# Establishing Common Nomenclature, Characterizing the Problem, and Identifying Future Opportunities in Multihazard Design

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## Introduction

Strong interest in extending the service life of critical infrastructure, compounded by the severity of damages during major disasters, such as Hurricane Katrina in 2005 (FEMA 2006) and the Tohoku earthquake in 2011 (NILIM and BRI 2011), has triggered a growing interest in design concepts that account for cascading effects and the interaction of multiple hazards. Traditionally, design is focused on the effects of various kinds of individual single hazards. In today's structural design practice, the impacts of various single hazards are translated into *equivalent forces*. Modern design codes account for concurrence and combinations of multiple hazards by suggesting *load combinations* and *load factors* intended to include uncertainties and significance of different hazards. A structural system that is designed to resist maximum load effects is expected to survive the damaging effects of multiple hazards. In recent years, other concepts such as displacement-based design and performance-based design were developed for hazards such as earthquakes. However, current design philosophies fail to consider the complex and intertwined effects of multiple hazards at system-wide and societal levels. Some of the shortcomings of the current design philosophies in reflecting the complex nature of multiple hazards can be identified as follows:

- The effects of many hazards cannot be meaningfully translated into "equivalent forces"; for instance, the damage caused by a fire is better represented by material decay than by thermal forces;
- Successions of hazards impacting a structure are not explicitly included; for example, earthquakes can have a different impact on structures that suffer from corrosion damage compared with pristine structures (Burke and Bruneau 2016; Shiraki et al. 2007); similarly, scour has a great impact on the seismic fragility of reinforced concrete bridges (Wang et al. 2014);
- Magnifying effects of hazards acting together are typically ignored; in the case of the catastrophic collapse of the World Trade Center towers, the impact due to the airplane crash shattered the fire protection coatings, which exposed the load carrying elements to extreme heat effects (FEMA 2002);
- Analyses are commonly performed on models of intact structures; during the 2011 Tohoku earthquake, several structures that had been damaged by the mainshock suffered further damage in aftershocks (Li et al. 2014); and
- System- and society-level consequences of multiple hazards are not explicitly included; current design philosophies tend to focus on individual components of a system in isolation (e.g., bridges in a transportation system); to minimize the adverse social and economic impacts of multiple hazards, a holistic approach is necessary to account for different scenarios that may impair system function; for example, an earthquake that causes a landslide that blocks access to a hospital could have a catastrophic system-level impact once supplies dwindle that would be similar to that of the earthquake causing structural damage to the hospital directly.

In designing for the effects of multiple hazards, several other deficiencies may be present in current design practice. The concept of superposition of different hazards cannot always accurately predict the risk of damage. The effects of multiple hazards, acting concurrently or over time, can significantly increase the damaging impact of individual hazards. Therefore, an explicit multihazard design is necessary to achieve robustness and resiliency (as further defined later) at a large scale. Multihazard design requires an in-depth understanding of the nature of various hazards and their interactions. It must also include the effects that the hazards have on one another and on the behavior of structures or physical components of a system.

Design for multihazard mitigation is a multifaceted and complex challenge that may prohibit the development of a unified approach.

This forum paper is not intended to provide guidelines and/or recommendations for multihazard design, but aims to present ideas and provoke future discussions on this subject. Ideally, these future discussions will ultimately lead to the development of a general framework for multihazard design. Such a framework should be practical, inclusive of different hazards, applicable to various types of structures and design objectives, easily extensible, and not in stark contrast to current design guidelines. Specifically, this paper discusses (1) the classification of various hazards and their possible effects, (2) potential interactions between individual hazards, (3) the importance of a probabilistic framework for multihazard risk assessment, (4) the need for a multihazard design framework, and (5) the current knowledge gaps in the area of multihazard mitigation. Discussions around this topic may raise awareness in designers and stakeholders that current methods may not satisfy the demands of a multihazard reality.

## Need for Establishing Common Nomenclature

Establishing a common nomenclature of multihazard design is critical for effective communication in the technical community. The current literature lacks a uniform use of terminology and classification for possible *interactions* of hazards. These interactions are referred to as cascades, cascading effects, cascading; chains; coincidence of hazards in space and time; coinciding hazards; compound hazards; coupled events; cross-hazards effects; domino effects; follow-on events; interactions; interconnections; interrelations; knock-on effects; multiple hazards; synergic effects; and triggering effects (Kappes et al. 2012). In addition, some studies do not specify if the discussed interactions are between hazards, as with tsunami and earthquake, or are through impacts of hazards on physical components and systems, as with corrosion damage and earthquake. The classification of hazards is not consistent throughout the literature because different criteria are used; this greatly hinders the ability to develop a universal design framework.

In addition to defining hazard interactions, it is important to present a clear definition of the objective of multihazard design. In the current literature, *design for multihazard resilience*, *design for multihazard robustness*, and *design for multihazard mitigation* are terms that are being used interchangeably. Although this terminology is essentially used to communicate the same concept, particular attention should be paid to preventing ambiguity. The term *resilience* is defined as an ability to recover from or adjust easily to misfortune or change; *robustness* implies a capability to perform without failure under a broad range of conditions, or a property of allowing the severity of damage to be minimized in other instances; and *mitigation* means reducing the severity of a negative action or effect. In a robust system, the goal is that damage is minimized or prevented in the first place; however, in a resilient system, some level of damage is anticipated, but an additional objective is that the system should recovers 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 are geared more toward lowering global risks than toward provisions for robustness and resiliency, which may mainly focus on passive improvement of system responses to hazards.

## Identifying Hazards and Their Effects

This section aims to classify various hazards, both natural and man-made, in the context of their effects at a physical component-, system-, and societal-level. This multilevel approach reduces the complexity of multihazard design and facilitates understanding of possible hazard interactions. Infrastructure may be defined as *systems* of integrated and interrelated *physical components* enabling function and growth of a *society*. Examples of infrastructure systems include roads and bridges of transportation systems; electric power generation units and distribution grids of power systems; and water treatment and distribution facilities of water supply systems. Realizing the impacts of different hazards on physical components of a system and the system itself is necessary for evaluating multihazard risk and developing mitigation methods.

In recent years, several studies have attempted to develop a framework for natural interaction of a broad range of hazards such as earthquake and tsunami with hurricane and storm surge (Gill and Malamud 2014). In contrast, this forum paper characterizes hazards in terms of their impacts and not their nature—that is, intensity and spatial and temporal scales. This paper does not address direct impacts of hazardous events on human health such as toxic fumes during a fire, which are outside the scope of the current discussion. Different hazards may cause the following four inherently different, but possibly interacting, effects.

*Site effects* essentially define the hazard and represent the actions produced by the hazard at a given location. They are to be understood in the context of causality of the physical impact. The existence of these effects does not depend on the presence of a physical component or a system of physical components. For example, the site effects of an earthquake include ground vibrations and liquefaction/ground settlement, which are independent of the existence of the physical component. Similarly, site effects of a tornado are excessive loads, uplift loads, and flying debris. Hazards that are caused or triggered by another hazard are not listed as site effects. For instance, a tsunami resulting from an earthquake is not considered as a site effect of the earthquake hazard; instead, it is regarded as an additional hazard.

*Physical impacts* are modifications of the behavior and/or function of a physical component and are assumed to be directly caused by one or multiple site effects associated with hazards. They are not necessarily independent or mutually exclusive. For example, the physical impacts of a flood hazard include foundation/support damage and change in material properties of a structure's elements (physical components) because of the hazard's site effects—that is, water overflow/accumulation and corrosive chemicals such as saltwater.

*Network and system disruptions* are defined as interrupting or impairing effects on the function of a system or network at large scales. In the case of a significant storm surge, inundation of subway tunnels may cause a significant interruption of the public transportation system.

*Social and economic consequences* recognize the role that affected structures and infrastructure systems play in societal functioning and human behavior. In the case of a tsunami, extensive damage to infrastructure may cause a mass migration of a local population.

Fig. 1 shows different hazards in a way that aids visualization of their effects and promotes understanding of their possible interactions through *site effects* and *physical impacts*. It presents possible main and subsidiary site effects and physical impacts of hazards (dark and light gray, respectively). The *main* effects/impacts are defined as those that are more probable and more damaging, whereas the *subsidiary* effects/impacts are those that are less probable or less severe. This differentiation between main and subsidiary effects/impacts is based mainly on the engineering judgment of the authors on the basis of their review of past damage reports. The site effects are categorized as *transient* or *perpetual* in

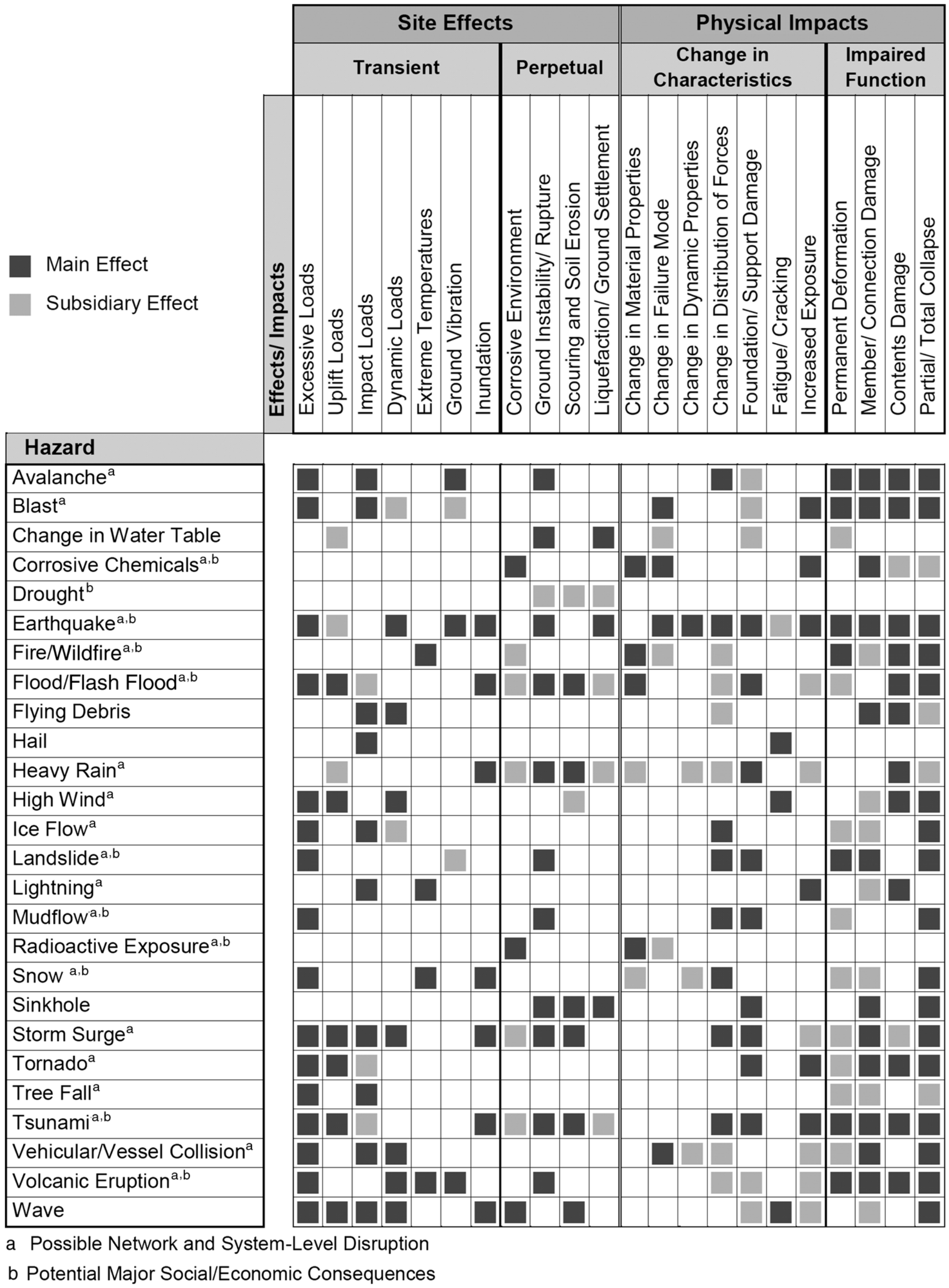


**Fig. 1.** Site effects and physical impacts of hazards

terms of temporal scales. The physical impacts are categorized as a *change in characteristics* or as *impaired function*. In Fig. 1, changes in characteristics are essentially the possible impacts of a hazard on a structure. Impaired functionality is an occurrence that limits or interrupts a structure's intended function and performance. Changes in characteristics may directly result in impaired functionality, or they may alter a structure such that its response to other hazards becomes different from that of the structure when intact. It should be noted that hazards that are induced by other hazards are not considered effects for the purpose of Fig. 1—for example, high wind and blizzard. The hazards causing potentially significant network- or system-level *disruptions* and social and economic *consequences* are identified in the figure footnote.

The authors have taken care when differentiating *extreme events* and *hazards*. Extreme events essentially consist of several hazards. For example, a hurricane is an extreme event that consists of high winds, heavy rain, and storm surge, among several other hazards. Another example of an extreme event is a thunderstorm that consists of heavy rain or hail and lightning hazards. Therefore, in Fig. 1 extreme events are not listed as hazards; instead, only the constituent hazards are listed. In the figure, flood/flashflood hazard may include river, coastal, or inland flooding; a high wind hazard may include both synoptic and nonsynoptic winds and hurricane-type winds. The hazards themselves are listed alphabetically and not ordered by significance or prevalence. It is acknowledged that consideration of different hazards in design may vary according to the structural or infrastructure system of interest.

## Interaction of Hazards

This section identifies possible modes of interaction between various hazards. Understanding interactions between hazards and their effects is necessary to properly evaluate the risk associated with multihazard environments. The multihazard risk may not be properly assessed by superimposing the risks of the individual hazards. For example, for a mainshock-aftershock situation in an earthquake event, the probability of damage due to the combination of the two hazards is not equivalent to the summation of the probabilities calculated for two independent earthquake events. The reason is that the mainshock causes damage and changes a structure's dynamic characteristics. The aftershock then acts on the previously damaged structure. Thus, combining the level of damage obtained from independent analyses of the undamaged structure under the mainshock and the aftershock does not yield the correct result. In this situation, the structure can be analyzed under a ground acceleration that includes both mainshock and aftershock in a single time series or by subjecting the structure, already damaged by the mainshock, to a suite of seismic records appropriately representing the aftershocks. For a realistic assessment of multihazard effects, the possible interaction of different hazards should be realized at two levels: (1) the nature of the hazards and (2) the effects of the hazards, named here Level-I and Level-II interactions, respectively.

### *Interaction through the Nature of Hazards: Level-I Interactions*

Hazards are either interacting or independent in terms of their source, time and frequency of occurrence, magnitude, and region of impact. Natural interactions of hazards are independent of the presence of physical components. High wind and earthquake are naturally independent because neither one triggers or intensifies the other one; moreover, they do not correlate in nature or occur as the result of a common source event (or extreme event). Naturally interacting hazards can be categorized as (1) concurrent hazards and (2) successive hazards. Concurrent hazards are multiple hazards that occur at the same time or overlap for some period of time. The duration of the overlap may directly influence multihazard effects. Examples of concurrent hazards include storm surge, waves, and high wind that co-occur during a hurricane (Bjarnadottir et al. 2014; Ataei and Padgett 2013; Barbato et al. 2013; Li et al. 2012a, b). Hereafter, successive hazards are defined as multiple hazards where one triggers, intensifies, or broadens the region of impact of another. Examples of successive hazards include earthquake and tsunami, earthquake and avalanche, and heavy rainfall and landslides.

Fig. 2 proposes an interaction matrix for the hazards presented in Fig. 1, suggesting only the perceivable natural interactions of hazards. The term *first hazard* denotes a hazard that occurs independently; the term *secondary hazard* denotes a hazard that may be concurrent with or successive to the primary hazard. In the figure, light and dark gray identify concurrent and successive hazards, respectively.

### *Interaction of Hazards through Their Effects: Level-II Interactions*

From another perspective, the interaction among multiple hazards can be analyzed based on their interaction through site effects, impacts on physical components, network and system disruptions, and social and economic consequences (Fig. 1). Hazards that cause the same site effect can magnify the effects of each other in two ways: (1) hazards with similar *transient* site effects that overlap in space and time (e.g., a co-occurrence of storm surge and riverine flooding may intensify the inundation effect); and (2) hazards with *perpetual* effects that overlap in space and can interact by causing accumulating effects. For example, river flooding and storm surges may both cause scour; if the spatial overlap of these hazards is probable, the scour after the successive hazard will be added over that from the previous hazard, even if the two hazards are separated by a significant period of time.

The interaction of hazards can happen through their impact on physical components, such as infrastructure, in two forms: (1) by *changing the characteristics* of the physical component and (2) by *impairing the functionality* of the physical component. Changes in the physical component's characteristics include changing material properties, altering the dynamic behavior of a structure, exposing a structure or its elements to other hazards, or changing support and foundation conditions. Examples of these modes of interaction are corrosion and earthquake (Shiraki et al. 2007), additional mass due to snow accumulation and earthquake (Ellingwood and Rosowsky 1996; Park et al. 2014; Yin and Li 2011), earthquake and fire following earthquake (Imani et al. 2014; Scawthorn et al. 2005), and scour and earthquake (Wang et al. 2014). A change in characteristics can make the structure more vulnerable to other hazards through Level-II interactions. Physical interactions through impaired functionality can be due to permanent deformation, fatigue, connection damage, or partial collapse. For example, if the contents of a building such as a fire sprinkler system are damaged by an earthquake, the building itself is made more vulnerable to fire hazard (Zaghi et al. 2012).

Current design codes are strength-based and generally consider multihazard interaction only through load combinations and load factors. However, modern design codes usually do not account for possible changes in the characteristics of structures because of individual hazards.

Hazards can also interact through their network or system-level effects and cause a more severe disruption. For example, in a major earthquake the interruption of the transportation network is more catastrophic if road closures due to a landslide coincide with the failure of a bridge due to ground vibration. Hazards may interact through their social and economic effects and cause more severe consequences. For example, Superstorm Sandy merged with an arctic front, which produced a severe blizzard and magnified the devastation of properties, businesses, and communities along the east coast of the United States (FEMA 2013). Explorations of such consequences of multihazards are still in their infancy.

## Multihazard Risk/Loss Assessment Framework

Based on the terminology proposed by the Performance-Based Earthquake Engineering (PBEE) framework developed by the Pacific Earthquake Engineering Research Center (PEER), for a single hazard it is customary to express the risk associated with a specific damage level in terms of mean annual rate of exceedance of the specified damage level, $\lambda_D$. This means that the annual rate of exceedance can be obtained by the convolution integral given by (Porter 2016; Jalayer and Cornell 2003)

$$\lambda_D = \int_{im=0}^{\infty} -F(im)\frac{dG(im)}{dim}dim = \int_{im=0}^{\infty} G(im)\frac{dF(im)}{dim}dim \quad (1)$$

where $im$ = specific realization of a scalar intensity measure $IM$ (i.e., a parameter measuring the intensity of the hazard action); $F(im)$ = cumulative distribution function of the specified damage state conditional to $IM = im$ (also known as fragility function); and $G(im)$ = mean annual frequency of the intensity measure $IM$ exceeding $im$ (also known as hazard curve). Therefore,

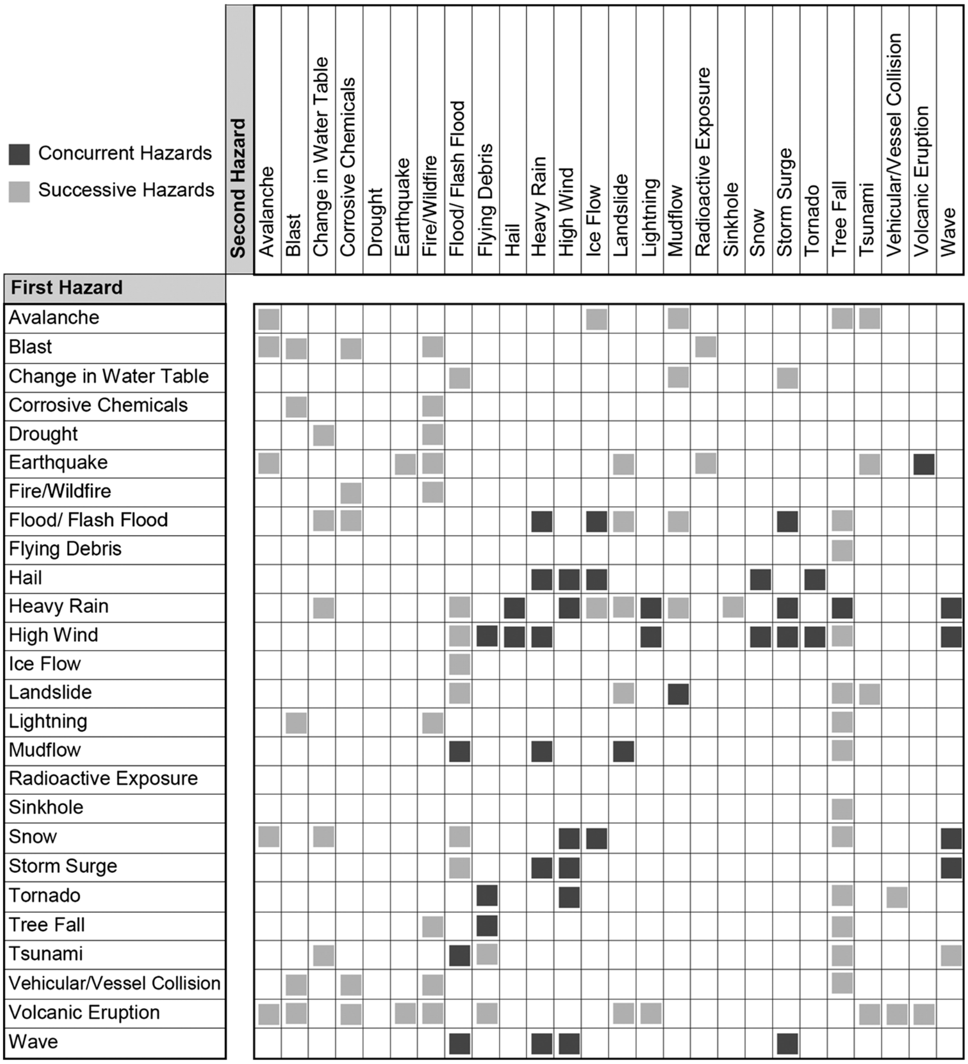


**Fig. 2.** Interaction through the nature of hazards (Level-I interaction)

$-dG(im)/dim$ represents the mean number of events per year corresponding to $IM = im$. It is noteworthy that the fragility and hazard functions are traditionally developed for intact structures and single hazards, respectively.

Because of the complexity of interactions between different hazards, the risk of damage due to multihazards cannot be obtained by simply superimposing or combining the risk of damage due to several hazards considered independently. In a multihazard context, hazard functions can be multidimensional, i.e., hazard surfaces, because of the natural interaction of multiple hazards—that is, Level-I interactions. These hazard surfaces should be developed to account for possible interactions of hazards as joint probability density functions or joint cumulative distribution functions of multiple intensity measures describing different hazards (Wang and Rosowsky 2013). In addition, fragility functions can change as a result of interaction among the physical impacts of different hazards—that is, Level-II interactions. For example, to correctly capture the risk of a specified level of seismic damage to a bridge structure in a corrosive coastal environment, the effects of gradually deteriorating concrete and steel material in columns need to be considered (Zhong et al. 2012). This goal may be achieved by analyzing structures with different levels of corrosion damage under seismic excitation to find the corresponding fragility functions. In practice, the parameters of fragility functions need to be adjusted to incorporate the impact of corrosion. In more complex cases, the joint hazard model is required. An example for such cases is a stability analysis of retaining structures during a hurricane, where the interaction of flooding, high wind, and storm surge should be considered.

Multihazard risk and loss assessment requires the development of appropriate fully probabilistic frameworks that can account for the complex interaction among hazards. This interaction can affect structural and infrastructural behavior not only because of the correlation of different intensity measures describing different hazards but also through hazard chains and degradation/changes in structural system properties when subjected to multiple hazards. It is noteworthy that a first attempt to develop such a framework was carried out in hurricane engineering, in which a performance-based hurricane engineering (PBHE) framework was proposed that takes into account the interaction among different concurrent subhazards —wind, wind-borne debris, storm surge, and rain (Unnikrishnan and Barbato 2016; Barbato et al. 2013). As the understanding of hazard interaction and multihazard impacts on fragility and hazard functions expands, it will become apparent that there is a need for more advanced probabilistic models (e.g., multiparameter marginal probability density functions, high-dimensional joint probability density functions, and more informative statistical data such as high-order statistical moments) that will better describe both marginal distributions of intensity measures and correlation coefficients between different intensity measures. Until more studies are performed on multihazard risk and loss assessment and until more data are collected to probabilistically describe the interaction among different hazards, expert judgment will play a critical role in practical assessments and in the derivation of fragility and hazard functions.

## Possible Multihazard Mitigation Strategies for Physical Components

Multihazard mitigation can be approached from different perspectives. For the purpose of this forum paper, the focus is on mitigation strategies for physical components such as infrastructures. Traditionally, added strength and ductility are known as effective mitigation measures for single hazards. Given the varied and complex nature of impacts resulting from hazards, this traditional approach may not be an effective mitigation strategy. On the other hand, guidelines that overcomplicate or transform current design methodologies may not be easily adopted or accepted by the engineering community. In addition, the present limited understanding of multihazard effects hinders the development of design guidelines that rigorously account for these effects. In general, the physical response to multiple hazards varies from structure to structure; thus, adequate design adaptations should consider the diverse nature of structures and/or materials used.

One innovative approach that might effectively mitigate multihazard effects is reducing the level of hazard interaction, possibly by decoupling the physical impacts of different hazards. This strategy could be used to reduce a complex, multihazard environment that explicitly considers interactions among multiple hazards down to a simplified, single-hazard environment that indirectly considers interaction among different hazards through the use of load combination coefficients and factors. This approach might allow designers to continue using existing design provisions that are essentially developed for multiple hazards acting independently. Decoupling could be achieved in different ways depending on the type of interaction—for example, the Level-I and Level-II interactions discussed earlier. When hazards naturally interact, actual decoupling of their effects may be infeasible. For example, the interaction of mainshock and aftershock cannot be eliminated. However, designing a more robust structure can lessen the damage magnification effects typical of aftershocks and thus serve as a mitigation measure for mainshock-aftershock interaction effects. Where hazards interact through their effects, the decoupling of these effects could effectively minimize multihazard damages and losses. A large number of strategies may be devised to achieve this goal which could be as simple as protecting a structure against corrosive environments, thus preserving its capacity to resist any other hazard. Minimizing the interaction of multiple hazards may require creative solutions, which may not yet be developed or not used routinely in structural/infrastructural design.

## Knowledge Gaps in Multihazard Design

Multihazard design (as defined here, in contrast to simpledesign for multiple hazards) is a relatively new topic in engineering, leaving considerable room for future research. An underlying knowledge of the interrelations among multiple hazards is key to the development of multihazard design guidelines and next-generation multihazard robust structural materials and systems. Although not exhaustive, the following list of the most pressing needs in the field of multihazard design is proposed:

- Developing a thorough definition of what multihazard design encompasses, what it requires, where and when it is needed, and how it should be evaluated;
- Providing consistent characterization and definition of all hazards to be used by entities involved in evaluating and mitigating hazards (FEMA 1997);
- Developing protocols for the experimental and analytical investigation of realistic behavior of structures at material, component, and system levels in multihazard environments; cutting-edge specialized testing facilities should be constructed to enable performance of such experimental studies; the capabilities of analytical simulation tools should be expanded to enable study of multihazard effects; in addition, to generate new experimental and analytical data, existing data from past events should be interpreted in a multihazard environment; these data should ultimately inform fragility assessment of structures;
- Acknowledging the inherent shortcomings and inadequacy of century-old construction materials and structural systems in a multihazard environment (Echevarria et al. 2015); the design community should realize that multihazard robustness may not be achieved simply by strengthening conventional materials and increasing the size of structural components; it is critical to devote significant effort to developing and adopting next-generation, cost-effective construction materials and structural systems that offer improved performance in multihazard environments; composites, nontraditional alloys, and novel cementitious materials, for example, present unique potential to achieve multihazard resiliency (Fouché et. al 2016; Echevarria et al. 2015; Fujikura and Bruneau 2012);
- Carrying out a multidisciplinary dialogue between the structural design community and hazard scientists from areas such as atmospheric sciences, seismology, and geology to establish a holistic risk assessment framework that accounts for the true nature of hazard interactions; other stakeholders should be involved to devise integrated lifecycle models for risk assessment and design of multihazards, including mitigation strategies to reduce damage and losses;
- Evaluating current design codes, guidelines, and practices and identifying their shortcomings with respect to multihazard assessment, mitigation, and design; a dedicated task force should be formed to synthesize the best knowledge available on promising measures to address multihazard design; this task force can ultimately propose refinements to existing codes and standards and suggest specific multihazard design and mitigation practices;
- Extending design concepts and performance evaluations for single hazards to multiple hazards; this effort should identify situations (1) where multihazard effects can be mitigated through similar designs (i.e., when the design approaches for different hazards increase or at least do not diminish each other's effectiveness) and (2) where multihazard effects require different and, in some situations, conflicting design solutions; in the latter situation, designing for one hazard may not increase, or may even decrease, the robustness under another hazard (Li et al. 2012);
- Identifying situations where analysis of intact structures may provide inaccurate results; current design codes are strength-based and, generally, consider multiple hazard interaction only through load combinations and load factors; they usually do not account for possible changes in characteristics of structures due to individual hazards;
- Supporting ongoing evaluation of mitigation by developing procedures for assessing the performance of infrastructures while

conducting reconnaissance after man-made and natural disasters; field investigation procedures should be designed such that multihazard effects and their consequences are documented both immediately and over time to better understand the associated resiliency;
- Promoting the advancement of innovative design and retrofit guidelines and techniques that address multihazard conditions (Li et al. 2012); and
- Developing models to include network- and system-level disruptions and the socioeconomic consequences of multihazard interactions; this may facilitate the enhancement of component-, system-, and operational-level strategies for multihazard robustness and resilience within communities.

## Conclusions

This forum paper introduced the concept of multihazard design, differentiating it from the more traditional concept of design for multiple independent or noninteracting hazards. The main goal was to stimulate future discussions to advance this newly proposed concept. Shortcomings of current methodologies were acknowledged to identify the potential focus points of future multihazard design guidelines. The need for common terminology was established to enable effective communication across the multihazard technical community. Multihazard risk assessment and design should consider four types of effect: (1) site effects, (2) physical impacts, (3) network and system disruptions, and (4) social and economic consequences. Hazards were classified in the context of their effects. Hazard interactions, through their nature or through their effects, were identified and presented to further understanding of multihazard complexity. Possible risk and loss assessment concepts and physical component mitigation strategies were suggested to promote further discussion. Finally, significant knowledge gaps in multihazard assessment, mitigation, and design, along with future research needs, were briefly discussed.


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## References


Ataei, N., and Padgett, J. E. (2013). "Limit state capacities for global performance assessment of bridges exposed to hurricane surge and wave." *Struct. Saf.*, 41, 73–81.

Barbato, M., Petrini, F., Unnikrishnan, V. U., and Ciampoli, M. (2013). "Performance-based hurricane engineering (PBHE) framework." *Struct. Saf.*, 45, 24–35.

Bjarnadottir, S., Li, Y., and Stewart, M. G. (2014). "Regional loss due to hurricane wind and hurricane-induced surge considering climate variability." *Struct. Infrastruct. Eng.*, 10(11), 1369–1384.

Burke, S., and Bruneau, M. (2016). "Effect of surface roughness on cyclic ductility of corroded steel." *J. Struct. Eng.*, 10.1061/(ASCE)ST.1943-541X.0001425, 04016014.

Echevarria, A., Zaghi, A., Christenson, R., and Accorsi, M. (2015). "CFFT bridge columns for multihazard resilience." *J. Struct. Eng.*, 10.1061/(ASCE)ST.1943-541X.0001292, C4015002.

Ellingwood, B., and Rosowsky, D. (1996). "Combining snow and earthquake loads for limit state designs." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(1996)122:11(1364), 1364–1368.

FEMA (Federal Emergency Management Agency). (1997). "Multi hazard identification and risk assessment (MHIRA), a cornerstone of the National mitigation strategy." New York.

FEMA (Federal Emergency Management Agency). (2002). "World Trade Center building performance study." *FEMA 403*, New York.

FEMA (Federal Emergency Management Agency). (2006). "Hurricane Katrina in the Gulf Coast: Mitigation assessment team report—Building performance observations, recommendations, and technical guidance." *FEMA 549*, New York.

FEMA (Federal Emergency Management Agency). (2013). "Hurricane Sandy FEMA after-action report." New York.

Fouché, P., Bruneau, M., and Chiarito, V. (2016). "Modified steel-jacketed columns for combined blast and seismic retrofit of existing bridge columns." *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000882, 04016035.

Fujikura, S., and Bruneau, M. (2012). "Dynamic analysis of multi-hazard resistant bridge piers having concrete-filled steel tube under blast loading." *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000270, 249–258.

Gill, J. C., and Malamud, B. D. (2014). "Reviewing and visualizing the interactions of natural hazards." *Rev. Geophys.*, 52(4), 680–722.

Imani, R., Mosqueda, G., and Bruneau, M. (2014). "Experimental study on post-earthquake fire resistance of ductile concrete-filled double-skin tube columns." *J. Struct. Eng.*, 10.1061/(ASCE)ST.1943-541X.0001168, 04014192.

Jalayer, F., and Cornell, C. A. (2003). "A technical framework for probability-based demand and capacity factor design (DCFD) seismic formats." Univ. of California, Berkeley, CA.

Kappes, M. S., Papathmoa-Kohle, M., and Keiler, M. (2012). "Assessing physical vulnerability for multi-hazards using an indicator-based methodology." *Appl. Geogr.*, 32(2), 577–590.

Li, Y., Ahuja, A., and Padgett, J. E. (2012a). "Review of methods to assess, design for, and mitigate multiple hazards." *J. Perf. Constr. Facil.*, 10.1061/(ASCE)CF.1943-5509.0000279, 104–117.

Li, Y., Song, R., and Van De Lindt, J. W. (2014). "Collapse fragility of steel structures subjected to earthquake mainshock-aftershock sequences." *J. Struct. Eng.*, 10.1061/(ASCE)ST.1943-541X.0001019, 04014095.

Li, Y., Van De Lindt, J. W., Dao, T., Bjarnadottir, S., and Ahuja, A. (2012b). "Loss analysis for combined wind and surge in hurricanes." *Nat. Hazards Rev.*, 10.1061/(ASCE)NH.1527-6996.0000058, 1–10.

National Institute for Land and Infrastructure Management (NILIM) and the Building Research Institute (BRI). (2011). "Summary of the field survey and research on the 2011 off the Pacific Coast of Tohoku earthquake (the great east Japan earthquake)." Ministry of Land, Infrastructure, Transport and Tourism and Incorporated Administrative Agency, Ibaraki, Japan.

Park, S., Van De Lindt, W., and Li, Y. (2014). "ABV procedure combined with mechanistic response modeling for roof- and surge-loss estimation in hurricanes." *J. Perf. Constr. Facil.*, 10.1061/(ASCE)CF.1943-5509.0000397, 206–215.

Porter, K. (2016). *A beginner's guide to fragility, vulnerability, and risk*, Univ. of Colorado, Boulder, CO, 86.

Scawthorn, C. E., Eidinger, J. M., and Schiff, A. J. (2005). *Fire following earthquake*, ASCE, Reston, VA.

Shiraki, N., Shinozuka, M., Moore, J. E., II, Chang, S. E., Kameda, H., and Tanaka, S. (2007). "System risk curves: Probabilistic performance scenarios for highway networks subject to earthquake damage." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2007)13:1(43), 43–54.

Unnikrishnan, V., and Barbato, M. (2016). "Performance-based comparison of different storm mitigation techniques for residential buildings." *J. Struct. Eng.*, 10.1061/(ASCE)ST.1943-541X.0001469, 04016011.

Wang, Y., and Rosowsky, D. V. (2013). "Characterization of joint wind-snow hazard for performance-based deisgn." *Struct. Saf.*, 43, 21–27.

Wang, Z., Dueñas-Osorio, L., and Padgett, J. E. (2014). "Influence of scour effects on the seismic response of reinforced concrete bridges." *Eng. Struct.*, 76, 202–214.

Yin, Y., and Li, Y. (2011). "Probabilistic loss assessment of light-frame wood construction subjected to combined seismic and snow loads." *Eng. Struct.*, 33(2), 380–390.

Zaghi, A. E., Maragakis, E. M., Itani, A., and Goodwin, E. (2012). "Experimental and analytical studies of hospital piping assemblies subjected to seismic loading." *Earthquake Spectra*, 28(1), 367–384.

Zhong, J., Gardoni, P., and Rosowsky, D. (2012). "Seismic fragility estimates for corroding reinforced concrete bridges." *Struct. Infrastruct. Eng.*, 8(1), 55–69.