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Resilience of aging structures and infrastructure systems with emphasis on seismic resilience of bridges and road networks: Review

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ABSTRACT

Risk assessment and mitigation programs have been carried out over the last decades in the attempt to reduce transportation infrastructure downtime and post-disaster recovery costs. Recently, the concept of resilience gained increasing importance in design, assessment, maintenance, and rehabilitation structures and infrastructure systems, particularly bridges and transportation networks, exposed to natural and man-made hazards. In the field of disaster mitigation, frameworks have been proposed to provide a basis for development of qualitative and quantitative models quantifying the functionality and resilience at various scales, including components, groups and systems within infrastructure networks and communities. In these frameworks, the effects of aging and environmental aggressiveness must be explicitly considered, affecting the structural performance and functionality of civil infrastructure systems. Significant efforts have been made to incorporate risk and resilience assessment frameworks into informed decision making to decide how to best use resources to minimize the impact of hazards on civil infrastructure systems. This review paper is part of these efforts. It presents an overview of the main principles and concepts, methods and strategies, advances and accomplishments in the field of life-cycle reliability, risk and resilience of structures and infrastructure systems, with emphasis on seismic resilience of bridges and road networks.

Introduction

The quality of life of modern communities strongly relies on the ability of infrastructure networks to cope with hazards when they occur, absorbing the impact of disastrous events and restoring as soon as possible the pre-event or better conditions. Designing lifelines and infrastructure components to meet modern safety standards and planning proper management policies are key tasks to satisfy the primary needs of communities not only under operational conditions, but also in a state of emergency [1–4]. In this context, structure and infrastructure systems, such as buildings, bridges, and transportation networks play a key role in the aftermath of hazardous events. Bridges and infrastructure facilities guarantee the connectivity between origins and destinations of daily trips carried out by commuters in urban areas and ensure a quick deployment of emergency aids and resources to distressed communities. This is essential for a prompt repair of damaged lifeline components and buildings. Among all the elements within transportation systems, bridges are crucial components highly vulnerable to natural and man-made hazards, as narrow and fragile "bottlenecks" seamlessly interacting with the environment where they operate. They are not easily detoured, since they are designed to go either over or underneath an obstacle such as a road or water body. Moreover, they cannot be treated as standalone elements, as they are essential in preventing or minimizing outages and disruptions at the community level. Furthermore, the detrimental effects of aging and deterioration processes due to aggressive chemical attacks and other physical damage mechanisms can lead structure and infrastructure systems to exhibit over time unsatisfactory performance under service loadings or accidental actions and extreme events, such as earthquakes [5–9].

During the last decades, risk assessment and mitigation programs have been carried out in an attempt to reduce future losses and post-disaster recovery costs [10]. Despite the scientific and practical advances in civil and structural engineering resulting in new design and construction policies, there has not been enough progress in developing methodologies and best practices for life-cycle design, assessment, maintenance and management of bridges located in seismic regions. Bridge damage can cause direct monetary losses due to the necessary repair interventions to be carried out to restore the bridge carrying capacity and transit safety, as well as indirect losses due to network downtime and traffic delay. Therefore, it is fundamental to relate the vulnerability of critical bridges and the impact of their damage on the operability of affected communities. It is hence necessary to relate the functional

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connectivity provided by critical viaducts within the transportation network and the load-carrying capacity of vulnerable bridges under hardly foreseeable load patterns.

In this context, *resilience* is becoming a driving concept for new generations of Building Codes and Standards and informing innovative trends and practical policies for performance-based design and management of critical structures and infrastructure facilities. Resilience can be related to the capability of structures, infrastructure systems, and entire communities, to withstand the effects of extreme events and to recover efficiently the original performance and functionality [11,12]. In the field of disaster mitigation, frameworks have been proposed to provide a basis for development of qualitative and quantitative models measuring the functionality and resilience at various scales, including communities and societies [11,13–20] as well as lifeline components and systems, such as health care facilities [21–23] and road networks [24–32].

From the semantic point of view, the meaning of the term resilience harks back to the Latin word "resilio", which means "to jump back" or "to bounce back". In general, the concept of resilience represents a comprehensive synthesis of the ability of the investigated system to cope with the emergency conditions induced by sudden disruptive events [33–37]. The definition of optimal ex-ante preventive retrofit interventions and ex-post effective recovery actions for key system components becomes critical to ensure suitable resilience levels of road infrastructure networks. Furthermore, structural systems are subjected not only to sudden harmful events that may impair the emergency response of the affected communities, but they are also called to cope with deterioration mechanisms and relentless aging. Nonetheless, the time-variant performance of structures and infrastructure systems should be evaluated in probabilistic terms, accounting for the uncertainties propagating over during their lifetime and associated with the loadings and resistances of structural components [38–42], structural systems [2,6,43–45,46] and critical infrastructure networks [47–51]. Resilience of aging structures and infrastructure systems depends on the time of occurrence of extreme events and a proper resilience quantification must be based on the assessment of the structural systems over their entire life-cycles by taking into account the effects of deterioration processes [27,52,53], time-variant environmental stressors [30], and maintenance and repair interventions under uncertainty [54–56].

This paper presents a review of the main principles and concepts, methods and strategies, advances and accomplishments in the field of life-cycle reliability, risk and resilience of structures and infrastructure systems, with emphasis on seismic resilience of bridges and road networks under uncertainties. Existing reviews on the subject of resilience are mainly emphasizing the available definitions of resilience in the context of disaster risk reduction. Significant reviews oriented to the definition of resilience indicators of critical infrastructure systems are available, mostly regarding different dimensions [57], taxonomy [58], computational tools [59]. Among all hazards and critical infrastructure, particular efforts have been devoted to seismic risk assessment [60,61] of transportation systems [62–64], with specific focus on bridge networks [65–67]. Probabilistic frameworks for life-cycle seismic risk and assessment based on performance indicators of system resilience covering the emergency response under seismic and other natural hazards of vulnerable components are considered. In most of these frameworks the physical damage suffered by vulnerable bridges in the aftermath of hazardous events is associated with traffic limitations enforced by infrastructure managers to ensure the users' safety, temporarily impairing the system functionality. Then, the post-event repair actions enable the progressive release of the imposed restrictions under the attainment of structural capacity targets, leading to the definition of a comprehensive measure of network resilience. The likelihood of occurrence of extensive and prolonged network functionality losses depends on several factors largely affected by uncertainties, such as the occurrence rate of detrimental events, the capacity of crucial bridges to remain functional under the imposed demand, and the actual availability of resources and redundancies to efficiently restore the system operability quickly after the disaster strikes. In this context, the effects of aging and environmental aggressiveness must be considered, since they are affecting the structural performance and functionality and, consequently, enforcing the dependency of system resilience on the time of occurrence of extreme events. Recent efforts made to develop these frameworks and incorporate them into practical policies to inform and support the decision making process of public authorities, owners and political system for life-cycle management of aging structural systems and infrastructure networks, particularly in earthquake prone regions, are reviewed and discussed.

This review paper addresses the past and recent developments related to resilience of aging structures and infrastructure systems with emphasis on seismic resilience of bridges and road networks. The structure of the paper is conceived to convey these developments by incorporating life-cycle concepts in the seismic resilience of aging bridge networks under uncertainties associated with seismic hazard and interaction with environmental stressors. Through the lessons learnt from past seismic events, Section "Concepts and methodologies for infrastructure resilience assessment" presents the motivation and formalizes qualitative definitions and quantitative frameworks to capture features, dimensions, means, goals of infrastructure resilience. Then, Section "Resilience under a probabilistic life-cycle perspective" focuses on the key perspective offered by this review paper, which is the focus on a life-cycle and probabilistic approach to seismic resilience assessment of aging bridge networks. Section "Probabilistic seismic damage assessment of structural systems and infrastructure networks" reviews available methodologies and open issues on regional seismic hazard and fragility assessment of spatially-distributed deteriorating bridges. Finally, Section "Performance and recovery of infrastructure road networks" reviews the commonly adopted methodologies for impact analysis and metrics for functionality quantification of road networks as well as strategies and models for bridge recovery assessment for life-cycle resilience assessment under uncertainties.

Concepts and methodologies for infrastructure resilience assessment

Lessons from the past

The impact of recent and ancient disasters on physical infrastructure and communities provides clear examples of the need to build resilient facilities to foster the ability of communities to cope with catastrophic events. From the technical point of view, developing comparative analysis of the historical data helps to identify vulnerabilities in the infrastructure systems to avoid disruptions of daily operational activities of stricken communities. Nonetheless, learning lessons from past experiences and building awareness in societies and individuals help communities to avoid repeating the same mistakes. In the past two decades and in different parts of the world, severe seismic events have caused physical damage, economical upsetting and tragic fatalities that profoundly shocked the communities affected by the earthquake both in the emergency response and in the long-term. These events also lead to the first examples of empirical calibration of seismic fragility curves and large-scale assessment of seismic damage and economic losses encompassing structural, infrastructure, and community levels [68,69].

In 1989 the Loma Prieta earthquake occurred on California's Central Coast and hit the Bay Area in San Francisco. The earthquake impaired 91 state highway bridges and forced the closure of 13 of them [70]. Severe disservice in the transportation network has been documented due to the closure of major infrastructure elements such as the San Francisco-Oakland Bay Bridge and the Cypress Street viaducts. The latter was one of the busiest routes in the city of Oakland and the collapse of its viaducts caused the highest number (i.e., 42) of earthquake-induced fatalities, about two thirds of the total [71]. Based on traffic estimates, the preliminary death toll could have been worse. In fact, many local residents who would have normally been on the freeways were already at home during rush hour [72]. The reduction of traffic capacity of the transportation system induced heavy traffic congestion, since the temporary closure of important routes forced the daily users of the bridges to find alternative ways to reach their destinations, dramatically increasing average travel times and distances [73]. Loma Prieta earthquake made local communities realize the importance of risk mitigation policies in such a high-risk environment [74]. Besides causing significant damage to physical facilities, the earthquake also overloaded the health care system in the San Francisco Bay area, increasing by 15% the total number of patients in hospitals [75]. The severity of the consequences of Loma Prieta earthquake exceeded all predictions, pointing out the importance of performance-based earthquake engineering in the USA [76].

Five years after Loma Prieta earthquake, another major seismic event occurred in California. The 1994 Northridge earthquake caused damage to 286 bridges along four major freeways in the area of Los Angeles [68,77,78]. These routes have been restored within several months and it has been estimated that traffic delays and infrastructure recovery accounted for $1.5 billion in indirect losses due to business interruptions, nearly a quarter of the total economic disruption in the Los Angeles metropolitan area [34,70,79]. The disastrous consequences of Northridge earthquake are acknowledged to be mainly due to structural inadequacy of the steel connections of the bridges, pointing out the importance of ductility in the design and construction practices [76]. Northridge earthquake provides interesting examples of latent interdependencies across urban infrastructure systems. Electric power was lost for nearly a day in the Van Norman complex, which treated about 75% of the potable water in the city of Los Angeles. A smaller station with combustion engine pumps partially made up for the failure of the city pumping system but refueling was impaired by the damage to the transportation network [80].

In 1995, the Hyogoken Nanbu earthquake in Japan lead to severe consequences on the highly populated region surrounding the city of Kobe [81]. The epicenter was close to the second largest urban area in Japan, causing thousands of fatalities and injuries. Widespread of physical assets was reported, causing outages to the transportation network for about two years, as well as to electric power and telecommunication lines for over a week, water and natural gas supply systems for two to three months, and railways for up to seven months [34]. The most affected element within the transportation network was the highway branch between Kobe and Ashiya providing an important connection between the metropolitan areas of Osaka and Kobe. Nearly 30 km were closed, and the entire route was reopened after more than 20 months. Major viaducts as the Meishin and the Chugoku National Expressways were severely damaged. From the structural point of view, Kobe earthquake led to widespread collapse of foundations due to soil settlements and slope instability. Scientists and practitioners tried to promptly use the lessons from the disastrous evidence of the earthquake. The Japanese Road Association Code for bridge design was modified the year following the mainshock [76]. Kobe earthquake provides an outstanding example of the key role played by the transportation lifeline in the early hours after the mainshock, since the interruption of the access routes limited the work of firefighters and first responders and amplified the damage induced by the earthquake with a total amount of 5500 fatalities [71]. The lack of service largely affected the nationwide economy due to the temporary suspension of various activities and due to the additional travel distances and times [70]. Immediately following the earthquake, the traffic conditions in the city of Kobe were in a “a state of confusion” for three days to one week, in which traffic volumes dropped sharply with extreme congestion at daytime followed by an increased traffic volume at night [82]. “A state of settlement” began the first week following the earthquake, with a gradual return of daytime traffic levels beginning to gradually return to their pre-event conditions, until “a state of stability” was reached the month following the earthquake. In terms of long-term permanent effects, the habits of commuters substantially changed at the regional level [73]. Furthermore, Kobe used to host the sixth largest container port worldwide in terms of cargo throughput. At repair completion two years after the earthquake, the port was ranked seventeenth [17].

In 2011, major seismic events harmed large Pacific urban communities in Japan and New Zealand. During the Tohoku-oki earthquake, over 1500 highway bridges were damaged and about 30% of them suffered traffic limitations [83]. Damage included minor nonstructural damage as well as collapse and large-scale cracking damage to main roads superstructure [84]. Bridge damage due to ground shaking and the subsequent aftershocks was minor, mainly to bridges not yet retrofitted since Kobe earthquake. Although many bridges survived despite being totally submerged, tsunami-related damage included complete loss of span and erosion of backfills. On the other hand, the Christchurch earthquake was characterized by not particularly high magnitude, but shallow focus and close proximity resulted in locally very high ground motions with widespread liquefaction [85]. The majority of the damaged bridges suffered rotations of their abutments due to lateral spreading and were closed for a few days immediately after the earthquake while their safety was assessed [86].

Definition of resilience

One of the first scientific field that aimed to comprehensively define and to quantitatively assess resilience can be found in biophysics and ecology. Holling [87] provided the first definition of ecosystems resilience as “the amount of disturbance that can be sustained by a system before a change in system control or structure occurs”; “it could be measured by the magnitude of disturbance the system can tolerate and still persist”. Ecosystems are perceived as “a mosaic of spatial elements with distinct biological, physical, and chemical characteristics that are linked by mechanisms of biological and physical transport”. This work provided the first guidelines for the definition of models for resilience quantification perceiving the multi-faceted issues relating system post-shock response with the entity of the disturbance the system has to cope with and its ability to learn, adapt and self-organize. Holling’s original definition of resilience has been revised and extended over the years in the biosystems framework to incorporate key concepts concerning the relationship between human communities and their infrastructure [88], the speed with which a system returns to its original state following a perturbation [89], the entity of the perturbation [90], and the phases of ecosystems adaptive processes [91].

After the seminal paper by Holling [87], the concept of resilience has evolved from the disciplines of materials science and environmental studies to become extensively used and applied to several engineering branches [92,93]. In material science, the concept of resilience is commonly associated to the mechanical properties of tested specimens. Even though the mechanical behavior of the majority of metallic materials is characterized by ductility and toughness, these materials may experience brittle failures in presence of adverse factors such as flaws, low temperature, fast rate of load application. A resilient material is able to absorb high amounts of energy before it collapses and this amount of energy is a measure of the susceptibility to brittle or ductile failures.

The concept of resilience finds numerous applications also in psychology and health sciences, especially in the aftermath of COVID-19 pandemic [94–96]. Mental resilience is the ability of people to prevent the growth of mental disorders and to thrive in the face of adverse conditions. Improving resilience is the target of any a priori prophylaxis and post-traumatic treatment. The research upon this topic is particularly heterogeneous and a comprehensive review was proposed in Davydov et al. [97]. The mechanisms behind the comprehension of mental resilience can be either neuronal or genetic. Resilience can be fostered by harm-reduction approaches to quickly recover from stress, by protection approaches to empower self-defense mechanisms, and by promotion approaches to build barriers in the immune system and specific trainings to overcome fears and negative experiences. It is worth noting that concepts and definitions of resilience in mental health sciences and emergency management of critical infrastructure are rather comparable, despite their differences in the fields of applications. Similar patterns characterize, on the one hand, the patients' ability to recover from psychological distress and, on the other hand, the ability of an infrastructure system to restore its functionality through the recovery of its damaged components.

The conceptual patterns defined and developed for ecosystems can be extended to different kinds of systems, such as societies, economies, nations or enterprises seeking for a stability and equilibrium of forces and wellness. Like in ecosystems, resilience is a property of communities as a whole and it concerns the quality of life of the society that makes use of the infrastructure facilities. Furthermore, resilience is not only a matter of resisting disturbances, but it also concerns with the presence/lack of means and resources allowing for effective and prompt recovery: prolonged severe distress on ecosystem components may lead to extended and possibly irreversible disruptions, dramatically affecting the community welfare. Promoting the concept of resilience of communities and societies is a key issue that several researchers tried to systematically frame, in order to define guidelines and promote good practices at the societal level [98,74,99,100] and at the economic level [80,101,20].

Community resilience is further conceptualized embracing four dimensions [102,11]:

1 The *technical* dimension is related to the ability of physical systems to maintain desirable performance levels when the shock occurs.
2 The *organizational* dimension is associated with the ability of all stakeholders involved in the management of critical facilities to take effective actions.
3 The *social* dimension refers to all countermeasures taken in order to mitigate the impact of the disruptive event on society and its territory.
4 The *economic* dimension concerns the capacity to reduce direct and indirect financial losses resulting from impactful hazards.

Drawing an idealistic comparison with the medical science, the four dimensions of resilience are all as crucial to foster community resilience as vital organs for the survival of human bodies [74]. Technical and organizational resilience is guaranteed by physical lifelines and infrastructure managers, which are the "body" of the city or region of interest as they play the role of bones, arteries and muscles within living beings. Social and economic resilience is achieved when the "brain" of the city functions properly, which is the set of institutional components such as schools, agencies, and all enterprises and organizations allowing the community to direct its activities, to respond to its needs and to learn from past experiences.

Features, dimensions, means and goals of infrastructure resilience metrics

One of the most common and well-established frameworks that gave the basis to current guidelines for resilience assessment and enhancement of civil infrastructure systems has been provided in Bruneau et al. [11], with specific focus on seismic hazard. Disaster resilience represents the capability of a system to:

1 *Resist* an extreme event, limiting operational outages and irreversible damage
2 *Absorb* its impact in terms of performance downtime and physical disruptions inducing direct monetary or indirect socio-economic losses
3 *Recover* promptly the pre-event condition, "bouncing back" as rapidly as possible to adequate operability conditions.

Since resilience covers social and technical aspects too broadly, there is no single generally accepted definition [65,54,103]. The quantification of this three-fold qualitative definition of resilience relies on the definition of a functionality metric Q, which describes the system performance by a comprehensive quality index. Functionality is monitored between the occurrence time t_0, i.e., the instant in which the event occurs, and the horizon time t_h, i.e., a fixed "control time" set to compare the results with under different hazard scenarios and recovery strategies. The resilience R after an extreme event is often defined as [11,17,21,27]:

$$R = \int_{t_0}^{t_h} Q(t)dt \tag{1a}$$

Alternatively, the value of resilience can be normalized with respect to the investigated time horizon in order to have a non-dimensional index [22,25,51,104]. This commonly adopted quantitative indicator of system resilience is represented by the integral mean of the functionality profile from the time of event occurrence t_0 up to the fixed horizon time t_h:

$$R = \frac{\int_{t_0}^{t_h} Q(t)dt}{t_h - t_0} \tag{1b}$$

An infrastructure system such as a network of bridges is resilient if a disruptive event does not induce severe short-term losses and if it can rapidly restore its functionality at the pre-event or better levels for the most critical components. Resilience is promoted by managers and decision makers if the actions taken positively affect both system robustness and recovery rapidity, which represent the ends to guarantee that the infrastructure is resilient. If robustness and rapidity are the desired goals, resourcefulness and redundancy are the properties representing the means for resilience enhancement. Robustness, rapidity, resourcefulness and redundancy represent the properties of resilience [11].

Concerning resilience ends, *robustness* is the ability of a system to withstand an external shock and maintain acceptable performance levels without suffering severe losses of functionality under a given disturbance, and it is also referred to as the residual functionality at occurrence time $Q(t_0)$=Q_0. *Rapidity* represents the capacity to achieve recovery goals in a timely manner and, being a feature of the post-event actions aiming to promptly restore sufficient performance levels. In general, the recovery process starts after an idle time t_i necessary to plan the recovery strategy for all damaged bridges in the network and to design the related repair activities to be carried out to restore the network functionality up to the final time t_r. Therefore, rapidity can be approximately measured as the ratio between residual functionality and recovery time interval $t_r - t_i$.

Concerning resilience means, *resourcefulness* refers to the ability of system managers and decision makers to apply proper knowledge and deploy the economic resources to effectively and rapidly cope with the occurrence of extreme events. In this context, resources such as economical investments in materials and human resources represent the set of skills needed to manage a disaster as it unfolds: a resourceful system manager is able to identify problems, establish priorities and mobilize materials and workforce in order to take prompt and effective decisions. The resourcefulness of a system also concerns with the ability to define ex-ante adequate emergency plans and recovery policies, but also to change them ex-post by learning from mistakes or even to improvise effectively in extreme conditions. On the other hand, *redundancy* represents the ability to mitigate the effects of the extreme event and increase the recovery rate based on underlying alternative ways to cope with disasters when some elements fail [105,106]. The properties of resilience are strongly interrelated. A system is redundant if it satisfies sufficient functional requirements after its partial disruption. Similar to the property of resourcefulness, it depends on the complex links and hidden interrelations between elements in a structure, structures in a network and networks in a community. Also, redundancy and resourcefulness can be seen as the two faces of the same medal: the availability of resources can activate redundancies that did not previously exist, whilst redundant systems are able to provide alternative resources to cope with uncertainties.

Frameworks for seismic resilience assessment of structural systems and networks

The consequences of natural and man-made catastrophes show how communities are heavily affected by outages and disruptions of critical facilities. Therefore, understanding their performance under extreme hazards is a key issue for scientific disciplines, such as civil and structural engineering. Communities are resilient to disruptive events if the interdependent infrastructure systems can maintain acceptable levels of functionality during and after the ground motion occurrence, since they enable efficient emergency response and long-term recovery. In particular, road infrastructure networks play an important role in the emergency response to seismic events and related hazards to ensure both a quick deployment of aids and resources to distressed communities and a prompt repair of the surrounding lifelines and buildings [26,31,107,108]. Different qualitative definitions of resilience have been developed by the scientific community, depending on the semantic and epistemological orientations as well as the theoretical background of the reference [92]. These developments have been reviewed and applied to resilience of bridges and infrastructure networks for the assessment of condition rating [109], risk mitigation and adaptation [110,111], optimal maintenance [51], retrofit design [112–115], and restoration strategies [24,25]. Over the last decade, specific methodologies have been developed and implemented for probabilistic quantitative assessment of resilience under seismic hazard of bridges and road networks [51] based on scenario events [116] or relying on integrated simulation procedures [117,26,27,54,118–120]. It is worth mentioning that in most of the research works that tackled the problem of quantifying resilience to support maintenance and management programs of aging and deteriorating structures the main focus was mainly associated with planning optimal retrofit strategies to reduce the risk of network inoperability due to the failure of existing vulnerable assets. Further research is needed to address network design and improvement strategies based on structural upgrade [121,122] in the context of large-scale infrastructure investments aimed at enhancing the system functionality [26,103,123,124].

Flowcharts summarizing the computational framework for integrating resilience and loss assessment, for the evaluation of probabilistic seismic resilience, rapidity, and socio-economic impact, and for determining retrofitting prioritization based on risk and resilience of road networks are indicated in Decò et al. [54], Li et al. [119], and Ishibashi et al. [107]. Moreover, flowcharts of computational frameworks for life-cycle probabilistic seismic resilience and cost-based seismic risk assessment of aging bridges and bridge networks are presented in Bocchini and Frangopol [25], Dong and Frangopol [29,31], Capacci and Biondini [26], Messore et al. [125], and Qian et al. [126]. The flowchart presented in Fig. 1 summarizes the procedural steps of a general methodology for life-cycle resilience assessment of bridges and road networks [127]. The physical damage s_b suffered by vulnerable bridges in the aftermath of sudden disruptive events (such as earthquakes) coupled with long-term deterioration (such as corrosion) is associated with traffic limitations d_b enforced by infrastructure managers to ensure the users' safety, temporarily impairing the system functionality Q given the traffic restriction combination $\mathbf{d}$ on every vulnerable system component. Given the damage state combination $\mathbf{s}$, the post-event repair actions $r_b(t)$ allow progressively releasing the imposed restrictions $d_b(t)$ under the attainment of specific capacity targets, leading to the definition of a stepwise functionality profile $Q(t)$ and the related measure of network resilience R. This stepwise functionality profile was quantified in the optimal resilience and cost-based post-disaster intervention prioritization for bridges in Bocchini and Frangopol [24]. Damage occurrence and repair rapidity are related to the vulnerability of key bridges within the network. Traffic limitations and their progressive release inform the exposure metrics of the transportation system, representing the large-scale consequences of damage and repair of network components in terms of system functionality loss, recovery and overall resilience.

Resilience under a probabilistic life-cycle perspective

Performance under uncertainty and risk-based frameworks

Enhancing the seismic resilience of infrastructure systems is a social need since the prosperity of communities can be heavily harmed by outages and disruptions of critical facilities. The economic impact on lifeline systems of sudden impactful events coupled with long-term deterioration processes can be exceptionally high, particularly for bridges and transportation networks. The concept of risk characterizes the underlying threats of a disastrous event both in terms of its likelihood of occurrence and the consequences that it would lead to. In particular, risk assessment allows quantifying the consequences of various hazardous scenarios with their related probabilities, whilst risk management consists in defining policies and taking action based on the involved uncertainties [128]. In several scientific fields and engineering disciplines, risk is merely quantified as the sum of the effects of a disruptive event weighted by their probability of occurrence. Within the civil engineering scientific community, analytical frameworks for risk assessment have been developed in the attempt to assess the seismic risk of structures, infrastructure systems and entire communities. In the attempt of planning risk mitigation strategies, several countries and institutions are currently devoting significant efforts in assessing the risk of the built environment in hazard-prone areas as well as the residual lifetime of critical existing facilities, including buildings, bridges, roads, railways, dams, ports, among other lifelines and infrastructure components. Along with the necessary monetary and technical efforts of infrastructure owners and managers, significant advances are necessary in many research fields related to modeling, analysis, maintenance, repair, and design of civil engineering systems. In general, risk varies dynamically upon changes to the combination of three components [129]:

1. Hazard, i.e., the detrimental event causing losses.
2. Vulnerability, i.e., the likelihood of damage occurrence when the hazard occurs.
3. Exposure, i.e., what or who is threatened by the hazard and is affected by disruptions of vulnerable elements.

The characteristics of phenomena for natural and built environments are related to the concept of hazard. Hazard assessment refers to the procedure of mapping intensity and frequency of occurrence of the triggering causes of failure and damage based on historical or empirical evidence and physics-based models. The sources of hazards for populations at the societal level can be natural, technological or socio-political. These categories can be further broken down into two typologies of events [130]: long-term gradual stress events (e.g., aging due to environmental aggressiveness, climate change, etc.) and short-term sudden shock events (e.g., earthquakes and landslides, snowfalls and avalanches, floods and tsunamis, storms and wildfire, large-scale strikes, crowded public events leading to traffic congestion and road closures, terrorist attacks, etc.). Seismic hazard and environmental hazards can be considered as a natural shock event and a natural gradual event, respectively. Seismic hazard assessment for a given geographical area generally relies on seismological studies based on historical data and the geophysical/seismogenic characteristics of the site. Researchers heavily relied on empirical evidence of historical events to predict the effects of future earthquake learning from the geophysical consequences addressed by past ground motions.

Vulnerability refers to the probability of occurrence of damage, failure or collapse of a structural system depends on the complex, uncertain and eventually unpredictable relationship between the demand imposed by hazardous events and the capacity to fulfill it. Vulnerability

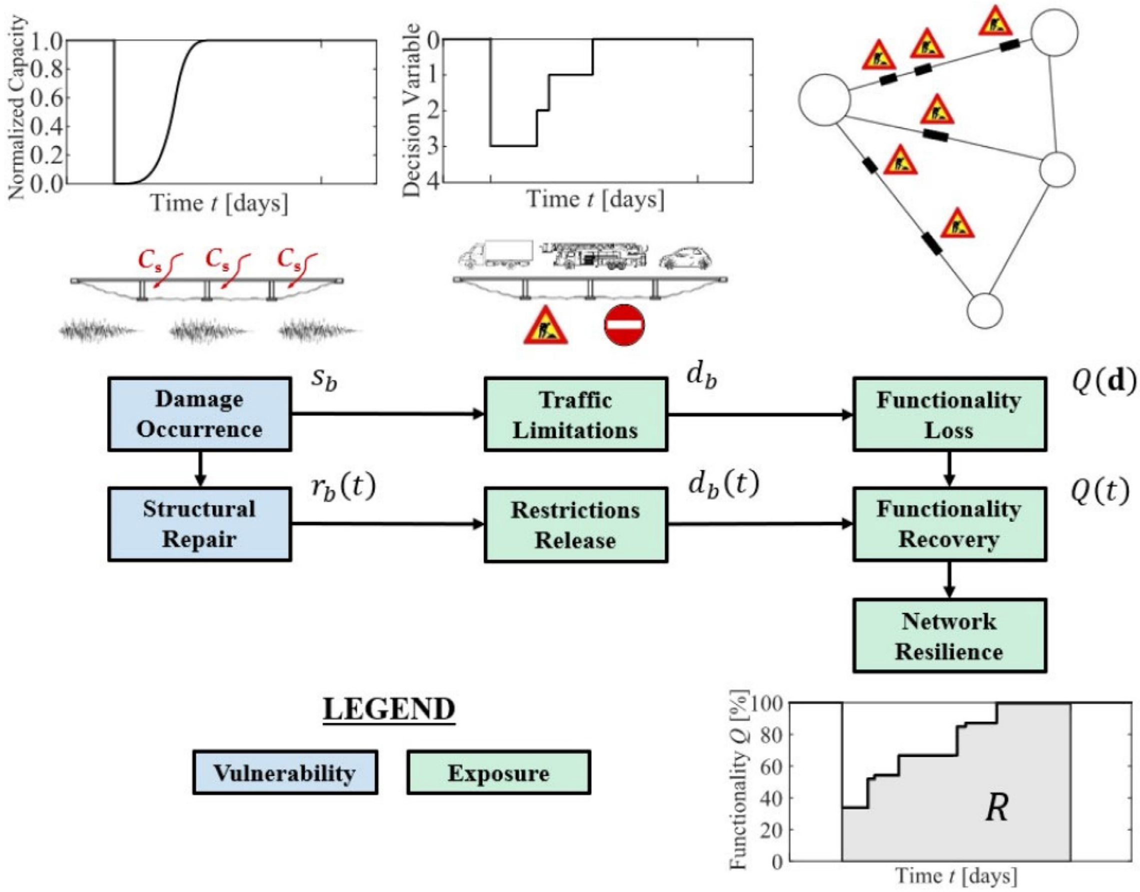


Fig. 1. Flowchart for resilience assessment of road networks with vulnerable bridges (Adapted from [127]).

is a property of the studied system, and it refers to the inherent possible inability of structures and infrastructure systems to cope with the impact of hazardous events. It is related to resisting patterns that provide the capacity to prevent damage to the exposed assets under the occurrence of hazardous events of given intensity. A common way to analytically and graphically assess the vulnerability of a system or one of its components is given by the fragility curves, which represent the conditional probability of occurrence of a specific disruptive event as a function of an appropriate hazard intensity measure (e.g., the likelihood of overcoming a specific structural limit state given the earthquake intensity). In practical applications, the seismic reliability assessment of infrastructure networks can be carried out based on simulation techniques [131] or analytical methods relying on suitable mathematical formulations [132]. Assessing the vulnerability of a large-scale network can be a challenging task not only due to the computational costs as well as incomplete information on the bridge vulnerability and on their statistical dependency [133,134].

In the context of community risk assessment, exposure represents physical assets (e.g., buildings and infrastructure), social communities (i.e., individuals and their organizational systems) and economic businesses at risk of losses in the aftermath of hazardous events [129]. Exposure assessment of vulnerable communities requires the quantification of the consequences of a disastrous event in impairing primary needs and basic safety of infrastructure users and people relying on lifelines. The exposure of communities to seismic hazard concerns with the health and safety of people who could be in danger during and after disruptive ground motions, as well as the users that may suffer from losses of functionality and temporary closure of critical facilities in the infrastructure systems. Both vulnerability and exposure of infrastructure systems and communities can be difficult not only to be quantitatively measured, but even to be qualitatively defined due to the interconnectedness between critical lifelines and their key components. For this reason, the infrastructure assessment should rely on systemic approaches. Exposure is often quantified by direct monetary losses induced by repair activities carried out to restore damaged assets. Nonetheless, issues such as delays in emergency response and long-term system operability cannot be easily translated in financial terms, providing a limited perspective on the real consequences of infrastructure damage. Therefore, exposure can be assessed indirectly based on performance metrics that quantify in non-monetary terms the disaster-induced losses at the community level. In this context, quantitative metrics of system resilience can be considered as a measure of system exposure under emergency in the aftermath of the occurrence of shock events, such as earthquakes [26–28,135,30,73,136,137].

An example of comprehensive research effort for risk mitigation is provided by SYNER-G, a European collaborative research project funded by the European Commission [138]. Its main objective is to develop an integrated methodology for the systemic seismic risk analysis of buildings, lifelines, infrastructures, transportation and utility systems and critical facilities accounting for the interactions between different components and systems. Another recent example is related to seismic risk of compliant structures designed with the current Italian Code, namely the ongoing RINTC joint research project of ReLUIS and EUCENTRE, two centers of competence for seismic risk assessment of the Italian civil protection [139]. The goal of this project is to assess in an explicit manner the seismic risk of code-compliant archetype structures associated with different typologies (masonry, reinforced concrete, precast reinforced concrete, steel, and seismically isolated buildings) at different sites spanning the seismic hazard scenarios at the national level.

Resilience under a life-cycle-oriented perspective

The economic impact of aging and deterioration processes on existing structures and infrastructure systems is exceptionally high, particularly for bridges and transportation networks [140]. Assessment and design of structural systems should be based on a probabilistic-oriented approaches that reliably and effectively model the deterioration mechanisms and time-variant loading conditions governing demand and capacity of structures at risk [141,142,6,1,7,143,103,41,123,144]. Depending on the environmental conditions to which structures are exposed, chemical attacks and physical damage may dramatically reduce the mechanical properties of key structural members [145]. The local damage at the structural element level is then reflected at the structural system level, harming the capacity of the structural system to withstand the demand imposed by service loadings or hazard-induced extreme actions. Analogously, the effects of complex aggressive phenomena on crucial components of infrastructure systems, such as bridges, may also impair over time the emergency response of communities in hazard-prone areas. These problems pose a major challenge to structural engineers used to the classical time-invariant criteria. Methodologies for design need to be reviewed to account for the actual behavior of structural systems throughout their entire life-cycle. Therefore, life-cycle structural and infrastructure performance should be investigated based on time-variant indicators [141,142,146,147] such as reliability [148,149], robustness [150–152], redundancy [153,154], risk [155,125], and sustainability [156,135,157,158,56].

In this context, resilience goals can be achieved by means of investment of resources. Enhancing the resourcefulness with retrofit and maintenance on vulnerable system components would increase the preparedness of the system to withstand the consequences of the disruption, whilst allocating resources in adequate restoring planning would increase the recovery rate. The outcomes of both strategies on resilience are reported in Franchin [159]. The beneficial effects of ex-ante preventive actions reduce vulnerability leading to higher post-shock system quality levels and likely faster recovery. The initial functionality drop may even be imperceptible if extremely effective (although expensive) prevention strategies are deployed. On the other hand, the beneficial effects of investment of resources on ex-post corrective actions are represented by the unaltered initial functionality drop under no preventive actions, whilst the system performance in the post-shock phase tends to regain its pre-event standards with rate proportional to the amount of invested resources.

As the hearsay goes "prevention is better than cure", it is likely that ex-ante prevention policies would reduce bridge recovery times and network functionality loss in a more effective manner with respect to ex-post restoration activities. Nevertheless, infrastructure resilience cannot be straightforwardly formulated in deterministic terms, since many uncertainties ultimately affect the decision-making process for resilience enhancement. In the context of lifeline risk analysis, uncertainties are associated with frequency of occurrence and intensity of hazardous events, with the vulnerability of critical bridges to damage and failure and with the large-scale consequences of transportation system downtime and its prompt restoration. Fig. 2 illustrates with qualitative probability density functions the uncertainties involved in the parameters of the functionality profile [54]. The rate of occurrence of rare hazards affects the occurrence time t_0, whilst the intensity of the hazard affects the post-event functionality Q_0 as well as the idle time t_i necessary to design and put in practice the necessary countermeasure to restore the system from the shock. Uncertainties also affect the recovery process in terms of recovery profile $Q(t)$ as well as repair completion time t_r and the related functionality after recovery Q_r.

Furthermore, resilience should not be intended as a static property of the infrastructure. Post-disaster functionality and recovery both depend on the time of occurrence of a shock event due to the long-term effects of bridge aging and deterioration [52,26,27,29,30,107,53]. The occurrence of disruptive events typically induces abrupt losses of network functionality, whilst environmental damage harms progressively in time the bridge structural capacity depending on the environmental aggressiveness. Fig. 3 qualitatively shows the difference in the time evolution of system functionality for non-deteriorating and deteriorating systems [52]. When no aging is considered, the residual functionality corresponds to the functionality drop ΔQ in the aftermath of a disruptive event, which only depends on shock event intensity and the resilience measure depends on the recovery profile $Q(t)$ from occurrence time t_0 to horizon time t_h (R_1=R_2 in Fig. 3a). The combined effects of shock events and environmental aging lead to a reduction over time of the post-event residual functionality and may also affect the recovery pattern (R_1>R_2 in Fig. 3b). The definition of lifetime resilience loss of deteriorating structures is provided in Yang and Frangopol [53] in the context of a general approach for life-cycle management based on renewal-reward processes.

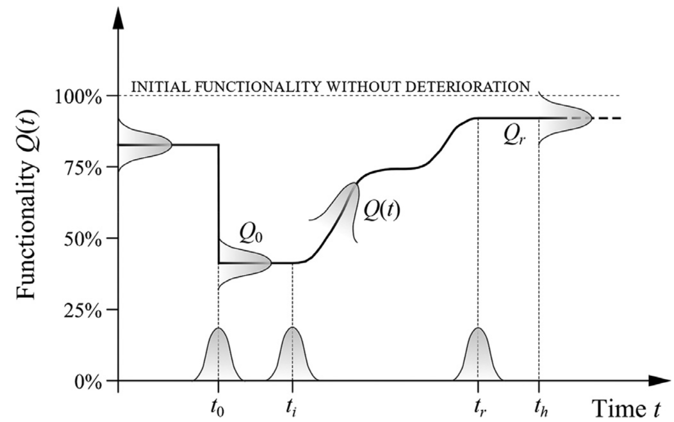


Fig. 2. Uncertainties involved in probabilistic resilience assessment (Adapted from [54]). Uncertainties are represented by qualitative PDFs.

Bridge network functionality profile and infrastructure system resilience vary according to the degree of environmental aggressiveness on vulnerable assets. Large concentrations of aggressive agents, low structural durability with respect to chemical and physical attacks, and fast deterioration rates of bridge load-carrying capacity after damage initiation are all features that reduce the residual bridge network functionality at a prescribed occurrence time t_0. This is highlighted in Fig. 4a, which allows comparing graphically the outcomes in terms of resilience measure given prescribed post-event losses of functionality ΔQ induced by (1) slight/moderate environmental exposure vs. (2) more severe aggressiveness. Programming preventive maintenance on bridge assets is an effective policy to extend the life-cycle serviceability of the exposed infrastructure network. Proactive bridge interventions at the operational time t_m would lead to an increase in infrastructure functionality ΔQ_m. This has a beneficial effect on the emergency response in terms of resilience at a subsequent event occurrence time t_0, as shown in Fig. 4b for recovery profile (1) with and (2) without a prescribed maintenance program. Finally, limited resources are generally available under emergency conditions to restore the system functionality and different bridge recovery strategies may affect differently the long-term network performance. Fig. 4c compares both resilience and post-recovery functionality profiles of a deteriorating system under two repair actions that either (1) fully or (2) partially restore the system functionality at the same final repair time t_f.

Probabilistic seismic damage assessment of structural systems and infrastructure networks

Seismic hazard of spatially-distributed structures

The severity of a seismic event can be measured by different quantitative indicators. Seismologists and researchers in seismic engineer-

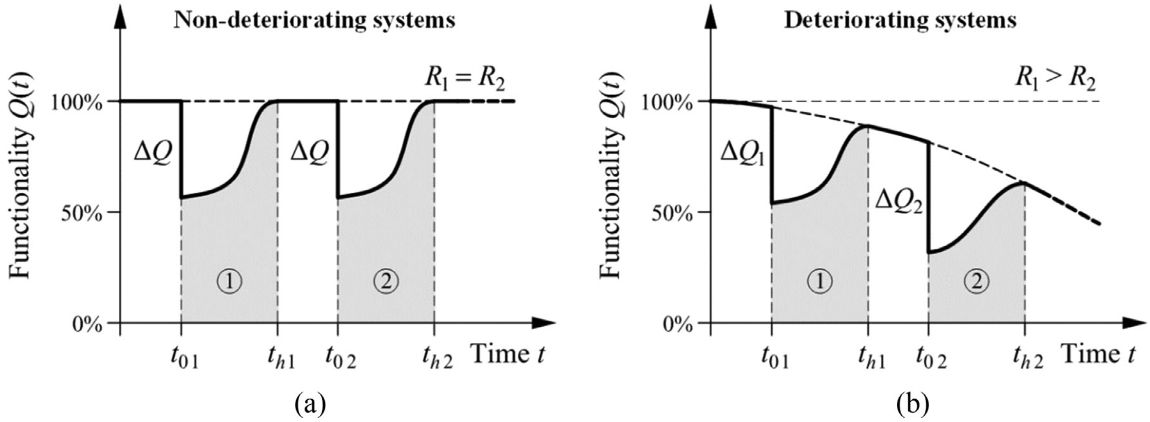


Fig. 3. Functionality Q and functionality losses ΔQ_k due to the occurrence of sequential extreme events $k = 1,2,\ldots$, of same magnitude at different time instants $t_{0,k}$ and recovery over the time intervals $[t_{i,k}; t_{f,k}]$, with $t_{i,k} = t_{0,k}$ and $t_{f,k}$=$t_{h,k}$. (a) Non-deteriorating systems. (b) Deteriorating systems. (Adapted from [52]).

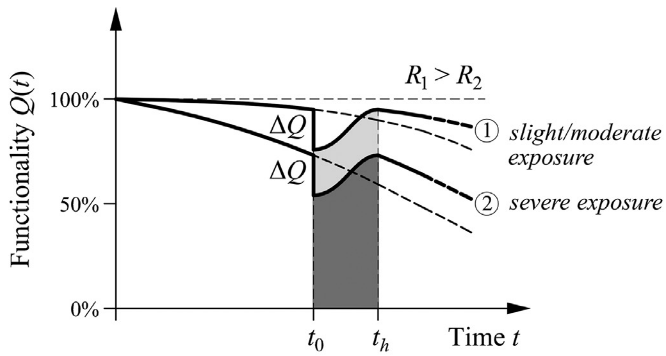
ing have proposed several measures representative of different aspects of ground motion events, such as the large-scale consequences of the earthquake at the community level, on the magnitude of the physical phenomenon that generated the ground shaking, and the descriptive parameters of the shaking at the location of a vulnerable structure. Decades of observations of seismic signals allowed seismologists to calibrate predictive models of earthquake intensity and occurrence rates [160,161]. Macroseismic measures of seismic intensity have been widely adopted and still play a role of paramount importance in those regions in the world that lack the modern instrumentation, being the only viable tool to quantify the consequences of seismic events [162,163]. The development of direct measures of earthquake magnitudes started along with the first applications of instruments capable of recording the displacement of earthquake-induced ground vibrations [164]. Gutenberg and Richter first observed from historical events that earthquake magnitude tends to be inversely proportional to the rate of ground shaking occurrence [165].

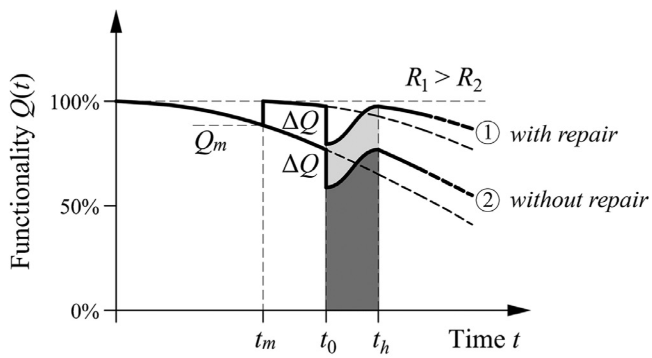
Classical approaches to Probabilistic Seismic Hazard Analysis (PSHA) are based on the assumption that earthquakes occur according to a Poisson process: earthquakes are therefore considered mutually independent, and the adopted model is stationary. For a Poissonian process, the occurrence probability of at least one event in a prescribed time window depends on its mean annual rate of occurrence [166]. The Poissonian assumption is considered a reasonably good tradeoff between the simplicity of the mathematical model and the accuracy with respect to empirical evidence. For this reason, they are widely used in PSHA, and they adequately represent medium-to-low intensity earthquakes. Nonetheless, they might lead to significant underestimation of recurrence rates for very large ground motion events cause by a single characteristic source [167,168]. Time-dependent hazard models may prove to be more representative of the physical sources of earthquake occurrence, mainly related to the sudden release of accumulated stresses in the Earth's crust. It is also worth mentioning that the main governing assumptions of traditional PSHA are generally valid when predicting mainshock events, whilst alternative frameworks should be adopted for aftershock hazard analysis [169–171]. In the aftermath of a mainshock, aftershocks can occur with frequency that tends to exponentially decay in time according to Omori's law [172,173]. Furthermore, aftershocks magnitude is generally lower with respect to the mainshock magnitude. According to Bath's law [174], it is possible to establish a relationship between the average magnitude difference between a mainshock and its largest aftershock (typically equal to 1.2). Different frameworks have been proposed to account for aftershocks hazard with the related consequences and uncertainties in seismic vulnerability and infrastructure risk assessment [175,30,176–180].

Regional seismic hazard assessment should account for the uncertainties not only related to the rate of occurrence of future major earthquakes, but also to their epicenter location informing the distance between the rupture zone and the sites of vulnerable facilities. Localization and modeling of active faults leads to the definition of the source-to-site distance based on the topographical features of the region of interest. Complex seismogenic models should be adopted for specific geological problems, such as subduction zones, whilst most detailed models rely on the definition of linear earthquake sources when it is feasible to geographically identify faults and rupture zones [181]. Alternatively, area sources are often used in practice to account for background seismicity associated with the lack of information on local active faults or when the complex nature of historical earthquakes discourages the choice of hazard models that attribute the epicenters to their causative fault [182].

In the context of PSHA, seismic Intensity Measures (IMs) provide explicit information on ground shaking induced by an earthquake at the location of a structure to be designed or assessed. IMs parameter of the ground motion at a reference site representative of its severity and their appropriate selection is a fundamental task to define reliable estimates of damage probability through seismic vulnerability assessment of single or groups of structures [183,184]. Even though it is inherently impossible to describe a complex phenomenon by a single number, and a great deal of information is inevitably lost when this is attempted, seismic vulnerability is traditionally assessed anchoring the ground motion severity to a single IM [185]. More refined models for probabilistic structural demand assessment can comprise multiple parameters defining the intensity measure [186,187]. Given the information on the seismogenic source at the regional level, suitable predictive models known as attenuation laws or Ground Motion Prediction Equations (GMPEs) can be adopted to estimate the probability that a structure may undergo large shaking intensity levels during future major earthquakes. GMPEs describe the underlying statistical model of the Intensity Measure given a set of seismic hazard scenarios in terms of earthquake magnitude, epicenter location, causative rupture mechanism, among other suitable seismic hazard descriptors. The typical strategy to account for the numerous parameters affecting the strong motions predictive model is to calibrate suitable scaling parameters that adjust the attenuation laws by means of multivariate regression analysis based on historical datasets [188–190]. Among these parameters, regional geological features and local soil conditions may have a significant role in amplifying the ground motions at the reference site [191–195]. In general, the median seismic intensity tends to linearly increase with earthquake magnitude and exponentially decay with the distance from the epicenter [181,196].

A critical issue when dealing with large-scale assets composed by spatially distributed vulnerable elements is the spatial correlation of the ground motion. The seismic intensity at any location in the region is generally modelled as a lognormal random field, from which it is possible to extrapolate the seismic intensities at the site of the vulnerable structures within the network. The involved uncertainties are related





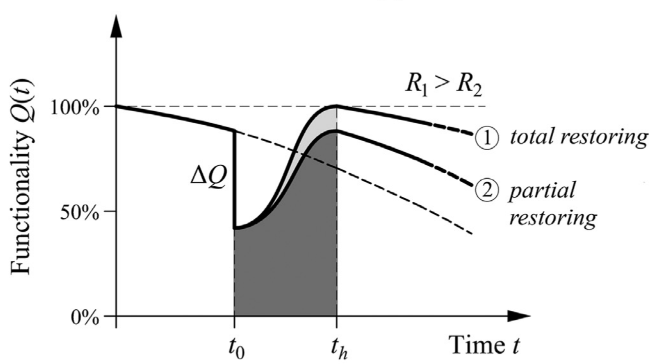


Fig. 4. Effects of the deterioration process and related factors on the time-variant system functionality $Q=Q(t)$ and resilience $R=R(t_0)$. (a) Environmental aggressiveness with ① slight/moderate exposure or ② severe exposure. (b) Maintenance programs ① with and ② without repair interventions. (c) Post-event recovery actions with ① total restoring of the initial functionality or ② partial restoring of the pre-event functionality (Adapted from [52]).

to the scatter in observed ground motion intensities for a given magnitude and source-to-site distance, as well as the within-event spatial correlation and the related site-to-site variability of the seismic demand [197–203]. In the context of risk assessment of spatially distributed infrastructure systems [70,28], the statistical seismic hazard models allow simulating seismic intensities maps at the sites of vulnerable components [204–208].

Seismic vulnerability assessment of aging bridges

Bridges are network components that highly affect the *robustness* dimension of resilience metrics, since the capacity of bridge structures to withstand external shocks enables the transportation infrastructure to maintain acceptable performance levels without suffering severe losses of functionality. Many research efforts have been dedicated to the development of seismic fragility assessment methodologies of vulnerable infrastructure systems. In this context, the concept of fragility curves is widely adopted [209]. Fragility curves represent the exceedance probability a damage state conditional on the occurrence of a ground motion of prescribed intensity [210,69]. With reference to the b-th bridge in a road network, fragility curves can be defined as the probability that the random variable $I_{s,b}$ representing the seismic capacity with respect to a prescribed damage state s_b is exceeded by the seismic intensity measure i_b:

$$P\left[S_b \geq s_b | i_b\right] = P\left[I_{s,b} \leq i_b\right] \tag{2}$$

Analytical fragility curves rely on a direct relationship between seismic actions and the effects on the mechanical response of structural systems. Several methodologies have been developed to frame the seismic vulnerability problem based on physical models typical of structural engineering discipline. Structures of paramount importance from the socio-economic point of view should be analyzed with constitutive models and load patterns that accurately reproduce the uncertainty in the mechanical behavior and the subsequent damage induced by earthquakes [211,212]. Alternatives to analytical frameworks based on refined physics-based models are empirical fragility curves, which correlate measured seismic intensities with damage datasets obtained via in-field reconnaissance reports to backtrack the seismic capacity of the built environment in the aftermath of past earthquakes [68]. It is also worth mentioning hybrid Bayesian frameworks that can combine different types of data (e.g., empirical and analytical) to generate fragility curves that aim to compensate the disadvantages of each methodology [213,214]. Depending on the available data related to earthquake-induced damage, several statistical procedures have been developed to calibrate the related fragility curves [215–217,69]. The lognormal analytical distribution is a simple yet historically highly adopted parametric model that suitably describe structural fragility to earthquake events [218].

One of the most adopted methodologies for seismic response assessment of structural systems involving non-linear time-history analysis is Incremental Dynamic Analysis (IDA), that is a parametric method for comprehensive assessment of the seismic performance of a structure based on the outcomes of a set of time-history non-linear dynamic analyses for a ground motion suite scaled to match different levels of seismic intensity [219,220]. IDA provides a complete overview of the structural response at different intensity levels from the elastic regime up to incipient collapse. The final outcome of the analysis is represented by the IDA capacity curve, as qualitatively shown in Fig. 5, providing the relationship between seismic intensity and an engineering demand parameter representative of the overall structural response and, in turn, of the degree of damage induced by the seismic event. The typical IDA curve is characterized by an initial elastic response that may be followed by a hardening branch, in which similar drift values are encountered over a certain range of intensity measures, generally related to energy dissipation enforced by hysteretic cycles. IDA curves tend to show decreasing slope approaching failure, reached when the numerical results of the time-history non-linear analysis experiences numerical instability and does not converge to a realistic solution. The accuracy of the seismic capacity estimate can be improved by bracketing the points around the flatline, reducing the distance between the highest non-collapse point and the actual dynamic collapse point. The qualitative response expected by IDA curves also inspires the traditional procedures adopted for their generation. Automated and simple algorithms that progressively scales the ground motions are adopted to obtain sub-optimal grids of intensity levels reproducing the structural response in the range of interest of the demand parameter representative of seismic damage. In the hunt phase, the intensity is progressively increased with step-wise regular intervals (Fig. 5a). In the bracketing phase (Fig. 5b), the resolution in proximity of the dynamic collapse condition is improved by adding intensity-demand points are obtained in proximity of the flatline with

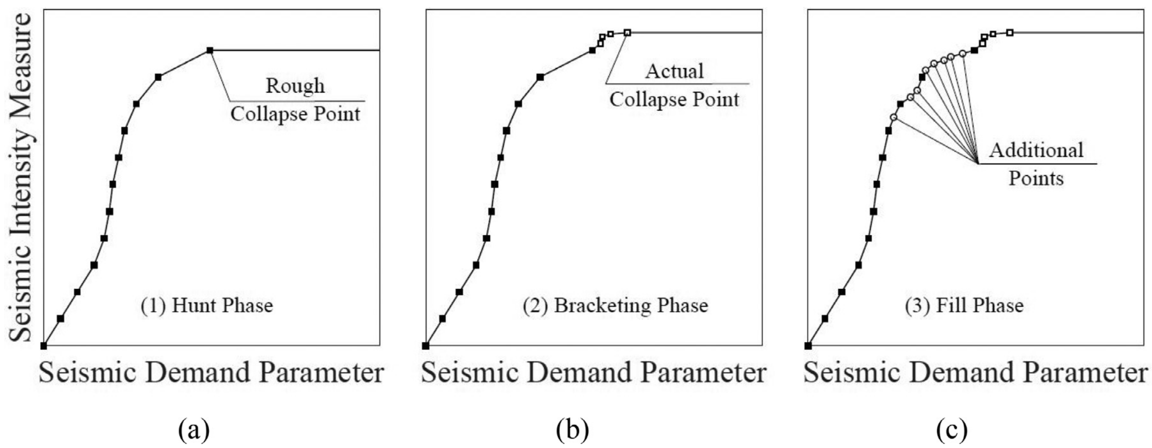


Fig. 5. Procedure for the generation of Incremental Dynamic Analysis (IDA) capacity curves: (a) Hunt phase, (b) Bracketing phase, and (c) Fill phase (Adapted from [127]).

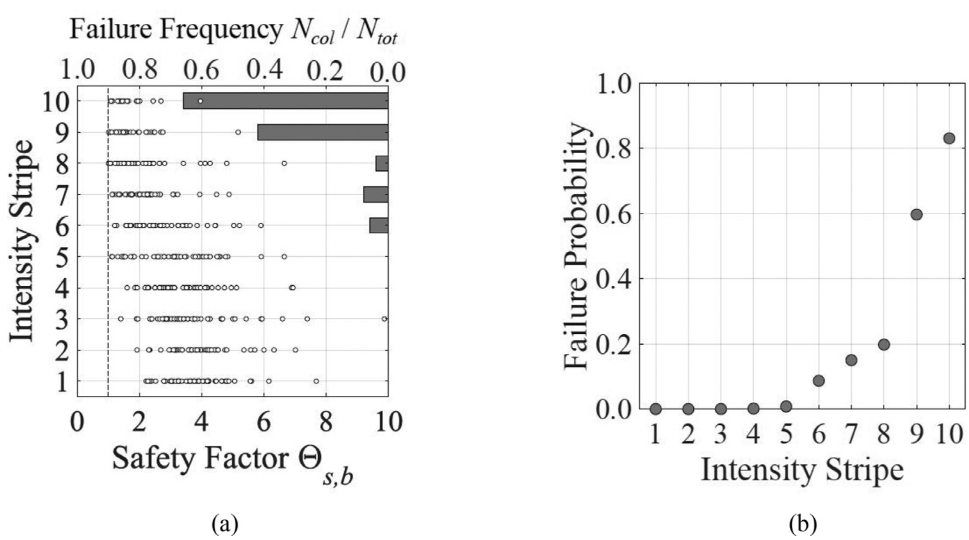


Fig. 6. Example of MSA results. (a) Safety factor samples and collapse frequency estimates for each stripe. (b) Failure probability estimates (Adapted from [127]).

a step-reducing routine based on simple numerical procedures, such as the bisection rule. Finally, the fill phase (Fig. 5c) consists in improving the resolution of the IDA curve also for intensity levels lower than the collapse capacity threshold. The overall IDA curve is finally obtained by interpolation, such as linear, coordinate-transformed splines or other function fitting methods.

Another prominent method currently gaining credit for seismic fragility analysis is Multi-Stripe Analysis (MSA), where IDA curves cover a wide range of seismic intensities spread along the interval between elastic response threshold and incipient dynamic collapse [221]. Nonetheless, non-linear time-history analyses can be time-consuming even for simple structural systems. An accurate reproduction of IDA curves comes with a computational cost that tends to increase with seismic intensities that force the structure to experience plastic strains and hysteretic dissipation. Fig. 6 illustrates the typical results obtained by MSA with respect to the attainment of a prescribed state for the b-th structure in the network s_b associated with safety factor $\Theta_{s,b}$. The dots in Fig. 6a represent 20 samples of the safety factor scattered across ten stripes associated with the seismic intensity $\hat{i}_b$, whilst the bars at each stripe represent the sample collapse frequencies N_{col} over the total number of analyses N_{tot}. The statistical representation of the safety factor $\Theta_{s,b}$ coupled with the estimate of the collapse frequencies allows assessing the failure probability of the reference stripe with intensity $\hat{i}_b$ represented in Fig. 6b. The failure probability can be estimated based on the sample failure probability $\hat{p}_f$ defined as the ratio between collapse frequency N_{col} and the total number of analyses N_{tot} for prescribed seismic intensity $\hat{i}_b$ and damage state s_b:

$$\hat{p}_f\left(\hat{i}_b, s_b\right) = \frac{N_{col}\left(\hat{i}_b, s_b\right)}{N_{tot}\left(\hat{i}_b\right)} \tag{3}$$

Based on the model adopted in Iervolino et al. [139] relying on the total probability theorem and on a lognormal statistical representation of the safety factor $\Theta_{s,b}$, the failure probability can be estimated as the sum of the sample failure probability $\hat{p}_f$ and the safety factor CDF evaluated at $\Theta_{s,b} \leq 1$ scaled by the sample safety probability $1 - \hat{p}_f$:

$$P\left[S_b \geq s_b | \hat{i}_b\right] = \hat{p}_f + \left(1 - \hat{p}_f\right) \cdot \Phi\left(-\frac{\lambda_{\Theta_{s,b}}}{\zeta_{\Theta_{s,b}}}\right) \tag{4}$$

where $\lambda_{\Theta_{s,b}} = \lambda_{\Theta_{s,b}}(\hat{i}_b, s_b)$ and $\lambda_{\Theta_{s,b}} = \zeta_{\Theta_{s,b}}(\hat{i}_b, s_b)$ are respectively mean and standard deviation of the logarithm of the safety factor $\Theta_{s,b}$. These numerical samples can be processed to calibrate a suitable parametric distribution [215]. The results of MSA are particularly suitable in the statistical characterization of the structural response over a pre-defined range of intensity levels: the failure probability with respect to a given limit state for each stripe as the proportion between failed analyses and total number of observations.

Both linear and non-linear models as well as static and dynamic methods for structural analysis should be considered as complimentary rather than competing in structural engineering practice [222]. Even though non-linear time-history analysis can seldom be replaced by simplified analysis tools in the assessment of key lifeline systems, making the definition of simplified static procedure a viable solution when computational costs are not sustainable. Several assessment approaches based on the capacity spectra have been proposed and adopted by standards and codes such as the ATC-40 approach [223], the coefficient method in FEMA-356 [224], and the N2 method [225,226–228]. These approaches do not account for the variability present in natural spectra derived using recorded ground motions signals, since they generally require a standardized reference spectrum commonly defined as a parametric function. They also require the natural vibration modes of the structural system to identify acceleration- and displacement-sensitive segments of the demand spectrum. Other methodologies also rely on static analyses for seismic fragility assessment limiting the computational cost [229–234].

Uncertainties involved in seismic fragility assessment are mostly related to record-to-record variability related to the input ground motion and the aleatory model uncertainties in the investigated structure. Regardless of the method used for structural assessment under seismic hazard, the characteristics of the acceleration time-histories may severely affect the accuracy of results of dynamic analyses for reliability assessment. Time-histories for seismic response analysis are either natural records, selected from past events and eventually scaled to match a target seismic scenario, or artificial ground motions, synthetically generated based on random vibration theory. The best description of ground motions in engineering applications is an ensemble of real or synthetic acceleration time-histories with appropriate intensity, duration, frequency characteristics, and consistency with previously recorded motions for a specific site [184]. In simulation-based approaches, it is necessary to adopt a sufficiently large ground motions dataset and the sample time-histories and/or spectra should reflect the seismic hazard of the particular site based on the regional seismicity and that selection of ground motion records should be carried out with appropriate procedures [235].

Since the majority of ground motion databases contain primarily small-to-moderate records, one of the main limitations to the use of natural ground motion is the scarce availability of large datasets to seek for strong ground motions. Unlike natural ground motions, artificial ground motions merely represent a mathematical description of the seismic phenomenon compatible with the reference spectrum and a set of prescribed parameters related to the input duration and they generally capture the frequency content of the earthquake in the strong motion phase. Even though artificially generated ground motions are acknowledged to lead to overload the structures with respect to real-life events, they are based on a standardized and automated procedure that guarantees the replicability of the numerical analyses for different structural analyses problems.

The number of recorded accelerograms has increased considerably in recent years owing to the large number of events that took place lately in countries with well-instrumented countries [236–239]. Physics-based numerical simulations of earthquake ground motion aim at complementing the recorded data providing simulated signals based on local source and site configurations [240]. Automated procedures for the selection of natural ground motion suites for seismic response analyses have been developed [241–243]. Concerning model uncertainties, seismic response analysis methods can be coupled with simulation-based techniques to account for uncertainties in structural model and in input ground motion. Accounting for these uncertainties, nonlinear time-history analyses and IDA capacity curves can show a wide range of behaviors that highlights how meaningful results can be obtained only adopting under a probabilistic- and risk-based perspective [244–250,209].

In the context of life-cycle fragility assessment, it is important to highlight that deterioration processes are characterized by several sources of uncertainty that propagate in time the variability of structural and seismic capacity of vulnerable network components. Seismic vulnerability assessment is traditionally carried out neglecting any deterioration mechanism that may adversely affect the performance of structural systems, implicitly assuming that structures are optimally maintained during their lifetime. Even though the vast majority of the analytical vulnerability studies and risk assessment frameworks assume that the mechanical properties of structural systems remain the same throughout time, fragility functions should depend on the age of deteriorating structural system accounting for aging mechanisms. The environmental hazard scenario can be taken into account based on a probabilistic modeling of the associated random variables, exacerbating the impact of model uncertainty in time-variant seismic reliability [38,251,252], fragility curves calibration [253–260], life-cycle costs estimate [261,262], lifetime performance assessment [263,264] and the related implications at the infrastructure level [47, 265]. Among the future research needs on the development of seismic fragility curves, particular efforts should be devoted to incorporating in the standard procedures for vulnerability analysis cumulative damage induced by multiple hazards [266,267] and aging effects [138]. Despite the recognized influence of deteriorating phenomena, their consideration can be challenging and in large-scale risk assessment [268].

Performance and recovery of infrastructure road networks

Topological and congestion-based functionality metrics

The choice of adequate metrics for performance assessment of roadway transportation networks is not an easy task, since the actual definition of the concept of network performance cannot be univocally established. A clear definition of standardized performance metrics for the transportation networks is not just a key issue in the quantification of resilience, but it is an important aspect also in the processes of policy making that can facilitate the communication between risk analysts and infrastructure managers [269]. Among all lifelines, transportation networks have the unique feature that all their nodes can be both origins and destinations of traffic demands. This characteristic property of transportation systems encourages the use of different analysis techniques with respect to reliability models used for other lifelines. These tools must take into account not only the physical model of the network, but also the sociological aspects that let drivers adapt their routes and destinations depending on the traffic conditions [51]. In analogy with fluid mechanics, the efficiency of the transportation service performance depends on the smoothness with which the traffic flow spreads all along the network. In general, measuring the performance of a road network can be done based on topological metrics, measuring accessibility and connectivity of the network such as the possibility of reaching some specific destinations from some specific origins, and congestion-based metrics, concerning with the system response and capacity in terms of traffic flows and travel times [270].

Consistently with graph theory, road networks can be modeled by a set of vertices connected by links. A graph G is defined as a pair of sets $G=\{V,E\}$. In the context of road network analysis, edges $E=\{e_1,e_2,\ldots,e_n\}$ represent road segments and bridges in series connecting specific pairs of nodes; vertices $V=\{v_1,v_2,\ldots,v_n\}$ contains specific starting and ending points of each and they can also be of interest used to define Origins and Destinations of trips transportation system users. Graphs connectivity can be described by the adjacency matrix A, a Boolean square matrix with same dimension of the nodes number. If nodes i and j are connected by one edge, $A_{ij}=1$, otherwise $A_{ij}=0$. Several topological performance metrics can be defined based on the graph layout. Topological metrics are particularly effective in capturing the system performance when evaluating lifelines such as water, electrical and gas supply systems; other functionality measures are directly referred to the serviceability of the system, such as the percentage of households suffering outages. In several works, different parameters characterizing the topology of complex networks have been proposed as road performance parameters ranking the network based on the connectivity between edges and nodes [271,272,118]. Topological metrics are often adopted for functionality assessment of other infrastructure systems, such as power and water distribution systems, characterized by fixed sources such as stations and reservoirs connecting the network of customers though distribution grids by transmission lines and pipelines. Nonetheless, the efficiency of these systems under emergency conditions can be more suitably assessed by flow-based methods that analyze the complete physical dynamics of power flow and water supply in a more realistic fashion than the simplistic measures of network connectivity provided by topological metrics [273,274].

Traffic analysis consists in evaluating the distribution of travels within the transportation network given travel demand and network topology [275]. Typical mathematical models for traffic assignment rely on free-flow analysis and congestion-based methods. In free-flow analysis, the traffic assignment problem is reduced to the definition of the shortest path between trips Origin and Destination nodes. Mathematical techniques such as Dijkstra's algorithm allow efficiently computing the shortest path from a single node to all the other nodes in the network [276]. On the other hand, congestion-based traffic assignment accounts for the actual traffic capacity of road segments. Most traffic analyses methods rely on the user-equilibrium assumption enforced by the Wardrop's gravitational model [277], which is based on the principle that traffic flows are distributed in the network such that travel times on all routes are minimized. Several works studied the transportation system with a congestion-based approach and taking into account the Origin-Destination demand of road networks [278,279,113,157,158,31,280–285]. Functionality metrics in terms of total travel times and total travel distance of road users accounting for the effect of partial or total closure of a bridge along a road and the consequent increase of travel time and distance due to the path detour have been proposed in Bocchini and Frangopol [265,286,287].

Traffic demand under emergency conditions

The definition of typical data related to Origin-Destination trips is generally obtained by surveys or traffic monitoring. Under operational conditions, sociological patterns and economical activities within the community lead traffic flows to dynamically fluctuate on a daily, weekly, and seasonal basis. Mathematical models often rely on static traffic data, averaging the users demand over prescribed time intervals, such as daytime or rush hours. Special care should also be taken in transferring at the network level the consequences at the social scale of physical damage suffered by individual bridges. Therefore, more refined and realistic traffic demand models should account for the elasticity of the traffic demand, which incorporates the impact of disservices in the transportation network in affecting the activities of road users.

Users' travel times depend on the post-earthquake conditions and on traffic restrictions applied to regulate the transit along bridges in the road network [288]. During long-term interruptions, drivers tend to modify their behavior to relieve the discomfort [289]. Connectivity of transportation networks plays a key role in social communities' daily life and sustainable growth [290]. Disruptions in the transportation service prevent drivers to perform economically valuable activities such as working or shopping, changing the drivers' trends and needs [291–293]. Besides direct costs of infrastructure repair, business interruption may induce significant indirect losses also due to the change in traffic patterns of road users. Several studies investigated the assessment of users' costs induced by bridge closure and subsequent traffic capacity limitations due to ongoing maintenance and rehabilitation activities [294–298], inadequacies during normal operations [299,300], and the occurrence of damage induced by multiple hazards [110,301,125,302,303]. In general, travelers can react to transport infrastructure failure in different ways, not only detouring failed links using the portion of the network in service, but also changing the travel modes and the destination of their planned tasks, or even eliminating such activity suppressing the trips in the process [280]. In this context, there is evidence that the prevailing behavior of road users in emergency conditions is to modify routes and departing times, whilst the cancelation of the trip is a limited reaction [304–307]. Drivers' reactions to infrastructure disservice would lead to a modification of the behavior of the network users and, in turn, jeopardize of system performance. Thus, refined traffic analysis models should also take into account sociological aspects under emergency conditions that may abrupt changes in users' planned trip as well as irrational behavior of drivers eventually exacerbated by the unavailability of traffic information [308]. Finally, the fulfillment of modern requirements associated with traffic flow capacity during the entire service life of transportation facilities should guide road management policies towards the compliance of old roads to new construction standards [309].

Restoration of damaged components

Structural repair activities consist in the actions needed to recover strength, stiffness, ductility and/or other mechanical properties that deteriorated due to adverse loading and/or environmental conditions. Whilst retrofit refers to the act of upgrading the capacity of a structure inadequately designed or detailed to meet the current standards and requirements, repair is associated with restoring to some extent a damaged structure to its original as-built conditions. Even though repair has become a viable option for restoring the use of earthquake-damaged RC elements, even when severely damaged, practical guidelines for design and implementation of structural repair actions for bridges damaged by extreme events such as earthquakes are yet to be standardized [310,311].

In seismic design of bridge structures, pier ends are often designed to dissipate energy sustaining inelastic deformations during strong ground motions [312]. In reinforced concrete bridges, piers may experience damage such as crushing and spalling of concrete cover, pullout of longitudinal steel bars, and buckling or fracture of longitudinal or transverse steel bars. Jacketing is the most common method to repair damaged concrete columns [313]. For example, concrete jacketing consists in covering the damaged concrete with a new layer of reinforcement and self-compacting concrete with dowel bars or steel connectors to improve the bonding between preexisting and newly casted concrete. The interface between the surfaces of damaged column and jacket should be roughened and treated with epoxy resin to improve bonding and avoid the jacket to slip from the member [314]. Like traditional repair solutions based on ordinary concrete, jacketing can be obtained by high-performance fiber-reinforced cementitious composites (HPFRCC), which proved to be efficient in restoring ductility and durability of precast reinforced concrete columns [315], and hybrid fiber-reinforced engineered cementitious composite [316]. Besides the use of cementitious material, steel jacketing is another traditional repair technique consisting in restoring the cross-section with a new concrete layer and installing a structural steel coating in adherence with the newly casted concrete with the aid of cement-based grout [317,313] or by mechanically imposed pressure [318]. Also prestressed steel jacketing (PSJ) with strands wrapped around the tubular metal sheets can be adopted for fast and permanent repair of columns damaged by seismic events [319].

Among the most investigated techniques in recent years, the adoption of shape memory alloys (SMAs) represents an innovative and widely investigated application to restore the mechanical properties of critical regions of structural members where plastic hinges are expected to develop under possible future shocks [320,321]. The application of SMA spirals generally consists in wrapping prestressed wires along the external surface of damaged regions. The distinctive feature of SMAs is their self-centering ability, which permits them to experience large de-

Table 1
Performance levels, limit states and plastic limits a to attain system displacement threshold $\Delta=\Delta_y+a\Delta_p$ (Adapted from [52]).

Performance Level	Limit State	Plastic Limit a
SP-1	Fully Operational	0.00
SP-2	Operational	0.30
SP-3	Life Safe	0.60
SP-4	Near Collapse	0.80
SP-5	Collapse	1.00

Table 2
Damage states, failure mechanisms, repair interventions, and downtime for concrete bridges (Adapted from [247]).

Damage State	Failure Mechanism	Repair Required	Outage
DS-1	Pre-Yielding	None	None
DS-2	Minor Spalling	Inspect, Patch	< 3 days
DS-3	Bar Buckling	Repair Components	< 3 weeks
DS-4	Bar Fracture	Rebuild Components	< 3 months
DS-5	Collapse	Rebuild Structure	> 3 months

formations without impairing their mechanical properties and retrieve its original shape upon load removal, as well as high durability depending on the types of allows designed for each application.

Effective and rapid design solutions are also provided by externally bonded carbon fiber reinforced polymer (CFRP) solutions for damaged bridge piers [322–325,313] and girders [326,327]. Steel-reinforced CFRP jackets filled with non-shrink concrete can be adopted to relocate the plastic hinge of damaged piers in proximity of foundation footings and pier caps [328]. The effectiveness of these relatively cheap techniques may be prone to debonding failures between repaired member and polymer coating that may impair its effectiveness [329]. Other composite materials can be adopted to externally confine and strengthen damaged bridge components such as piers and abutments, such as basalt fibers (BFRP) [330], glass fibers (GFRP) [331], and soil-rubber mixtures [332], among others.

The formulation of recovery models is an integral part of resilience assessment. This formulation captures analytically the concept of *rapidity* (i.e., one of the constitutive properties of resilience). The design of repair activities of damaged bridges is directly related to the calibration of the recovery models basic parameters and, subsequently, the achievement of rapidity goals for prompt restoration of adequate performance at the infrastructure level. Effective analytical models to capture the recovery pattern have been proposed in several works. The calibration of each model can be based on expert surveys, statistical analysis from empirical data or engineering judgment. It also depends on the restoration process and on the severity of the event that affected the system [293]. Several analytical models with different peculiarities and complexities can be found in ATC [223], FEMA [333], Padgett and DesRoches [334], HAZUS [335], Bocchini and Frangopol [286,24], Decò et al. [54], Biondini et al. [52], Karamlou and Bocchini [336,337], Sharma et al. [338], Misra et al. [339], Mitoulis et al. [340], Frangopol and Kim [32].

Different limit states could be established for buildings, bridges and other structures depending on the structural typology [333]. Table 1 provides an example of structural performance (SP) levels and limit states identified with respect to the displacement demand, where Δ_y and Δ_u are the displacement capacities of the structural system at first yielding and ultimate states, respectively, and $\Delta_p=\Delta_u$-Δ_y is the available plastic displacement [263,52] Threshold values of the diplacement demand are expressed in terms of the plastic limit coefficient a spanning from 0 (i.e., first yielding condition) to 1 (i.e., ultimate state). Depending on the type of structure, recovery actions can be based on a suitable set of limit state thresholds and discrete functionality states. This approach is particularly effective in post-earthquake evaluation procedures with damage levels qualitatively assessed by visual inspection. Table 2 gives an example of observed damage states and related repair interventions for concrete bridges [333], with estimation of the bridge outage [247]. Continuous nonlinear or constant stepwise relationships could be chosen to relate structural performance levels (SP) to damage states (DS) to establish suitable post-event repair and recovery actions.

Conclusions

This paper provided a review of past research and recent advances in the fields of life-cycle resilience of aging structures and infrastructure systems with emphasis on seismic resilience of bridges and road networks. An overview of the main principles, concepts, methods, and strategies for resilience assessment is presented to address existing frameworks developed for supporting the design, assessment, maintenance, and rehabilitation of structures and infrastructure systems, particularly bridges and transportation networks under seismic hazard. These developments are reviewed to also provide a basis for further advances on qualitative and quantitative models measuring the functionality and resilience at various scale, including components, groups and systems within infrastructure networks and communities. The effects of aging and environmental aggressiveness have been highlighted, showing that they affect structural performance and functionality and subsequently make the system resilience dependent on the time of occurrence of extreme events. The decay in time of seismic resilience due to aging processes can remarkably depend on the ground motion scenario in terms of earthquake magnitude, focal distance and seismogenic features of the reference region. Consequently, the impact of environmental aggressiveness in exacerbating the effect of seismic events on infrastructure resilience may lead to increase the likelihood of occurrence of large functionality drops and late restoration processes.

The efforts made to incorporate risk and probabilistic resilience assessment frameworks into practical policies to inform and support the decision-making process of public authorities have been also reviewed and discussed. Uncertainties are associated with multiple variables governing the investigated processes, including the time-variant seismic vulnerability of spatially distributed bridges in transportation road network, the assessment of the recovery times, and recovery patterns affecting resilience under combined post-earthquake damage states. Such uncertainties tend to propagate along with the infrastructure age and the severity of the hazardous event.

Additional efforts are needed to achieve a more complete understanding of the processes involved in the earthquake-induced disruptions of structures and infrastructure systems, particularly bridges and road networks and communities and their effective and prompt recovery by prioritizing maintenance and repair interventions. This includes the role of several features of the recovery process, such as idle time, recovery time, target functionality, horizon time, and recovery profiles with time-variant parameters related to type, severity, and location of seismic damage. In addition, recovery models should be further investigated in order to establish robust estimates of their parameters and incorporate additional features such as interdependence of repair interventions, number and capacity of available construction firms, market setting under emergency that is different from pre-earthquake conditions, work plan and organization over multiple bridges, and funds availability. The effects of maintenance activities and repair interventions need also to be incorporated in existing frameworks for lifetime probabilistic assessment of seismic resilience of deteriorating structures and infrastructure systems. In this context, the detrimental effects of aging can also be mitigated by upgrading interventions that improve network connectivity by means of new road branches and alternative travel paths. However, it is worth noting that the initial beneficial effects of the upgrading can be substantially reduced in the long-term by the detrimental impact of deterioration of bridges located along the new routes.

Concerning the time-variant vulnerability assessment of aging bridges, existing frameworks should be adapted to take into account more in-depth knowledge on the mutual interaction of different earthquake-related hazards on spatially distributed vulnerable structures, such as landslides, site amplification effects, liquefaction, and cumulative damage induced by multiple mainshocks or mainshock-aftershock sequences, among others. Furthermore, the effects of climate change on the life-cycle seismic resilience of aging and deteriorating structures and infrastructure systems need to be further investigated to incorporate the detrimental impact at the road network level of warming scenarios on the deterioration process and the rate of occurrence of extreme events, harming the system performance and functionality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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