users and affected communities. Many outstanding issues have still to be resolved before formal risk analysis methods are implemented in actual system design, maintenance, and management processes. On the demand side, these issues include the consideration of natural and epistemic uncertainties in probabilistic modeling of applied loads, definition of functional requirements, human errors, as well as the occurrence and intensities of human-made or extreme natural hazards accounting for long-term variability due to societal, economic and environmental changes and the paucity of data. On the capacity side, difficulties arise in modeling the strengths, failure mechanisms, and long-term behavior of a system's components subjected to deterioration processes; in accounting for component, system and network interactions and interdependencies; and in analyzing the nonlinear dynamic response of systems to various stochastic extreme hazards and their combinations, accounting for changes in critical failure modes and load redistributions due to material and geometric nonlinearity. Intensive research is making progress in providing techniques of various levels of efficiency and accuracy to address these issues. These often imperfect yet practically useful techniques can be used to define reliability-based and risk-informed structural member, system, and infrastructure network-performance measures which, in conjunction with experience from previous critical events and engineering judgment, will help decision makers evaluate and compare alternative design and rehabilitation options and optimize the use of limited financial resources (Melchers 1999; Ang and Tang 1984; Thoft-Christensen and Baker 1982; Ditlevsen and Madsen 1996; Rausand and Høyland 2004; Haimes 2015).

As observed by Ghosn et al. (2016), higher success has been achieved in applying reliability-based and risk-informed methods for evaluating the performance of individual structural members rather than systems. Evaluating the reliability of members is a necessary step for evaluating an entire structural system which must account for the interaction between its members to assess the probability that the system is no longer functional or that it collapses. Also, relating the system performance and reliability of a network to that of its components helps in assessing the effects of partial failures and sudden changes in demand or supply of commodities that have significant implications for risk assessment and community resilience. Modeling the interaction between member and system reliabilities is also important for assessing the risk of catastrophic failures of multicomponent engineering systems, such as nuclear power plants or interdependent infrastructure systems, which have major public safety, societal, and economic repercussions.

A basic approach for system reliability analysis is to convert a complex system into a combination of simple subsystems such as components in parallel or in series, or a series of subsystems formed by components in parallel configurations. When analyzing the reliability of a structure, the basic approach requires the enumeration of all critical failure modes, formulating these using simple analytical expressions, evaluating the reliability of each mode, and combining them to find the reliability of the entire structure. Analytical algorithms, simulation, and heuristic techniques for the reliability analysis of structural systems are continuously being refined and are being tested and compared for models of simple structures for which accurate solutions are available (Melchers 1999; Ang and Tang 1984; Thoft-Christensen and Baker 1982; Ditlevsen and Madsen 1996).

Similarly, the reliability of an infrastructure network is underlined by the reliability of its components and its layout or topology, also referred to as graph, which controls the way in which the network flow is transmitted and distributed and commodities are transported. In their simplest forms, networks are modeled as collections of nodes (say electric substations, pumps, traffic origins, and destinations) connected by links (transmission lines, pipelines, highways). The reliability of the network is assured during and in the aftermath of a hazard event if connectivity between origin and destination nodes is maintained and flow of commodities is sustained at an adequate level to meet demand. Classical network reliability analyses methods are also based on modeling the system in series of parallel subsystems and finding the shortest path and minimum cut set. The shortest path is the path that goes over the minimum number of links to connect an origin node to a destination at minimum cost without violating operating constraints (Poyrazoglu and Oh 2015). A cut is a subset of components in a system such that if the components of this subset have failed, then the destination node is completely disconnected from the origin. The minimum cut set is the set that contains the minimum number of components. Finding all disjoint shortest paths and cut sets determines a network's reliability and probability of failure, respectively. This is relatively easy to achieve for simple networks but requires prohibitive computational effort for complex systems with high numbers of components. Researchers continue to develop analytical, simulation, and heuristic techniques to obtain the reliability of realistic-size networks, many of which are consistent with those applicable for structural systems (Barlow and Proschan 1996).

Even though the fundamentals of system reliability theory have long been established, a main reason for the observed lag between the implementation of member-level and system-level reliability methods for structures and infrastructure networks is the difficulty of relating the performance of the system to that of its components because of variations in component and system behavior (aggravated by material and geometric nonlinearities in structures), large numbers of components, complicated system topologies and interconnectivity, and complex component and system interdependencies and statistical correlations, which may not be amenable to representation using combinations of series and parallel subsystems, especially where partial failures, spread of damage, or functionality limits rather than system collapse are of concern. For these reasons, system reliability algorithms are being connected to nonlinear structural analysis, finite-element software, and network-simulation packages. The reliability analysis problems are further exacerbated by the stochastic nature of the loads and hazards given current limitations in our ability to even model the behavior of complex deterministic systems especially when the loads and structural response are dynamic in nature (Hurtado and Alvarez 2010).

While system reliability analysis methods are being improved by various researchers with the aim of developing formal risk analysis methodologies, another issue hampering the implementation of system-level reliability analyses is the difficulty encountered by engineers in establishing adequate performance indicators for structural systems and networks that can be used in conjunction with intermediate-step system reliability-based and risk-informed, and eventually formal risk analysis, decision processes. This issue is the focus of this paper, which presents a review of recent proposals for establishing reliability-based and other performance criteria for structural systems and infrastructure networks. Specifically, this paper addresses structural systems and network performance including performance-based design methods, system redundancy, robustness, progressive collapse, and cascading failure quantification metrics, which ultimately support community resilience and risk-based design and decision-making processes. Specifically, section "Structural System Safety and Performance Based Design" of this paper discusses structural system safety and performance-based design. Section "Structural Redundancy, Robustness and Progressive Collapse" focuses on structural redundancy, robustness and progressive collapse as approaches that have gained practical use. Section "Systemic Performance Metrics" expands on systemic structural and infrastructure resilience perspectives as well as network-performance metrics. Section "Conclusions" presents conclusions and ideas for risk-informed systemic design.

Structural System Safety and Performance-Based Design

Structural System Safety

In most applications, current structural design and evaluation techniques deal with individual members and do not fully account for the behavior of the complete structural system. As currently performed, the safety check verifies that the strength of each member is capable of carrying the effects of the applied loads by an acceptable safety margin. The safety margin is provided through the application of safety factors (load and/or resistance factors) that are calibrated on the basis of engineering judgment and structural reliability methods. In addition to assuring member safety, member serviceability under service loads is also checked. Although this traditional member-oriented approach has been successfully used for years, it does not provide an adequate representation of the safety of structural systems that in many instances can continue to carry load after the failure of a main member. In recent years, advances have been made in developing performance-based design (PBD) methods that consider system limit states that reflect the level of damage that can be tolerated in a structural system (Der Kiureghian 2005). For example, all structures should be designed to avoid collapse under the maximum considered load, important structures can be allowed to sustain repairable damage, while critical structures should be designed for minimum damage (Ciampoli et al. 2011; Hamburger et al. 2003). A similar performance-based view is also starting to take root for the design of infrastructure systems (NEHRP Consultants Joint Venture 2014). Thus, PBD principles apply at the member level (Ghosn et al. 2016), while scaling naturally to structural system and even infrastructure network levels. For example, besides evaluating potential damage to members, and structural systems, consideration should be made during highway bridge design processes to ensure some minimum level of traffic flow between different geographic locations following major events such as a high magnitude earthquake or large floods. This section addresses the performance of structural systems, while latter sections of this paper will address performance at the network level.

Conceptually, the response of a structural system to applied loads can be represented as shown in Fig. 1, which captures the behavior of a structure and the different levels that should

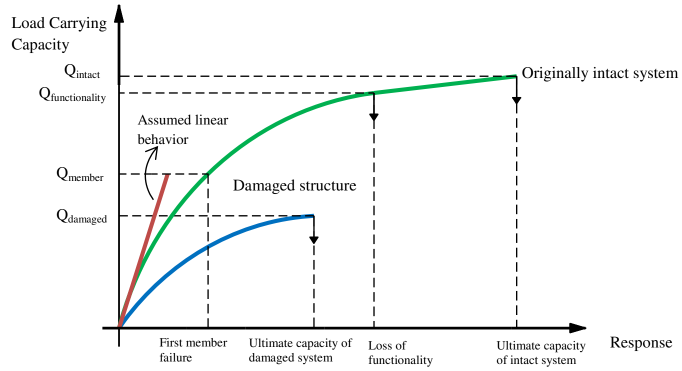

Fig. 1. Representation of typical behavior of structural systems

be considered when evaluating member-level and system-level safety. The curve labeled *Originally intact system* represents the applied load versus response, which is often expressed in terms of the maximum displacement, of a typical structure subjected to increasing loads. In this case, a load capacity evaluation may be performed to study the behavior of an *intact system* that was not previously subjected to any damaging load or event using a nonlinear pushover or pushdown analysis, or a full incremental dynamic analysis. In traditional design practice, the analysis is typically executed assuming linear elastic behavior following the straight line in Fig. 1 without considering potential sources of nonlinearity. Eventually, the first structural member fails when the applied load reaches Q_{member}. If the structure is nonredundant with brittle members, the system may reach its ultimate capacity at Q_{member}. In most cases, due to the presence of ductility, reserve strength, or redundancy in load path, the structure does not fail when Q_{member} is reached, but it enters into nonlinear deformation regimens until the ultimate capacity of the entire structure is reached at Q_{intact}, which would give an evaluation of system safety. Large deformations or significant damage rendering the structure unfit for use are reached when the load attains $Q_{\text{functionality}}$, which gives a measure of system functionality at which point the system may not collapse but could no longer adequately serve its intended purpose.

Structural systems that are exposed to the environment also need to consider deterioration processes and the consequences of local damage. Examples of local damage caused by deterioration processes include steel corrosion, concrete delamination, or fatigue stresses that may lead to reduction or complete loss of load-carrying capacity or the fracture of a main member. In addition, human-made hazards such as fires, blasts, or accidents, such as collisions by a truck, ship, train, or debris, could cause the loss of one or several members. To ensure the safety of the public, structural systems should be able to sustain these damages and still survive with sufficient capacity to allow for the safe evacuation of the users and occupants and in many cases to permit their repair or safe dismantling. Therefore, in addition to verifying the safety of the originally intact structure, the evaluation of a structure's performance should consider the consequences of the failure of a critical member or set of members. If the structure has sustained some level of damage or the brittle failure of one or more of its members, its behavior follows the curve in Fig. 1 labeled *Damaged system*. The ultimate capacity of the damaged structure can be represented by Q_{damaged}.

According to the structural-performance curves, a structure can be considered safe if it provides adequate levels of desired strength represented by Q_{member}, $Q_{\text{functionality}}$, Q_{intact}, and Q_{damaged}. This concept is the basis for what has been known as performance-based design, which seeks to have a structure sustain different levels of damage for different levels of applied loads. The concept is sufficiently broad to be applicable to all types of structural and infrastructure systems and forms an important element for the quantification of risk. The presence of uncertainties in demand and capacity requires that system performance and design criteria be established based on system reliability principles. However, despite the improvements in computer technology and the developments of advanced simulation techniques, there still are difficulties in efficiently evaluating the reliability of dynamically excited large-scale complex systems that may have a multitude of failure modes with low probabilities of failure. For this reason, performance-based design methods have been proposed to bridge the gap between traditional member oriented design methods and direct system reliability assessments.

Performance-Based Design

In seismic engineering, the use of performance-based design (PBD) at the system level has been encouraged and tools have been developed for designing buildings to withstand acceptable levels of damage, typically described as performance levels should the design earthquake event take place (PEER 2010). According to the guidelines developed by FEMA, building owners make the determination, with their structural engineer, of their building's desired performance level. Performance levels can include (1) operational, (2) immediate occupancy, (3) life safety, and (4) collapse prevention [Applied Technology Council (ATC) 2006]. These levels can be tied to the performance of an originally intact system (Fig. 1), where a system would remain operational if the response of the structure to a seismic event remains significantly below Q_{member}. Immediate occupancy is assured if none of the structural members reaches its limiting capacity at Q_{member}. Life safety is related to $Q_{\mathrm{functionality}}$ and the capacity to resist collapse is related to Q_{intact}. By specifically targeting the performance level that building owners deem necessary while recognizing the cost implications of the design and the consequence of exceeding specified damage levels, performance-based designs are considered to be superior to traditional code-specified design methods. To encourage the implementation of the concept, ongoing activities are focusing on developing improved tools for assessing the seismic demand and the seismic response of buildings [Applied Technology Council (ATC) 2012b, a]. Extensions to other hazards are also being pursued (Barbato et al. 2014; Spence and Kareem 2014).

System-level performance-based design concepts are currently advancing in seismic engineering practice and have been adopted in the ASCE 7 standard (ASCE 2010), which proposes different performance levels related to the response of structures and the consequences of exceeding specified damage levels. A simplified version of the concept has been adopted in the AASHTO *Guide Specifications for LRFD Seismic Bridge Design* (AASHTO 2011), which proposes a displacement-based approach for designing bridges for life safety but does not provide the flexibility of selecting other performance levels. The ASCE 7–design earthquake levels are calibrated using probabilistic analyses to achieve a 1% probability of collapse for a 50-year service period. The AASHTO-design earthquakes are selected to have a 1,000-year return period that is approximately equivalent to a 7% probability of exceedance in a 75-year service period, but the structural design process was not calibrated on a probabilistic basis. Current research in seismic PBD focuses on structural performance in terms of the probability of incurring a particular value of annual costs that include casualties, repairs and repair times, all toward developing risk-based design methods (ATC 2012a; Han et al. 2013).

Although the principles of system-level performance-based design continue gaining acceptance, their direct application in structural design standards or in structural engineering practice beyond seismic engineering is still in its early stages and is currently based on more simplified approaches. As discussed by Ghosn et al. (2016), ASCE 7 and other standards have proposed adjustments to target member reliabilities based on an assessment of the consequences of a member's failure due to nonseismic hazards. But the reliability evaluation was retained at the member level. This is in part due to the difficulty of modeling the probabilistic nonlinear behavior of structural members and the nonlinear interaction between the members of complex systems. Another issue is the difficulty of defining measurable criteria that can be used during nonlinear structural analyses to identify the points when a structure collapses, when life safety limits are exceeded, or when the structural responses reach different levels of repairable or nonrepairable damage. Furthermore, in contrast to structural design standards based on member-oriented target reliability levels and load and resistance factors, no consensus has yet been reached with regard to establishing target reliability levels for the performance of entire systems. To side-step the difficulties in performing probabilistic hazard assessments in practice, there has been renewed interest in using fragility analyses as part of the safety assessment of structural systems.

Fragility Analysis

The fragility of a structural system refers to its tendency to be damaged or destroyed given a disruptive hazard level, and is represented in terms of conditional probabilities. Fragility analysis was embraced for the seismic evaluation of nuclear power plants and has been extended over the years to the safety assessment of all types of structural systems and infrastructure networks subjected to forces caused by extreme hazards and rare events (Grigoriu et al. 1979; Casciati and Faravelli 1991; Ghiocel et al. 1998; Hwang and Huo 1998). The analysis results are presented as fragility curves that express the conditional probability that the structural response to a given hazard intensity exceeds structural capacity defined by a limit state, such as those in Fig. 1. Fragility analyses are particularly suitable when analyzing rare events, including malicious attacks that cannot be assigned numerical probabilities of occurrence. In such cases, the performance levels required for a set of specified hazard intensities are determined based on perceptions of risk (Reid 1999).

Commentary

There has been considerable progress in developing and implementing fragility analyses, as well as more involved performance-based design methods to evaluate the response of entire structural systems. The PBD principles are applicable at multiple scales, from members to systems, while being compatible with resilience-based design and risk-based decision making. Implementation of PBD principles is currently more advanced in seismic design of buildings but is gaining traction across other hazards and systems such as the seismic design of bridges (Wang et al. 2014), and the design and safety assessment of structures subjected to different hazards including fire and blast (Grosshandler 2006). The PBD methods can ultimately account for the material and geometric nonlinear dynamic response of structural components, the interaction of the components of the system, the relation between structural response and damage levels, as well as the consequences of damage that may be represented in monetary terms. The consideration of the uncertainties in estimating the hazards, the response of the system, the resulting damage, and the consequences of damage including direct and indirect costs all contribute to the adoption of formal risk-based design methods in structural and infrastructure engineering (SIE). In addition, to gain acceptance in practice, risk communication must be transparent and systematic. However, much work is still needed to generalize the implementation of risk-based system-level design approaches. This includes the training of multidisciplinary professionals, owners and stakeholders who are comfortable with engineering, statistics, and probability, and decision-analysis principles. In the meantime, researchers are proposing partial solutions to address the immediate need of ensuring performance and safety of civil infrastructure systems in engineering practice. Such solutions include the explicit consideration of redundancy, robustness, and resilience principles.

Structural Redundancy, Robustness, and Progressive Collapse

Background

Traditionally, structural design has focused on providing adequate safety levels to sustain the maximum loads expected within the service life of a structure. Increased threats from different types of human-made and natural hazards, accelerated environmental degradation processes combined with limited resources for maintaining and upgrading our aging civil infrastructures have necessitated a review of the design process to include features that help reduce the probability of collapse should a structure undergo some level of deterioration, or is exposed to low probability extreme events or unforeseen threats. Because it is difficult to develop probabilistic models for uncertain extreme threats and apply these to assess the safety of structures under their effects, the consideration of structural redundancy, structural robustness and the potential for progressive collapse have become essential components of engineering designs. These structural characteristics are related to the structural topology and member detailing and are independent of the threats that may trigger the initial damage and thus form a stepping stone toward multihazard, resilience-based, and risk-based design. These characteristics are all related to the behavior of the structural system and the interaction between its components, which would allow the system to carry loads after the capacity of individual members are exceeded or after the removal or deterioration of components.

Using current convention, structural redundancy can be defined as the ability of a structural system to redistribute loads and continue to carry additional load after one or more of its members reach their full capacity. Thus, a redundant structure may be defined as a structure that has additional structural capacity and reserve strength, allowing it to carry a higher overload than anticipated when considering the capacity of individual members. The ability of a structure to carry service loads to assure the safe evacuation of its users or occupants after one or several main structural components are damaged is also becoming known as structural robustness, which reflects the relative insensitivity of the system to local failures or damage. Robustness depends on the presence of multiple load paths as well as structural ties, ductility, and strength that would allow the load to redistribute around a damaged segment of the structure. Progressive collapse occurs if a sudden local structural damage causes a chain reaction of structural element failures that leads to the collapse of the entire structure or a disproportional portion of the structure. The term structural robustness has also been used to characterize the remaining strength of a damaged system, including infrastructure systems in the context of resilience, as well as the ability of a system to resist dynamic cascading failures and collapse.

Different industries have focused on ensuring the ability of the system to resist different types of damage. For buildings, one of the focuses has been on designs that reduce the potential for progressive collapse. According to Marjanishvili (2004), progressive collapse includes two types of loadings: (1) the primary load related to the abnormal hazard, such as blast pressures, which causes a structural element to fail; and (2) the secondary loads, which are generated due to the structural motions caused by the sudden brittle failure of the element. A focus on secondary loads makes the progressive collapse analysis process independent of the hazards that cause the initiating damage.

Ellingwood et al. (2007) provide the steps for risk-analysis approaches to progressive collapse, which include threat definition, event control, and structural design to resist the postulated events. An extensive review is provided of design methods to enhance a building's resistance to progressive collapse, including the indirect method (providing sufficient tie forces), the specific local resistance method (designing key elements to withstand abnormal loads), and the alternate load path method (allowing for redistribution of load in the event of the loss of a key member). Elsewhere, the Comité Européen de Normalisation (CEN) (2004) emphasizes the necessity of designing buildings to prevent the spreading of a potential local damage, while the U.S. General Services Administration, GSA (2013) provides guidelines to reduce the likelihood that federal buildings undergo progressive collapse. To promote adoption in practice, a linear elastic procedure is allowed in lieu of more complex nonlinear methods that require the use of either static or dynamic finite-element analysis models that capture both material and geometric nonlinearities.

For bridge structures, the focus is on using structural configurations that will resist collapse following the fatigue failure or corrosion to critical members or connections. Steel bridges that may collapse following a member's fracture are classified as fracture-critical or nonredundant structures. They can only be constructed under strict conditions and are subject to rigorous inspection schedules throughout their service lives. Traditionally, bridge engineers recognized three types of redundancy: (1) internal redundancy, where the failure of one element will not result in the failure of other elements of the same member; (2) structural indeterminacy, which is the result of continuity and the compatibility of the deformations within a load path; and (3) load-path redundancy, which is related to the number of supporting elements. For example, bridge engineers would consider two-girder steel bridges to be load-path nonredundant because the fracture of one girder may lead to structural collapse. On the other hand, continuous spans would be considered structurally redundant (Connor et al. 2005). However, these traditional definitions, which are descriptive in nature, may not provide accurate evaluations of redundancy in bridges, as in girder bridges the spacing between girders is a more important parameter of redundancy than the girder count and indeterminate structures do not always provide high redundancy levels (Ghosn and Yang 2014; Frangopol and Curley 1987; Biondini et al. 2008).

Although current design codes and standards for transportation structures specify design criteria or target reliability levels for members in redundant and nonredundant structures, little guidance is provided to engineers about the level of redundancy that a particular design provides and the types of detailing required for the adequate redistribution of loads [Crampton et al. 2007; AASHTO 2010; Canadian Standards Association (CSA) 2012]. To help alleviate this problem, Ghosn and Moses (1998) and

Ghosn and Yang (2014) have calibrated system factors that can be applied during the design and safety evaluation of bridges to reflect the ability of the structural configuration to redistribute the applied loads should the load capacity of a ductile member be exceeded or should a main member be deteriorated or completely damaged.

Providing structural redundancy or robustness is also important for offshore platform designs, whose members are susceptible to brittle fatigue fracture due to cyclic stresses from wave actions, severe damage and deterioration from harsh sea environments, as well as impacts from ship collisions. The ISO 19902 (ISO 2007) procedure for assessing the safety of existing platforms, as described by Ersdal (2005), involves five possible analysis levels of increasing sophistication. Level 1 is a linear analysis and component checks. Level 2 expands with refined assessment of actions and resistances. Level 3 is a linear elastic redundancy analysis. Level 4 is a nonlinear analysis on system level including component checks as an integrated part of the nonlinear system analysis. Level 5 is a check by using structural reliability analyses. If the structure is found acceptable at one level, no higher levels of checking are necessary. Levels 3 and 4 include assessments based on linear or nonlinear redundancy analysis (RSR analysis) after failure of a degraded critical member.

Despite these industry-specific efforts, generic design methodologies are still needed where common system-level principles govern their development and associated metrics for quantification. Proposed methods include deterministic and probabilistic approaches.

Deterministic Measures

While several structural design standards have incorporated the consideration of redundancy, robustness and progressive collapse, there remains much debate about how best to quantify these structural characteristics and on the benchmarks and criteria that should be used as the basis for the proposed procedures. Early work on structural redundancy and robustness initiated in bridge engineering and offshore platform design and similar concepts are being adopted for buildings that may be susceptible to progressive collapse. As an example, Frangopol and Nakib (1991) and related work (Wisniewski et al. 2006) proposed measures of redundancy that consider the reserve and residual strength of bridges. More specifically, Ghosn and Moses (1998) proposed quantifiable and simple measures of redundancy along with properly calibrated acceptance criteria that can be implemented in structural engineering practice based on system performance concepts, such as those in Fig. 1. In this case, two measures of redundancy are related to the overloading of the originally intact structure and are defined as the ability of the structural system to resist collapse or avoid the loss of structural functionality. A third measure is calculated for a damaged configuration of the structure to evaluate its capability to carry some emergency load after severe damage to some main members. These measures were applied for different loading conditions, to assess alternative bridge designs, and could potentially be extended to other structures and infrastructure systems. The noted metrics are given as

$$R_u = \frac{Q_{\text{intact}}}{Q_{\text{member}}}$$
$$R_f = \frac{Q_{\text{functionality}}}{Q_{\text{member}}}$$
$$R_d = \frac{Q_{\text{damaged}}}{Q_{\text{member}}} \tag{1}$$

where R_u, R_f, and R_d are respectively defined as the redundancy ratios for the ultimate collapse limit state of structures, for the functionality limit state defined as the load that causes a vertical deflection equal to span length/100 in bridges and for the collapse limit state of an already damaged system. Similar measures may also be applicable to utilities whereby R_u, may provide a measure of outage under over-demand, R_f would define some quality of service reduction and R_d would be applicable for outage limit state of an already damaged system.

Such generic redundancy criteria require calibration to specific industry practice. For instance, acceptable redundancy ratios for short to medium span multigirder bridges under vertical load $R_u \geq 1.30$, $R_f \geq 1.10$, and $R_d \geq 0.50$, were set to match the redundancy levels of bridges that have historically shown adequate levels of redundancy and robustness (Ghosn and Moses 1998). The simplicity and practicality of these indicators have led to their recent use in the design of new bridges or maintenance of existing ones (Bhattacharya et al. 2005; Hubbard et al. 2004). Following a similar approach, Wisniewski et al. (2006) includes redundancy criteria for the assessment of existing railway bridges.

Similar measures of redundancy and robustness have also been advanced by the offshore industry in ISO 19902 (ISO 2007) that defines the reserve strength ratio (RSR) as

$$\text{RSR} = \frac{Q_{\text{intact}}}{Q_{\text{design}}} \tag{2}$$

where Q_{design} = unfactored design load and Q_{intact} = load that causes the collapse of the originally intact system (Fig. 1). Another measure is the damaged strength ratio (DSR) defined as

$$\text{DSR} = \frac{Q_{\text{damaged}}}{Q_{\text{design}}} \tag{3}$$

where Q_{damaged} = load that causes the collapse of the damaged system. A structural redundancy (SR) ratio is also defined as

$$\text{SR} = \frac{Q_{\text{intact}}}{Q_{\text{member}}} \tag{4}$$

Whereas a residual strength ratio (RIF) is defined as

$$\text{RIF} = \frac{Q_{\text{damaged}}}{Q_{\text{intact}}} \tag{5}$$

Although ISO 19902 does not provide specific criteria that the above ratios should meet, Ersdal (2005) and others (Sorensen and Christensen 2006) propose to establish criteria for these parameters based on the probability of failure or consequences of failure. For example, the RSR reserve strength ratio should meet a value of $1.92 + 0.277\text{Re}$, where Re is the ratio of the gravity load to the lateral environmental load (wave and wind) on the structure. A structural redundancy ratio $\text{SR} = 1.38$ was deemed reasonable and a residual strength ratio $\text{RIF} = 0.80$ was also found to be acceptable. Although the SR value recommended by Ersdal (2005) is only slightly more conservative than the R_u limit proposed by Ghosn and Moses (1998), the RIF criterion would lead to a value more than two times that proposed for R_d in Eq. (1).

For buildings, ongoing efforts by the National Institute of Building Sciences and its participating agencies (including the Department of Defense) (2016) are reviewing and updating their existing structural design guidelines including current criteria to reduce the potential of the spreading of local damage and progressive collapse (DoD 2002). The current criteria associated with nonlinear analyses provide maximum allowable ductility and/or rotation limits for many structural components. For example, plastic rotation limits in the range of 6° for concrete beams and

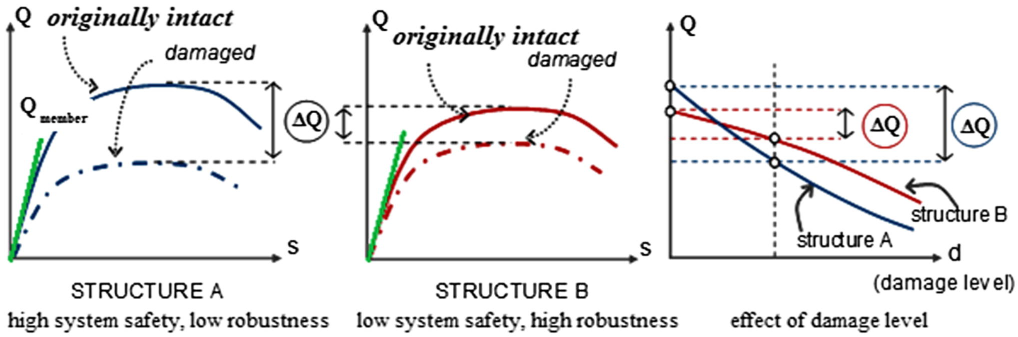

Fig. 2. Conceptual comparison of system safety, redundancy, and robustness of two competing structural designs

typical slabs, to 12° for steel members and concrete slabs with tension membranes, are recommended along with maximum sidesway limits equal to height/25. For connections, the plastic rotation limits are in the range of 1–2°. When nonlinear dynamic analysis procedures are used, it is recommended that the damaged building be able to support a vertical load consisting of 1.2 times the dead load plus 50% of the live load. When a static analysis is performed, a dynamic amplification factor equal to 2.0 is applied to the total vertical load. The GSA (2013) guidelines for linear procedures recommend the removal of a main member that is susceptible to sudden damage and applying the dead load plus 25% of the live load after amplifying both loads by a dynamic factor equal to 2.0. The procedure requires checking the demand over capacity ratio (DCR) for each member in the structure and removing all members with DCR values that exceed 2.0. If the moments in the removed members have been redistributed throughout the entire building and DCR values are still exceeded in areas outside specified allowable collapse regions, the structure will be considered to have a high potential for progressive collapse.

Two approaches have been adopted for evaluating redundancy, robustness, and progressive collapse of structures, and some of the criteria are calibrated to benchmark the performance of the originally intact system to that of its most critical member, or the performance of the damaged system to that of the originally intact system. Other strategies, such as those adopted for buildings, which usually have several alternate load paths, accept the fact that it will be difficult to contain failures to the initial damaged zone and instead concentrate on restricting the spread of the initial damage to a limited area.

A conceptual comparison between the performance of an originally intact system and that of the system in a damaged configuration was performed by Bontempi et al. (2008) based on the difference between their capacities ΔQ rather than ratios. ΔQ which is defined as

$$\Delta Q = Q_{\text{intact}} - Q_{\text{damaged}} \tag{6}$$

was also adopted as a measure of robustness by other researchers (Frangopol and Curley 1987; Giuliani 2012). Even though both Eqs. (1) and (6) convey the same information, Eq. (6) has a clear drawback because it is not dimensionless.

Fig. 2 illustrates how two different Structures A and B proportioned for the same design strength may exhibit different redundancy and robustness levels. In this case, even though Structures A and B may be designed using current member-oriented design codes to achieve the same member safety criteria, structure A shows a higher system capacity for the originally intact system than that of Structure B. Using the definitions of R_u in Eq. (1) or Eq. (4), this shows a higher redundancy level for Structure A for the ultimate limit state of the originally intact system. On the other hand, when one component in each structure deteriorates by the same amount, damaged structure B may have a higher damaged system capacity than Structure A, indicating that Structure B is more robust using the measures of R_d in Eqs. (1) and (5). Eq. (6) also indicates that Structure B with a lower value for ΔQ has a higher level of robustness. As the damage spreads throughout each of the structures, the differences in robustness may change as observed in the last frame of Fig. 2 and explained by Biondini et al. (2008), who emphasize the importance of considering the damage evolution process during the analysis of structural robustness.

As an example of systems that may behave as shown in Fig. 2, consider a column with continuous spirals (System A), which in its intact configuration is more redundant than a column designed to the same nominal capacity with discrete stirrups (System B). If a cut in the shearing reinforcement takes place, System A is found to be less robust than B because the discrete stirrups would arrest the spread of damage along the length of the column, as opposed to a single cut in the continuous spiral, which could unroll the entire tie. However, the advantage of having multiple ties may dissipate depending on the extent of damage to which the columns are exposed, which is uncertain to start with. This and other uncertainties in strength, demand, and the damage process highlights the need for probabilistic measures.

Probabilistic Measures

To account for the probabilistic nature of system safety assessment processes, the evaluation of performance can be executed using advanced structural and system reliability techniques. In adequately designed structures, the probability of a given limit state exceedance should not be higher than a threshold value. For example, if the performance goal is to avoid structural collapse, then

$$P(C) \leq P_{\text{threshold}} \tag{7}$$

where $P(C)$ is the probability of structural collapse which, using the notation of Fig. 1, can be represented as

$$P(C) = P(Q_{\text{intact}} \leq E_H) \tag{8}$$

where E_H = demand on the structural system due to hazard H. For the design to be adequate, $P(C)$ must remain below a target probability level ($P_{\text{threshold}}$) that can be determined based on public's risk acceptance, and experience with previous successful designs. To obtain a better appreciation for the various components influencing $P(C)$, Ellingwood and Wen (2005) and others suggested that it be expressed as a function of different damage scenarios (D) caused by multiple hazards (H), as

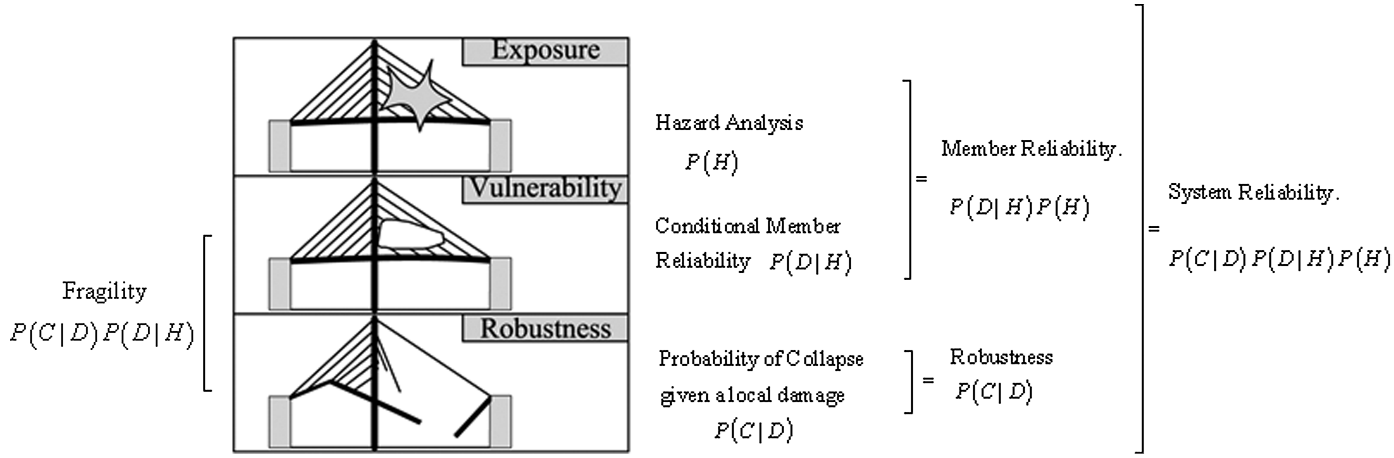

Fig. 3. Components of reliability-based system performance assessment

$$P(C) = \sum_H \sum_D P(C|D)P(D|H)P(H) \tag{9}$$

where $P(H)$ is the probability of occurrence of hazard H; $P(D|H)$ is the conditional probability of local failure D given the occurrence of H, and $P(C|D)$ is the probability of structural collapse given the occurrence of local damage scenario D. The probability of collapse is obtained by summing over all possible hazards and local failure scenarios.

A conceptual representation of the terms in Eq. (9) for a single hazard and damage scenario is provided in Fig. 3, where the hazard analysis, expressed in terms of $P(H)$, models the exposure of a system to hazard, H. The vulnerability of the members to the hazard is expressed in terms of the probability that H will lead to a local damage, $P(D|H)$. Structural robustness is related to the conditional probability of collapse, $P(C|D)$, which represents the response of the structure to a given damage scenario and can be considered to be independent of what hazard initiated the damage. This term can also explicitly consider damage evolution processes, and the entire process is consistent with system-level PBD.

Several other definitions and reliability-based indicators for structural redundancy and robustness have been introduced. For example, to obtain a measure of availability of warning before system failure, a redundancy index was proposed by Frangopol and Curley (1987) as

$$\mathrm{RI}_1 = \frac{P_{f(\text{damaged})} - P_{f(\text{intact})}}{P_{f(\text{intact})}} \tag{10}$$

where $P_{f(\text{damaged})}$ is the probability of failure of the damaged system and $P_{f(\text{intact})}$ is the probability of failure of the originally intact system. Related measures in terms of the probability of failure and reliability index β also exist (Frangopol and Nakib 1991; Kudsi 2005). For instance, Lind (1995) defined a system vulnerability index (V), as the ratio of the failure probability of the damaged system to the failure probability of the undamaged system

$$V = \frac{P(r_d, Q)}{P(r_0, Q)} \tag{11}$$

where r_d indicates a particular damage state, r_0 indicates a pristine system state, Q is the prospective loading, $P(r_d, Q)$ represents the probability of failure of the system in the damaged state, $P(r_0, Q)$ represents the probability of failure of the system in the originally intact state.

Other researchers have used similar measures, including Maes et al. (2006), who defined structural robustness of a system as

$$\mathrm{ROI}_1 = \min_i \frac{P_{f_0}}{P_{f_i}} \tag{12}$$

where P_{f_0} = system failure probability of the undamaged system; and P_{f_i} = system failure probability after damage to one critical member i.

The reliability-based measures adopted by Ghosn and Moses (1998) to complement the deterministic measures of Eq. (1) are defined in terms of the reliability index margins that measure the relative safety provided by the structural system compared to the reliability against first member failure

$$\begin{aligned} \Delta\beta_u &= \beta_{\text{intact}} - \beta_{\text{member}} \\ \Delta\beta_f &= \beta_{\text{functionality}} - \beta_{\text{member}} \\ \Delta\beta_d &= \beta_{\text{damaged}} - \beta_{\text{member}} \end{aligned} \tag{13}$$

where the liability indices of the system are expressed as β_{intact}, $\beta_{\text{functionality}}$, and β_{damaged}, respectively, for the collapse limit state of the originally intact system, the functionality limit state of the originally intact system, and the capacity of the damaged system as defined in Fig. 1. The liability index of the most critical member is represented by β_{member}. As an example in short to medium span multigirder bridge systems, Ghosn and Moses (1998) recommended a set of threshold values that the reliability measures in Eq. (13) should meet to classify bridges as adequately redundant and robust. The threshold values were selected to coincide with reliability margins of bridges that have historically shown satisfactory system performance and are given as $\Delta\beta_u \geq 0.85$, $\Delta\beta_f \geq 0.25$, and $\Delta\beta_d \geq -2.70$. Besides these metrics, a number of other proposals are emerging in the literature to deal with the complexities of different structural and infrastructure systems.

Other Performance Measures

All previous metrics are based on the load-carrying capacity of originally intact and damaged systems, and some researchers are expanding their scope by adding damage progression, optimization, and combinatorial principles, among others (Czarnecki and Nowak 2008; Biondini et al. 2008; Bontempi et al. 2008; Cavaco et al. 2013). As summarized by Giuliani (2012) other emerging measures, can be divided into the following groups:

- Topology-based: in this group, a central role is played by the structural hierarchy (Agarwal et al. 2003). Particularly, a parameter called *well-formedness* is identified in the system to account for the level of connection between structural elements. If properly adapted, this connectivity approach is also practical for infrastructure networks;
- Energy-based: this group is based on a comparison between the energy released by an element failure and the energy required for the next element to fail (Starossek 2009); and
- Risk-based: this approach is based on the investigation of different risk scenarios, determined on the basis of an event tree (Baker et al. 2008). To this aim, the assessment of the probability of occurrence of each leaf of the tree is required and an evaluation of the consequence of failure is expressed in terms of the cost associated with the risk. Specifically, the authors proposed a robustness index

$$I_{\mathrm{rob}} = \frac{R_{\mathrm{DIR}}}{R_{\mathrm{DIR}} + R_{\mathrm{Ind}}} \tag{14}$$

where R_{DIR} is the direct risk associated with the cost of local failure due to exposure to a hazard, whereas R_{Ind} is the indirect risk associated with the cost of collapse given a local damage. The risk is defined as the cost of failure times the probability of failure. The cost of failure can be tangible, related to the costs of repairing the local damage including those of the material and construction, as well as the costs of rehabilitating, repairing, or replacing the entire structure including the removal and disposal of the debris. The costs should also include those of the users accounting for their inconvenience, suffering and loss of life. The effect of the structural failure on the local, regional, and national economies as well as the societal and political costs are in principle captured by this and related community-scale metrics, including those where resilience is a component of risk analysis processes at the structural and infrastructure levels (Bocchini et al. 2014; Francis and Bekera 2014; McAllister 2015).

Commentary

This section highlights the importance of considering system redundancy, robustness, and resistance to progressive collapse for achieving safe and reliable structural systems. Different standards and specifications have recommended approaches for considering these structural characteristics during the design of new structures and the safety evaluation of existing structures. Deterministic approaches for the consideration of these characteristics are based on either limiting the spatial spread of an initial damage to the remaining parts of the structure or on ensuring that a damaged system will still be able to carry a minimum level of load to safely evacuate the occupants or users. The first approach has been mostly applied for buildings which can remain partially functional after damage, while the latter approach seems to have been adopted for systems with limited numbers of multiple paths and with a relatively even distribution of loads such as bridges and offshore platforms.

Most deterministic measures of performance compare the damaged system's capacity to that of the intact system. However, because current codes and standards are based on member safety criteria, the most practical measures of redundancy and robustness benchmark the system's ultimate capacity to that of the most critical member. This approach, although practical, still lacks consensus on how to determine the safety levels that a structural system should achieve although some proposal have been advanced for specific structures.

Following current structural design and evaluation approaches, the deterministic criteria for structural redundancy and robustness are being calibrated to achieve acceptable levels of reliability. For this reason, several researchers have also proposed probabilistic measures, which are mainly based on the ratio of the probability of failure of the damaged system to that of the originally intact system. The determination of acceptance criteria has also been hampered by the lack of consensus as to what constitutes an acceptable level for this ratio. To circumvent this difficulty, it has been suggested that, as done with the deterministic measures, the reliability indexes of the originally intact and damaged systems be benchmarked to the design and reliability indices of the members as well as those of well performing existing systems.

One area of consensus in the research community and leaders in the industry is that ideally, structural system safety should be based on an objective evaluation of the risk of failure. Hence, developing risk-based methods that inform system redundancy, robustness, and other systemic metrics, such as resilience, are consistent with current efforts to move the structural design processes from a member-based reliability approach to that of providing uniform levels of risk at the system level. A major hurdle slowing the implementation of risk-based principles is the difficulty of estimating the cost of failure. Considerable effort is currently being spent on guidelines to help structural engineers and owners estimate such costs in practice. For example, ISO-13824 (ISO 2009) outlines methods to conduct risk analysis including the estimation of the consequences of failure. Similar work is ongoing in the United States (ATC 2012a). In addition, to evaluate the costs of damage and repairs, recent risk evaluation efforts have explicitly included *time to recovery* as an important parameter through the evaluation of system resilience (Bruneau 2005; Francis and Bekera 2014; Lounis and McAllister 2016).

The lack of specific methods to estimate the cost of failure has not deterred researchers from applying risk-informed approaches to evaluate the robustness or other metrics for particular structural systems exposed to specific hazards using their own methods. Numerous such studies have been reported in the literature to analyze the effects of seismic and other hazards on individual structures or networks of structures (Kiremidjian et al. 2007). As an example, Björnsson and Thelandersson (2010) analyzed the robustness of a bridge over a railroad yard by estimating the risk of a train derailment, and the probability that a particular column would fail as a result of the impact of the train with the column. The implementation of the approach followed the performance-based process described in Eq. (9), where the probability of collapse is deemed acceptable if the risks associated with the collapse expressed in terms of the costs remained acceptable. Decò and Frangopol (2013) and others (Lee et al. 2011) have also performed advanced risk analyses of bridge structures and networks of bridges under multiple hazards using time-dependent reliability methods to account for long-term deterioration. In addition, the role of maintenance on structural system safety and reliability is garnering attention (Sánchez-Silva et al. 2016), while approaches to assess and manage risk, and the importance of risk communication when evaluating not only structures but also infrastructure systems, their performance, topologies, and effects on communities, are also under investigation (Brunsdon 2004).

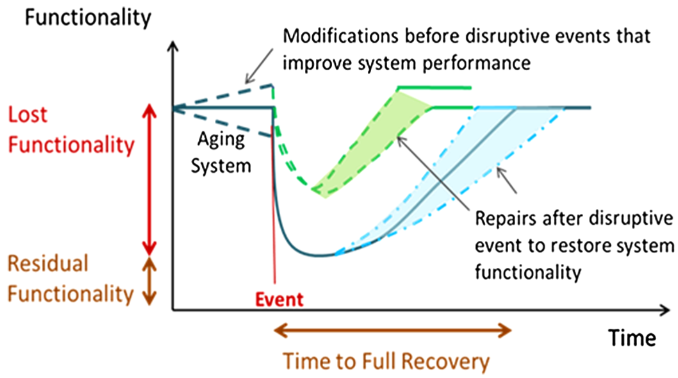

Fig. 4. Resilience concept of functionality versus recovery time for the performance of the built environment after a disruptive event (adapted from Bruneau et al. 2003 and McDaniels et al. 2008)

Systemic Performance Metrics

As communities turn their attention toward evaluating the performance of entire built environments, the establishment of new systemic metrics becomes more urgent. For instance, the resilience of the built environment can be defined in terms of functionality and recovery, which in turn affect risk-based performance objectives. The degree of functionality that should be maintained during and after a hazard event, and the time for recovery, will depend on the role and impact of a facility or infrastructure system on the community. Systems that are essential to the operation and recovery of a community from a hazard event should have higher performance requirements than other systems. For example, essential facilities (e.g., hospitals) and infrastructure systems (e.g., electric power) should maintain functionality during and after disruptive events and be able to recover full functionality within a specified period of time, usually on the order of hours to days (Poland 2009).

Fig. 4 illustrates concepts for the resilience of the built environment where both the degree of lost functionality after the event and the time to full recovery are random variables. If modifications are made to improve the performance of the built environment prior to disruptive events, the time to full recovery can be shortened. However, repairs and upgrades are typically made after a disruptive event and the time to full recovery is less predictable (Chang and Shinozuka 2004; McAllister 2013; Miles and Chang 2006).

The consideration of the concept of resilience as a component of performance-based and risk-based design requires the definition of clear and quantifiable performance measures. The most popular metric for resilience in the field of SIE was proposed by Bruneau et al. (2003), who defined resilience as the ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance), and to recover quickly after a shock (re-establish normal performance). According to their definition, a resilient system exhibits reduced failure probabilities, reduced consequences from failures in terms of lives lost, damage, and negative economic and social consequences, and reduced time to recovery. Based on the concept of functionality, several authors are converging to the following metric form for the quantification of resilience (*RES*) (Bocchini et al. 2014; Bruneau and Reinhorn 2007)

$$\mathrm{RES} = \frac{\int_{t_0}^{t_0+t_h} Q(t)dt}{t_h} \tag{15}$$

where t_0 = time at which the extreme event occurs; t_h = investigated time horizon; and $Q(t)$ = measure of the functionality level of the investigated system. Practical techniques for postevent assessments and pre-event predictions of the functionality recovery profile and of the resilience index have been provided for several structural and infrastructure systems, such as bridge networks (Bocchini and Frangopol 2012), bridges (Lounis and McAllister 2016), healthcare facilities (Cimellaro et al. 2010), and lifelines (Ouyang et al. 2012; Rose and Liao 2005). A rich list of references can be found in the paper by Zhou et al. (2009).

Given that resilience depends not only on the built environment, but also on the community that embeds it, which is responsible for the promptness, effectiveness, and efficiency of the postevent recovery (Bonstrom and Corotis 2014), methods to quantify the performance of entire infrastructure systems rather than particular structures are sorely needed. Practical approaches taking root in the SIE communities are presented next.

Network-Performance Assessment

Infrastructure systems, such as highways or utility generation, transmission, and distribution systems, should be modeled as networks formed by several subsystems and components interconnected in complex configurations. However, current standards from ASCE, the IEEE, and the American Water Works Association (AWWA) among others, tend to only provide specifications for the performance of individual components of infrastructure systems under operating conditions and extreme events, without explicitly considering the importance of the components to the lifeline or interdependencies between utility networks.

Some efforts to acknowledge systemic considerations include the AASHTO *LRFD Bridge Design Specifications* (AASHTO 2010), which recommend considering the criticality of bridges, but no mechanism or criteria are provided to classify them. Also, the American Lifeline Alliance (ALA) developed guidelines for the design of infrastructure systems to achieve a desired performance level when the systems are subjected to natural and human hazards. Identifying hazards, assessing the vulnerability of infrastructure systems, assessing their performance, and identifying actions to reduce their risk are the essence of the guidelines [American Lifelines Alliance (ALA) 2004, 2005a, b, c]. Here, the reduction of system serviceability, service restoration time, and persistent lifeline threats are used as direct impact performance metrics. Some indirect impacts of system functionality loss have also been considered by ALA as indicators of system performance, such as financial losses of customers or users, and environmental deterioration. Also, administrative impacts such as revenue loss and loss of public support are considered as indirect performance metrics. This and related efforts combine several dimensions, and their evaluation often calls for the experience of multiple operators, making the performance assessment process subjective and complex. Thus, practical measures and specific algorithms are still needed for the performance assessment and design of lifeline networks.

Researchers are proposing network-performance indicators that consider either the topology or functionality of networks, while keeping them tractable for practical applications. Topology relates to how the arrangement of components, such as electrical substations in power grids or bridges in road networks, affects network performance. Graph theory provides mathematical tools for assessing networks based on their layout (Jin et al. 2015; Ouyang and Dueñas-Osorio 2011; Yazdani and Jeffrey 2011). Although, topology-based measures provide useful information, they are not sufficient for practical applications alone. In practice, desirable performance measures should also quantify the changes in network functionality during normal operation and contingencies (Cotilla-Sanchez et al. 2012; Pagani and Aiello 2015; Zio 2007). Although some applications have evaluated network topology and functionality jointly, they tend to be deterministic, opening the door for research on probabilistic measures, which should be used to account for uncertainties, rely on advances in system reliability theory and computational complexity (Chakraborty et al. 2013; Karp et al. 1989), and ultimately support risk-based decision making for investment prioritization (Gómez et al. 2014; Der Kiureghian and Song 2008).

Topology-Based Performance Metrics

From a topological perspective, lifeline networks may be represented as abstract graphs $G(N, K)$ with a set of N nodes and a set of K links. The connections between each pair of nodes are represented by an $N \times N$ *adjacency* matrix $\mathbf{A}$, whose $\{a_{ij}\}$ entries equal to 1 if there is connection between node i and node j, and 0 otherwise. Under this adjacency representation, the performance of a lifeline network is often studied from the perspectives of connectivity and efficiency. The ability of a network to keep its connectivity after being subjected to hazard events is often assessed by the connectivity loss (C_L) metric (Albert et al. 2004; Dueñas-Osorio et al. 2007). Denote N_G as the number of connecting paths from every generation or supply node of a lifeline system to any of its N_D distribution or consumption nodes. Also, denote N_G^i as the number of generation units able to supply flow to distribution node i after a disruption. Then, C_L can be calculated as

$$C_L = 1 - \frac{1}{N_D} \sum_{i}^{N} \frac{N_G^i}{N_G} \tag{16}$$

where the averaging is done over all distribution nodes of the network, and the flow through transmission lines is assumed to be bidirectional. This metric is useful for most lifeline systems with clearly established source and demand nodes or regions. However, when dealing with other more distributed layouts, such as transportation or telecommunication systems, most nodes act as both travel sources and destinations, so adaptations are required (Bocchini and Frangopol 2013; Booker et al. 2010). Another important metric to evaluate network-performance topologically is network efficiency (E) (Latora and Marchiori 2007)

$$E = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}} \tag{17}$$

where d_{ij} = shortest path length between nodes i and j. It is assumed that $d_{ij} \to \infty$ when there is no path between two nodes. Hence, E measures how efficient the communication between different nodes in the network is on average. Based on this parameter, a related metric called efficiency loss (E_L) has been used to evaluate the network efficiency change before and after disruption as $E_L = (E - E_0/E)$, where E and E_0 are the efficiencies before and after disruption, respectively. To characterize the reliability of a complex infrastructure network, the topological E measure has been extended as a reliability efficiency loss (R_{EL}) (Eusgeld et al. 2009; Zio 2007), where, assuming statistical independence, d_{ij} is calculated as

$$d_{ij} = \min_{\gamma_{ij}} \left(\frac{1}{\prod_{mn \in \gamma_{ij}} p_{mn}} \right) \tag{18}$$

and the minimization is executed over all paths γ_{ij} from node i to node j, p_{mn} is the reliability of a link from node m to n in path γ_{ij}, and should be based on structural and system reliability concepts (Ditlevsen and Madsen 1996). Then d_{ij} is the length of the most reliable path between the two nodes. Other methods based on the eigenvalues and eigenvectors of the adjacency matrix are starting to emerge, which encode information for element importance and ranking (Langville and Meyer 2011; Newman 2010; Rokneddin et al. 2013). However, metrics that admit flow-based analyses are becoming more desirable to capture functional phenomena.

Flow-Based Functional Performance Metrics

Generic lifeline networks operate under different flow regimens among supply and demand nodes. Thus, it is important to establish performance metrics that combine network topology with flow patterns. Service flow reduction ($\boldsymbol{S_{FR}}$), and related metrics, consider flow capacity after a disruptive event, as well as supply/demand constraints in an optimization framework. The $\boldsymbol{S_{FR}}$ metric determines the amount of flow that a damaged network can provide compared to what it provided before damage (Dueñas-Osorio et al. 2007)

$$\boldsymbol{s_{FR}} = 1 - \frac{1}{\boldsymbol{N_D}} \sum_{i=1}^{\boldsymbol{N_D}} \frac{\boldsymbol{S_i}}{\boldsymbol{D_i}} \tag{19}$$

where S_i denotes the actual amount of flow supplied to distribution node i after disruption, and D_i represents the flow demand of node i before disruption. These flows are found via capacitated network flow algorithms, which are computationally efficient running in polynomial time as a function of problem size (e.g., number of nodes $|N|$). However, algorithms that deal with not only performance assessment, but also reconstruction sequences (to quantify resilience), require mixed-integer programming strategies, which are known to scale exponentially as a function of $|N|$ and thus constitute an area of active research in theory and practice via approximations and heuristics (Cavdaroglu et al. 2011; Lee et al. 2007; Poyrazoglu and Oh 2015). Approaches dealing with physics-based nonlinear differential equations are also time consuming and highly specialized, rendering them difficult to widespread implementation in practice (Machowski et al. 2011).

Recently, Nagurney and Qiang (2007) proposed the *N-Q efficiency measure* which has an explicit and generic consideration of demands and flows in networks especially in highway systems. For a given network topology G and fixed demand vector d, the metric is defined as

$$\varepsilon(G, d) = \frac{\sum_{w \in W} \frac{d_w}{\lambda_w}}{n_W} \tag{20}$$

where n_W = number of origin/destination (O/D) pairs in the network; d_W = equilibrium (or fixed) demand in the network, which is measured over a period of time; and λ_W = equilibrium disutility for O/D pair w. The N-Q efficiency measure captures the demands, flows, costs and behavior; based on this measure, it is possible to also define the importance of a network component as the relative N-Q efficiency drop after the removal of component g as $I_g = \Delta\varepsilon/\varepsilon = [\varepsilon(G, d) - \varepsilon(G - g, d)]/[\varepsilon(G, d)]$, where $G - g$ is the resulting network after component g is removed from network G. Ranking methods assist utilities setting the priorities for designing or retrofitting under constrained times and budgets. Extensions to dynamic networks and interdependent networks are also under development (Nagurney and Qiang 2008; Zhang et al. 2005). One of the benefits of time-dependent measures is that they are suitable for resilience analyses and thus should be actively pursued, either exactly or approximately to manage their computational demands.

Although the principles behind topological and flow-based performance metrics apply to different types of networks, differences in the timescales and operational requirements necessitate specialized adjustments to make such metrics implementable in specific industries. Hence, examples of metrics used in the performance evaluation of power, water, and transportation networks today are presented next.

Metrics for Power-Distribution Networks

Power-distribution networks are becoming critical portions of lifeline systems because their performance influences other infrastructure networks, and their study is less advanced than that for power transmission systems. For example, the extended loss of electric power at the distribution level—where transmission-level systems are often energized more expeditiously than distribution systems—could affect water distribution systems, telecommunication systems, traffic systems, in addition to the functionality of essential facilities. Hence, power-network performance can be evaluated using a number of criteria related to topology and flow, and measured at various hierarchical levels. Examples of performance measures at the bulk level include the difference between power supply after a hazard and that under normal operational conditions (i.e., residual power supply), or the time required to restore high-voltage networks (i.e., time to restoration) (Shinozuka et al. 2007). Zio and Piccinelli (2010) used the ratio of network-demanded load, defined as the average sum of the power generated from all sources, to network-received load, defined as the average sum of the flow reaching consumers. In addition, there are some customer-based measures that integrate technical and socioeconomic dimensions, such as the *percentage household without power after hazard* and the *reduction of regional gross product* (RGP) (Bruneau et al. 2003; Ouyang and Dueñas-Osorio 2014). In relation to customers, the Institute of Electric and Electronic Engineers (2004) established several service-reliability metrics related to the number of customers affected by outages registered at the power distribution system level, but whose root cause can be anywhere in the system. These include the system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), and customer average interruption duration index (CAIDI), among others. These metrics are widely used by utility operators and can be defined as

$$\mathrm{SAIDI} = \frac{\sum \text{Customer hours off for each interruption}}{\text{Total number of customers served}} \tag{21}$$

$$\mathrm{SAIFI} = \frac{\sum \text{Customers affected by each interruption}}{\text{Total number of customers served}} \tag{22}$$

$$\mathrm{CAIDI} = \frac{\mathrm{SAIDI}}{\mathrm{SAIFI}} \tag{23}$$

Utilities use these metrics to establish annual operational reliability targets, and are starting to use probabilistic methods to determine which events constitute outliers from normal operation. These outliers, or major event days (MED), are important to separate normal operation from extreme event operation and address reliability at two operational regimens. However, a link between target performance reliability at the customer level and structural performance at the facility or equipment level still needs to be established, as well as links between distribution-level customer metrics and transmission-level performance metrics, including loss of load probability (LOLP) or energy not supplied (ENS) (Billinton and Li 1994).

Lifeline system intelligence, real-time monitoring through active sensors, and system updating are becoming important features of network operation (Bensi et al. 2009). Using the smart grid as an example, it is clear that these features facilitate the interaction between customers, facilities, and networks. Dupont and Belmans (2010) proposed a framework to measure the capabilities of smart systems. The framework is based on six characteristics (U.S. DOE 2009). These are (1) enable informed participation by customers; (2) accommodate all generation and storage options; (3) sell more than kWhs; (4) provide power quality for the 21st century; (5) optimize assets and operate efficiently; and (6) operate resiliently to disturbances, attacks and natural disasters. Several key performance indicators (KPI) were proposed for assessing each characteristic totaling over 61 KPIs. One of these metrics is attuned to the fast operational regimens of power systems. The new metric is defined as the momentary average interruption frequency index (MAIFI)

$$\mathrm{MAIFI} = \frac{\text{Total number of customer interruptions less than the defined time}}{\text{Total number of customers served}} \tag{24}$$

To simplify the performance quantification of smart systems, Ouyang et al. (2012) observed that a grid's resilience as described in Fig. 4 synthesizes information encoded in many of the KPIs. They classified the performance response process of power networks following a disruptive event into three stages: (1) disaster prevention stage, (2) damage propagation stage, and (3) recovery stage. They modified Eq. (15) using a logarithmic function so that

$$\mathrm{RES}_{\log} = -\log_{10}\left[1 - \frac{\int_0^T Q(t)dt}{\int_0^T TQ(t)dt}\right] \tag{25}$$

where $TQ(t)$ = target performance; and T = time that could span an event or a lifetime. The adoption of the logarithm form in this case is done to express in a convenient scale small differences in resilience values, much like the structural reliability index β communicates reliability levels without the need to explicitly use very small probabilities of failure.

Metrics for Water Distribution Networks

Engelhardt et al. (2000) indicated that the performance of water distribution networks can be defined in terms of the probability that the system is operational (reliability); the percent of time that the system is operational (availability); or in terms of surrogate measures that reflect the operational requirements of the system (serviceability). Moghtaderi-Zadeh et al. (1982) proposed "reachability" of water as performance index, indicating the probability that a certain amount of water flow would reach key locations (nodes). Yang et al. (1996) and Xu and Goulter (1998) used the probability that all nodes are connected to the source nodes as a performance indicator for a water network. This definition is a probabilistic version of the topology-based connectivity metrics. As in power networks, researchers have also proposed customer-based (and flow-based) metrics for water networks. These include the volume of unserved demand (Jowitt and Xu 1993), the number of days of water outage (Walski 1987), the number of customers interrupted (Engelhardt 1999), and the ratio of the served demand to the total demand (Fujiwara and Tung 1991). Other measures focus on the damage of components in the systems. For example, Hwang et al. (1998) used a GIS-based method to evaluate the seismic performance of the water delivery network of Shelby County, Tennessee. Two types of pipe damage (leaks and breaks) were studied, along with the treatment of insufficient pressure and negative pressures. The information on water head ratios and output flow ratios can also be used to define the serviceability of demand nodes (Bonneau and O'Rourke 2009). In a recent paper, Adachi and Ellingwood (2009) used upper-bound and lower-bound approximations to component failure probabilities to evaluate the functionality of water systems under seismic hazards. However, integrated methods that combine physics with system reliability principles and that remain computable for implementation in practice are still needed.

Metrics for Transportation Networks

As with most lifeline systems, early research on transportation networks assessed the performance of individual components such as a road segment, a bridge, or a tunnel independently. In one of the earliest studies, Chang and Nojima (1998) proposed topology-based measures to evaluate the seismic performance of entire highway networks, including the total number of highway sections open, total length of highway open, and total weighted "connected" length of highway open. More recently, Ng and Efstathiou (2006) defined network disconnectedness as

$$\mathrm{NetDis} = \frac{\varepsilon}{l_{\max}} \tag{26}$$

where ε = number of unreachable pairs of highway nodes and $l_{\max}$ = maximum possible number of links.

Liu and Frangopol (2006) extended the above concepts to account for the inherent uncertainties in evaluating network performance, while Bocchini and Frangopol (2011) introduced the probabilistic *fully connected ratio* (FCR), which they defined as

$$\mathrm{FCR} = \frac{\text{Number of samples where all the nodes are reachable}}{\text{Total number of samples}} \cdot 100 \tag{27}$$

These simulation-based metrics provide rankings as a by-product. Other ranking approaches simultaneously capture the role of particular components in the network's topology as well as their vulnerability. One such metric is the *bridge rank* that builds upon spectral analyses of adjacency matrices (Rokneddin et al. 2013).

Among simple flow-based performance indicators that can be used in a deterministic or probabilistic fashion, travel time is defined as the time spent to reach a destination by all the users that depart within a fixed time window (Bocchini and Frangopol 2011; Scott et al. 2006). This indicator can be expressed using either one of the following formulations:

$$\mathrm{TTT}_1 = \sum_{i\epsilon I}\sum_{j\epsilon J}\int_0^{f_{ij}} \tau_{ij}(f)df \tag{28}$$

$$\mathrm{TTT}_2 = \sum_{i\epsilon I}\sum_{j\epsilon J} f_{ij}\tau_{ij} \tag{29}$$

where i and j = nodes of the network; I = set of network nodes; J = subset of nodes that can be reached from node i using a single highway segment ij; f_{ij} = traffic flow on segment ij; and τ_{ij} = time required to cover segment ij—the latter two computed via network flow analyses. Shinozuka et al. (2003) also developed a probabilistic model based on *drivers delay* to determine the effect of repairing bridge damage on the improvement of the network performance as days passed after an earthquake. Travel times and delays can also be related to total travel distance, TTD, computed as

$$\mathrm{TTD} = \sum_{i\epsilon I}\sum_{j\epsilon J} f_{ij}\lambda_{ij} \tag{30}$$

where λ_{ij} = length of segment ij. The time required to cover a segment and its length are linked by a strongly nonlinear function of the traffic flow. Associating TTT with a cost of user time and TTD with a cost per distance covered, the overall user cost, as a practical metric, can also be assessed deterministically or probabilistically.

As for ranking metrics that account for flow, Scott et al. (2006) presented a critical review of the literature about the use of the V/C ratio for such a purpose, defined as

$$\mathrm{V/C} = \frac{\text{Traffic volume on a highway segment}}{\text{Highway segment capacity}} \tag{31}$$

In the same study, a network robustness index (NRI), was also proposed to take into account the benefits to the entire network resulting from improvement to an individual segment capacity

$$\mathrm{NRI}_a = \sum_a f_a\tau_a\delta_a - \mathrm{TTT}_2 \tag{32}$$

where index a runs over the highway segments; f_a = traffic flow on segment a; τ_a = time required to cover segment a, both computed by the network analysis; δ_a is equal to 1.0 if segment a is not the one considered (removed) and 0 otherwise; and TTT_2 is computed as in Eq. (29), with all the bridges intact. NRI_a is estimated for every highway segment and it measures the performance loss due to the removal of a highway segment (caused for instance, by the failure of its bridges). Related flow-based performance indicators for total travel time, have been presented in reports intended for practical application (Lomax et al. 2003).

Integrating time-dependent reliability concepts, researchers can also consider bridge reliability importance factors to evaluate the critically of a particular bridge to the network (Lee et al. 2011; Liu and Frangopol 2005; Rokneddin et al. 2014). Expanding these concepts can lead to life-cycle performance metrics at the system level, which are consistent with current interests on community resilience. Complementary studies explore the effect of correlated seismic hazards (Jayaram and Baker 2009) and the effect of component failures and their dependence (Kiremidjian et al. 2007), along with efficient algorithms for computing such network-performance metrics (Kang et al. 2008; Rokneddin et al. 2013).

Commentary

Recent disasters caused by human-made and natural hazards such as Hurricane Katrina in 2005, the 2011 Tōhoku Earthquake and Tsunami, Hurricane Sandy in 2012, the U.S. Northeast power outage and blackout of 2003, among many others, have highlighted deficiencies in infrastructure design and performance evaluation methods. Many existing methods focus on failure of individual components rather than on the functionality of the systems. For these reasons, researchers are actively developing methods and metrics to assess the performance of infrastructure networks, the evolution of their performance over time, and the interdependencies between different networks. As observed in the progress made in the evaluation of the performance of structural systems, the evaluation of networks is also evolving, whereby individual equipment reliability measures are being replaced by measures of the reliability of entire systems constituted by a combination of structural and mechanical components (Longabard et al. 2011). These efforts are a step toward the establishment of performance-based design and management methods that handle multiple scales of the built environment from structural components to communities in which interdependent infrastructure networks are embedded (Dueñas-Osorio et al. 2007; Franchin 2014; Poljanšek et al. 2012). It is here where the notions of risk and resilience continue shifting the paradigm of performance assessment within the structure and infrastructure engineering field. Ongoing activities to develop and calibrate metrics that combine topology and function, are able to identify important components and are efficiently computable will produce important tools to help decision makers in their efforts to design, manage and maintain robust infrastructure systems that are resilient to natural and human-made disasters.

Related to these ambitious metrics, the sustainability of the built environment is also being raised as an important issue. Even though the research community and practitioners have not identified a common analytical approach for the quantification of sustainability, researchers are starting to explore methods to combine resilience and sustainability of infrastructure systems in a unified way [Bocchini et al. 2014; Institute for Sustainable Infrastructure (ISI) 2015; Lounis and McAllister 2016]. These perspectives need to also balance the fidelity of sophisticated physics-based models with the computational requirements that keep them practical for widespread implementation, thus admitting approximate methods with probabilistic strategies that quantify errors and confidence in performance estimates.

Conclusions

This paper extends the discussion presented in the accompanying paper by Ghosn et al. (2016) entitled "Reliability-Based Performance Indicators for Structural Members" that describes well-established reliability-based metrics that have been implemented in codified design but are directed at individual structural members for systems under service loads or subjected to manmade or natural extreme hazards. An overview of recent advances made toward considering system-level performance during the safety assessment of structural systems and infrastructure networks is presented. The paper summarizes how considerations of system-level characteristics, such as redundancy and robustness, are increasingly being adopted in practice as intermediate approaches to richer performance-based design and resilience-based assessment processes, which are poised to ultimately produce risk-based criteria applicable for optimizing structure and infrastructure design, operation and maintenance processes. The main observations can be summarized as follows:

- The absence of consistent system performance metrics, combined with difficulties in applying system reliability methods suitable for analyzing models of realistic-size time-variant complex systems under extreme hazards has delayed the implementation of reliability-based system evaluation methods in most applications. These are necessary tools for reaching the goal of developing procedures to balance risk and cost at the structural system, lifeline network, and the community levels;
- In an interim step toward reaching the risk-based assessment goal, progress has been made in developing risk-informed system-level performance-based seismic-design procedures that are being emulated for the evaluation of structural members and systems subjected to nonseismic hazards. These methods are applicable at multiple scale levels ranging from component, to system, and network. Like fragility analyses, performance-based design methods utilize probabilities of damage, failure or collapse conditional on the occurrence of hazards of specific levels of intensity. In PBD, the probabilistic hazard assessment step, which constitutes an important component of formal reliability analysis procedures, is replaced by the judgement of decision makers, owners and engineers who specify the performance level that a system should achieve for particular hazard intensities. This approach has been found to be suitable for systems subjected to various rare events for which data are scarce;
- In the same vein, deterministic and reliability-based methods and measures for considering structural redundancy, robustness, and propensity for disproportionate damage or collapse are reviewed along with proposed criteria that are implementable in engineering practice. The goal is to provide practical approaches for considering system reserve strength and the presence of alternate load paths for structures and infrastructure networks that may be subjected to overloads or partial damage due to extreme events. Like PBD methods, proposed robustness and progressive collapse measures side-step the challenge of modeling the damage-initiating hazards to focus on the system-characteristic requirements that would help reduce their effects; and
- Performance metrics to analyze network reliability and quantify performance are actively under development for implementation in various disciplines. A review of approaches for assessing the performance and resilience of power systems, water networks, and transportation systems showed an emerging consensus on the need to develop probabilistic metrics that consider both flow and connectivity requirements in combined formats. It is also observed that there currently is a lack of explicit system-level design and operation performance and restoration goals for most lifeline systems.

The system-level and infrastructure-level perspectives presented in this paper are expected to contribute to the development of next-generation design guidelines and standards that consider the performance of entire structural systems, networks, and communities to achieve uniform levels of risk and exhibit consistent resilience features. Anticipating a wider acceptance of risk-based principles in the field, it is important to identify how the many available proposals toward that end relate to each other. In particular, research and developments are necessary to link proposed performance metrics across multiple scales, in order to provide a fuller view of the role that structural systems and infrastructure networks play in ensuring community resilience.

It is acknowledged that many of the problems faced by the communities are too complex to elicit exact solutions. Therefore, at this stage of the state of art, developing risk-informed approximate evaluation methods and associated metrics and criteria that provide customized solution strategies applicable to multicomponent systems which take advantage of lessons learned from previous disasters and success stories augmented by engineering judgment, will help support decision making processes across different scale levels of the built environment to approximately approach optimum life-cycle solutions that meet desired lifetime performance goals for systems under multiple hazard conditions.

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