State of the Art of Multihazard Design

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Abstract: This paper provides perspectives on multihazard engineering in the contemporary structural engineering context in order to frame the breadth and multiple dimensions it encompasses, to summarize recent activities on selected relevant topics, and to highlight possible future directions in research and implementations. A comprehensive overview of all research and points of view on these broad topics is beyond the scope of this paper. Rather, the objective is to provide selected examples to illustrate the nature of the issues and possible solutions, with the understanding that multihazard design is a relatively new endeavor and that the accomplishments in this field for the most part lie ahead. Topics covered include description of the political context that led to multihazard design, review of current return periods and safety indices for various hazards in model design codes, issues related to hazard interaction and cascading effects, considerations for interdependent systems, and structural element optimization to provide multihazard resistance. **DOI: 10.1061/(ASCE)ST.1943-541X.0001893.** *© 2017 American Society of Civil Engineers.*

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Introduction

Structural engineers have designed structures to resist a broad range of static and dynamic loads and to survive many different extreme events without collapse (for the purpose of ensuring life safety rather than preservation of the structure). This approach is fundamentally at the root of structural engineering—a practice even predating the naming of the profession—and nowadays is embodied in design codes and specifications. However, *multihazard design*, as currently termed, is not only that. Multihazard design addresses a number of issues, ranging from the interactions and interdependencies of hazards and their cumulative damaging effects on structures to the development of new design concepts and structural systems to ensure inherently efficient outcomes that suitably address the often conflicting demands related to multiple hazards. It does so irrespective of design approach; even when performance-based design has been used to establish structural performance beyond life safety, it typically has focused on hazards individually rather than holistically.

In most fields of professional endeavor, be it emergency responders, insurance and reinsurance companies, or even structural engineers, the consideration of multiple hazards requires some initial decisions as to which specific hazards deserve consideration, and how much time and resources can reasonably be spent to provide an acceptable level of protection to property and/or human life. This typically has been implicitly or explicitly done on the basis of what constitutes a real or perceived threat at a specific point in time. For example, in the first few years following the events of September 11, 2001 (9-11), interest in blast-resistant design grew, and the level of such interest is likely to fluctuate as a function of the number of terrorist attacks occurring domestically over the next few years.

In some disciplines, accounting for some of the most arcane hazards can be easily accommodated. For example, homeowner and business insurance policies typically provide coverage against damage due to debris falling from outer space, such as asteroids, meteors, and even artificial satellites, but because the probability of such impact at any given location is so low, this effectively has no consequence on premiums. However, for structural engineers, considering impact forces from space debris for regular buildings would be a major undertaking, if not an impossible one from a deterministic perspective. Therefore the probabilistic determination of whether any hazard warrants consideration is achieved implicitly through the minimum requirements provided in design codes and standards (embodying the consensus professional opinion of peers), although it sometimes extends beyond that framework when required by client-specific needs. As a result, it is accepted that simple structures generally are designed only to address the conditions most likely to occur, such as dead loads, live loads, temperature changes, rain/snow/ice, fires, wind forces, and earthquakes. It also is accepted that structures having a strategic purpose or whose failures would have enormous undesirable consequences would be designed to survive rarer events, such as accidental or deliberate blasts, tsunamis, impact forces (due to collision with trucks, boats, and even, in some cases, airplanes), and others, with the understanding that some forms of damage may be acceptable.

Although this engineering philosophy in many ways is sound and undoubtedly has served society well in managing the resources of owners and communities, the general public often is surprised to discover, after a damaging specific hazard occurs, that *structural engineering coverage* is not as extensive as expected, and definitely not *all-hazards* comprehensive (except in those circumstances

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where the owners actively have been involved in deciding the level of damage for which they are willing to pay, which is the exception rather than the norm, as demonstrated by past earthquakes). Multihazard design provides opportunities to revisit some aspects of structural engineering practice and investigate new ones, to better understand how to effectively address and enhance many of the design issues generated by a holistic consideration of hazards in design.

As such, this paper provides some perspectives on what multihazard engineering is in the contemporary context, in order to frame the breadth and multiple dimensions it encompasses, to summarize some recent activities on selected relevant topics, and to highlight possible future directions in research and implementations. A comprehensive overview of all research and points of view on these broad topics is beyond the scope of this paper. Rather, the objective is to provide selected examples to illustrate the nature of the issues and possible solutions, with the understanding that multihazard design is a relatively new endeavor and that the accomplishments in this field for the most part lie ahead.

Following a brief review of the political context that has emboldened multihazard design, a brief survey of recent research on the following topics is presented: (1) current return periods and safety indices for various hazards in model design codes; (2) hazard interaction and cascading effects; (3) considerations for interdependent systems; and (4) structural system and element optimization to provide multihazard resistance.

In the context of multihazard design of structures, it is important to present a clear terminology. In the current literature, *design for multihazard resilience*, *design for multihazard robustness*, and *design for multihazard mitigation* are terms that are used interchangeably. Although this terminology essentially is used to communicate the same concept, particular attention should be paid to preventing ambiguity. To this end, Zaghi et al. (2016) presented a definition of terms. They defined *resilience* as an ability to recover quickly from or adjust easily to misfortune or change; for example, during an earthquake, a seismic-resilient building may suffer only minimal damage (i.e., local yielding of beams), which easily can be repaired to recover its functionality. *Resistance* refers to characteristics of a structural system to withstand the effects of a damaging external stressor, such as high wind loads or a corrosive environment. *Robustness* implies the capability of a structural system to maintain its function without failure under a broad range of conditions, or a property of allowing the severity of damage to be minimized in other instances. *Mitigation* means reducing the severity of a negative action or effect. In a robust system, the goal is to minimize or prevent damage in the first place; however, in a resilient system, some level of damage is anticipated, but an additional objective is that the system should recover efficiently. Mitigation may be achieved through design for resilience or robustness of a system or by diminishing the damaging effect of the hazards themselves, independent of their impact on a system. Mitigation measures thus are broader than provisions for robustness and resiliency, which may focus mainly on passive improvement of system responses to hazards.

Grand Challenges for Disaster Reduction

Within the realm of policy making, the necessity to consider all hazards that could produce national disasters has been long recognized, as evidenced for example by the creation in 1988 of the Subcommittee on Disaster Reduction (SDR). The SDR is a federal interagency body mandated to advise the White House's Office of Science and Technology Policy (OSTP) about the risk reduction resources of its 15 chartered federal departments and agencies: Department of Defense (DoD), Department of Energy (DoE), Department of Homeland Security (DHS), Department of Transportation (DoT), National Aeronautics and Space Agency (NASA), National Science Foundation (NSF), and many more (SDR 2016). The SDR has formulated lists of challenges that must be addressed to implement disaster reduction for coastal inundation, drought, earthquake, flood, heat wave, human and ecosystem health, hurricane, landslide and debris flow, space weather, technological disasters, tornado, tsunami, volcano, wildland fire, and winter storm, all brought together under an overarching Grand Challenges for Disaster Reduction plan formulated in 2005 (SDR 2005). These lists of challenges consider each hazard independently. In parallel, research addressing individual hazards has taken place in the last decades to various degrees, through funding from these agencies and various other sources. As a possibly unmatched example, the National Earthquake Hazards Reduction Program (NEHRP), enacted in 1977 as a result of political pressure following the damaging 1964 Alaska and 1971 San Fernando earthquakes (Hamilton 2003), has invested approximately \$3 billion in earthquake-related mitigation and paredness activities, from \$50 million/year in 1978, up to roughly \$120 million/year more recently (U.S. Congress 1995; NEHRP 2014).

At the turn of the century, the collapse of the World Trade Center subsequent to the 9-11 terrorist attack, and devastation along the Gulf Coast due to Hurricane Katrina, shifted the political climate. Many in the earthquake engineering community felt that some of the substantial knowledge that had been created through decades of NEHRP-funded research to address problems related to earthquakes could be extended to enhance resilience against other hazards. One expression of this perception was articulated in a white paper written under the auspices of the Multidisciplinary Center for Earthquake Engineering Research (MCEER), which volunteered perspectives that should be considered in the formulation of a national research strategy for disaster loss reduction in response to the SDR Grand Challenges for Disaster Reduction report (Bruneau et al. 2005). It stated

> A critical part of this research effort should focus on the mitigation of, and response to, the impact of extreme events on critical facilities and lifelines. The failure of these key infrastructure systems is the cause of most of the disruption during and following disasters. In this context, national needs require that solutions be integrated across various hazards. However, the objective to achieve a synergy of solutions across the continuum of hazards is something that has just barely begun to be exploited or even investigated.

The white paper's executive summary recommended ten research initiatives, which remain timely and critical active research endeavors at the time of this writing. Five of the initiatives are directly relevant to structural engineering:

1. "Develop intelligent or 'smart' public buildings and lifelines that provide real-time monitoring and decision making that is useful for both regular maintenance purposes and also for occupant safety, security and health monitoring to allow for rapid evacuation in the event collapse is imminent and for locating survivors within collapsed structures."
2. "Develop reliable methods to design structures to meet several specific performance levels under increasing levels of hazard intensity, providing design/retrofit concepts from a multihazard perspective and overcoming the shortcomings of purely 'life-safety' design procedures."

3. "Investigate how new materials and advanced technologies developed for seismic retrofit can be modified or adapted to provide enhanced resilience of various critical facilities and lifelines against other hazards."
4. "Identify new mitigation strategies and technologies that can provide simultaneous protection against more than one hazard, for a single cost, and similarly develop new technologies that achieve the broadest possible level of protection at the least possible cost, aiming at more uniform, nationwide adoption of these technologies."
5. "Develop technologies to prevent cascading failures of complex lifeline systems that duly consider proximity of critical infrastructures, interoperability of various lifeline systems, and interactions among the institutions operating the lifeline networks, for a broad range of natural, technological and human-induced hazards."

Several of the other five recommendations not presented here benefit from multidisciplinary teaming including input by the structural engineering community. Furthermore, the recommendations to expand the resilience framework presented in Bruneau et al. (2003) to various hazards already has been adopted and expanded upon by various researchers and government agencies [e.g., see Cimellaro (2016) for a comprehensive discussion on resilience].

Whereas Hurricane Katrina led to a resurgence of research funding focused on wind engineering and storm surge, the 9-11 events broadened activities in the fields of blast-resistant design, collapse prevention, fire engineering, and the interaction of these hazards among themselves and with other hazards. However, a structural engineering solution is not always the best solution for all hazards. In fact, for the hazard of plane collisions, the logical solution lay in better-securing access to the cockpits of airplanes; gone are the days when passengers were welcome to visit the pilot—or even sit in the cockpit during landing, a courtesy that the first author once experienced on a commercial flight in a more casual era. Even though significant advances have taken place to address the needed integration of solutions across hazards, the objective to achieve a synergy of solutions across the continuum of hazards remains something that has just barely begun to be exploited or even investigated.

Subsequent sections of this paper explore some of these accomplishments and opportunities. The paper emphasizes topics that can involve structural engineering activities. For example, a review of the extensive remote-sensing technologies developed for earthquake reconnaissance that already have proven their value for other hazards (e.g., Adams and Eguchi 2008; Adams and McMillan 2008; Gusella et al. 2008; McMillan et al. 2008; Womble et al. 2008) is beyond the scope of this paper. Likewise, although 9-11 and Hurricane Katrina acted as catalysts for multihazard integration in policy making, emergency preparedness, responders' activities, and social science research (to name a few), and many funding agencies recognized the need and seized this opportunity to expand their activities/research/operations/planning in these fields to achieve readiness for multiple hazards, those endeavors are not core structural engineering activities and therefore are beyond the scope of this paper.

Cross-Hazard Synergies

Optimistically, it can be expected that reducing vulnerability against a set number of extreme events will simultaneously result in infrastructures that are robust when subjected to other extreme events or even service conditions. However, realistically, this reduced vulnerability for a subset of hazards is not by itself a guarantee for reduced vulnerability to a different set of hazards. With respect to extreme events, although it has been argued or demonstrated that certain types of seismically designed structural systems can indirectly provide benefits against damage or progressive collapse due to some blast scenarios (e.g., Corley et al. 1998; Yi et al. 2014), some solutions commonly used to provide resilience against specific hazards can be detrimental to performance when subjected to other hazards. For example, adding mass is deemed an excellent solution to enhance blast resistance and reduce wind uplift, but additional mass translates into greater inertial forces when it comes to seismic resistance. Likewise, a bridge that is highly robust against blast loads and earthquakes still could be too buoyant to perform adequately during a tsunami or storm surge. When it comes to service conditions, the best design strategies to achieve robustness against multiple hazards still could be implemented with poor details prone to accelerated corrosion or fatigue failure. Thus, although it is true that enhanced integrity and ductility will result from the design of more robust and resilient structures, one should be suspicious of broad generalizations suggesting that expected indirect benefits alone are sufficient to obviate a holistic approach to multihazard design.

Nonetheless, with the above caveat, it remains possible in some cases to identify synergies between hazards that make an integrated multihazard design approach possible. For example, one cannot miss the similarities in bridge span collapses observed after storm surge and earthquakes, illustrated in Figs. 1 and 2, respectively. Although the demands that led to these failures were dramatically different, the vulnerability of bridge bearings to those two hazards was expressed in similar failure modes, which inescapably suggests that a multihazard solution could be developed to enhance performance in both cases. As a result, the viability of translating specific design details or retrofits typically used to target improved performance under one hazard has been suggested for mitigating the adverse effects of others (Padgett et al. 2008).

Although the goal of multihazard engineering is to holistically approach the conflicting demands and complex interaction effects of different hazards in search of unified solutions, it would appear that some hazards are more *compatible* than others when

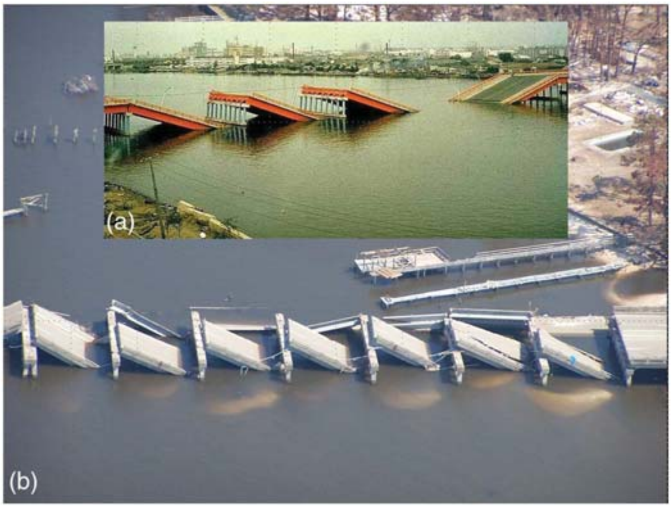

Fig. 1. Similarities in bridge span collapses observed: (a) after the 1964 Niigata earthquake (reproduced from Steinbrugge Collection, NISEE-PEER, University of California, Berkeley, with permission from NISEE-PEER); (b) following the 2005 Hurricane Katrina storm surge near New Orleans (across Lake Pontchartrain) (reprinted from O'Connor and McAnary 2008, photo used with permission, courtesy of MCEER)

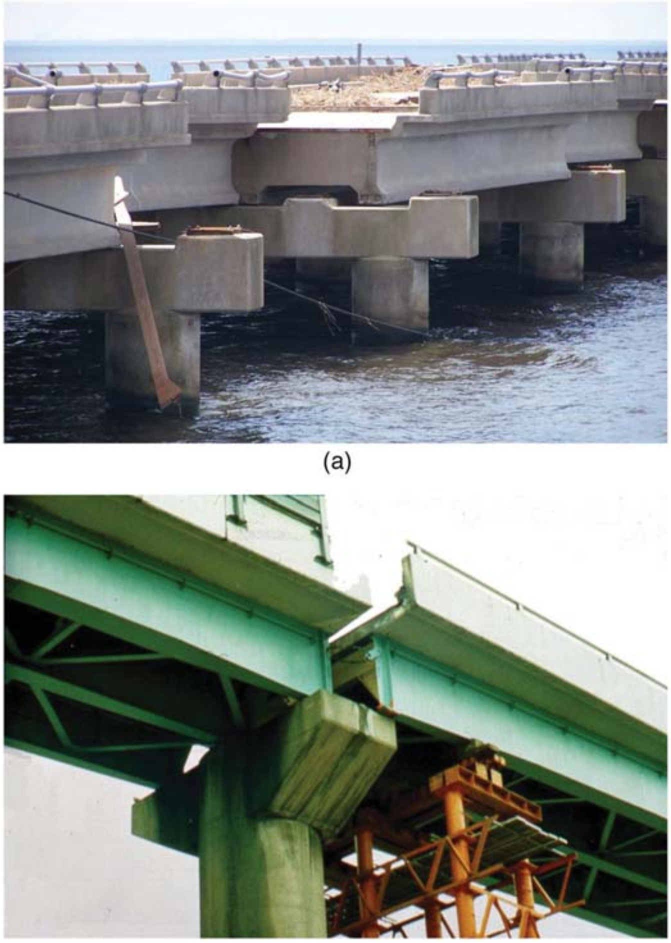

Fig. 2. Similarities in damage to bridge bearings observed: (a) after the 2005 Hurricane Katrina storm surge near New Orleans (across Lake Pontchartrain) (reprinted from O'Connor and McAnary 2008, photo used with permission, courtesy of MCEER); (b) after the 1995 Kobe earthquake (image by Michel Bruneau)

considering structural design. As an example of possibly lower compatibility, structures generally are designed to elastically resist the demands from long-duration, low-frequency hurricane winds, whereas inelastic response is relied upon to survive short-duration, high-frequency, and large-amplitude extreme earthquake and blast forces. In some cases, design parameters optimal for one hazard may be at odds with another, and hence a trade-off in design parameter selection may be made, referred to in the literature as a case of *competing hazards* (Padgett and Kameshwar 2016). However, in contrast, some synergy may be possible when designing concurrently for blast and earthquake forces, even though blasts typically impart inelastic demands in a more localized and asymmetric manner than earthquakes do, and even though the dynamic excitation created by blast and earthquakes are dramatically different in duration and frequency content, and induce responses at significantly different strain rates (Stewart and Durant 2016). Although this synergy definitely is true at the element level of design (as is shown in a later section of this paper), it is less conclusive at the system level for complex structures depending on design approaches and for combinations of hazards considered. For example, in case studies for a 49-story building, Freeman et al. (2005) found that a multihazard design, when the final structural system was selected considering wind and seismic effects simultaneously, led to 3.5% savings of the total cost of the structural system. Those case studies also showed that retrofitting the building to enhance its blast resistance alone could translate into a higher lifecycle cost, because doing so would detrimentally affect its seismic performance.

Future studies are needed to determine how multihazard interactions can affect total structure costs, particularly from a lifecycle perspective, and to shed light on which conditions must exist to achieve beneficial synergies between hazards. From this perspective, it is interesting to note that the federally funded research portfolio on structural engineering research related to hazards currently is distributed across various agencies, with blast-resilient design under DHS, fire-resilient design under the National Institute of Standards and Technology (NIST), and NSF specifically excluding those hazards from its own research portfolio and largely focusing its multihazard research funding on wind and earthquake engineering (although NIST and DHS are expanding their portfolios toward addressing other hazards). This focus separation could create challenges for researchers interested in tackling multihazard research more holistically. The fact that some of these hazards are cascading events, and thus are inextricably interrelated, further complicates the situation (Li et al. 2012a; Zaghi et al. 2016).

Finally, the words *multihazard design* sometimes are misunderstood to refer narrowly to protection against concurrent multiple hazards at their most damaging intensity or near that level. This is not the case. In fact, in many situations this concurrence scenario generally is explicitly excluded from consideration [e.g., Tobias et al. (2014) for Accelerated Bridge Construction (ABC)] and is rarely considered in design unless the severity of consequences warrants it and/or the owner's financial investments or resources can justify it. Traditionally, this position has been supported by the limited studies that have investigated this issue for extreme events of relatively limited durations, because the probability of two severe extreme events occurring at damaging levels is quite low (e.g., Shinozuka et al. 1984; Bhartia and Vanmarcke 1988; Kafali and Grigoriu 2008). As demonstrated in the following sections of this paper, the scope of multihazard design is more complex and broader than the above erroneous and narrow interpretation.

Structural Engineering Issues

Within the realm of structural engineering, the pursuit of multihazard design has proceeded on a number of fronts. The following sections present a summary of recent findings in select fields.

Current Return Periods and Safety Indices for Various Hazards in Model Design Codes

Return periods are the basis for the design events that are stipulated in model design codes, such as ASCE 7-10 (ASCE 2010), but to date the approaches taken to characterize them have not been uniform. The following review of recent practice highlights some of the discrepancies in approaches.

Currently, the return periods associated with natural hazards that can cause significant economic losses, social disruption, and downtime in the local business community differ for a number of reasons. For example, the design return period for wind hazard typically is shorter than that for earthquakes, for many economical, engineering, and pragmatic reasons; e.g., because the threat to life safety from hurricanes is mitigated by advanced warning systems (Li and Ellingwood 2009). In comparison, the lack of advanced warning makes the life-safety objective paramount for earthquakes (Li and van de Lindt 2012). In addition, structural responses are more predictable and mainly linear for structural members in the main frame of buildings under wind loads, whereas the responses may be nonlinear under severe earthquakes. It should be noted that the response of elements such as those in the envelope system can be complex during both hurricanes and earthquakes. The design wind speed defined by the peak 3-s gust wind in ASCE 7-98 (ASCE 1998) through ASCE 7-05 (ASCE 2005) was based on a 50-year return period for areas in the central United States, whereas along the coast it corresponded roughly to a 100-year return period for the Allowable Strength Design (ASD) method and 700-year return period for the Load and Resistance Factor Design (LRFD) method (Li and Ellingwood 2009). Note that the 3-s gust wind speed was introduced in ASCE 7-95 (ASCE 1995) to replace fastest-mile wind speeds. Starting in ASCE 7-10, Risk Category replaced the term Occupancy Category. There are four Risk Categories, ranging from lowest hazard to human life (Category I) to highest hazard to human life (Category IV). Table 1.5-1 in ASCE 7-10 defines the risk categories of buildings and other structures subjected to flood, wind, snow, earthquake, and ice hazards, which are based on the risk associated with unacceptable performance (ASCE 2010).

ASCE 7-10 wind maps were based on the LRFD-method wind speeds, as opposed to the ASD-method wind speeds that were used in the previous ASCE 7 specifications. The goal was to provide a more consistent and uniform reliability under various loading conditions (ASCE 7-10). ASCE 7-10 introduced three new basic wind speed maps with much longer return periods, including a 300-year return period, or 15% probability of exceedance in 50 years for Risk Category I; a 700-year return period, or 7% probability of exceedance in 50 years for Risk Category II; and a 1,700-year return period, or 3% probability of exceedance in 50 years for Risk Categories III and IV. Consequently, the factor for wind load to use in the load combination listed in Section 2.3.2 of ASCE 7-10 (ASCE 2010) changed from 1.6 to 1.0. The Applied Technology Council (ATC) provides a website (http://www.atcouncil.org/windspeed/) that lists site-specific wind requirements (including wind speed values for return periods of 10, 25, 50, 100, 300, 700 and 1,700 years) or any specific location in the United States.

Table 1. Importance Factors by Risk Category of Buildings and Other Structures for Snow, Ice, and Earthquake Loads (Reprinted from ASCE 2010, Table 1.5-2, © ASCE)

Risk category from Table 1.5-1	Snow importance factor, I_s	Ice importance factor—thickness, I_i	Ice importance factor—wind, I_w	Seismic importance factor, I_e
I	0.80	0.80	1.00	1.00
II	1.00	1.00	1.00	1.00
III	1.10	1.25	1.00	1.25
IV	1.20	1.25	1.00	1.50

Note: The component importance factor, I, applicable to earthquake loads, is not included in this table because it is dependent on the importance of the individual component rather than that of the building as a whole, or its occupancy. Refer to Section 13.1.3 (ASCE 2010).

Until recently (i.e., from ASCE 7-05), the ground motion parameters for seismic design were set as those corresponding to earthquakes having a return period of 475 years. Conversely, seismic hazard maps were provided in terms of spectral acceleration for a 2% probability of exceedance in 50 years [abbreviated here as a 2%/50-year event and termed the *Maximum Considered Earthquake (MCE)* in ASCE 7-05], corresponding to a 2,475-year return period. The design spectral acceleration shall be taken as 2/3 of the seismic intensity corresponding to the MCE and adjusted for site class effects. Starting with ASCE 7-10, the uniform-hazard ground motion (2% probability in 50-year seismic hazard level) was replaced by a risk-targeted (e.g., 1% probability of collapse in 50-year) ground motion (Luco et al. 2007; FEMA 2009).

For flooding, the return period is 100 years, which is equivalent to the flood having a 1% probability of exceedance in any given year (ASCE 2010). Snow loads were developed from a statistical analysis of weather records of snow on the ground (Ellingwood and Redfield 1983), which have a 50-year return period (2% annual probability of exceedance).

The minimum design loads for structures need to include the applicable importance factors given in Table 1.5-2 of ASCE 7-10 for seismic, snow, and ice loads (Table 1). The importance factors for wind loads have been deleted with the adoption of the new wind hazard maps that consider the different return periods associated with various risk categories, as discussed previously.

In probability-based limit state design, the reliability index, β, is related to the probability of failure by $P_f = \Phi(-\beta)$, where Φ denotes the standard normal cumulative distribution function. The reliability benchmarks differ for various limit states. When the failure mode is relatively ductile and consequences are not serious, β typically is in the range of 2.5–3.0. In comparison, when the failure mode is brittle and consequences are severe, β is at least 4.0. The target reliabilities are based on a survey of reliabilities inherent in existing design practice. The load factors presented in Section 2.3.2 of ASCE 7-10 and the resistance factors in the LRFD method were determined to meet these reliability objectives (Ellingwood et al. 1982; Galambos et al. 1982; ASCE 2010). Specifically, the load combinations and the companion resistances should provide reliabilities approximately similar to those indicated in Tables C.1.3.1a and C1.3.1b of ASCE 7-10, which are shown in Tables 2 and 3. Table 2 provides the reliability indexes, β, for a 50-year service period, whereas the probabilities of failure have been annualized. Table 3 shows the anticipated reliability for earthquake loading, in which the probability of failure is a conditional probability on maximum considered earthquake shaking or maximum considered effects.

The AASHTO codes for transportation facilities followed considerations similar to those used to develop load and resistance factors, and reliability indices for buildings and other structures in the different versions of ASCE 7. In particular, Nowak (1993, 1995) and Nowak et al. (1994) provided the probabilistic basis for the development of LRFD in the AASHTO manual for rating (AASHTO 2003) and design (AASHTO 2004) of highway bridges.

Table 2. Acceptable Reliability (Maximum Annual Probability of Failure) and Associated Reliability Indexes (β) for Load Conditions That Do Not Include Earthquake: Occupancy Category (Reprinted from ASCE 2010, Table C.1.3.1a, © ASCE)

Basis	I	II	III	IV
Failure that is not sudden and does not lead to widespread progression of damage	$PF = 1.25 \times 10^{-4}/\text{year}$ $\beta = 2.5$	$PF = 3.0 \times 10^{-5}/\text{year}$ $\beta = 3.0$	$PF = 1.25 \times 10^{-5}/\text{year}$ $\beta = 3.25$	$PF = 5.0 \times 10^{-6}/\text{year}$ $\beta = 3.5$
Failure that is either sudden or leads to widespread progression of damage	$PF = 3.0 \times 10^{-5}/\text{year}$ $\beta = 3.0$	$PF = 5.0 \times 10^{-6}/\text{year}$ $\beta = 3.5$	$PF = 2.0 \times 10^{-6}/\text{year}$ $\beta = 3.75$	$PF = 7.0 \times 10^{-7}/\text{year}$ $\beta = 4.0$
Failure that is sudden and results in widespread progression of damage	$PF = 5.0 \times 10^{-6}/\text{year}$ $\beta = 3.5$	$PF = 7.0 \times 10^{-7}/\text{year}$ $\beta = 4.0$	$PF = 2.5 \times 10^{-7}/\text{year}$ $\beta = 4.25$	$PF = 1.0 \times 10^{-7}/\text{year}$ $\beta = 4.5$

Table 3. Anticipated Reliability for Earthquake (Adapted from ASCE 2010, Table C.1.3.1b, © ASCE)

Risk category	Description
Risk categories I and II	
Total or partial structural collapse	10% conditioned on the occurrence of maximum considered earthquake shaking
Failure that could result in endangerment of individual lives	25% conditioned on the occurrence of maximum considered effects
Risk category III	
Total or partial structural collapse	6% conditioned on the occurrence of maximum considered earthquake shaking
Failure that could result in endangerment of individual lives	15% conditioned on the occurrence of maximum considered earthquake shaking
Risk category IV	
Total or partial structural collapse	3% conditioned on the occurrence of maximum considered earthquake shaking
Failure that could result in endangerment of individual lives	10% conditioned on the occurrence of maximum considered earthquake shaking

The treatment of hazards generally has been similar to what was described previously for buildings, but with some differences in emphasis, analysis, and design approaches, and not necessarily in agreement.

Most areas of the world are subjected to one or more independent natural hazards, such as earthquakes, tsunamis, hurricanes (cyclones), snow storms, costal inundation, and/or river flooding (Corotis 2007; Li et al. 2012a). For example, in Charleston, South Carolina both hurricane and earthquake hazards pose a threat to the built environment (Li and Ellingwood 2009), even though the probability of both hazards occurring simultaneously is virtually zero. In such areas, building design and construction practices should address both hazards in an integrated manner. Li and Ellingwood (2009) compared the damage risk due to both hazards based on hazard return period, design parameters (wind speed versus spectral acceleration), and annual probability of damage for eight locations in the United States. Fig. 3 shows the probability of hurricane and earthquake damage to a residence with the minimum construction practices in Charleston as a function of the return period.

Wen and Kang (2001) proposed a general lifecycle cost analysis framework for buildings subject to single and multiple hazards. This framework can be used to minimize the expected total lifecycle cost of a building given the design load and resistance. It explicitly accounts for (1) load and resistance variability; (2) costs of construction, maintenance, and failure consequences; (3) discounting cost over time; and (4) structural life length. The authors found that for multiple hazards the optimal design generally is controlled by hazards that have large uncertainty and/or severe failure consequences. Salman and Li (2016) presented a framework for multihazard risk assessment of electric power systems subjected to seismic and hurricane wind hazards. The framework included hazard and structural component vulnerability models, system reliability analysis, and multihazard risk assessment. Potra and Simiu (2009) examined how to achieve safer and more economical designs for structures exposed to multiple hazards. Li and van de Lindt (2012) summarized a loss-based formulation to evaluate the risk to buildings from multiple hazards. Table 4 shows the annual probability of various levels of loss (e.g., 10–30% of replacement value) for an example two-story timber building exposed to hurricane wind, earthquake, snow, and flood hazards at four representative locations in the United States. Duthinh and Simiu (2014) discussed issues in codification of load combination criteria for regions subjected to both earthquakes and hurricanes. Kameshwar and Padgett (2014) evaluated the risk profile to bridges exposed to earthquakes and hurricane induced storm surge and wave loading, highlighting the influence of parameter variation on the relative risk profile for multiple hazards.

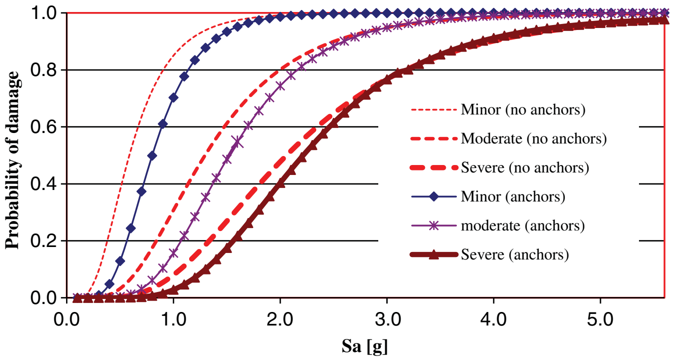

Fig. 3. Probability of hurricane and earthquake damage (Charleston) (reprinted from Li and Ellingwood 2009, © ASCE)

In spite of all the above recent developments, model codes fundamentally continue to treat each hazard individually, and with different approaches with respect to return period and safety indexes. However, although nothing has been formalized at the time of this writing (to the best of the authors' knowledge), some model code committees have undertaken efforts toward addressing multihazard issues.

Hazard Interaction and Cascading Effects

One of the complexities associated with a multihazard approach in structural engineering is the understanding and modeling of hazard interactions and cascading effects. Gill and Malamud (2014) presented a detailed literature review and classification of natural hazard interactions. They investigated the spatial and temporal scales for 21 natural hazards divided into five hazard groups (i.e., geophysical, hydrological, shallow earth processes, atmospheric, and biophysical hazards). Based on a literature review and on the analysis of relevant case studies, they classified four categories of hazard interactions: (1) interactions which trigger a hazard, (2) interactions which increase the probability of a hazard, (3) interactions which decrease the probability of a hazard, and (4) events involving the spatial and temporal coincidence of natural hazards. They also evaluated the extent to which secondary hazards (i.e., triggered effects) can be forecasted given that the primary hazard event has occurred (triggering effect) based on the concepts of spatial overlap and temporal likelihood. Finally, they identified the explicit analysis of hazard interactions as the main feature of a proper holistic multihazard approach to assessing hazard potential. To better highlight this feature, they introduced the term *multilayer single hazard* approaches for methodologies that are based on the independent analysis of multiple different hazards. Zaghi et al. (2016) suggested a similar differentiation between multihazard and multiple hazard design approaches, and noted that "modern design codes account for concurrence and combinations of multiple hazards by suggesting load combinations and load factors intended to include

Table 4. Annual Probability of Loss at Representative Sites Subjected to Multiple Hazards (Data from Li and van de Lindt 2012)

			Lower standard—R1			Higher standard—R2		
			Fragility parameters		Annual probabiliy of loss	Fragility parameters		Annual probability of loss
Site	Hazard	Loss (%)	λ_R	ζ_R		λ_R	ζ_R	
Biloxi, Mississippi	Hurricane	5–10	4.250	0.163	0.264	4.648	0.162	0.080
	Weibull	10–30	4.340	0.164	0.214	4.743	0.173	0.055
	$\mu = 58.96$	30–50	4.556	0.197	0.118	4.907	0.098	0.018
	$\alpha = 1.725$	50–100	4.641	0.161	0.082	5.016	0.153	0.011
	Flood	5–10	ABV to		0.00376	ABV to		1.58×10^{-6}
	Gumbel	10–30	determine annual		0.00011	determine annual		8.55×10^{-8}
	$\mu = -30.46$	30–50	loss		9.50×10^{-11}	loss		3.99×10^{-14}
	$\alpha = -0.162$	50–100			7.90×10^{-15}			0
Yakima, Washington	Seismic	1–5	0.348	0.480	5.30×10^{-5}	0.723	0.493	2.30×10^{-5}
	Power law	5–10	0.553	0.543	3.90×10^{-5}	0.944	0.533	1.55×10^{-5}
	$k_o = 6.37 \times 10^{-5}$	10–30	0.607	0.548	3.50E-05	0.998	0.534	1.37×10^{-5}
	$K = 2.288$	30–50	0.709	0.536	2.70×10^{-5}	1.058	0.524	1.16×10^{-5}
		50–100	0.775	0.542	2.30×10^{-5}	1.097	0.503	1.00×10^{-5}
	Snow	5–10	4.144	0.290	0.00197	4.225	0.287	0.00145
	Lognormal	10–30	4.376	0.299	0.00086	4.554	0.302	0.00043
	$\lambda = 1.61$	30–50	4.662	0.301	0.00027	4.846	0.297	0.00012
	$\zeta = 0.83$	50–100	5.070	0.302	0.00004	5.252	0.303	0.00002
Fargo, North Dakota	Flood	5–10	ABV to		0.02348	ABV to		0.001786
	Gumbel	10–30	determine annual		0.00723	determine annual		0.000677
	$\mu = -65.385$	30–50	loss		7.00×10^{-5}	loss		5.30×10^{-6}
	$\alpha = -0.0539$	50–100			3.10×10^{-6}			6.13×10^{-7}
	Snow	5–10	4.144	0.290	0.014	4.225	0.287	0.011
	Lognormal	10–30	4.376	0.299	0.0074	4.554	0.302	0.0044
	$\lambda = 2$	30–50	4.662	0.301	0.0032	4.846	0.297	0.0017
	$\zeta = 0.93$	50–100	5.070	0.302	0.0008	5.252	0.303	0.0004
Charleston, South Carolina	Hurricane	5–10	4.250	0.163	0.148	4.648	0.162	0.040
	Weibull	10–30	4.340	0.164	0.116	4.743	0.173	0.027
	$\mu = 43.47$	30–50	4.556	0.197	0.061	4.695	0.097	0.028
	$\alpha = 1.402$	50–100	4.641	0.161	0.041	5.016	0.153	0.005
	Seismic	1–5	0.348	0.480	0.001	0.723	0.493	0.000
	Power law	5–10	0.553	0.543	0.00042	0.944	0.533	0.00027
	$k_o = 0.000647$	10–30	0.607	0.548	0.00040	0.998	0.534	0.00026
	$K = 1.091$	30–50	0.709	0.536	0.00035	1.058	0.524	0.00024
		50–100	0.775	0.542	0.00033	1.097	0.503	0.00023
	Flood	5–10	ABV to		0.00644	ABV to		3.62×10^{-5}
	Gumbel	10–30	determine annual		0.0006	determine annual		5.18×10^{-6}
	$\mu = -42.692$	30–50	loss		5.60×10^{-8}	loss		3.11×10^{-10}
	$\alpha = -0.108$	50–100			1.10×10^{-10}			4.14×10^{-12}

Note: Units for fragility parameters λ_R: Hurricane (mph); Snow (psf); Flood (ft).

uncertainties and significance of different hazards," whereas "multihazard design requires an in-depth understanding of the nature of various hazards and their interactions." Garcia-Aristizabal and Marzocchi (2013) categorized multihazard assessment into two possible processes: (1) "assessing different (independent) hazards threatening a given (common) area," and (2) "assessing possible interactions and/or cascade effects among the different types of hazardous events." They concluded that a holistic multihazard approach should include both processes. Zaghi et al. (2016) also identified two levels of hazard interactions: (1) interactions through the nature of hazards (Level I interactions), which encompass the interactions that are independent of the presence of structural or infrastructure components; and (2) interactions through the effects of hazards (Level II interactions), which comprise the interactions through "site effects, impacts on physical components, network and system disruptions, and social and economic consequences." The classification of hazard interactions proposed by Gill and Malamud (2014) focuses on the hazards considered independently from their effects on structures and infrastructures, and thus applies only to the Level I interactions as defined in Zaghi et al. (2016).

This paper reviews current research on hazard interactions and cascading effects with respect to structural applications in terms of a combination of classifications from Gill and Malamud (2014) and Zaghi et al. (2016). Note that some interactions are combinations of different effects (e.g., triggering effects also can modify hazard probabilities and/or modify the impacts of the different hazards on physical components) and the classifications used in this paper have some components of subjectivity in the identification of the predominant feature of the interactions considered.

Hazard Interactions Which Trigger a Hazard

Significant research efforts have been devoted to investigating the interaction between primary hazards (triggering effects) and secondary hazards (triggered effects). Within a multihazard approach as defined by Zaghi et al. (2016), the investigation of primary/secondary hazard interactions should involve (1) the probabilistic characterization of the secondary hazards given the primary hazard event (e.g., triggering probability and intensity distribution); and (2) the evaluation of the joint effects on structural response, damage, and losses produced by the combined actions from primary and secondary hazards (e.g., structural behavior under secondary hazards of the structure as damaged by the primary hazard).

In the field of earthquake engineering, particular attention has been given to mainshock–aftershock sequences. Older studies focused on forecasting the properties of the aftershocks given the mainshock (Omori 1894; Utsu 1961; Båth 1965). The following paragraph briefly describes more recent studies which focused on the effects of mainshock–aftershock sequences on structural response and performance through the use of nonlinear dynamic finite-element analysis.

Yin and Li (2011a) developed an object-oriented framework to estimate seismic losses of light-frame wood buildings subject to mainshock–aftershock sequences. They used homogeneous and nonhomogeneous Poisson processes to simulate series of mainshock–aftershock sequences and adopted back-to-back mainshock–aftershock nonlinear dynamic analysis to determine the maximum interstory drift attributable to each earthquake occurrence. They concluded that aftershocks and downtime cost are important contributors to total seismic losses. Ruiz-García and Negrete-Manriquez (2011) investigated the peak and residual drift demands of steel framed buildings under as-recorded mainshock–aftershock seismic sequences. They found that the frequency contents of mainshock and main aftershock are only weakly correlated for as-recorded seismic sequences. They concluded that as-recorded aftershocks do not significantly increase peak and residual drift demands, and artificial seismic sequences could significantly overestimate these demands. Nazari et al. (2015) integrated aftershock hazard into performance-based earthquake engineering (PBEE) for wood-frame buildings. They used incremental dynamic analysis (IDA) based on a sequence of mainshock–aftershock ground motions to develop aftershock fragilities. They found that aftershocks have a small effect on collapse probability for buildings that survive the mainshock and that the effect of aftershocks is relatively more significant on damage states other than collapse for low-rise wood-frame buildings. They concluded that the inclusion of aftershock hazard can significantly affect performance-based seismic design of low-rise wood-frame buildings. Zhang et al. (2013) investigated aftershock effects on the accumulated damage of concrete gravity dams. They used nonlinear dynamic finite-element analysis in conjunction with 30 as-recorded mainshock–aftershock seismic sequences to estimate the seismic damage process of a concrete gravity dam, and found that the as-recorded sequences of ground motions have a significant effect on the accumulated damage and on the design of concrete gravity dams. Li et al. (2014) investigated the collapse probability of mainshock-damaged steel buildings in aftershocks as an essential part of developing a framework to integrate aftershock seismic hazard into PBEE. Ribeiro et al. (2014) proposed a reliability-based framework for quantifying the structural robustness of steel buildings subject to mainshock–aftershocks sequences. They subjected two-dimensional nonlinear finite-element models of buildings designed using pre-Northridge codes to multiple mainshock–aftershock seismic sequences to estimate a reliability-based robustness indicator. They observed that aftershocks have a significant effect on the robustness indicator and that the structural robustness is influenced by the structure's capability to redistribute damage. Ghosh et al. (2015) presented a framework for modeling seismic damage accumulation in bridges. They explored the evolution of damage potential using predictive models of bridge behavior under repeated earthquake events along with a time-dependent aftershock hazard occurrence rate and nonhomogeneous Poisson process assumption. Dong and Frangopol (2015) extended this framework for probabilistic seismic performance assessment of highway bridges subjected to mainshock–aftershocks sequences to investigate probabilistic direct loss, indirect loss, and resilience metrics of bridges. Song et al. (2016) proposed a framework for probabilistic loss estimation of steel structures subjected to mainshock–aftershock sequences, and found that even if the aftershock effects on structural response are small, they still may have a significant impact on seismic loss.

Other aspects that have received significant attention from researchers are the investigation of the relation between volcanic eruptions and triggered earthquakes (e.g., Walter and Amelung 2006; Feuillet et al. 2006; Neri et al. 2008, 2013; Jiménez et al. 2009) and between early seismic activity and subsequent eruptions (e.g., Harrington and Brodsky 2007; Gabrieli et al. 2015; White and McCausland 2016; Bonini et al. 2016). However, the literature on multihazard effects of volcanic eruptions and corresponding triggered effects on structural systems is very limited. Zuccaro et al. (2008) proposed a model to assess the impact of different volcanic hazards (including earthquakes, pyroclastic flows, and ash falls) on masonry and reinforced concrete (RC) building structures. Baxter et al. (2008) developed an evidence-based approach using event tree scenarios to quantify the consequences of an eruption at Vesuvius. They investigated the risk assessment for disaster planning and the potential risk–benefit of different mitigation measures, including timely evacuation, building protection, and hardening of infrastructure systems and lifelines.

Other earthquake-triggered hazards have been extensively investigated, such as earthquake and soil liquefaction (Bowers 2007; Kramer et al. 2008; Elgamal et al. 2008; Zhang et al. 2008; Brandenberg et al. 2011), earthquake and tsunami (Akiyama and Frangopol 2014a; Burns 2015), earthquake and landslides (Kojima et al. 2014; Zhang et al. 2014), earthquake and fire (Sekizawa et al. 2003; Chen et al. 2004; Kim 2014; Imani et al. 2015a, b; Meacham 2016), and earthquake and blast (Fujikura and Bruneau 2008, 2012; Jalayer et al. 2011). In particular, Jalayer et al. (2011) proposed a methodology to evaluate the expected lifecycle cost of a critical infrastructure subject to multiple hazards and applied the proposed methodology to the case of earthquake and blast. This methodology accounts for both the uncertainty in the occurrence of different extreme hazardous events and the deterioration of the structure due to different subsequent extreme events. The literature regarding the interaction between other primary hazards and their triggered effects is comparatively scarcer, e.g., see Wu and Hao (2005) and Haciefendioğlu et al. (2015) for blast-induced ground motion and Butler et al. (1991) for landslide-induced floods.

Hazard Interactions Which Increase or Decrease Probability of a Hazard

Kappes et al. (2010, 2012a) described the effects of one hazard that can change environmental conditions and thus affect the frequency and/or the magnitude of other hazards. Under these conditions, one hazard does not directly trigger another hazard, but it can modify (positively or negatively) the probability of occurrence and the intensity of hazardous events. It is noteworthy that most of the existing research tends to focus on hazard interactions that increase undesirable hazard effects (Gill and Malamud 2014).

Hazard interactions which increase or decrease the probability of a hazard have been extensively investigated. In hurricane engineering, several studies have clearly highlighted the importance of the interaction among hazards. Vickery et al. (2006a, b) proposed appropriate wind–windborne debris damage states for residential buildings, which were integrated within the *HAZUS-MH* hurricane model methodology (FEMA 2012). Womble et al. (2006)

developed a joint hurricane wind–surge damage scale based on a loss-consistent approach. Phan et al. (2007) proposed a methodology for creating site-specific joint distributions of combined hurricane wind and surge. They combined the use of full hurricane tracks to estimate the wind speed, and the Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model (Jelesnianski et al. 1992) to evaluate the corresponding surge heights. Lin and Vanmarcke (2010a, b) proposed a vulnerability model that explicitly included the effects of correlation between wind-borne debris and wind pressure damage. Li et al. (2012) estimated the combined losses caused by hurricane wind, storm surge, and rainwater intrusion for residential buildings. Pita et al. (2012) proposed a methodology for assessment of hurricane-induced interior building damage by considering the co-occurrence of wind and rain. Li and van de Lindt (2012) considered the use of joint statistical distributions to characterize the combined effects of wind, wave height, and current velocity in the ocean. Li et al. (2012) and Park et al. (2014) used an assembly-based vulnerability procedure combined with mechanistic response modeling for hurricane wind-surge loss estimation, in which the hurricane-induced surge heights were based on the three hurricane parameters (i.e., radius to maximum wind speed, maximum wind speed, and central pressure deficit) obtained from historical hurricanes. Bjarnadottir et al. (2013) expanded this procedure to investigate regional loss estimation due to hurricane wind and hurricane-induced surge considering climate variability, with three case study locations (Miami-Dade County, Florida; New Hanover County, North Carolina; and Galveston County, Texas). Pei et al. (2014) developed joint hazard maps of combined hurricane wind and surge for Charleston, South Carolina, and Pang et al. (2014) performed a loss analysis for the same location considering these joint hazard maps. Rosowsky et al. (2016) investigated the impact of climate change on the joint wind–rain hurricane hazard for the northeastern U.S. coastline. Mudd et al. (2017) developed a joint probabilistic hurricane wind–rainfall model for numerical simulation of tropical cyclones. Based on simulation results including climate change effects, they concluded that hurricanes are projected to intensify and reduce in size.

More recent research efforts have been dedicated to the extension of the performance-based engineering philosophy to hurricane engineering. Based on the total probability theorem, Barbato et al. (2013) developed a performance-based hurricane engineering (PBHE) framework for risk assessment and loss analysis of structural and infrastructure systems subject to hurricane hazard. The proposed PBHE framework considered the multihazard nature of hurricane events, the interaction of different hazard sources (i.e., wind, wind-borne debris, storm surge, and rain), and the potential cascading effects of these distinct hazards. Unnikrishnan and Barbato (2017) used the PBHE framework to investigate the effects of interaction among wind, wind-borne debris, storm surge, and rain hazards on the loss analysis for wood-frame houses in hurricane-prone regions. They examined the use of different hazard-modeling techniques and vulnerability analysis approaches and proposed a new consistent terminology to classify different hazard-modeling techniques. They concluded that the use of different hazard models and vulnerability approaches can significantly affect the loss analysis results for low-rise wood-frame houses subject to hurricane hazard.

Interaction effects between flood and sea-level rise also have received significant attention from several researchers. Nicholls et al. (1999) investigated the potential impact of sea-level rise and coastal subsidence on coastal flooding and coastal wetland losses at both global and regional levels. When accounting for the expected increase in coastal population, they predicted that by the 2080s (1) the number of people yearly affected by storm surge flood will be more than five times higher compared with a scenario with constant sea level, and (2) up to 22% of the world's coastal wetlands will be lost due to sea-level rise. Purvis et al. (2008) presented a methodology to estimate the probability of future coastal flooding when accounting for sea-level rise uncertainty. Hinkel et al. (2014) assessed coastal flood damage and adaptation costs under 21st century sea-level rise on a global scale. They took into account uncertainties in continental topography data, population data, protection strategies, socioeconomic development, and sea-level rise. They concluded that expected flood damages by the end of the 21st century are more sensitive to the adopted protection strategy than to climate and socioeconomic changes.

A few studies considered other hazard interactions in which the probability of occurrence of a hazard is modified. Bunya et al. (2010) and Dietrich et al. (2010) developed a coupled riverine flow, tide, wind, wind wave, and storm surge model for southern Louisiana and Mississippi and applied it to model the effects of Hurricanes Katrina and Rita. Several studies focused on modeling and prediction of rainfall-induced slope failures (e.g., Crosta and Frattini 2003; Arnone et al. 2011; Chen et al. 2016). Cannon et al. (2008, 2010) investigated the increased probability of debris flows in areas affected by wildfires.

Hazard Interactions due to Spatial and/or Temporal Coincidence of Natural Hazards

Hazard interactions due to spatial and/or temporal coincidence of natural hazards traditionally have been considered using factored load coefficients, as done, for example, in ASCE 7-10 (ASCE 2010). However, this approach neglects potential compounding effects among concurring hazards (Tarvainen et al. 2006; Gill and Malamoud 2014) and conditions in which different uncorrelated hazards may act at the same time with intensities that are smaller than their design intensities.

Research focusing on this particular hazard-interaction type is relatively scarce. Several researchers (Chester 1993; Umbal and Rodolfo 1996; Self 2006) investigated the eruption of Mount Pinatubo in 1991, which coincided with Typhoon Yunya. The combination of heavy rainfall from the typhoon and thick ash deposits from the eruption triggered lahars and structural failures due to the significant additional gravity loads associated with the presence of wet ash (Chester 1993). Wahl et al. (2015) investigated the increasing risk of flooding due to compounding effects of storm surge and heavy rainfall in the U.S. Yin and Li (2011b) proposed a probabilistic loss assessment methodology of light-frame wood construction subjected to combined effects of seismic and snow loads. This approach explicitly accounted for snow accumulation.

Hazard Interactions through Impacts on Physical Components

Hazard interactions through impacts on physical components are those interactions in which the effects of a hazard on structural performance are magnified by the changes produced on the considered structure by another hazard (e.g., modification of the dynamic properties and strength reduction due to existing damage). This section focuses on studies that have explicitly investigated these specific cascading effects.

Interactions between scour and seismic action on the structural response and performance of bridges (which, arguably, could also be considered spatially and temporally coinciding events) have been widely examined. Alipour and Shafei (2012) developed seismic fragility curves for RC bridges under different scour scenarios. They used nonlinear finite-element time history analysis to evaluate the seismic response of bridge structures affected by scour. They considered the uncertainties associated with scour depth and modeled the scour effect on bridges by increasing the length of the piers by an amount equal to the scour depth. From the fragility curves developed using the joint probabilities of scouring and seismic loading, they concluded that the lateral load bearing capacity of a bridge decreases with the increase of the scour depth. Alipour et al. (2013) used the same finite-element modeling approach to (1) evaluate the failure probability for bridges subject to a combination of scour and seismic loads, and (2) determine scour–load modification factors to satisfy code-specified design requirements. Wang et al. (2012) presented a methodology to derive earthquake–scour fragility surfaces for bridges. Based on preliminary results obtained from two benchmark bridges, they highlighted the effects of foundation overstrength on bridge fragility, with failure modes that can move from the piers to the foundation piles for increasing scour depth. Prasad and Banerje (2013) also investigated the effects of flood-induced scour on bridge seismic fragility curves and concluded that the fragility increases nonlinearly with the increase of scour depth. Liang and Lee (2013a, b) presented a probability-based methodology to estimate the combined hazard effects on bridge reliability due to truck loads, earthquake actions, and scour effects. Wang et al. (2014a, b) investigated the influence of scour on the response of RC bridges and presented the calibration of partial load factors for design of RC bridges under the combined hazard effects of earthquake and scour.

Another structural engineering subfield that has attracted extensive research interest is the analysis of aging effects on the performance of structures subjected to different hazards. Numerous studies investigated the time-variant response, fragility, reliability, lifecycle cost, and sustainability of RC elements and structures subject to corrosion and seismic hazards (e.g., Choe et al. 2008; Kumar et al. 2009; Li et al. 2009; Simon et al. 2010; Ghosh and Padgett 2010, 2011, 2012; Akiyama et al. 2011; Alipour et al. 2011; Rokneddin et al. 2013; Akiyama and Frangopol 2014b; Thanapol et al. 2016). A few researchers have considered the combined effects of aging and hazards other than seismic loading; Padgett et al. (2010) investigated the aging effects on the dynamic response of RC bridges subjected to seismic and coupled surge/wave loading induced by hurricanes, and Guo et al. (2011) performed a probabilistic assessment of the performance of aging prestressed concrete bridges under increased vehicle loads.

The interactions of other hazards through their effects on structural systems also have received some attention. Kudzys (2006) investigated the time-dependent reliability of power transmission structures under combined extreme windstorm, ice deposit, and broken conductor events. Unobe and Sorensen (2015) considered the detrimental effects of wind fatigue on a wind turbine foundation and studied the corresponding increase in failure probability under seismic loading. Unnikrishnan and Barbato (2016) used the PBHE framework to compare different storm mitigation techniques for low-rise residential building subject to combined wind and wind-borne debris hazards. The analysis included the cascading effects related to changes in the interior pressure coefficients due to breaching of the building envelope by wind-borne debris. They observed that, for the specific application example considered in their paper, explicitly including the interaction between wind and wind-borne debris produced expected annual loss estimates approximately 15% higher than the sum of the expected annual losses due to each individual hazard. They concluded that a significant level of interaction existed among the different hazards for the case study considered.

Approaches for Distributed Infrastructure

Multihazard design and risk assessment can be extended beyond emphasis on individual structures to address the multihazard performance of infrastructure, including regional portfolios of structures and infrastructure systems comprised of multiple networked components. This section reviews the current state and unique considerations when extending the multihazard assessment and design concepts previously presented for individual structures to evaluate the performance of spatially distributed infrastructure. Portfolios of structures are considered as regional inventories of structures, such as portfolios of school buildings, residential housing, or bridges. Infrastructure systems are interconnected components that collectively provide services necessary to support social and economic activity. Although critical infrastructure systems also have been defined in the literature to include organizational systems, financial systems, and human capital and services (Moteff and Parfomak 2004), this section focuses on extending multihazard concepts specifically for distributed physical infrastructure systems (e.g., transportation, power, water supply, and telecommunications systems).

A number of frameworks have been proposed in the literature or incorporated into regional risk assessment and loss estimation packages to evaluate the performance of distributed infrastructure in the face of multiple hazards (Ayyub et al. 2007; Kappes et al. 2012b; van Westen et al. 2014; FEMA 2015; Hackl et al. 2015; Clarke and Obrien 2016). These works vary in their address of multihazard effects, such as the simultaneous occurrence of two or more hazards or the influence of triggered or cascading hazards on network performance. More commonly, relative risks from different hazards are assessed individually and compared (Grünthal et al. 2006; Schmidt et al. 2011). Such an assessment for networked infrastructure requires (1) definition of a mathematical model for the network, (2) identification of criteria for the analysis (i.e., system performance indicators such as resistance, connectivity, flow, serviceability, or associated costs), and (3) analysis of the physically varying network model when subjected to individual or multiple hazards using either a deterministic or a probabilistic method to determine the performance. The approach to infrastructure system abstraction (e.g., through planar graphs, shortest paths, or series–parallel systems) often is implicitly related to the adopted network analysis method for system performance assessment. Beyond assessment, design of networks often requires not only a forward analysis of system performance but also inverse problem solving to derive component performance targets or optimal interventions. Fewer works exist that explicitly address the multihazard design of infrastructure systems. As with the design of individual structures, infrastructure systems often are designed by evaluating performance under various hazards individually. For some systems, discussions of community-driven network-level performance targets are emerging (SPUR 2009), thus guiding the design targets derived for individual constituents. However, for many systems, such as the highway system, the design practice for constituents such as bridges does not necessarily reflect network-level objectives, although recent research has begun to suggest methods to achieve this vision (Wang 2014a). Efficient methods and practical design guidelines that achieve network-level risk targets, given multihazard exposure, remain areas ripe for continued contribution.

The variety of structural characteristics exhibited within structural portfolios and infrastructure systems poses distinct challenges when conducting multihazard risk analyses for the purposes of design or risk management activities. Because structural portfolios and infrastructure systems comprise multiple constituents that may vary in age, geometry, and design detail, among other features, vulnerability models often are required for many distinct structures across a region that may be exposed to multiple hazards. To address this challenge, researchers have either adopted very simple models (e.g., single-degree-of-freedom representation of buildings) that are practical for portfolio application (e.g., Mitrani-Reiser et al. 2009; Marano et al. 2011), fragility models representative of overall classes or subclasses of structures (e.g., FEMA 2012), or (more recently) parameterized fragility models that incorporate various structural predictors in addition to intensity measures for multiple hazards (e.g., Kameshwar and Padgett 2014). At the network level, parameterized fragility models also have been proposed recently to depict system performance as a function of multiple hazard intensity measures, such as the empirically derived electrical power–network fragilities developed by Reed et al. (2016) conditioned on rainfall, surge inundation, and wind speed. As indicated by Kappes et al. (2012a), few integrated approaches exist to develop vulnerability functions in a multihazard context, and often a lack of consistency exists in the level of fidelity for assessing the fragility of infrastructure portfolios even across multiple individual hazards.

The distributed nature of infrastructure also leads to unique challenges when designing or assessing multihazard risk. First, probabilistic hazard models are required along with efficient strategies for simulating the spatial variation in intensity of multiple single, concurrent, and/or cascading hazard events. Unfortunately, readily available probabilistic hazard models are lacking for many multihazard cases or their development is still in early stages, for example, for joint wind–surge–wave events (Phan et al. 2007; Taflanidis et al. 2013), coupled rainfall runoff and coastal surge (Torres et al. 2015; Sebastian et al. 2017), or tsunami following earthquake (De Risi and Goda 2016; Burns et al. 2017; Park et al. 2017). Furthermore, several studies that focus on risk assessment of infrastructures under natural hazards have incorporated and tested the importance of correlated failures arising from the correlation in hazard intensity—either interevent or intraevent correlations (Crowley and Bommer 2006)—or sources of correlation in component vulnerability. For example, correlations in seismic intensities have been considered for damage and loss estimation for portfolios of buildings (Goda and Hong 2008; Sokolov and Wenzel 2011), serviceability assessment of water distribution systems (Adachi and Ellingwood 2009), and reliability assessment of other lifeline systems, such as the gas distribution network (Song and Ok 2010). This concept has yet to be fully extended to distributed infrastructure under multihazard loading. Select studies are emerging, however, that have introduced the consideration of hazard-induced correlations when assessing risk under multiple individual hazards, such as the work by Corotis and Bonstrom (2015) that considered losses to building portfolios exposed to hurricane winds and earthquakes. Correlations in component failures under natural hazards also may stem from similarities in design and construction details, age, and level of degradation, among many other factors. Although the quantification of these correlations in component vulnerability may be challenging to assess, their importance has been underscored for hazard risk assessment of structural portfolios and infrastructure systems (Lee and Kiremidjian 2007).

An additional challenge introduced when assessing multihazard performance of distributed infrastructure is the resulting variation in exposure of infrastructure components to degrading environmental elements. For example, coastal structures may be sited in marine zones subjected to sea spray, whereas inland structures are limited to atmospheric exposure. Although few studies integrate continual environmental deterioration into hazard risk analyses for structural portfolios or infrastructure systems, select examples exist, although they typically emphasize single-hazard exposure, such as for bridge and transportation networks under seismic loads (Lee et al. 2011; Rokneddin et al. 2014; Ghosh et al. 2014) or for wood poles in power-distribution networks under wind loads (Shafieezadeh et al. 2014). Such studies introduce the concept of lifecycle degradation in infrastructure performance under natural hazards to reflect the reduced capacity of infrastructure components to sustain hazard loading throughout their lifetimes. Select studies extend this consideration of time-dependent component reliability when assessing multihazard performance of infrastructure (Decò and Frangopol 2011). Further work is required to fully explore lifecycle multihazard performance for a range of structural portfolios, infrastructure networks, and hazards.

Considerations for Interdependent Systems

Distributed structural portfolios and infrastructure systems collectively provide services to communities that are necessary for daily (and postdisaster) functioning. Many of these distributed networks have interdependencies on other systems, which are needed to function properly and must be considered carefully in multihazard risk assessment. Several types of interdependencies can be found in critical infrastructure systems. *Physical interdependencies* arise from physical links between the inputs and outputs of two distributed systems (Rinaldi et al. 2001; Dudenhoeffer et al. 2006; Zhang and Peeta 2011). An energy network, whose power plants require the water system for cooling, is an example of a physical dependency. *Geospatial interdependencies* arise when the components of one system geographically coincide with another system (Rinaldi et al. 2001; Zimmerman 2010; Wallace et al. 2003; Lee et al. 2007). An example of geospatial dependency is the installation of utility facilities on highway structures, typically located above the underside of the superstructure and inside the fascia elements. As cyber and information technology continues to mature, regional portfolios of structures and infrastructure systems continue to grow *cyber interdependent* on information transmitted through the information network (Rinaldi et al. 2001). For example, the healthcare network is extremely dependent on electronic medical records and information networks for administering pharmaceuticals. Other nonphysical interdependencies can exist as well, such as logical (Rinaldi et al. 2001) and economic (Zhang and Peeta 2011). A geographically distributed portfolio of structures and infrastructure systems is an example of a complex system with all of the above types of interdependencies. Mieler and Mitrani-Reiser define portfolios of structures and infrastructure systems as a critical infrastructure-based societal system (CIbSS) (Mieler and Mitrani-Reiser 2016)

A CIbSS, shown graphically in Fig. 4, is an interdependent infrastructure system that provides key community functions and is linked by occupancy type, people, policies, information, geographic location, and/or building services. The top layer of the CIbSS in Fig. 4 shows a portfolio of structures that together serve a community function and that are dependent on underlying networks of critical lifelines (i.e., water, wastewater, power, natural gas, communications and cyber, and transportation). The arrows in the diagram denote the directionality of dependencies (single arrowheads) and interdependencies (double arrowheads). An example of a CIbSS is a school district, in which all district schools make up the portfolio, because they all have the same occupancy type (i.e., education facility) and are managed by a single stakeholder (i.e., the school district). Like school districts, many types of CIbSS are common to most communities (e.g., government, education, emergency services, healthcare, banking/finance, business). However, other building portfolios specific to a location may be critical to that specific location's economic well-being (e.g., hospitality infrastructure is necessary for the tourism economy in Florida). Assessing the performance of distributed complex infrastructure systems and understanding the complex nature of their

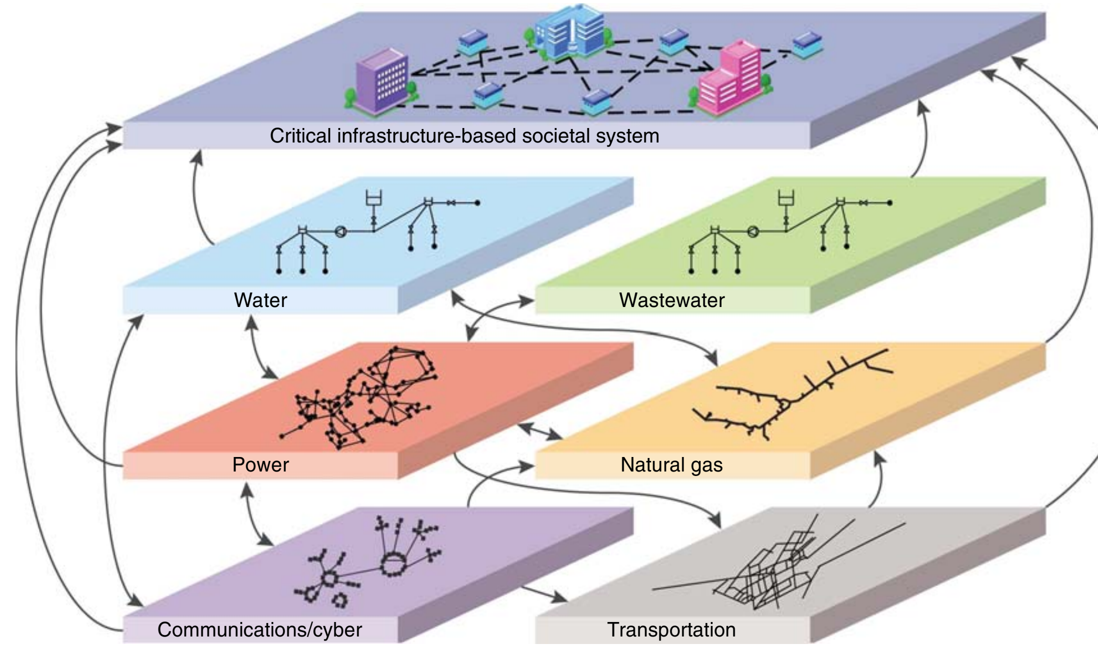

Fig. 4. Interdependent CIbSS (reproduced from M. W. Mieler and J. Mitrani-Reiser, "Mitigating multi-scale earthquake impacts: A review of the state-of-the-art in assessing loss of functionality in buildings," submitted, *J. Struct. Eng.*, ASCE, Reston, Virginia)

interdependencies will result in a deeper understanding of individual communities' vulnerabilities to future hazards.

The literature describing system-level risk-assessment methods for interdependent infrastructure systems is rich, including empirical approaches (e.g., McDaniels et al. 2007), systems dynamics methods (e.g., Brailsford 2008), input-output models (e.g., Santos and Haimes 2004), network-based models (e.g., Holden et al. 2013), agent-based models (e.g., Barton and Stamber 2000), and advanced hybrid models (e.g., Satumtira and Dueñas-Osorio 2010). Ouyang (2014) presented a comprehensive overview of the required risk-assessment methods.

Although some challenges exist in the multihazard design of individual distributed infrastructure systems, the interdependencies present in complex networks composed of several types of distributed systems increase the potential for cascading failures (Penderson et al. 2006) and highlight that a failure of just a small number of nodes in one network may lead to catastrophic fragmentation of a system of several interdependent networks (Buldyrev et al. 2009), such as power blackouts. In order to address hidden vulnerabilities that may exist in interconnected networks, it is important to mathematically characterize the connectivity within and between networks (i.e., Leicht and D'Souza 2009), use reliability methods that account for redistribution of flow in the network (Duenas-Osorio and Vemuru 2009), and apply global assessment metrics to account for the potential of cascading effects. For example, Ouyang and Duenas-Osorio (2011) offered a global assessment strategy, including their *global annual cascading failure effect* metric, for the design of coupled infrastructure systems because an optimum design under one hazard type may not be effective under other types of hazards.

Structural Systems and Elements Optimal for Multihazard Resistance

An important innovative activity in multihazard design is to identify or develop new structural concepts, systems, mitigation strategies, and technologies that can provide simultaneous protection against more than one hazard (without increasing cost over that for a single-hazard design). This paper highlighted previously that synergies can be found in the strategies to mitigate *structural* damage due to blasts and earthquakes because they both rely on ductile response of structures to achieve satisfactory performance, in spite of major differences in demands. Similar synergies may also exist to mitigate *nonstructural* damage for blasts, hurricanes, and earthquakes, but the few examples provided hereinafter focus on structural systems. The following subsections present some selected recent research highlights on how such possible synergies have been addressed. In the long term, it is expected that those technologies that are shown to achieve the broadest possible level of protection at the least possible cost will be more likely to be adopted.

Potra and Simiu (2009) correctly pointed out that the type of optimization to which this paper refers is not a rigorous mathematical optimization as commonly performed in the field of structural optimization; the term is used here instead to refer to the designer's broad search for structural systems that can be "as effective, perfect, or useful as possible" (according to the dictionary definition of *Optimizing*), relying on a synthesis of the structural engineer's experience, judgment, and insights into structural behavior and design constraints, which may be all that is possible at this point in time when multihazard design is still in its infancy.

Multihazard Resistant Bridge Piers

Interestingly, much research on multihazard structural systems has focused on bridge piers. This circumstance may be a consequence of the fact that bridges, already exposed to many hazards, became a concern following the 9-11 events as threats were received targeting landmark bridges across the nation. The concern naturally then extended to highway bridges, recognizing that they are more accessible and vulnerable than landmark bridges, which are closely monitored. In many instances, the destruction of a highway bridge can have profound effects on the economy it serves. This elevated the topic of blast-resistant design in the national discussions on bridge infrastructure (FHWA 2003; Williamson and Winget 2005; Winget et al. 2005, 2008; Anwarul Islam and Yazdani 2006;

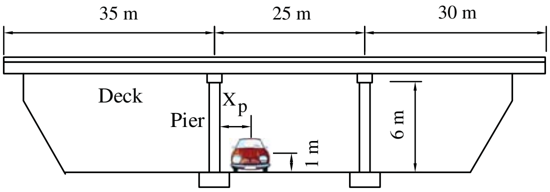

Fig. 5. Schematics of prototype bridge and assumed blast scenario

Ray 2006; ASCE 2008; Agrawal et al. 2009; Williamson and Williams 2009; Davis et al. 2009; Yi 2009; and others summarized in Fujikura and Bruneau 2008), which naturally also led to the consideration of multihazard solutions, from the perspective of developing optimized solutions that can provide protections against multiple hazards (e.g., Agrawal et al. 2009) or, in other words, searching for a single design concept able to satisfactorily fulfill the demands of multiple hazards and their possible interactions.

Toward that goal, various researchers (e.g., Fujikura and Bruneau 2008, 2011; Williamson et al. 2011a, b; Burrell et al. 2015; Echevarria et al. 2016a) analytically and experimentally investigated the blast and seismic behavior of a series of different bridge column designs. Columns are, in most bridges, the ductile structural element relied upon to resist earthquakes; the ability of those columns to survive the blast scenario created by the detonation of explosives located inside a small vehicle below the bridge deck at close distance to the column (Fig. 5) became the archetypal consideration; although most studies increased the intensity of blast forces beyond that scenario for the purpose of investigating the ultimate failure modes of the columns.

Bridge Piers with Concrete-Filled Steel Tubes

In the aforementioned perspective, Fujikura and Bruneau (2008, 2011) proposed and demonstrated analytically and experimentally that a multicolumn pier-bent system with concrete-filled steel tube (CFST) columns could provide significant ductile behavior under seismic excitations and blast loading (Marson and Bruneau 2004; Fujikura et al. 2007, 2008). Fig. 6 shows ductile column deformations for an extreme case of blast pressures exceeding those related to the considered scenario. The columns are effective for blast loadings because CFST columns prevent breaching and spalling of concrete.

Experiments also were performed on conventional seismically detailed ductile RC columns and nonductile RC columns retrofitted with steel jackets to become ductile (Fujikura and Bruneau 2008, 2011). Steel jacketing commonly has been used on the West Coast of the United States to ensure ductile flexural behavior and prevent shear failure of nonductile columns (Chai et al. 1991). However, although a column retrofitted with a steel jacket visually resembles a CFST column, it typically is discontinuous at the column top and base in order to avoid undesirable overload of the adjacent members (i.e., footing or cap beam) due to composite action that would significantly increase the flexural strength of the column (Buckle et al. 2006). The RC columns, in spite of being designed and detailed in compliance with the latest seismic requirements to achieve ductile response, were not found to exhibit a ductile behavior under blast loading, and failed in direct shear at their bases rather than by flexural yielding (Fig. 7). Identical failure occurred for the jacketed columns. The CFST columns of identical flexural strength subjected to similar and even greater blast forces failed in a ductile manner.


(a) (b)

Fig. 6. CFST bridge column specimen after extreme blast test (images by Michel Bruneau): (a) column deformation; (b) foundation

(a) (b)

Fig. 7. Direct shear failures from blast test (images by Michel Bruneau): (a) seismically detailed reinforced concrete column specimen; (b) steel-jacketed concrete columns

Building on those results, Fouché and Bruneau (2014) proposed columns consisting of concrete-filled double-skin steel tubes (CFDSTs), which consist of two concentric steel tubes separated by a concrete core (Fig. 8), to optimize material use, provide redundancy, enhance ductility, provide dowel action against direct shear failure in more extreme events, and provide enhanced fire resistance. In a multihazard context, the significant ductility of the system benefits its robustness by preventing any nonductile mode of failure under extreme events that may push the structure beyond its elastic limits.

In parallel, to retrofit the previously observed direct-shear failure vulnerability of jacketed columns detected at the gaps between the jacket and the surrounding footing and cap beam when exposed to blast, a modified steel-jacketed column (MSJC) concept was proposed and tested (Fouche and Bruneau 2014; Fouche et al. 2016). Structural steel collars were placed around the gaps and tied

Fig. 8. Concrete-filled double-skin tube (image by Michel Bruneau)

Fig. 9. Deformation of MSJC after blast test: (a) global; (b) local [(a and b) images by Michel Bruneau]

to the adjacent elements with postinstalled anchors (Fig. 9) to help increase the shear strength locally.

The CFDSTs and MSJCs were subjected to blast, and in some cases cyclic inelastic tests (Fig. 10), to investigate their applicability as candidate multihazard systems for bridge applications. Satisfactory behavior was obtained in all cases. Large ductile flexural deformations were achievable during both seismic and blast tests.

Expanding on the preceding studies and considering an additional hazard, analytical and experimental studies were conducted to examine the behavior of CFDSTs exposed to fire after being subjected to simulated seismic loads, and, conversely, seismic loading after being exposed to fire (Imani and Bruneau 2014; Imani et al. 2015a, b). This investigation was done because the internal tube in CFDSTs can significantly enhance fire resistance compared with CFSTs. Specimens first were subjected to quasi-static cyclic lateral loads, imposing varying degrees of lateral drift, before being exposed to fire in accordance with the standard ASTM E119 (ASTM 2008) temperature-time curve while sustaining an axial load until the column failed due to global buckling (Fig. 11). Overall, the results provided evidence for the resilient performance of these columns under postearthquake fire scenarios.

Bridge Piers with Concrete-Filled Fiber-Reinforced Polymer Tubes

Another alternative system to conventional RC columns is concrete-filled fiber-reinforced polymer (FRP) tubes (CFFTs). In recent years, the CFFT system has been widely studied as a durable and cost-effective alternative structural system to its RC counterpart (Echevarria et al. 2016a; AASHTO 2012). The desire to combine

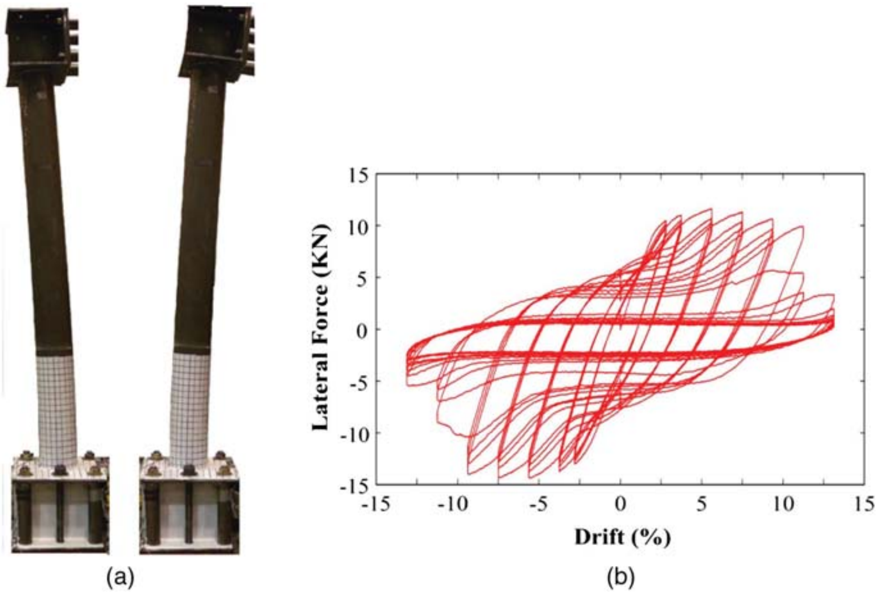

Fig. 10. (a) CFDST specimen; (b) typical hysteretic loop

Fig. 11. Local and global buckling of specimen columns tested in fire (images by Michel Bruneau)

the improved strength and ductility shown by the CFST system with the inherent corrosion resistance of FRP materials led to the development of the CFFT system by Mirmiran and Shahawy (1995) for marine applications and other highly corrosive environments.

The CFFT system comprises a prefabricated exterior FRP shell with either a circular or a noncircular shape filled with regular concrete. The fiber type, angle, and layup can be designed to provide different levels of longitudinal and hoop reinforcement. Unlike FRP jackets that are mostly used in retrofitting of existing deficient columns, the FRP tube in the CFFT system serves as both formwork and structural reinforcement for new construction. Static and cyclic tests showed that the structural performance of this column system significantly benefits from the composite action of the FRP tube and the concrete core (Mirmiran and Shahawy 1995, 1996, 1997; Mirmiran et al. 1999, 2000; Fam 2000; Fam and Rizkalla 2002; Fam et al. 2003, 2007; Ozbakkaloglu and Akin 2012; Mohamed and Masmoudi 2012; Ozbakkaloglu 2013; Qasrawi et al. 2016).

However, the absence of metal reinforcement in the traditional CFFT system reduces ductility, because the yielding of the longitudinal bars is a major source of energy dissipation in conventional columns (Priestly et al. 1996). To address this shortcoming, researchers have studied an improved CFFT design with longitudinal steel bars to provide the ductility and energy dissipation required to resist extreme events such as earthquakes, impacts, and blasts (Ozbakkaloglu and Saatcioglu 2007; Shi et al. 2013; Zaghi et al. 2012; Zaghi and Saiidi 2010). A series of shake table tests were conducted on a two-column bent with one RC and one CFFT column (Zaghi et al. 2012) and on a four-span bridge model incorporating CFFT columns (Kavianipour and Saiidi 2012). Fig. 12 shows the plastic hinge region at the bases of the columns after being subjected to input accelerations equivalent to approximately 2.5 times those of the Northridge Earthquake.

The robustness of the CFFT system also has been investigated under extreme events other than earthquakes. Echevarria et al. (2016a) compared the residual axial load–carrying capacities of a series of CFFT columns with those of RC columns following exposure to earthquake, blast, and fire effects. Preserving axial capacity of damaged columns increases the likelihood of resisting total collapse under an extreme event or series of events, which is critical for the multihazard robustness of a structure. Echevarria et al. (2016b, 2015) investigated the residual axial capacity of CFFT columns after being subjected to blast loads. The system experienced no significant decrease in axial capacity, whereas the comparable RC columns failed prematurely because of the invisible shear crack at the bottom that was initiated by the blasts (Fig. 13). The blast-damaged CFFT columns failed in the same fashion as the intact columns. This demonstrated the CFFT system's resistance to

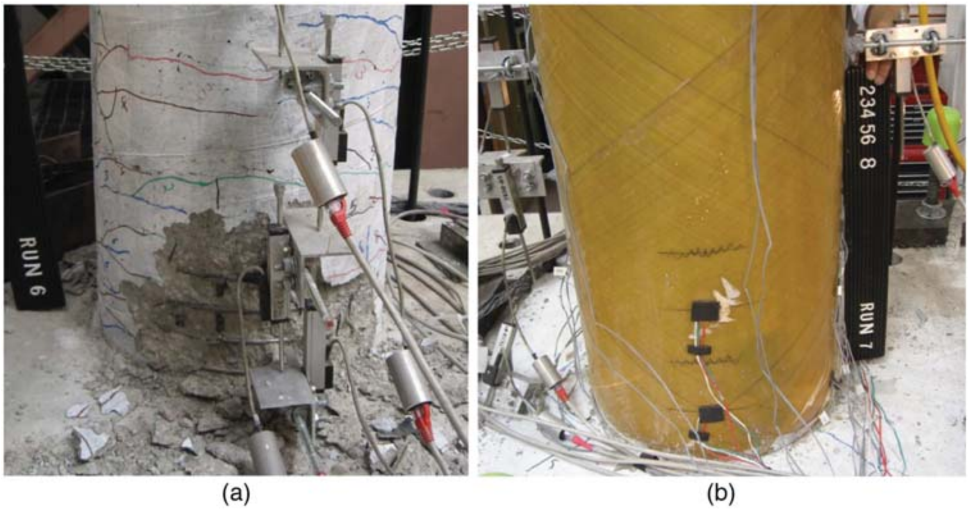

Fig. 12. Damage state at the bases of the columns in the two-column pier shaking table experiments [(a) reprinted from Esmaili Zaghi 2009; (b) image by Arash E. Zaghi]

Fig. 13. Failure of the RC column under axial loading due to a shear crack initiated under blast loading (image by Arash E. Zaghi)

cumulative damage in a multihazard environment. The fire resistance of the CFFT system also was investigated. Because polymers are inherently vulnerable to extreme heat, the CFFT columns had to be covered with a thin coat of commercial fire-protection product (Bisby et al. 2005; Kodur et al. 2007; Gefu et al. 2008; Fyfe 2013). Following the fire test, the CFFT columns experienced no decrease in axial capacity. The residual axial capacities of columns exposed to seismic loading were determined using analytical models developed in *OpenSees* (2012). The results showed that axial capacities of the CFFT columns were not impacted significantly.

Qasrawi et al. (2015a, b, 2016) studied the robustness of the CFFT system with steel reinforcement under dynamic impact and blast loadings by comparing the performance of CFFT and RC columns. They found that an increase in steel reinforcement ratio improved energy absorption. Under blast loads, residual displacements were smaller and localized damage was less severe in the CFFT columns than in their RC counterparts.

Other Multihazard Issues

The field of multihazard robust design is still emerging and, as such, guidelines and novel technologies are evolving but still limited. One area that has been identified as a gap in multihazard design is the need for multihazard connection details. Connection design is of particular importance in ABC. The lack of guidelines for design of multihazard robust connections has prevented the widespread use of ABC. A project to develop Best Practices Regarding Performance of ABC Connections in Bridges Subjected to Multihazard and Extreme Events (Kapur et al. 2012) summarized current ABC connection details, provided suggestions on how to improve them to achieve satisfactory extreme event performance, and identified multiple candidate designs for application in multihazard environments.

In addition to novel structural systems recently developed for new design, the multihazard robustness of various repair and retrofit options for columns has been studied by Fakharifar et al. (2015) and Chandrasekaran and Banerjee (2015). Fakharifar et al. (2015) studied the efficiency of FRP, conventional thick steel, and hybrid repair jackets on the aftershock performance of RC bridge columns. Studying the postmainshock behavior of columns shows the remaining resilience of the system. In addition, these findings can be expanded to a more widespread multihazard definition rather than solely to aftershocks. They found that the fragilities for the unrepaired and repaired bridge showed large deviation under severe damage states. Among the repair techniques, the conventional thick steel jacket ranked lowest compared with FRP and hybrid jackets. Chandrasekaran and Banerjee (2015) studied the multihazard effect of earthquake and flood-induced scour on bridges retrofitted with steel, carbon fiber, and glass fiber composites. They found that jacketing provided enhanced performance for all retrofit materials. Among three jacketing materials, the carbon fiber composite was found to be the most effective.

High Performance Materials

In recent years, several novel structural materials have been developed and studied that present a significant potential for construction of multihazard robust structures. These materials include ultrahigh-performance fiber-reinforced concrete (UHPFRC) (Lai et al. 2015; Li et al. 2015; Aoude et al. 2015), high-performance fiber-reinforced concrete (HPFRC) (Canbolat 2005; Lequesne et al. 2010; Hung and El-Tawil 2011), engineered cementitious composites (ECC) (Kesner and Billington 2005; Zhang et al. 2007; Maalej et al. 2005; Hung et al. 2016), shape memory alloys (SMA) (Song et al. 2006; Youssef et al. 2008; Meo et al. 2013), and hybrid composites (Callens et al. 2014; McBride et al. 2017). Integrating innovation at both the material and system levels is an effective approach toward improving the robustness of infrastructure. However, more research is needed to improve the understanding of the performance of structural components and connections made of these materials under multiple extreme events. From the multihazard perspective, the robustness of structural components also should be evaluated through experiments that show how an element damaged by one extreme event performs when subjected to the same or different types of hazards.

Alternative Concepts

Finally, earthquakes, vehicle collisions, tsunamis, and blast were considered from the onset in a project intended to develop an alternative multihazard bridge pier system (Keller and Bruneau 2008; Bruneau et al. 2010). This project incorporated concepts from steel plate shear wall (SPSW) design; these concepts have been implemented in buildings, but never incorporated into bridges. Steel plate shear walls are ductile, offer significant redundancy, and can be easy to repair. The ability to sustain gravity loads and maintaining integrity after occurrence of any of the other hazards also was critical. Additionally, the project sought a design that had aesthetic appeal. Various concepts were explored before eventually converging on the four-column box pier solution shown in Fig. 14. The project adopted a continuous three-span steel plate girder prototype superstructure from a seismic design example developed for the Federal Highway Administration (Mast et al. 1996). The pier cap was made integral with the superstructure and the SPSW pier system, which was found to be advantageous. The pier assembly also was made reasonably narrow in the longitudinal direction to reduce the plate surface area subject to wave loads arising from surging water transverse to the bridge. The system was designed for a given seismic hazard and then analyzed for the other hazards. This procedure was possible only because of the multihazard approach taken in conceiving this study at the onset, which consisted of considering various prototype designs and modifying the layout and features of the lateral load resisting elements from prototype to prototype based on engineering experience, judgment, and insights into structural behavior and design constraints until a multihazard solution deemed worthy of further investigations (using more complex analyses) was singled out. Design followed established principles for SPSW design (Sabelli and Bruneau 2006; Bruneau et al. 2011),

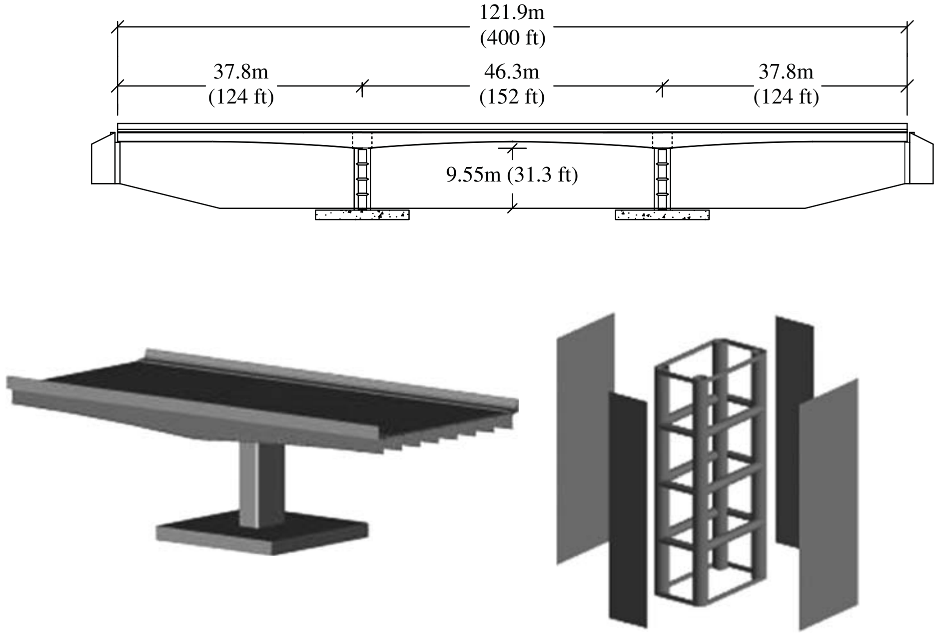

Fig. 14. Four-column multihazard bridge box-pier concept, with transverse elevation, three-dimensional rendering of typical pier and deck segment, and exploded view showing plates welded on tubular pier frame

and nonlinear pushover analysis verified the structural performance using *ABAQUS*. The plates buckled in compression and developed tension field action, as is characteristic of SPSW systems (Fig. 15).

Although detailed results are not presented here due to space constraints, the pier concept proved adequate to resist vehicle collision. For tsunami (including both surge forces and debris impact forces and hydrostatic, hydrodynamic, and debris impact forces), the plates yielded and acted as sacrificial elements, and the boundary frame remained stable without developing any plastic hinges. For blast, the plates offered little resistance and were sacrificial, and finite element analysis showed that the hollow tubes used for the boundary frame could be vulnerable, which led to the recommendation to use CFSTs for columns (with the design concept remaining identical otherwise) (Fig. 16).

Non-Engineering Challenges to Multihazard Design

The preceding summary of existing research on multihazard design highlighted—or inferred, in many instances—the needs for further knowledge in many subdisciplines of this broad field. However, note that nationwide implementation of multihazard design faces some significant challenges. One major challenge is that when retrofit activities take place, they typically are done to address a single hazard, and generally are done only in regions where an acute awareness exists of that specific hazard. Significantly less (or no) such work is done in other regions where awareness is low, even if the risk and consequence of a disaster is high. As a consequence of this prevailing *stove-pipe* approach to disaster mitigation, immediately following a disaster measures are enacted regionally to enhance resilience for the hazard that has led to the latest disaster,

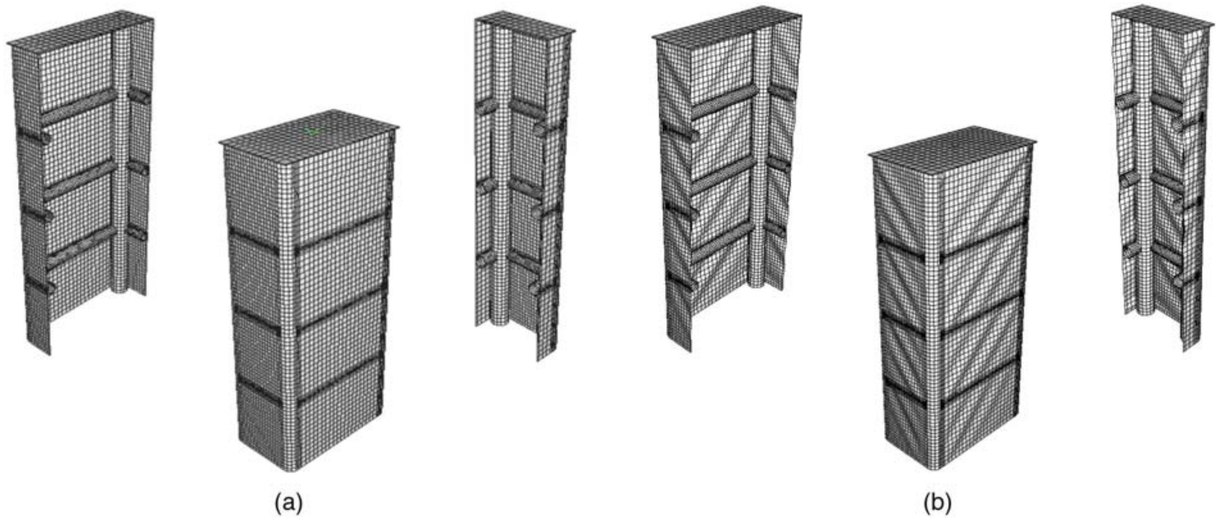

Fig. 15. Global view (and exploded cut-out views) of finite-element model (a) before and (b) after pushover analyses, showing development of diagonal tension field action in steel plates

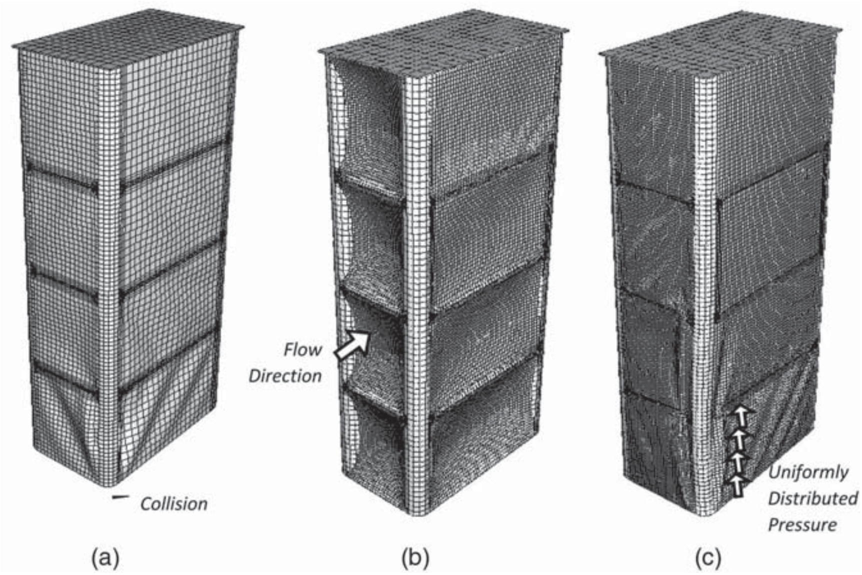

Fig. 16. Deformed shapes from finite element results obtained for (a) collision; (b) tsunami; and (c) blast forces hazard analyses

and relaxation of these measures inevitably occurs when a long period has elapsed since the last occurrence. Arguably, good and bad outcomes result from this approach: where such actions are taken, they can be highly effective in enhancing resilience against that specific hazard regionally, but they could be of limited effectiveness beyond that (and even decrease resilience against other hazards). Another challenge is that some hazards generally are not considered in structural design unless specifically requested by owners (e.g., blast). The preceding examples are provided only to underscore that multiple societal challenges exist that go beyond engineering issues dealing with single hazards, and that these effectively compound in complexity when dealing with multihazard design.

Finally, note that although multihazard design can contribute to the attainment of more-resilient communities, infrastructure resilience is another broad and completely different topic in itself (e.g., Cimellaro 2016), and is beyond the scope of this paper. However, the authors believe that advances in both multihazard design and engineering resilience are necessary to mitigate future potential disasters effectively.

Conclusions

As demonstrated in this paper, multihazard design addresses a number of issues, ranging from the interactions and interdependencies of hazards to the development of new design concepts to ensure inherently efficient outcomes that suitably address the often conflicting demands related to multiple hazards. This paper provided an extensive overview of the accomplishments in this field, mostly from work conducted in the recent decades, highlighting some gaps and inconsistencies in current state of knowledge, recognizing that there exists much additional work that could not be included here due to space constrains (or that simply accidentally escaped the attention of the authors).

It is hoped that the multiple examples cited in this work will inspire readers to undertake research in one or many of the areas described here, given that multihazard is a relatively new endeavor and that the bulk of the research and development work needed to achieve multihazard resistant infrastructure remains to be done.

Acknowledgments

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