Structural Engineering Dilemmas, Resilient EPCOT, and Other Perspectives on the Road to Engineering Resilience

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Introduction

The first time the authors heard the word resilience (R) used in a professional context was in 2002 when participating as members of a Multidisciplinary Center for Earthquake Engineering Research (MCEER) Task Group that was mandated to identify the most pressing challenge to be addressed by earthquake engineering research for decades forward. As the main outcome of this effort, the need to establish earthquake-resilient communities was determined to be the most important priority to enhance the state-of-the-art and state-of-practice in this field; the proposed framework that resulted from this process was documented by Bruneau et al. (2003). Little did they know that resilience was then to become a buzzword that would drive research and implementation activities to its current extent throughout the entire world.

In the 15 years following the pioneering work of that task group, major initiatives conducted under the banner of resilience of critical (and noncritical) infrastructures have appeared almost everywhere. For example, San Francisco celebrated resilience weekend in 2003, Tokyo established an initiative for a lower carbon and resilient city, New York used *A stronger and more resilient New York* as one of its logos, and the Rockefeller foundation established the 100 Resilient Cities initiative. Even within the professional earthquake engineering community, the 2013 Distinguished Lecturer Award was given to Mary Comerio for her lecture on Resilience and Engineering Challenge, and the byline of the 16th World Conference in Earthquake Engineering was *Resilience, the new challenge in earthquake engineering* (which, interestingly, could be interpreted in more than one way).

The purpose of this paper is to provide some perspectives on what (in the minds of the two authors) are important dimensions to consider in resilience research to be relevant to the definition of disaster resilience as originally conceived, and that should be considered in the formulation of resilience frameworks. Furthermore, building on those perspectives, the objective is to highlight some challenges that exist, from a structural engineering perspective, to achieve disaster resilient communities. The focus is on seismic resilience, with an understanding that many of the stated principles could be adapted to encompass other hazards and disasters.

Dilution of Resilience's Essence: Need to Focus on Functionality

In the span of 15 years, resilience has grown from a rarely used word intended to describe the ability to recover from a trauma, stress, or deformation, to become an overly used buzz word, even in the fields of disaster research. The emerging popularity of the term can be informally assessed with Google searches (which, although not a rigorously scientific approach, is nonetheless informative). In July 2016, searches on the word resilience alone returned 47,000,000 hits on the internet, up from 7,880,000 6 years earlier. Most significantly, combining the words Obama and resilience returned nearly ¾ million hits, up from roughly 0.4 million hits 6 years earlier, which is not surprising because President Obama issued a presidential directive requiring all federal agencies to implement policies enhancing resilience (White House 2013). Searching for the combination *engineering resilience*, found 17,300 results, up from 6,200 6 years earlier. The combination *quantifying resilience* was found only 2,470 times, up from 953 6 years earlier, and the combination *quantification of engineering resilience* was found only 3 times, up from only 1 result 6 years earlier (a Google search returning a single hit is called a Googlewhack, and is a rare event). Interestingly, the numbers of hits obtained from these searches show that results have approximately tripled from 2010 to 2016, except for the case of resilience alone, which has increased sixfold.

The preceding results also indicate that activities focusing on the quantification of resilience may not have been as extensive as one may wish, from an engineering perspective. Furthermore, the immense number of hits returned by the search on resilience suggests an inordinate use of the term, and possibly more definitions than the term warrants; perusal of some of the hits indeed revealed a considerable diversity in what is considered to be resilience.

In one example that caught the eyes of the authors, as an example of resilience that perhaps defies quantification, the US Department of State has a web page devoted to the definition of resilience (US Department of State 2017). There, following a general definition of resilience, a bulleted list provided under the heading Ways to become more resilient spells out ways to increase individual resilience; the last bullet point in that list recommends laughing: "Laugh: Even when things seem to be falling apart around you, try to find time to smile and laugh. It is very healing and it will help you forgive your worries for a few moments. Rent a movie that makes you laugh or spend time with a friend with a good sense of humor."

Either the term resilience has evolved with an incredible elasticity while remaining relevant, or the preceding example suggests that resilience may have become the foundation of a new Tower of Babel in which all the occupants talk without necessarily

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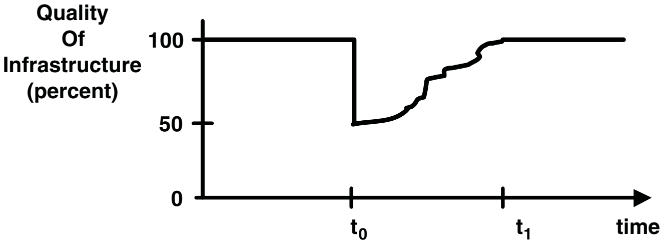

Fig. 1. Schematic representation of seismic resilience concept.

understanding each other. Arguably, a concept of resilience that means everything and anything for anybody is not a particularly useful concept as it escapes definition and qualification, therefore making it an intangible concept for practical purposes when the goal is to enhance resilience of the community in a measurable way. This underscores the urgency to re-establish some principles and rigor on the use of resilience within that specific context. This is done subsequently, focusing on resilience in a way that is relevant for engineers.

Although dictionary definitions are never similar from one dictionary to the other, all of them agree on a number of common characteristics when it comes to defining resilience. First, resilience in physical terms is defined as the ability of something to "recover its size and shape after deformation" (Merriam-Webster 2017). Some definitions specify "return to the original form" (Dictionary.com 2017), "resume its original shape" (American Heritage Dictionary 2017), "spring back into shape" (Oxford Living Dictionary 2017), and other variants. Second, dictionaries define it in life terms as the ability to recover readily from illness, change, depression, adversity, misfortune, or the like. Some definitions specify "recover quickly" (American Heritage Dictionary 2017), "become healthy, happy, or strong again" (Merriam-Webster 2017), and other variances. In all the dictionary definitions, however, resilience is essentially and fundamentally the quality of being able to return quickly to a previous good condition after problems have occurred. This is the concept embodied initially by Bruneau et al. (2003) in Fig. 1, which has been widely used in the literature and needs no detailed explanation here.

This highlights the fact that any functional definition of resilience must refer to a baseline that defines the original condition. In essence, to define and quantify resilience, this baseline must be defined as a functionality of some kind, which could be, for example, the functionality to maintain the operation or the intended function of communities, services, organizations, infrastructures, or physical facilities, either individually or considering their combined interactions. Furthermore, quantification of resilience must be able to address both the loss of functionality (which can be quite sudden in the case of a disastrous event, such as an earthquake or extreme hazards), and the path of this recovery of functionality both in time and space, as presented by Renschler et al. (2010) and Cimellaro et al. (2016b).

In other words, functionality is at the core of a workable definition of resilience that can be quantified. In that perspective, functionality can be defined in a number of ways that vary as a function of the services that are provided. For example, functionality can be expressed as (1) residual strength divided by needed strength for the quantification of physical infrastructures; (2) available space divided by original space for the physical, economic, and environmental dimensions of resilience; (3) the number of customers served compared with the total number of customers for infrastructure networks, health of a population, or organizational networks; or even (4) waiting time in emergency conditions compared with waiting time in normal conditions for public transportation, distribution of goods, and emergency roams. These are only some examples among many.

There could be many definitions of functionality for a given service, depending on the objective sought, constraints in the availability of data, or the resources needed to achieve quantification. For example, residents in seismic areas have expressed their strong expectation that acute care facilities should be available and operational following an earthquake (Alexander 1996; Nigg 1998). To quantify the seismic resilience of acute care facilities, the measure of functionality shown by the vertical axis of Fig. 1 must first be defined. This could be done in a number of different ways, depending on the type and range of mitigation actions that are contemplated. Two alternative options of functionality are discussed subsequently, one addressing quality of life and the other addressing the capacity to provide treatment.

A first option is to quantify quality of life as functionality expressed as the percentage of healthy population, with 100% on the vertical axis representing the healthy population that resides in an area prior to a scenario earthquake. A first decrease in population health would occur due to death in seismically deficient structures or from other causes (Peek-Asa et al. 1998). Injuries suffered during the earthquake would account for the remaining reduction in the healthy population at time t_0. In the best of scenario, in absence of hospital losses, all these injuries would heal, and no more deaths would be added to the toll. Conversely, deaths and debilitating injuries would occur due to loss in health care capacity and inability to offer treatments. This functionality measure has the advantage that it seeks to quantify a true global societal measure of seismic resilience for a community, which is probably a significant measure for the purpose of policy making. However, it suffers a number of shortcomings related to the difficulties in obtaining quantifiable data with limited resources in affected areas. Furthermore, it is very difficult for professionals to determine the linkage between population health (functionality) and engineered infrastructure.

The second option focuses on relating the functionality of acute care facilities to the number of patients/day that can be provided treatment (Bruneau and Reinhorn 2007). This could be done for a single institution or for all facilities across a geographical region. This approach can capture (1) the major loss of patients/day capacity directly attributed to the earthquake, (2) the effects of lost capacity due to elimination of unretrofitted seismic deficient facilities [consequent to California Senate Bill 1953 (Legislative Counsel's Digest 1994)], and (3) a short burst of recovered patients/day capacity provided in the aftermath of the disaster as a consequence of the parking-lot mobile army surgical hospital (MASH)-like medicine often provided outside of hospital facilities that have suffered debilitating damage. The advantage of this second approach is that it focuses on the physical infrastructures and their ability to provide their intended function, which facilitates engineering quantification (Chang et al. 2016). This is not to imply that engineering issues are more important than the health issues described in the previous option, but only that this framework makes it possible for a coordinated engineering research effort to contribute in a focused and effective manner to the broader problem. The engineering quantification tools that might result from coordinated engineering and socioeconomic-governmental research could be used in decision support. The tools could assess whether the seismic resilience is enhanced or not, i.e., (1) whether a specific intervention (or set of interventions) effectively and significantly reduces the probability of a loss in patient-day capacity, (2) if a specific overflow locally can be absorbed globally or regionally, and (3) how long it might take to restore this capacity.

Although this approach is more suitable for engineering quantification, it nonetheless remains a complex endeavor when accounting for all equipment and units in a given hospital, their interdependencies, and linkages between geographically distributed hospitals. Cimellaro et al. (2010a) showed that actual relationships can also depend on the postearthquake condition of the transportation network needed to establish effective linkages, which therefore requires knowledge of the fragilities of that network.

If anything, this illustrates how defining functionality in a manner that can lead to quantification of resilience is a challenge for which extensive research is still needed. Engineers can play an important role in that process and within the broader field of disaster resilience. Obviously, engineers can create resilient infrastructure to minimize loss of functionality, and to achieve fast recovery at minimum cost. Beyond that, however, engineers should participate in the discussions and decision-making activities to formulate multidisciplinary, multidimensional platforms that will be used to quantify resilience, because they can help define the weight to give to the resilience of the physical (engineered) infrastructure in an integrated global resilience framework spanning many dimensions (Renschler et al. 2010; Cimellaro et al. 2016b), as discussed subsequently. In particular, one of the engineers' most important roles when part of such discussions (and beyond) is to emphasize that the mitigation of disastrous effect is key to the implementation of any resilience framework if one wishes to manage and prevent disasters. As such, they can help engineer the entire decision-making process (Bruneau et al. 2003) to break the disaster cycle.

Structural engineers, however, must contend with a number of dilemmas while trying to serve in the aforementioned role. These are not trivial. This opinion paper provides an overview of three of those dilemmas and highlights some of the challenges that must be overcome in these regards.

First Dilemma

Resilience of the engineered infrastructure is something that most people do not care about until after a disaster occurs.

Most people in North America are familiar with the Three Little Pigs story (many versions of it can be easily found on YouTube). The Three Little Pigs analogy was used by a colleague of the authors after a major earthquake to explain to homeowners who had suffered losses that not all houses are created equal when it comes to resisting disasters. However, as pointed out by that same colleague in private philosophical discussions, it remains that, in the Three Little Pigs story, if no wolf ever comes, the first two little pigs have had a more enjoyable life (i.e., more free time and resources)–which is essentially the archetype underscored by the nursery rhyme. Likewise, when it comes to earthquakes, investments in earthquake protection measures, although they enhance resilience, may never actually provide any return on investment in the lifetime of the investor if no damaging earthquake occurs. The same is true for other extreme hazards. Even in full awareness of the risks, probabilistically speaking, betting on the absence of a disaster occurring and hoping to reap an immediate benefit rather than a possible future one is always an option. Tolerance to risk is a complex topic, and a fundamental driver of human behavior. However, in societies that encourage and value immediate rewards, advocating disaster resilience can be an uphill battle.

The problem is partly compounded by the fact that the design philosophy embedded in building codes is one of life safety, not damage prevention nor continuing functionality, which is often not communicated or not completely understood by the consumer. This philosophy is often justified, by analogy, by the rational decision to buy a car with good crash-test ratings that would provide high expectations of survival of passengers in a major collision but where the car itself would be totaled. This philosophy of minimum design for life-safety performance often comes as a surprise to the public, generally after an earthquake when structural and nonstructural damage has occurred, but also to those contracting a project at the design stage when the structural engineering consultant is offered the opportunity to discuss issues of seismic performance. In those latter cases, faced with the option of buying superior seismic performance at the onset, many owners chose the less expensive life-safety option. Arguably, it is effectively a decision to bet against the occurrence of an extreme event and use the liquidity for other immediate purposes, which can be a defendable position provided it is a conscientious decision, recognizing the consequences, and using insurance instead (or self-insurance) to cover the risk. Fundamentally, this is a pay-now versus pay-later decision, with all the trappings that come with it.

However, a fatal flaw of the car crash analogy lies in the fact that car collisions, most of the time, involve no more than a few vehicles. When the majority of buildings in an urban area are designed following the life-safety perspective, the proper analogy should be that of a massive car pile-up involving hundreds of vehicles (the type that sometimes happen on icy roads in foggy driving conditions), in which everyone ends up in the same car crash at the same time. When it comes to buildings, such widespread damage can lead to paralysis of a region or urban center, as happened following the New Zealand's Christchurch earthquake when the entire central business district was evacuated, cordoned, and then fenced-off for months to all except professionals involved in authorized response and recovery activities. Owners and residents were prevented access to the area, even if only to recover their belonging, effectively turning the central business district into a ghost town (the first author witnessed restaurants with food rotting on the counters, stores with intact inventory exposed through broken windows, and belongings and passports left in hotel rooms. As harshly criticized as this tight control was, it nonetheless happened. On the second anniversary of the earthquake, a large percentage of the central business district was still fenced-off, with new types of damage progressively taking root as a consequence of delayed repairs/reconstruction.

Seven years after that earthquake, most of the buildings in the central business district had been demolished and the area was in the midst of a massive rebuilding (recovery) effort that is expected to continue until 2020 (Bruneau and MacRae 2017). Interestingly, a major debate is still raging about the desire of parishioners to rebuild the heavily damaged Christchurch cathedral in the same stone masonry from which it was originally built, but possibly strengthened to achieve a collapse-prevention level (thus, again prone to damage in a future earthquake).

To some degree, denial of risk when it comes to rare extreme events may be rooted in human nature and urban legends. Many Californians (prior to the Loma Prieta and Northridge earthquakes) stated that earthquakes were not a big deal and were nothing to worry about (these were obviously not words from engineers, but mindboggling nonetheless considering the history of San Francisco and the 1906 earthquake. Interestingly, the same attitude is found to exist with other hazards; over the years, the first author has met multiple residents of Florida living along the coast from Saint Augustine to Melbourne who adamantly believed that this particular part of Florida could not be hit by a hurricane, due to either the shape of the ocean floor, the shape of the coast where Cape Canaveral projects into the ocean, or both. Interestingly, with the 2016 Hurricane Matthew hugging the coastline short of landfall, and producing extensive wind and storm-surge damage along a part of that coast north of Cape Canaveral, this urban legend has been quieted (for now). Unfortunately, many of the current economic-political decision systems are based on the aforementioned perceptions (or misperceptions). Whether such denial of risk is a mechanism to cope with the vagaries of life is a topic best left to psychologists, anthropologists, and other such specialists. However, the preceding illustrates that promoting disaster resilience is not something that clients will readily embrace, which is a challenge to structural engineers interested in enhancing the resilience of communities.

Second Dilemma

How can a structural engineer contribute to quantifying resilience?

Much research is ongoing to quantify or measure resilience. To a large degree, this valuable work focuses on the resilience of distributed networks or of communities. If engineers are to contribute to such quantification/measurement, then a few things are needed for this purpose, namely

- a resilience framework that defines both resilience and what is to be measured;
- a method to quantify resilience;
- multidisciplinary collaborations to comprehensively address the community resilience; and
- strategies to enhance resilience (i.e., to engineer greater resilience).

These are considered in this section.

Resilience Framework That Defines Both Resilience and What Is to Be Measured

If resilience is defined as a measure of changes in functionality in time and space, consistently with the previous definitions of resilience (Fig. 1), a functionality must be defined and measured—one that will vary depending on the specific application considered. An integrated approach to resilience requires that resilience be considered at many levels, from global (community) resilience, various dimensions of resilience of dimensions (i.e., subsystems of a community), to components within such dimensions.

Many approaches can be used for this purpose (Cimellaro et al. 2016a). For example, the MCEER population and demographics, environmental/ecosystem, organized governmental services, physical constructed infrastructure, lifestyle and community competence, economic development, and social-cultural capital (PEOPLES) framework (Renschler et al. 2010; Cimellaro et al. 2016a) provides seven functionality dimensions (i.e., seven realms of a community), that each regroup a resilience component (i.e., components within a dimension of a community, which incidentally can have interdependencies with resilience components of other dimensions), and corresponding resilience indicators (which are quantitative measure of resilience/systems functionality based on quantitative and/or qualitative data sources). The proposed PEOPLES Resilience Framework provides the basis for development of quantitative and qualitative temporal–spatial models that measure continuously the changes of functionality and resilience of communities against extreme events, or disasters, in any individual or combination of the aforementioned dimensions. Over the longer term, this framework will enable the development of geospatial and temporal decision-support software tools (Cimellaro 2016) to help planners and other key decision makers and stakeholders assess and enhance the resilience of their communities.

The preceding is used for illustration purpose, and other frameworks are possible. No universally accepted framework exists in this regard, as described subsequently.

Method for Quantify Resilience

Once the resilience framework has been selected, resilience must be quantified. Here, again, no consensus has been reached.

Cutter (2016) stated that "the landscape of disaster resilience indicators is littered with wide range of tools, scorecards, indices that purport to measure disaster resilience in some manner," and described the advantages and disadvantages of the major ones developed in the United States. Although there are different expressions of resilience and frameworks that measure it, a large number of those consist of qualitative checklists or score sheets that give either a score or an aggregated index of resilience. Such score sheets are convenient because they can provide measures that are readily usable by communities that need something immediately and cannot wait for further research developments, but they risk becoming enshrined in standard operations of the adopting community and becoming unquestioned over the years in spite of their shortcomings. Arguably, these might also be less compatible with the goal of developing and using engineering tools and approaches to enhance resilience.

The frameworks that may be more appropriate for this purpose are those that have been explicitly created with the goal to quantify using a mathematical framework that treats the resilience data as a continuum rather than as discrete or subjective measures. The main drawbacks of quantitative continuum approaches are that they are data intensive and the tools to achieve the quantification itself are still the subject of ongoing research (and the scale of multidisciplinary research needed to fulfill the vision may be orders of magnitude greater than the funding levels currently devoted to the task). The promise is that rigorous mathematical formulations allow integrating resilience across dimensions, and also investigating sensitivity of various factors of either global (community) resilience or the resilience of dimensions (subsystems of a community) or components within such dimensions.

A common quantitative approach to quantify resilience is related to the variations in the functionality curve (Fig. 2), which can be specified for a given building, bridge, lifeline network, or community over a period defined as the control time (T_{LC}). The control time is usually decided by building owners or society at large, for example, and can be taken to correspond to the expected life cycle or life span of the building or other system, or to any other fixed time reference. Resilience is defined graphically as the normalized shaded area underneath the function describing the functionality of a system, defined as $Q(t)$, which is a nonstationary stochastic process, and each ensemble is a piecewise

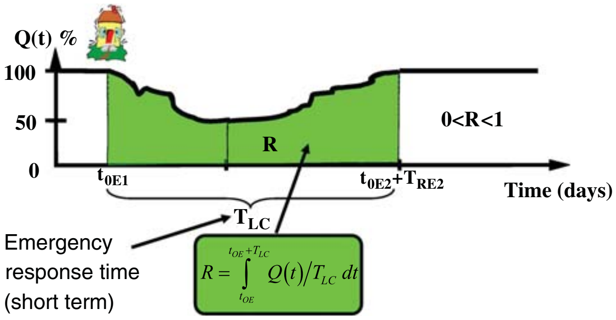

Fig. 2. Functionality curve and resilience.

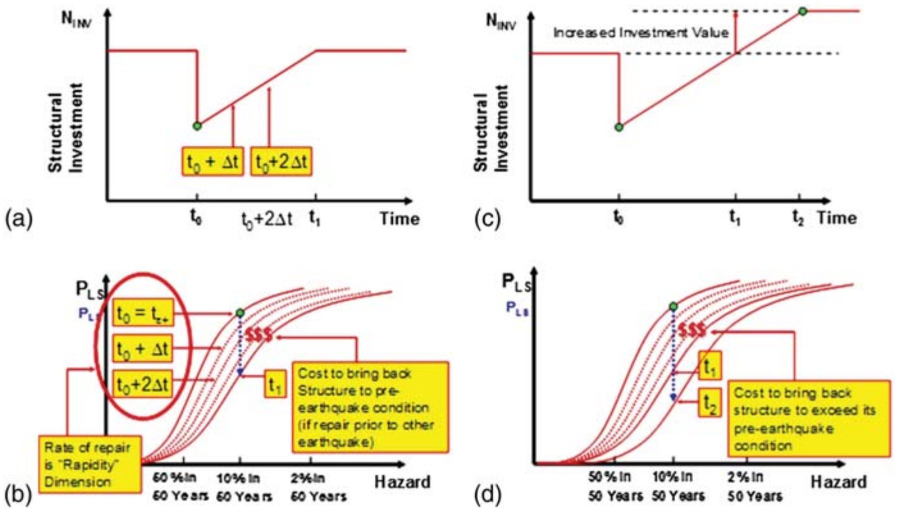

Fig. 3. Case of nonlinear structural seismic response: (a) improvement in structural resilience as structure is repaired over time; (b) corresponding reduction in probability of structural losses; (c) increased resiliency to pre-earthquake condition; and (d) corresponding improvement in probability of structural losses.

continuous function as in Fig. 4, where $Q(t)$ is the functionality of the region considered.

The change in functionality due to extreme events is characterized by a decrease, representing a loss of functionality, and a rise, representing its recovery. For communities, the loss of functionality can be gradual (Fig. 2), or it can be sudden (Fig. 1), as from earthquakes (e.g., Bruneau and Reinhorn 2007).

Again, functionality in quantitative approaches is key to the original definition of resilience, to the extent applicable to the field of disaster mitigation, in which the loss and recovery of functionality over time is what matters. In some applications, this information can be readily acquired, particularly when functionality is a service and its measure is embedded in a metered distribution network (such as electricity or water). Not surprisingly, a dominant segment of all resilience studies focused on such distribution networks. However, one must carefully interpret these data. For instance, the electrical grid can report the number of households served by the power utility, but the community may be much more resilient than indicated by this measure. This is the case in many neighborhoods (such as that of one of the author's) in which many owners, having suffered through a severely disruptive multiday power outage, have added back-up gas-powered generation capabilities to their residence or business, freeing themselves from the grid's unreliability, thus rendering inaccurate all measures of resilience based solely on data from the utility providers.

For individual engineered structures, the achievement of a resilient design is less directly obvious, particularly because considering resilience in its greater context can effectively void efforts invested in making more resilient a single structure that is part of the total urban landscape. No consensus has emerged on how this could be done, but for illustration purposes, in one approach to quantify seismic resilience, Bruneau and Reinhorn (2007) used the normalized investment value as a measure of functionality. Moreover, they used a two-probability distribution of the effects of earthquakes to calculate the probability that response exceeds a specific limit state, thus determining the fragility curves and corresponding resilience curves (Fig. 3).

Figs. 3(a and b) also illustrate how structural repairs can affect the expected responses during the recovery process (arbitrarily shown at equal time increments here) by progressively shifting the curve of functionality back to the original condition that existed at the instant before t_0 (thus equal to the condition at t_1). This required a financial investment, and one can quantify the cost required to shift from one probabilistic curve to another (unlikely to be a linear relationship). The rate of repair also provides a measure of the rapidity dimension of the resilience curve. Repairs to nonstructural components may also be required [Figs. 3(c and d)], and it is possible to increase the value of the investments (on the basis of the same nonstructural components and equipment here, not by adding more of them) to above the pre-earthquake condition, enhancing seismic resilience by reducing the probability of losses in a future repeat of the same earthquake. More sophisticated approaches focusing on the structural problem are also possible.

Multidisciplinary Collaborations to Comprehensively Address Community Resilience

The quantification of community resilience is a complex temporal and spatial problem (Renschler et al. 2010) that also evidently requires an integrated multidisciplinary effort commensurate with the inherent multidisciplinary nature of the problem. Whatever framework is chosen, engineers must ensure that the weight given to infrastructure as part of this quantification recognizes the predominant impact that infrastructure damage has on a region's resiliency.

For example, taking again the PEOPLES Resilience Framework (Renschler et al. 2010) for illustration purposes, consider that each dimension and/or service and its indicators or terms of functionality can be represented with a GIS layer of the area of interest (Fig. 4). In Fig. 4, Q_{POP} is the functionality of the population in the community; Q_{ENV} is the functionality of the environmental fabric; Q_{ORG} is the functionality of organizations; and Q_{PHY} is the functionality of physical infrastructure systems; all of which are functions of location (r) and of time (t). The other temporal functionality maps include lifestyles, economics, and social/cultural aspects. For each layer, it is possible to define a resilience index contour map after integrating the functionality for the control time (T_{LC}).

Each dimensional layer has a specific spatial functionality dictated by the influence area of the grid, jurisdiction, economic

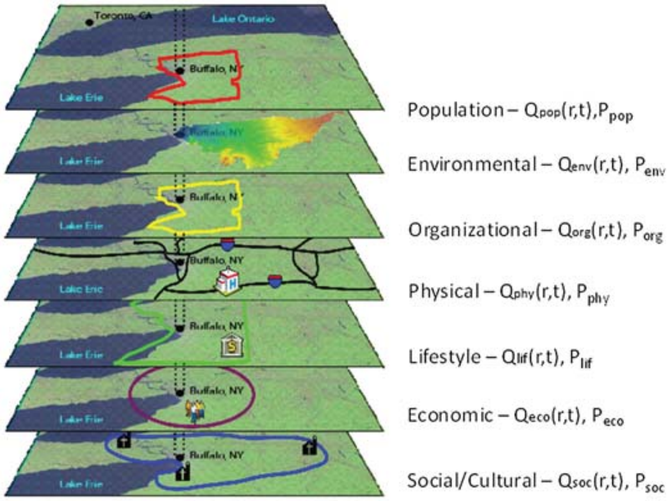

Fig. 4. Schematic representation of time-dependent community functionality maps. (Image courtesy of Chris S. Renschler, Department of Geography, University at Buffalo, Buffalo, NY.)

environment, social cultural fabric, and so forth (Fig. 4). Moreover, each layer of component functionality in Fig. 4 can be represented by a combination of subdimensions (or layers), each having spatial-temporal dependent functionalities, each representing a subcomponent.

A global community resilience index can be obtained to assess the entire community by summing (or integrating) over space and time the total functionality that combines the different dimensions of resilience, to obtain a final community resilience index (Renschler et al. 2010). Doing so, however, requires weighing (by using a priority factor in the integrals) the relative importance of each dimension to the total resilience index. It is obvious that some of the priorities in the global functionalities may be small and may be ignored, resulting in a reduced-order decision system. It is the responsibility of engineers to ensure that the predominant significance of infrastructure is appropriately recognized in such reduced-order models.

Moreover, the same framework and computational approach are applied to each individual dimension layer in Fig. 4, such as for the physical component. This dimension layer includes the (1) housing, (2) transportation, (3) electrical/power, (4) water, (5) sewage, (6) gas distribution, and (7) communication networks for which functionalities are determined (Renschler et al. 2010).

The single resilience index obtained by integrating all resilience dimensions of a region can be valuable, but must also be subject to careful interpretation. For example, Fig. 5 shows a regional resilience index calculated for every region by combining, using probabilistic weighting coefficients, the individual functionality-based resilience curves for the power, water, and gas networks obtained following the 2011 Tohoku earthquake (Cimellaro et al. 2014). On that map, different prefectures are shown to have different resilience indexes. However, those with higher indexes are not necessarily more resilient communities—they only happened to be communities farther from the earthquake epicenter and thus were less disturbed by the event. Their resilience might have all been identical had they had been at the same distance from the epicenter. This suggests the need to develop techniques to normalize resiliency measures as a function of the intensity of the hazard (in terms of earthquake magnitude and epicentral distance, for example).

Strategies to Enhance Resilience

Mitigation, which involves either retrofitting the existing infrastructure or making new construction more resilient, is key to achieve the goal of resilient communities, but that is often forgotten or dismissed on the premise that it is too expensive. Obviously, this raises the question *too expensive compared with what?* There seems to be quite a generous cost tolerance to eliminate all risks in some other regulated areas, for example, calling for crews in hazmat suits to remove traces of asbestos, or requiring baby car seats to be discarded after a few years due to aging of the plastic.

It is imperative to recognize that, complementary to improvements in response/recovery, enhancing the disaster resilience of a region or country requires mitigating the disaster vulnerability of its facilities and lifelines, i.e., reducing loss of functionality. A perfect response and recovery plan will not eliminate the massive initial losses. Mitigation is needed; otherwise, communities (and the nation) will be stuck in an endless cycle of destruction-reconstruction-destruction. Strangely, even though the public expects critical facilities and lifelines to be functional-operational following a disaster, this is not necessarily the case—not to mention the rest of the infrastructure.

It is generally difficult to upgrade design codes and specifications for new construction beyond minimum requirements, or to a level above life-safety protection (e.g., Bruneau and MacRae 2017; SEI 2018), even though life safety alone implies that most buildings will suffer considerable damage during an earthquake, thus greatly affecting the functionality and consequently the resilience of the affected communities. It is not the purpose here to analyze the economic pressures or mindsets that justify this approach. However, continuing to build less resilient (or even to build disaster-vulnerable) facilities and lifelines simply adds to the inventory of such infrastructure, which is not helpful. For example, in 2001, the United States National Home Builders Association reported building 2,000,000 new homes per year, and reported a total inventory of 119,117,000 housing units in the United States (NHBA Representative, personal communication, 2001). Two decades later, at that rate, they will have added 40,000,000 new homes, which will be 30% of the existing inventory. Any new measure implemented in 2001 would therefore now be found in a progressively growing number of homes. The argument that adding new requirements to enhance resilience of homes is prohibitively expensive is of dubious merit, because the cost of residential homes has increased significantly during that same 20-year period without the addition of any disaster-resilience features. Except for a lapse of a few years due to the implosion of the housing bubble, homes are still bought and sold (and prices are going up again).

When it comes to mitigation, generally speaking, enhancing the robustness of the infrastructure simultaneously translates into a greater rapidity to recover. In the context of Fig. 1, robustness refers to the inherent strength of a system and its ability to reduce the initial loss/degradation in functionality, and rapidity refers to the rate of recovering functionality to an acceptable level of performance either lower than, identical to, or higher than previously (Bruneau et al. 2003).

In the perspective of mitigation, the Christchurch reconstruction experience shows that some new structural engineering concepts that prevent/minimize disruption can be implemented without necessarily incurring higher initial cost (Bruneau and MacRae 2017). In particular, most of Christchurch is being reconstructed (partly consciously, partly unconsciously) with structural systems that will allow a more rapid return to functionality following future earthquakes. As such, RC frames are not used anymore, and as part of the new inventory of steel structures, most structures rely on

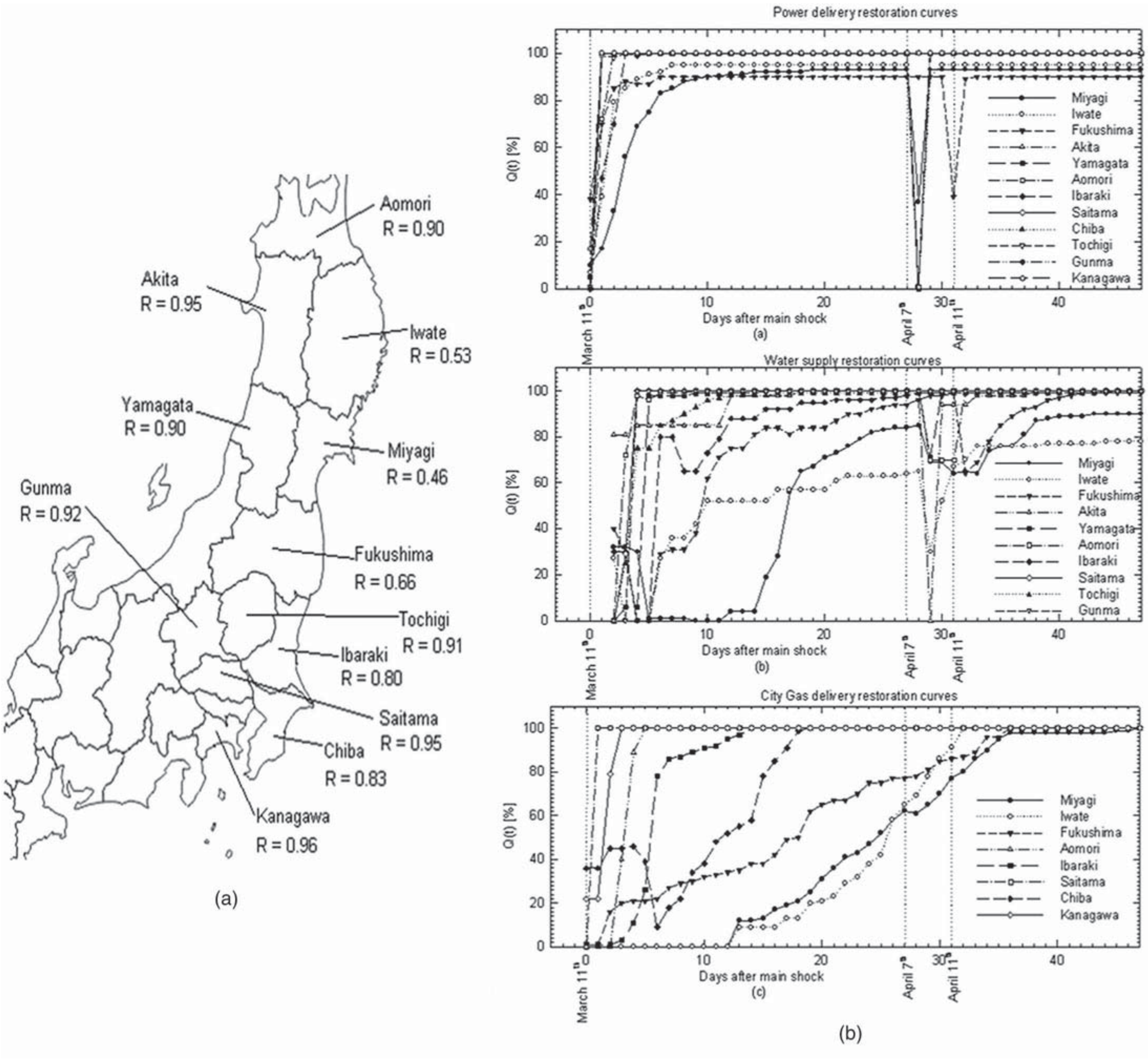

Fig. 5. Resilience index calculated following the 2011 Tohoku earthquake, in Japan: (a) regional resilience indexes; and (b) resilience curves for various utilities. (Image courtesy of Gian Paolo Cimellaro, Civil Engineering Department, University of Torino, Italy.)

buckling restrained braces, which have a large low-cycle fatigue life and can sustain multiple earthquakes, and eccentrically braced frames, with either conventional links, which past experience has shown to be expeditiously repairable, or with specially detailed replaceable ductile links intended to further accelerate postearthquake repairs (Fig. 6), consistent with the philosophy that hysteretic energy dissipation should instead occur in disposable structural fuse elements [a more rigorous definition of structural fuses was presented by Vargas and Bruneau (2009a, b)]. As indicated previously, rocking frames, base isolation, dampers, and other types of advanced structural engineering strategies are also occasionally implemented as part of this reconstruction effort.

Similarly, multihazard design also holds a promise of producing more resilient infrastructure, because the development of single

Fig. 6. Close-up of replaceable link in an eccentrically braced frame. (Image by Michel Bruneau.)

structural systems able to provide adequate performance against multiple hazards can be cost-effective. For example, past research has shown that concrete-filled steel tubes fall within this category (Fujikura et al. 2008; Imani et al. 2015; Zaghi et al. 2016). These are only some of the areas within which the structural engineer is poised to make great contributions to resilience.

Third Dilemma

Making a disaster-resilient community requires multiple owners and stakeholders (with varied priorities, values, and interests) to similarly embrace resilience.

Much of the work on the quantification of resilience has been done on network systems, such as highway networks, power grids, water distribution systems, and other similar networks. These networks are fundamentally different from the ensemble of buildings within a community for a number of reasons.

- First, the assets within a network system are typically owned either by a single owner or by a consortium of a few interdependent large owners. For example, the highways in a state are, with a few exceptions, owned by the state DOT.
- Second, the design of these networks is often self-regulated, meaning that the design requirements of these facilities are adopted by specification committees on which only these owners have the right to vote.
- As a consequence of the preceding two points, these owners have the ability to proceed and set priorities regarding the resilience of their infrastructure; for example, state DOTs have taken the initiative to identify critical routes on which infrastructure should be functional after an earthquake, typically designated lifeline roads and bridges.

The situation is quite different for the ensemble of buildings within a community. First of all, it is generally the case that there are a large number of owners within a specific community. Furthermore, the concept of a lifeline building does not exist, unless that building is surrounded entirely by lifeline buildings, on a self-sufficient lifeline island. Even if a single building had been made resilient to earthquakes, it could suffer damage from other surrounding buildings, as shown in Fig. 7, in which the low-rise building might have had, by itself, a satisfactory performance during the earthquake, but was nonetheless destroyed under the shower of bricks created by the out-of-plane failure of the neighboring building's unreinforced masonry wall. Likewise, many buildings that performed well during the Christchurch earthquake were rendered inaccessible (and therefore had no functionality) when owners were kept out of the Christchurch Business District after the earthquake. For these reasons, truly resilient communities may be decades away for some hazards.

Fig. 7. Damage to low-rise building in Santa Cruz, California, due to collapsed parapet from adjacent building during 1989 Loma Prieta earthquake. (Image by Michel Bruneau.)

This is further complicated by the fact that achieving resilience requires integrated interaction between stakeholders in the various dimensions (Fig. 4). This was illustrated by Cimellaro et al. (2010b), who calculated the resilience of a hospital network with or without the existence of a coordination agent (Operative Center). Without the benefit of this coordination center, patients typically go to the nearest hospital. In a scenario in which functionality is defined as the waiting time in emergency rooms, the nearest hospital is overwhelmed and its resilience is low (long waiting times), while a hospital farther away is underutilized and its resilience is high (low waiting time). With the benefit of the coordination center, patients were optimally distributed according to a rule that considers both the waiting times at the respective hospitals and the corresponding transportation time to reach each hospital, and the resulting resilience of the hospital network taken as a whole was found to be higher.

Possible Solutions to Core Resilience Problem

It has been argued before that the key to making a community resilient is to ensure that its critical infrastructure will be operational in a postdisaster context. However, a community cannot really be considered resilient when all its lifelines (such as bridges along major evacuation and supply routes, and/or hospitals designed to strict state-enforced guidelines) are made resilient if no other buildings and components are resilient. This was demonstrated by the situation in Christchurch, where hospitals were functional following the earthquake, and adequate road access to the Central Business District remained, but where the Central Business District lost its functionality for years—and still has not recovered to its pre-earthquake condition, more than 7 years after the event. Although some have said that Christchurch was highly resilient during the February 22, 2011, earthquake, because only two buildings collapsed, in a context in which resilience is tied to functionality, one can only disagree. In that perspective, whenever resilience is pursued without ensuring that regular buildings are resilient, it could be said that community efforts at enhancing resilience are counter to the best intentions of structural engineers.

Therefore, if resilience is to be achieved, there needs to be a mechanism to ensure that resilience is part of the discussion in the design of all buildings. Because it is unlikely that building codes and specifications will require resilient design in the foreseeable future, and because the interest in achieving resilient infrastructure has a tendency to subside as time from past damaging earthquakes increases, it is not clear how such a discussion will proceed. It is commendable that the US Resiliency Council (USRC) has proposed an Earthquake Building Rating System, similar to the LEED rating system for green buildings, in which buildings volunteered for such an evaluation will be rated from one to five stars for the respective performance measures of safety, damage (in terms of repair cost), and recovery (in terms of time to return to pre-earthquake functionality). Although there is a risk that this initiative may give the wrong impression that all is known about resilience, it is commendable that it engages owners in a dialogue on some of the key issues on this topic. In such a case, the criticisms must be weighed against the benefits, and time will be needed to perform such an assessment because implementation of the rating system is still in its infancy.

In the meantime

- most owners do not want resilience (or do not know why they should want it);

- a resilient building may be pointless unless the entire community is collectively resilient; and
- resilient buildings are good, but community resilience requires more than resilient buildings.

Therefore, achieving community resilience one building at a time may end up taking a long time. This creates an overwhelming challenge.

It will be interesting to see how the challenge is met over time, but if one wishes to speed things up, as with all challenges of that magnitude, unorthodox ideas might be needed (in the same manner that spanning the Golden Gate with a bridge, or sending a human to the moon, were once deemed to be absolutely unachievable endeavors). In that mindset, the authors propose the Lifeline (Resilient) Building District concept. Figuratively speaking, such a community would be a self-contained island of buildings, all having a five-star USRC resiliency rating, connected to a transportation lifeline (to prevent Christchurch-type encapsulation and to link to critical facilities, if needed), and having emergency back-up power generation, independent water purification and waste-treatment capabilities, and (possibly if too close to other nonresilient communities) its own security forces. By analogy to the original Experimental Prototype Community of Tomorrow (EPCOT) that was envisioned by Walt Disney [the living community EPCOT, not the amusement park EPCOT, as described by the-original-epcot.com (2002)], the proposed Lifeline (Resilient) Building District would be a Resilient EPCOT. As originally envisioned, EPCOT was to be a prototype community built from scratch on a virgin plot of land, and systematically created to include a business district, an industrial park, a commercial zone, a residential green belt, and an airport of the future, among other things, all relying on the latest technologies and advanced designs—in essence, it was Walt Disney's expression of urban planning, with aspects conceived, designed, and engineered from the onset to match his vision. As he stated himself, EPCOT was to be "like the city of tomorrow ought to be. A city that caters to the people as a service function. It will be a planned, controlled community, a showcase for American industry and research, schools, cultural and educational opportunities." However, Disney died in 1966 and all efforts toward that goal stopped a few years later.

Conceptually, the Resilient EPCOT could be modeled in many shapes and forms on the EPCOT model, because it would be an entirely new community built from scratch, but built to be highly resilient, and thus able to most rapidly (or maybe even immediately) return to full functionality of all its systems and parts after an extreme event. In the globally integrated economic context, an earthquake in Japan can have a ripple effect across the entire world, but a resilient island is still better than no resilient island.

This unrealistic idea is subject to receive the same social criticisms that the original EPCOT concept did, and it may be argued to reek of elitism and exclusivity. However, whereas only Lincolns and Cadillacs offered power windows in the 1950s (i.e., exclusivity), many automakers nowadays offer no models with hand-crank windows (it might not necessarily be a cheaper option anymore) Furthermore, given the current trend in many parts of the United States toward gated communities, the step to a full Resilient EPCOT is much smaller now than it was in Disney's 1960s.

Whether the Resilient EPCOT idea is desirable and achievable or not, only time will tell. In the meantime, while waiting for bolder practical ideas, it will not hurt to follow the advice from the State Department to be more resilient.

Conclusions

The concept of resilience is intricately tied to the expression and quantification in time and space of the functionality of communities and its components. To achieve resilient communities, one therefore needs (1) a resilience framework, (2) methods to quantify resilience, (3) multidisciplinary collaborations between components, and (4) strategies to enhance resilience. Most critically, it requires the ability to track how the functionality of all systems and buildings within a specific geographical space evolves over time after a specific event of interest.

Innovative and integrated solutions are key to enhance the resilience of infrastructure against extreme events. The need to expand single-hazard solutions to address satisfactorily multiple hazards (without incremental costs) is desirable in that perspective. Multidisciplinary research requires a substantial investment of time and resources, which will be desirable to help acquire a better understanding of how to achieve truly resilient communities.

A community will never be resilient unless it has a resilient infrastructure. However, by the same token, a community peppered with a handful of resilient infrastructures (be they critical infrastructures or not) risks not being as resilient as intended. An integral approach is necessary. Therefore, it is proposed that developing one or many Resilient EPCOTs might be the best approach to provide a possible integrated solution to achieve resilient communities.

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References

Alexander, D. 1996. "The health effects of earthquakes in the mid-1990's." *Disasters* 20 (3): 231–247. https://doi.org/10.1111/j.1467-7717.1996.tb01036.x.

American Heritage Dictionary. 2017. "Resilience." 5th ed., Houghton Mifflin Harcourt. Accessed September 23, 2017. https://ahdictionary.com/.

Bruneau, M., S. E. Chang, R. T. Eguchi, G. C. Lee, T. D. O'Rourke, A. M. Reinhorn, M. Shinozuka, K. Tierney, W. A. Wallace, and D. Von Winterfeldt. 2003. "A framework to quantitatively assess and enhance the seismic resilience of communities." *Earthquake Spectra* 19 (4): 733–752. https://doi.org/10.1193/1.1623497.

Bruneau, M., and G. MacRae. 2017. *Reconstructing Christchurch: A seismic shift in building structural systems*, 170. Canterbury, New Zealand: Quake Centre, Univ. of Canterbury.

Bruneau, M., and A. Reinhorn. 2007. "Exploring the concept of seismic resilience for acute care facilities." *EERI Spectra J.* 23 (1): 41–62. https://doi.org/10.1193/1.2431396.

Chang, S. E., W. D. Svekla, and M. Shinozuka. 2016. "Linking infrastructure and urban economy—Simulation of water disruption impacts in earthquakes." *Environ. Plan. B: Plan Disasters* 29 (2): 281–301. https://doi.org/10.1068/b2789.

Cimellaro, G. C., A. M. Reinhorn, and M. Bruneau. 2010a. "Organizational model of a hospital system." In *Proc., 2010 New Zealand Society for Earthquake Engineering Annual Technical Conf.* Reston, VA: ASCE.

Cimellaro, G. P. 2016. *Urban resilience for emergency response and recovery—Fundamental concepts and applications*. Dordrecht, Netherlands: Springer.

Cimellaro, G. P., L. Duenas-Osorio, and A. M. Reinhorn. 2016a. “Special issue on resilience-based analysis and design of structures and infrastructure systems.” *J. Struct. Eng.* 142 (8): C2016001. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001592.

Cimellaro, G. P., A. M. Reinhorn, and M. Bruneau. 2010b. “Framework for analytical quantification of disaster resilience.” *Eng. Struct.* 32 (11): 3639–3649. https://doi.org/10.1016/j.engstruct.2010.08.008.

Cimellaro, G. P., C. Renschler, A. M. Reinhorn, and L. Arendt. 2016b. “PEOPLES: A framework for evaluating resilience.” *J. Struct. Eng.* 142 (10): 04016063. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001514.

Cimellaro, G. P., D. Solari, and M. Bruneau. 2014. “Physical infrastructure interdependency and regional resilience index after 2011 Tohoku Earthquake in Japan.” *Earthquake Eng. Struct. Dyn.* 43 (12): 1763–1784. https://doi.org/10.1002/eqe.2422.

Cutter, S. L. 2016. “The landscape of disaster resilience indicators in the USA.” *Nat. Hazards* 80 (2): 741–758. https://doi.org/10.1007/s11069-015-1993-2.

Dictionary.com. 2017. “Resilience.” Accessed September 23, 2017. http://www.dictionary.com/browse/resilience?s=t.

Fujikura, S., M. Bruneau, and D. Lopez-Garcia. 2008. “Experimental investigation of multihazard resistant bridge piers having concrete-filled steel tube under blast loading.” *J. Bridge Eng.* 13 (6): 586–594. https://doi.org/10.1061/(ASCE)1084-0702(2008)13:6(586).

Imani, R., G. Mosqueda, and M. Bruneau. 2015. “Experimental study on post-earthquake fire resistance of ductile concrete filled double-skin tube columns.” *J. Struct. Eng.* 141 (8): 04014192. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001168.

Legislative Counsel’s Digest. 1994. *California Senate Bill 1953—Chapter 740—Amend the Health and Safety Code, relating to building standards*. SB1953. Sacramento, CA: Legislative Counsel’s Digest.

Merriam-Webster. 2017. “Resilience.” Merriam-Webster Dictionary. Accessed September 23, 2017. https://www.merriam-webster.com/dictionary/resilience.

Nigg, J. M. 1998. *Empirical findings based on research conducted under NSF Grant No. CMS-9812556, Perceptions of earthquake impacts and loss*. Reduction Policy Preferences among Community. Buffalo, NY: MCEER.

Oxford Living Dictionary. 2017. “Resilience.” Oxford University Press. Accessed September 23, 2017. https://en.oxforddictionaries.com/definition/resilience.

Peek-Asa, C., J. F. Kraus, L. B. Bourque, D. Vimalachandra, J. Yu, and J. Abrams. 1998. “Fatal and hospitalized injuries resulting from the 1994 Northridge earthquake.” *Int. J. Epidemiol.* 27 (3): 459–465. https://doi.org/10.1093/ije/27.3.459.

Renschler, C. S., A. E. Frazier, L. A. Arendt, G. P. Cimellaro, A. M. Reinhorn, and M. Bruneau. 2010. *Framework for defining and measuring resilience at the community scale: The PEOPLES resilience framework*. Technical Rep. to Sponsor—NIST GCR 10-930. Gaithersburg, MD: US Dept. of Commerce, NIST, Office of Applied Economics Engineering Laboratory.

SEI (Structural Engineering Institute). 2018. *Advocating for performance-based design*. Rep. to the Structural Engineering Institute Board of Governors submitted by the Task Committee on Performance- Based Design. Washington, DC: SEI.

the-original-epcot.com. 2002. “Walt Disney’s original E.P.C.O.T.” Accessed March 7, 2017. https://sites.google.com/site/theoriginalepcot/the-florida-project.

The White House. 2013. “Presidential policy directive—Critical infrastructure security and resilience.” Presidential Policy Directive/PPD-21, The White House, Office of the Press Secretary. Accessed February 27, 2017. https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil.

US Department of State. 2017. “What is resilience?” Accessed March 7, 2017. https://www.state.gov/m/med/dsmp/c44950.htm.

Vargas, R., and M. Bruneau. 2009a. “Analytical response of buildings designed with metallic structural fuses.” *J. Struct. Eng.* 135 (4): 386–393. https://doi.org/10.1061/(ASCE)0733-9445(2009)135:4(386).

Vargas, R., and M. Bruneau. 2009b. “Experimental response of buildings designed with metallic structural fuses.” *J. Struct. Eng.* 135 (4): 394–403. https://doi.org/10.1061/(ASCE)0733-9445(2009)135:4(394).

Zaghi, A. E., J. E. Padgett, M. Bruneau, M. Barbato, Y. Li, J. Mitrani-Reiser, and A. McBride. 2016. “Establishing common nomenclature, characterizing the problem, and identifying future opportunities in multi-hazard design.” *J. Struct. Eng.* 142 (12): H2516001. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001586.

ASCE-ASME J. Risk Uncertainty Eng. Syst., Part A: Civ. Eng., 2019, 5(3): 02519001