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Review on resilience in literature and standards for critical built-infrastructure

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Abstract

A review of system resilience ideas found in literature and standards is conducted. Attention is particularly focused in the built-infrastructure, where both natural and man-made hazards are considered. In order to highlight the fragility of critical infrastructures and communities to hazards and the serious consequences of disruptions and failures, some examples of major disasters are presented. Various definitions for resilience are included and discussed in order to provide the necessary, basic concepts and background. An attempt is made to introduce some resilience properties and metrics in terms of functionality, recovery time etc. The interrelation of structural resilience and fragility curves is put into evidence and the need of some form of Guidelines along with the required research are indicated.

Internal Report

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June 2014

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1 Introduction

Hazards pose continuing and significant threats to building and infrastructure systems. Hazards type and magnitude vary by location, making resilience of buildings and infrastructures, also referred to as built environment, a national or supranational issue. In fact, considering the European Union, which developed political and technological infrastructure links between countries, a failure in one critical infrastructure can heavily impact many countries, especially where the infrastructure is a cross-border link or a feeds one (Lewis et al., 2013).

Despite substantial progress in science and technology towards improved performance of the built environment, natural and man-made hazards are responsible for loss of life, disruption of commerce and financial networks, damage property, and loss of business continuity and essential services. The risk across European Union for damage due to hazard events continue to increase and many physical infrastructures are susceptible to natural hazards (e.g. along coastlines and in earthquake-prone regions) and man-made hazards. Moreover, many infrastructures are vulnerable due to aging effects resulting in a diminishing capacity to resist disaster scenarios. In fact, even if European Union is a highly developed modern society (three of the world's ten busiest passenger airport (A.C.I., 2013), the world's largest financial center (Z/Yen-Group, 2011) and a higher number of mobile phones than people are present in the EU) it is also part of the "Old World", its infrastructures are the result of a long history and many of them were built before the EU was created (Lewis et al., 2013).

Source: *www.attivissimo.net*

Figure 1: A representation of how Italy would have appeared from space on the night of the blackout of September 2003

In order to highlight the fragility of European communities and World with respect to critical infrastructures failure and hazards some examples are provided. Italian electrical black out of September 2003 (Bacher et al., 2003) is a key incident that must be considered. The blackout was initiated when two power lines in Switzerland flashed over in an alpine storm, causing the Italian grid to increase demand from, and overload other lines that brought power to France, and then causing blackouts across the entire Italian grid and failures in Switzerland (Figure 1). This is not the only example concerning electrical grid, in fact in 2006 an outage occurred when a power line crossing the River Ems in Germany was switched off to allow a cruise ship to pass (Figure 2), causing an unintentionally trigger blackouts that spread to France, Italy, Spain and Portugal. Power system elements were also tripped in Austria, Hungary, Croatia, Bosnia, Ukraine, Romania and Marocco (UCTE, 2007).

Source: *http://news.nationalgeographic.com*

Figure 2: Norwegian Pearl ship in the Papenburg, Germany, shipyard in November 2006. The ship indirectly caused a two-hour power outage on the evening of November 4, 2006

Tunnels represent another example of important infrastructure links. Many important road and rail tunnels are the main cross border routes in Europe. Tunnels are vulnerable to explosion and fire. Examples include the Mont Blanc and Tauern Tunnel fires (UN (2001), Figures 3 and 4 and the Channel Tunnel fires of 1996 (Figure 5), 2006 and 2008 (CTSA, 1997; RAIB, 2007; BEA-TT and RAIB, 2010).

When a protection of critical infrastructures is considered, terrorism remains a major worry. Europol (2012) recorded 316 attacks in the EU in 2009, 249 in 2010 and 174 in 2011 and an increase use of improvised explosive devices (IEDs) by terrorists of various affiliations. The components required for the construction of IEDs are easy to procure, their production requires expertise that can be obtained through open source information, and the chemical precursors can be

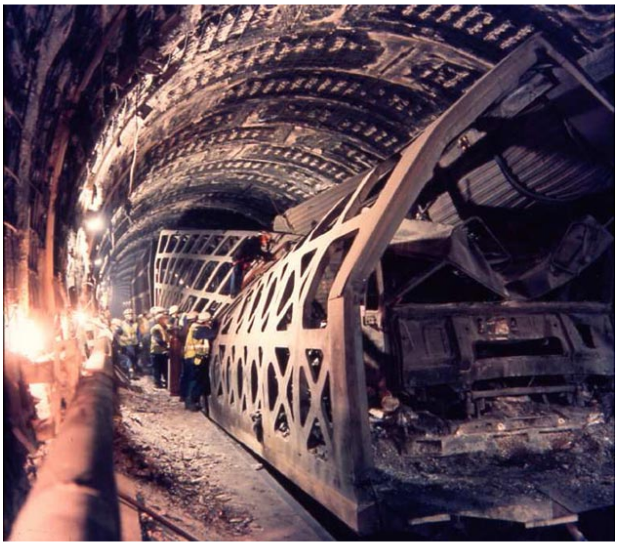
Source: *http://www.tunneltalk.com*

Figure 3: Aftermath of the fierce fire that claimed 39 lives in the Mont Blanc tunnel.

Source: *http://www.landroverclub.net*

Figure 4: The Tauern Tunnel fire. The main site in the rear burned at over 1000°C. A thick coat of foam covers the ground and parts of the roof hanging down against the fiery background.

legally obtained in EU Member States. Improvised devices like incendiary devices (IIDs) were used in a coordinated action to target railway infrastructures in Germany in October 2011. Railway infrastructures and their occupants were the target of terroristic attacks in London and Madrid. Three days before the Spain's election, during the peak of Madrid morning rush hour of Thursday, 11 March 2004, ten explosions occurred aboard four commuter trains (Figure 6(a)). All the target trains were traveling between Alcalá de Henares and the Atocha station in Madrid in the same direction, three bombs exploded in the Atocha station, two bombs exploded in different carriages in the El Pozo del Tío Raimundo Station,



Source: *http://www.tunneltalk.com*

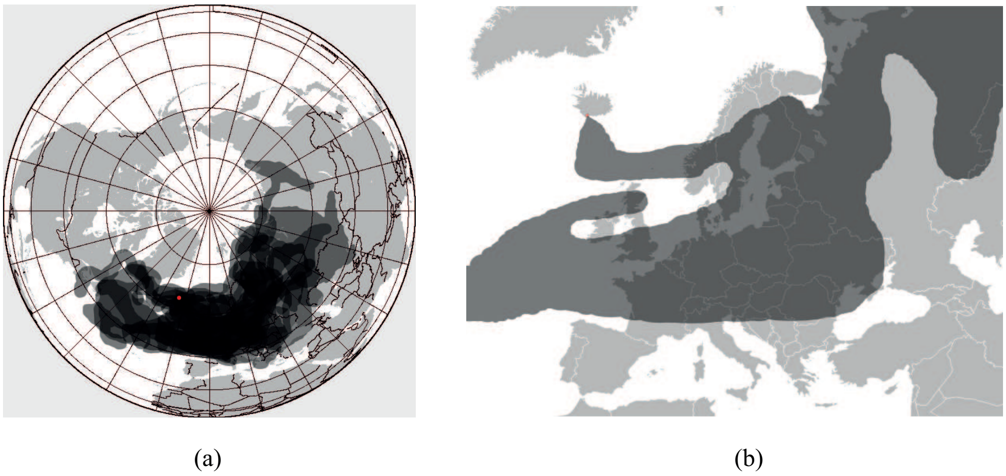
Figure 5: Damage caused by the 1996 freight shuttle train fire in the Channel Tunnel.

(a) (b)

Source (a): *http://www.telegraph.co.uk* Source (b): *http://www.dailymail.co.uk*

Figure 6: Terroristic attacks in rail transport system in Europe: a) Madrid, 2004; b) London, 2005.

one explosion occurred in the Santa Eugenia Station and the last one exploded in different coaches of the train approximately 800 meters from Atocha Station. The explosions killed 191 people and wounded 1.800. One year after Madrid's attacks, on 7 July 2005, a series of coordinated suicide attacks in central London were conducted by four terrorists, they targeted civilians using the public transport system during the morning rush hour (Figure 6(b)). Two attacks were conducted on two Circle line sub-surface train, while the third one targeted a Piccadilly line deep-level underground train traveling southbound from King's Cross-St. Pancras



(a) (b)

Source: *http://en.wikipedia.org*

Figure 7: Composite map of the volcanic ash cloud spanning in 14-25 April 2010 for the Eyjafjallajökull eruption.

Source: *http://www.tboeckel.de*

Figure 8: Aerial image from Eyjafjallajökull volcano eruption. Ash cloud on May 12, 2010.

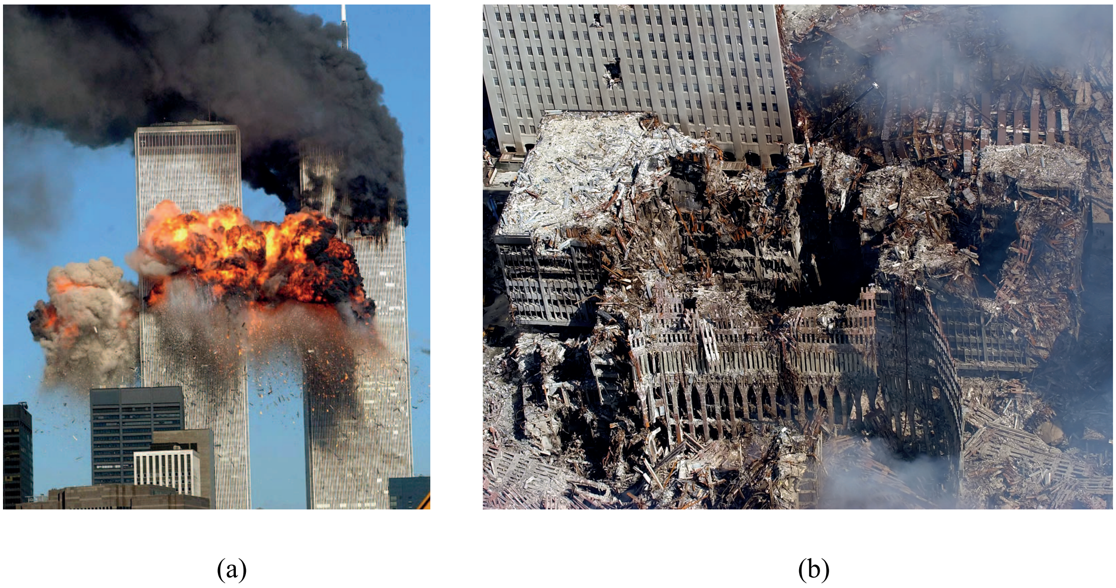
and Russell Square and it damaged also the surrounding tunnel. Finally one hour after the first attack a bomb was detonated on the top deck of a double-decker bus. Naturally these events caused serious disruptions in the rail transport system of the two cities, and it took several days for a full recovery.

Although Europe is imagined to be relatively free of severe natural hazards, significant risks are present and can potentially be extreme due to the high density of population in the region. EEA (2003) recorded the highest loss of life from natural events in the period 1998–2009 to be from heat waves while floods and storms caused the greatest economic loss. Those are not the only examples of natural hazards, in April 2010 the eruption of the Eyjafjallajökull volcano in Ice-


(a) (b)

Source (a): *http://earthsky.org Image credit: NASA* Source (b): *https://www.tcpalm.com*

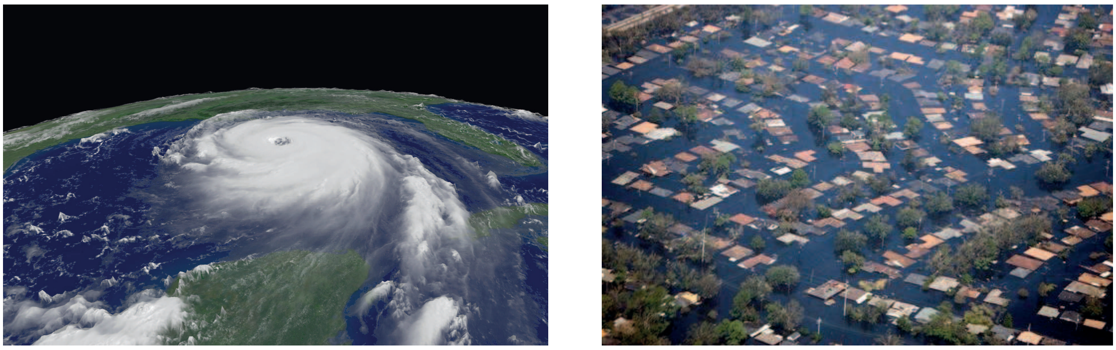
Figure 9: Hurricane Andrew: a) three views of Andrew on 23, 24 and 25 August 1992 as the hurricane moves from East to West; b) the Florida City water tower is almost all that remains standing in August 1992 after the coastal community was hit by Hurricane Andrew.


(a) (b)

Source (a): *http://libertesedosistema.blogspot.it* Source (b): *http://en.wikipedia.org*

Figure 10: The World Trade Center attack: a) 9^{th} September 2001, Flight 175 crashes into 2 WTC; b) the remains of 6 World Trade Center, 7 World Trade Center, and 1 World Trade Center on September 17, 2001.

land compromised the European air traffic for weeks showing how an unexpected phenomenon can influence critical infrastructures, even if they are not directly hit (Figure 7 and 8).



(a) (b)

Source (a): *http://www.satimagingcorp.com* Source (b): *http://de.wikipedia.org*

Figure 11: Hurricane Katrina: a) satellite image of the hurricane; b) flooding caused by Hurricane Katrina in the New Orleans area, August 31^{st}, 2005.

Obviously, Europe is subjected to and is prone to hazards like many other countries such as the United States, where in particular three disaster events significantly influenced the development of resilience concepts. Hurricane Andrew in 1992, the World Trade Center (WTC) and Pentagon terroristic attacks in 2001, and Hurricane Katrina in 2005 (McAllister, 2013). Andrew struck Dade County on August 24^{th}, the storm devastated Dade County and it caused an estimated 25 billion of dollar in damage and it destroyed approximately 49 000 homes (Figure 9). On September 11, 2001, large aircrafts were flown into the World Trade Center buildings and Pentagon by terrorists. The fires following the impact caused WTC 1 and WTC 2 buildings to collapse within approximately 1 to 1.5 hours. When the buildings collapse the fire spread to the WTC 7 building where the emergency Operations Centre was located (Kendra and Wachtendorf (2003), Figure 10). The collapse of WTC buildings led to major damage to surrounding buildings and loss of power, communication and water in lower Manhattan as well as interruption of financial markets. The loss of life by occupants and responders, and the damage of the surrounding buildings and infrastructure systems, raised the issue about how building collapse can affect the entire built community (NIST, 2008). Hurricane Katrina struck the Gulf Coast region and rapidly reached Category 5 with maximum sustained winds of 78 m/s. Storm surge and associated wave action led to breaches in the flood protection system in New Orleans, resulting in substantial structural damage to residences in the immediate vicinity of breaches and flooding in approximately 75% of the city (Figure 11). Bridges were damaged due to the uplift and lateral loads imparted by storm surge and associated wave action. Moreover, industrial facilities, such as seaports, petrochemical facilities and utilities also sustained damage due to storm surge and flooding (NIST, 2006).

The extensive, multi-state damage from Hurricane Katrina in 2005 reminded that natural disasters continue to be a significant threat to our communities. The unprecedented level of destruction brought renewed focus on the need to address natural disasters, in addition to protection from man-made hazards. Tragic events, previously described, forced the scientific community to investigate the concept of resilience and to move their attention from vulnerability and risk assessment to a new design and evaluation approaches that have to consider and involve many different disciplines: economics, political science, engineering, environmental planning, social science, etc.. The evolution towards resilience thinking is far from trivial, resilience as a concept is more dynamic, it is non-linear and cross-linked, complex so to say and it embraces uncertainty (Stumpp, 2013). Current thinking on resilience is the product of theoretical and practical constructs that have seen refining and reshaping of the disaster paradigm over the past three decades. This has led to a multiple of definitions and the need of new terminology and/or metrics that should be harmonized. For this reason in the next section various definitions are presented and discussed in order to give the basic knowledge needed to develop further research in the field of critical infrastructure resilience.

2 Definition and terminology

Resilience is derived from Latin word resilio, meaning “to jump back” (Klein et al., 2003). The resilience concept is applied in many fields and the original one is still contested: some say ecology (Batabyal, 1998), while other researchers say physics (Van der Leeuw and Leygonie, 2000). However, most of the literature states that the study of resilience evolved from disciplines of psychology and psychiatry in the 1940s (Waller, 2001; Johnson and Wiechelt, 2004). Today resilience is being applied in many fields, especially disaster management.

The concept of resilience started to lead a new way to tackling disaster and provide policy options. However in order to enhance resilience it is necessary to have a good initial understanding of what it is, its determinant factors (Klein et al., 1998) and how it can be measured, maintained and improved (Klein et al., 2003).

Table 1: Definitions of resilience (Manyena, 2006)

Author	Definition
Wildavsky (1988)	Resilience is the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back.
Hoiling et al. (1997)	It is the buffer capacity or the ability to a system to absorb perturbation, or magnitude of disturbance that can be absorbed before a system changes its structure by changing the variables.

Table 1: continues on next page

Table 1: continued from previous page

Author	Definition
Horne and Orr (1997)	Resilience is a fundamental quality of individuals, group and organisations, and systems as a whole to respond productively to significant change that disrupts the expected pattern of events without engaging in an extended period of regressive behaviour.
Mallak (1998)	Resilience is the ability of an individual or organisation to expeditiously design and implement positive adaptive behaviours matched to the immediate situation, while enduring minimal stress.
Mileti (1999)	Local resiliency with regard to disasters means that a locale is able to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity, or quality of life without a large amount of assistance from outside the community.
Comfort (1999)	The capacity to adapt existing resources and skills to new systems and operating conditions.
Paton et al. (2000)	Resilience describes an active process of self-righting, learned resourcefulness and growth the ability to function psychologically at a level far greater than expected given the individual's capabilities and previous experiences.
Kendra and Wachtendorf (2003)	The ability to respond to unique and singular events.
Cardona (2003)	The capacity of the damaged ecosystem or community to absorb negative impacts and recover from these.
Pelling (2003)	The ability of an actor to cope with or adapt to hazard stress.

Table 1: continues on next page

Table 1: continued from previous page

Author	Definition
UNISDR (2005)	The capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organising itself to increase this capacity for learning from past disaster for better future protection and to improve risk reduction measures.

Table 1: concluded from previous page

Different authors have proposed diverse definitions, reflecting the complexity of matter, society and thinking on disaster and building resilience. In Table 1 some of the definitions are listed. What can be pointed out is how the resilience has been defined in two ways: as a desired outcome or as a process leading to a desired outcome (Kaplan, 2002). Focusing the attention on Table 1, a gradual refinement in the resilience definition can be highlighted: from a more outcome-oriented to more process-oriented. In the early stage authors were thinking of resilience as a process to reach an outcome and the use of words like “cope”, “bounce back”, “absorb negative impacts” to return to normal in the shortest possible time might be more appropiate for objects capable or regaining their original shape after a deformation (Manyena, 2006). On the other hand, when people are considered, resilience centres on quick recovery from shock, illness or hardship (Vickers and Kouzmin, 2001). The goal of disaster resilience and more in general to disaster risk management is to guarantee a minimal loss of life and livelihoods and allow the affected system or environment to return to normal within the shortest possible time. From this point of view it is important to underline that resilience is arguably linked on people’s capacity far beyond the minimum of being able to cope.

On the basis of these first observations, it appears clear that merely a definition of resilience on the basis of minimum standards of development and requirements may be an inadequate conceptual and practical application of the approach. The danger of viewing disaster resilience as an outcome is the tendency to reinforce the traditional practice of disaster management, which takes a reactive stance, leading to a propensity to follow a paternalistic mode that can lead to the skewing of activities towards supply rather than demand as underlined by Manyena (2006). Activities such as community capacity building, mitigation and emergency preparedness planning, which impact greatly on response and recovery operations, may be neglected (McEntire et al., 2002). Moreover, these observations can be transferred in the engineering field when the concept of resilience is used for buildings, building communities and critical infrastructures.

In the last years researchers, engineers and specialists have posed a lot of attention in the concept of resilience, pushed by the catastrophic events previously described and led reaction of societies and politicians (PPD, 2013; European Commission, 2006); they are trying to not only define and clarify resilience concept but also implement strategies to enhance it in the new and old building systems. However, these strategies can not be limited to minimum prescription in standards and codes but should define new design procedures in requirements like for disaster management, where many different social-economic aspects and complex interactions are taken into account, as highlighted by McEntire et al. (2002).

3 Critical infrastructures and structures

Critical infrastructures is a term used to describe systems or assets that are essential for the functioning of a society and economy. In the common use of the word, the term is associated to assets and facilities linked to:

- electricity generation, transmission and distribution;
- oil and oil products production, transport and distribution;
- gas production, transport and distribution;
- water supply (drinking water, waste water/sewage, stemming of surface water (e.g. dikes and sluices));
- heating (e.g. natural gas, fuel oil, district heating);
- telecommunication and cyberspace;
- transportation systems (fuel supply, railway network, airports, harbours, inland shipping);
- financial services (banking, clearing);
- public health (hospitals, ambulances);
- security services (police, military).

The whole asset listed above represents key point for governments and institutions, however some different classification and definitions can be considered by different authorities. The United States defined critical infrastructure as those “systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters.” (Public Law 107–56 (2001)). On the other hand, the European Commission proposed a slightly different definition (European Commission, 2006) due to its particular political nature: “European Critical Infrastructures constitute those designated critical infrastructures which are of the highest importance for the Community and which if disrupted or destroyed would affect two or more Member State, or a single Member State if the critical infrastructure is located in another Member State. This includes transboundary effects resulting from interdependencies between interconnected infrastructures across various sectors.”

The threat from terrorism and man-made hazards are usually considered as a priority for critical infrastructure, however protection of them should be based on an all-hazards approach. Terrorism, other criminal activities, natural hazards and other causes of accidents are not constrained by geographical national and international borders. Threats cannot be seen in a purely regional context; this means that the external dimension of a critical infrastructure need to be fully and carefully taken into account, the interconnected and interdependent nature of the today’s economy and society lead to increase tremendously the system complexity: even a disruption outside of the national borders or EU’s border may have serious impact on the community.

For the above-listed critical infrastructures, buildings and other types of civil engineering structures form an important integral part and thus they play a significant role in contributing to the community resilience. For the term *“critical structure”* there is no specific definition in literature, however it is convenient to introduce one for the document purposes. *Critical structure* could be defined as an element and/or structure inside a critical infrastructure that is essential for the system functionality or structures which if disrupted would decrease sensibly the functionality. Moreover, it would be useful to extend this definition in order to include some other building and structures that are disconnected from an infrastructural system but have an important role for governments, like embassies, consulates, etc.

3.1 A conceptual framework for resilience

Due to the extent of the catastrophic consequences that an earthquake can have, seismic resilience of communities has received early attention by researchers, designers, urban planners and administrators. For example, the Disaster Mitigation Act of 2000 in the United States, which provides the legal basis for FEMA mitigation planning, has promoted mitigation, preparedness and the strengthening of communities against disasters. Following the 1994 Northridge Earthquake, California has taken further steps in this direction by enacting ordinance SB1953 (Meade and Kulick, 2007). This ordinance requires that acute care facilities must be retrofitted by 2030 (with two intermediate milestones of 2008 and 2013) to the level that would allow them to be fully operational following an earthquake.

3.1.1 Dimensions of Resilience

Working in the field of seismic mitigation, Bruneau et al. (2003) have suggested that resilience can be conceptualized along four interrelated dimensions: **technical, organizational, social** and **economic** (referred under the acronym: TOSE).

Technical resilience refers to the response and performance of the physical systems when subjected to earthquake forces. Organizational resilience refers to the capacity and ability of agencies/organizations to respond to emergencies and carry out critical functions. Social resilience refers to the capacity to reduce the negative societal consequences of loss of critical services in the aftermath of catastrophic events. Economic resilience refers to the ability to reduce the direct and indirect economic losses resulting from destructive earthquakes. As argued, of these four dimensions, the technical and organizational dimensions are most pertinent to the performance and resilience of critical systems such as electric power, water, hospital and emergency response. The social and economic dimensions are most relevant to the performance and resilience of the community as a whole.

3.1.2 Properties of Resilience

Bruneau et al. (2003) further suggest that resilience has four main properties: **robustness, rapidity, redundancy** and **resourcefulness** (abbreviated as: 4 R's). Robustness refers to the strength, or the ability of elements, systems and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function. Rapidity can be thought as the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption. Redundancy refers to the availability of substitutable elements or systems that can be activated when earthquake-related disruptions occur. Finally, resourcefulness is the capacity to mobilize and apply material and human resources to achieve goals in the event of disruptions. Of these four properties, it is useful to view robustness and rapidity as the desired ends of resilience-enhancing measures, and redundancy and resourcefulness as some of the means to these ends, respectively.

Regarding seismic resilience of communities, of the several factors that can affect it, it appears logical to start by focusing on organizations and facilities, whose function is essential for community well-being in the aftermath of earthquake disasters. These critical facilities include electrical power and water lifelines, public health (acute-care hospitals), and services that have the responsibility for emergency management at the local community level. Such organizations form the "backbone" for community functioning. For these situations Bruneau et al. (2003) propose a set of several illustrative measures of resilience, which relate to the above four dimensions and four properties. Those measures referring to the "global" system performance are reported in Table 2. However, as is stated, such measures and performance matrices serve mainly to illustrate the definitions, and through research these measures should be refined to be more consistent with the notion of system and community resilience. Indeed, as resilience is a multidimensional concept, developing measures of resilience that are quantifiable, succinct and meaningful remains always the principal challenge. An attempt for such a setting is presented in the following chapters.

Table 2: Example of global performance measures according to Bruneau et al. (2003)

PERFORMANCE MEASURE	**PERFORMANCE CRITERIA**			
	ROBUSTNESS	REDUNDANCY	RESOURCEFULNESS	RAPIDITY
TECHNICAL	Damage avoidance and continued service provision	Backup/duplicate systems, equipment and supplies	Diagnostic and damage detection technologies and methodologies	Optimizing time to return to pre-event functional levels
ORGANIZATIONAL	Continued ability to carry out designated functions	Backup resources to sustain operations (e.g. alternative sites)	Plans and resources to cope with damage and disruption (e.g., mutual aid, emergency plans, decision support systems)	Minimize time needed to restore services and perform key response tasks
SOCIAL	Avoidance of casualties and disruption in the community	Alternative means of providing for community needs	Plans and resources to meet community needs	Optimizing time to return to pre-event functional levels
ECONOMIC	Avoidance of direct and indirect economic losses	Untapped or excess economic capacity (e.g., inventories, suppliers)	Stabilizing measures (e.g., capacity enhancement and demand modification, external assistance, optimizing recovery strategies)	Optimizing time to return to pre-event functional levels

4 Resilience of critical structures and Metrics

Resilience concepts could be applied at different structural levels. The term resilience is commonly used for materials and the definitions presented in Section 2 can be applied for structural elements, structures and infrastructures. For the finality of the present document only structures and built-infrastructure will be considered, in particular this section is devoted to resilience applications on structures. Applying the definitions presented above in the structural field without any modification or adaptation is a very difficult task. Some formal and quantitative variables should be introduced in order to quantify the resilience of a critical structure. In this sense Bruneau and Reinhorn (2007) and subsequently Cimellaro et al. (2010) have introduced a useful definition of resilience:

Resilience (R) *is defined as a function indicating the capability to sustain a level of functionality or performance for a given building, bridge, lifeline networks, or community, over a period defined as the control time* (T_{LC}) *that is usually decided by owners, or society.*

Hence, resilience is a function that can vary in time due to external events like earthquake or explosion which can reduce it or because of actions focused on performance improvement. Due to this time variability and the framework considered it is important to introduce a new variable called recovery time (Porter et al., 2001; Bruneau and Reinhorn, 2007; Cimellaro et al., 2009, 2010):

The recovery time (T_{RE}) *is the period necessary to restore the functionality of a structure, and infrastructure system to a desired level that can operate or function the same, or close to, or better than the original one.*

The time recovery is a random variable with high uncertainties depending on the socio-economic environment where the critical structure is placed, a fact that could play an important role in the construction recovery time and the business interruption time; however, T_{RE} should be smaller than T_{LC}. The definitions proposed by Bruneau and Reinhorn (2007), Cimellaro et al. (2010) were introduced in an earthquake engineering framework using the Multidisciplinary Center of Earthquake Engineering to Extreme Event (MCEER) background and terminology. In this context the seismic performance of the structure/system is measured through a unique decision variable (DV) named "Resilience" that combines other variables (economic losses, life losses, recovery time, etc.). All these concepts can be used for a large number of different hazards implementing the necessary changes to the various models and equations that will be presented later on.
On the basis of the previous discussion and definitions the Resilience can be computed through the following equation (Cimellaro et al., 2010):

$$R = \int_{t_{0E}}^{t_{0E}+T_{RE}} \frac{Q(t)}{T_{RE}}\, dt \tag{1}$$

The Resilience is defined graphically as the normalized area subtended by the functionality function defined as Q(t). Q(t) is a non-stationary stochastic process and can be expressed as follow:

$$Q(t) = 1 - L(I, T_{RE}) \cdot [H(t - t_{0E}) - H(t - (t_{0E} + T_{RE}))] \cdot f_{Rec}(t, t_{0E}, T_{RE}) \tag{2}$$

where $L(I, T_{RE})$ is the loss function; $f_{Rec}(t, t_{0E}, T_{RE})$ is the recovery function; $H()$ is the Heaviside function, t_{0E} is the time of the occurred event E and I is its intensity. The values of the quantities in this equation are less than one, as the desired full functionality is equal to 100% =1.

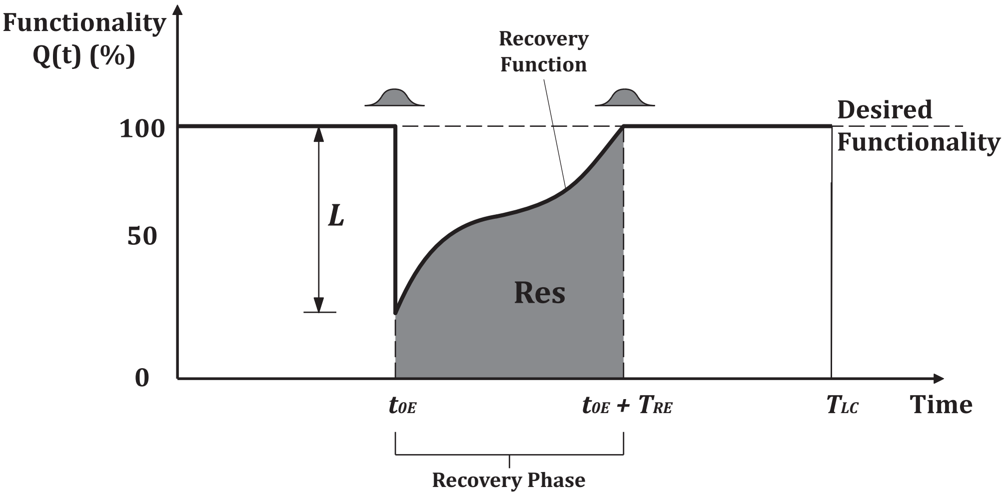


Figure 12: Schematic representation of resilience over the recovery time T$_{RE}$ (Cimellaro et al., 2010)

In Equation 1 resilience is computed with reference to a single disrupting event E at time t_{0E} and the subtended area is normalized with respect to the recovery time T_{RE}, Figure 12. This normalization with respect to the recovery time T_{RE} should be considered if more emphasis has to be placed on the recovery phase. In order to take into account the long term or time effects on resilience Equation 1 should be changed: the integral limits have to be extended from 0 to T_{LC} and the normalization time should be set equal to T_{LC}, Figure 13. Civil structures and the main activities inside or linked to them could have some functionality reduction in the time due to age problem or degradation induced by external/environmental agents, in some cases it could be interesting to evaluate the resilience of such kind of structures (see Figure 14).

As highlighted in Section 2 defining resilience is challenging, but probably identifying the aspects that can enhance resilience can be even more difficult. As mentioned above, Bruneau et al. (2003) have identified four properties along which

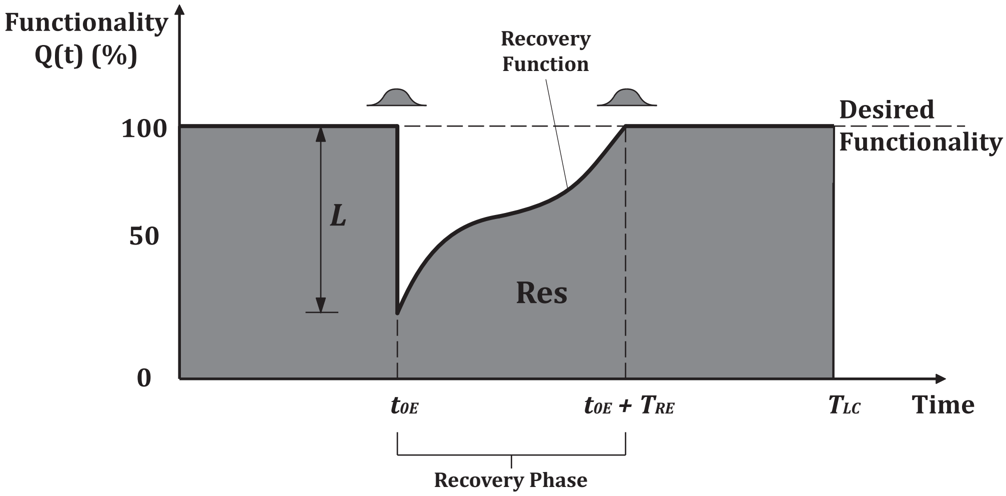


Figure 13: Schematic representation of resilience over the control time T_{LC} (Cimellaro et al., 2010)

resilience can be improved: rapidity, robustness, redundancy and resourcefulness.

Rapidity (θ) *is the "capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption"*

Mathematically it represents the slope of the functionality curve during the recovery period as illustrated in Figure 15 and it can be expressed by the following equation:

$$\theta = \frac{dQ(t)}{dt} \tag{3}$$

where d/dt is the differential operator, $Q(t)$ is the functionality function. An average estimation of the rapidity can be defined as in Equation 4 when total losses L and time recovery T_{RE} are known:

$$\theta = \frac{L}{T_{RE}} \tag{4}$$

Robustness is the "ability of elements, structure or system to withstand a given level of stress, or demand without suffering disproportionate degradation or loss of function"

It is therefore the residual functionality after an extreme event as described by the following equation:

$$Robustness = 1 - \tilde{L}\,(m_L, \sigma_L) \tag{5}$$

where $\tilde{L}$ is a random variable expressed as a function of the mean m_L and the standard deviation σ_L. A more direct way to compute robustness is to consider the dispersion of losses expressed directly as follows:

$$Robustness = 1 - \tilde{L}\,(m_L + a \cdot \sigma_L) \tag{6}$$

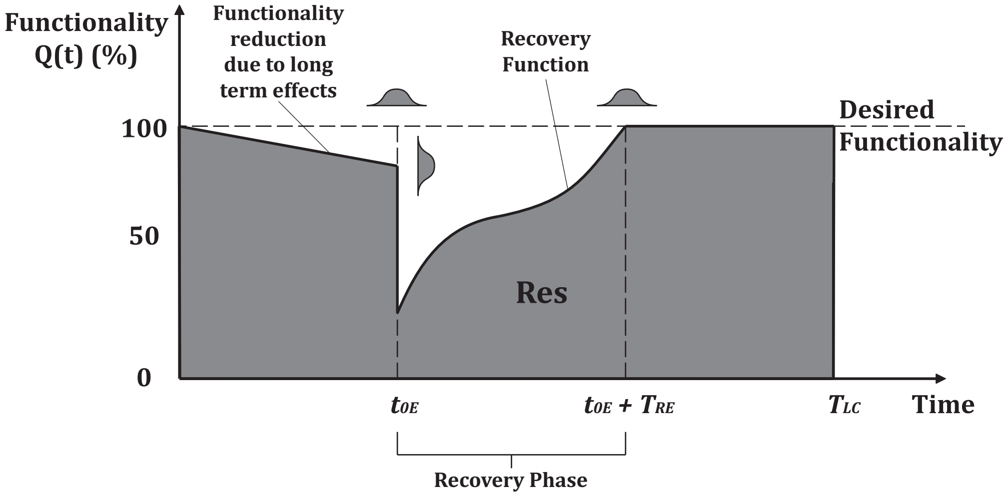


Figure 14: Schematic representation of resilience and the effects of long term agents

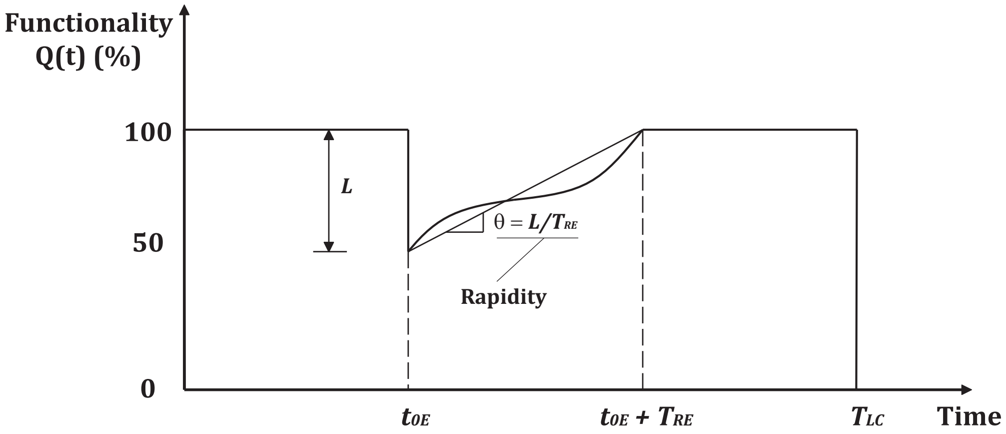


Figure 15: Schematic representation of rapidity concept (Cimellaro et al., 2010)

where a is a weight parameter of the standard deviation corresponding to a specific level of losses; in this definition robustness can be considered also the capacity of keeping the variability of losses within a narrow band (Figure 16). A way to decrease uncertainty in robustness is to reduce the dispersion in the losses represented by σ_L. The concept of redundancy according to the earthquake engineering field, as reported by Cimellaro et al. (2010), Bruneau and Reinhorn (2007), is next considered:

Redundancy is the "quality of having alternative paths in the structure by which the lateral forces can be transferred, which allows the structure to remain stable following the failure of any single element" (ASCE and FEMA, 2000)

In order to have a complete overview of the resilience problems also the definition of redundancy in the structural field is reported:

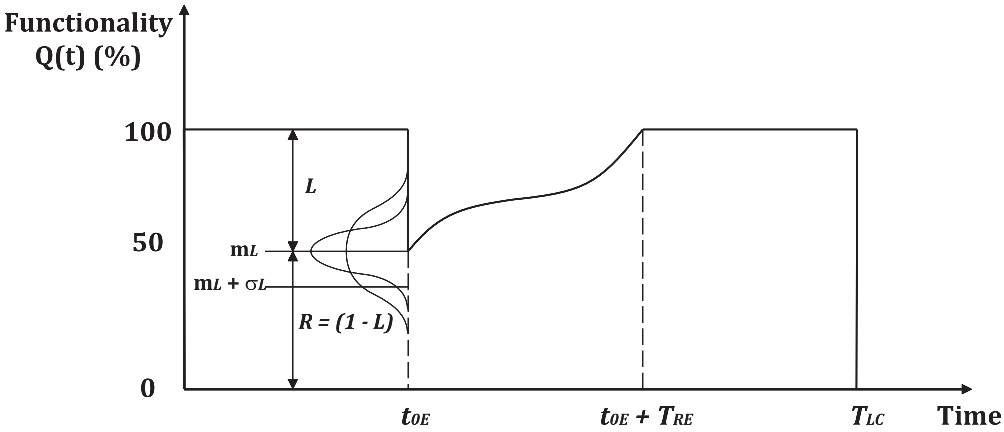


Figure 16: Schematic representation of robustness concept (Cimellaro et al., 2010)

Structural redundancy refers to the multiple availability of load-carrying components or multiple load paths which can bear additional loads in the event of failure. If one or more components fail, the remaining structure is able to redistribute the loads and thus prevent a failure of the entire system. Redundancy depends on the geometry of the structure and the properties of the individual load-carrying elements (Frangopol and Curley, 1987).

Redundancy is a very important attribute of resilience, since it represents the capability to use alternative resource when the main ones are insufficient or missing. If the redundancy is not part of our structure or system ,changes can be done, such as duplicating components in order to provide alternatives in case of failure. The fourth and last component introduced by MCEER is the resourcefulness.

Resourcefulness is "the capacity to identify problems, establish priorities, and mobilize resource when condition exist that threaten to disrupt some element, structure, system or other unit of analysis (Bruneau and Reinhorn, 2007).

Resourcefulness and Redundancy are strongly interconnected, for example resourcefulness can create redundancies that did not exist before. Moreover, resourcefulness and redundancy can affect the shape and the rapidity of the recovery function and the recovery time. As illustrated in Figure 17, where a third axis is added to consider resourcefulness, adding resources can reduce time recovery beyond what is expected by the benchmark normal condition. In theory, if infinite resources were available, time recovery would asymptotically approach zero. Practically, even in the presence of enormous financial and labor capabilities a practical minimum time recovery exists. An example is the replacement of the Santa Monica freeway bridges following the 1994 Northridge earthquake. The replacement of this critical structure was accomplished 2.5 months faster than in the original planning, at a reported bonus cost of over 14 million of dollars paid to the contractor for early completion. Likewise in less advanced societies where resources are scarce, time

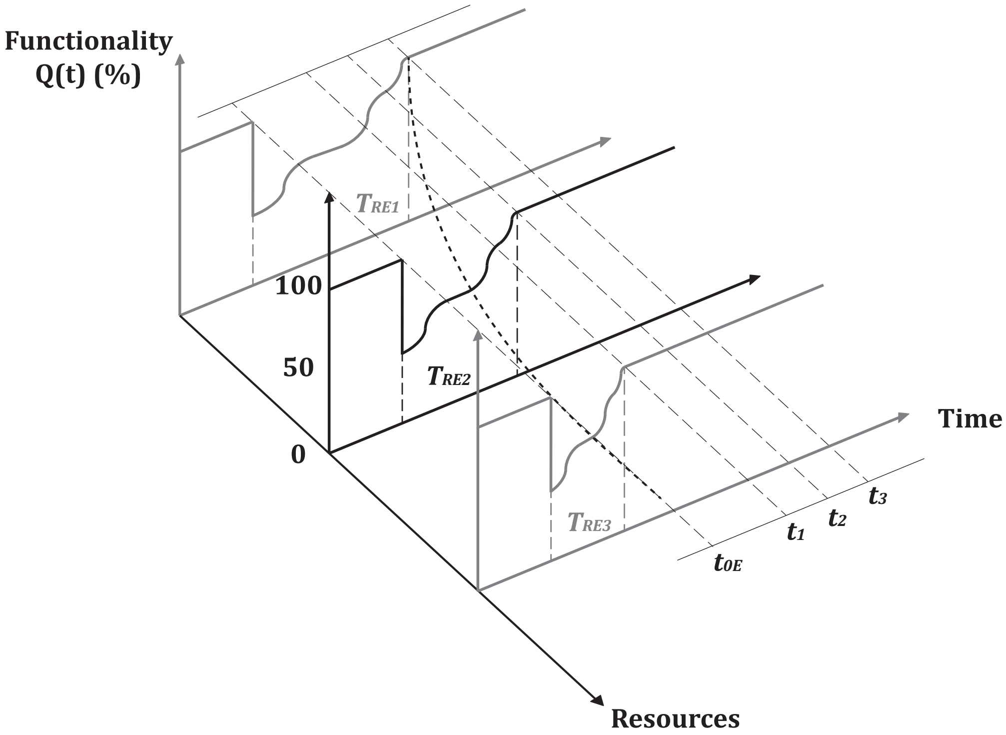


Figure 17: The influence of resourcefulness on resilience (Bruneau and Reinhorn, 2007)

recovery could approach infinity. However, also in resourceful societies the time recovery could be significantly longer than necessary due to inadequate planning, organizational failures or ineffective policies. Resourcefulness and robustness are also linked, it can be argued that investing in limiting initial losses (improving the robustness) might, in some cases, be the preferred approach to enhance resilience as it automatically translates into a consequent reduction in time recovery; the retrofitting investment is an investment that pays benefits both axes.
Looking at Equations 1 and 2 it is clear that the loss function (L), the recovery function (f_{Rec}) and the time recovery (T_{Re}) play an important role in engineering evaluation of resilience; in the next subsection these three components will be discussed in more depth.

4.1 Loss Function

Losses in an exceptional event like terroristic attack, blast or other man-made disaster are very uncertain and are different for every scenario considered. However, some common classification can be made and various types of losses defined. The function of losses $L(I, T_{RE})$ can be considered as additive function composed of two main contribution: **direct losses** (L_D) and **indirect losses** (L_I).

$$L(I, T_{RE}) = L_D + \alpha_I \cdot L_I \tag{7}$$

Direct losses (L_D) occur "instantaneously" during the event, while the indirect ones have also temporary dependence. In Equation 7 the indirect losses are multiplied by a weight factor (α_I) dependent on the structure importance and influence of the structure on other systems. Direct and indirect losses can be divided into two subgroups: **Economic losses** ($L_{DE}; L_{IE}$) and **Casualties losses** ($L_{DC}; L_{IC}$). Direct economic losses are mainly physical structural and non-structural losses that can be expressed as the ratio between building repair and replacement costs as indicated in Equation 8

$$L_{DE,\,k}(I) = \sum_{j=1}^{n} \left[\frac{C_{s,j}}{I_s} \prod_{i=1}^{t_i} \frac{(1+\delta_i)}{(1+r_i)} \right] \cdot P_j \left\{ \bigcup_{i=1}^{n} (R_i \geq r_{lim\,i}) \mid I \right\} \tag{8}$$

where P_J is the conditional probability of exceeding a performance limit state j when an extreme event of intensity I occurs, this probability is also known as fragility function and will be discussed in detail in the Section 5; $C_{s,j}$ are the building repair costs associated with a j damage state; I_S are the replacement building costs; r_i is the annual discount rate applied for the time range in years t_i between the initial investment and the extreme event; δ_i is the annual depreciation rate. Direct economic losses ($L_{DE\,i}$) are obtained for every structural and non structural k element, then the "global" direct economic losses are computed using the following weight average expression:

$$L_{DE}(I) = \frac{\left(\sum_{k=1}^{n} w_k \cdot L_{DE,k}(I)\right)}{N} \tag{9}$$

In Equation 9 w_k is a weight factor associated to each structural and non-structural component in the building while N is the total number of structural and non-structural component such as ceilings, elevators, mechanical and electrical equipment, piping, partitions, glass etc.

Direct casualties losses L_{DC} are measured as the ratio of instantaneous number of injured or dead N_{in} and the total number of occupants N_{tot}:

$$L_{DC} = \frac{N_{in}}{N_{tot}} \tag{10}$$

The number of injured people N_in depends on multiple factors such as the type of structure and building, the time of the day of the extreme event occurrence etc., and this makes quite difficult to estimate in a proper way the direct casualties losses.

The indirect economic losses $L_{IE}(I, T_{RE})$ are time dependent and they are the most difficult to quantify because of the different forms they can have: business interruptions, relocation expenses, rental income losses, etc. Losses of revenue can be caused by damage on structure or non-structural elements and they are most important for manufacturing, retail facilities and to lifelines. Damage to the former could lead to reduction in delivered resources like electricity, water natural gas or transportation and can be more significant than direct losses. Indirect economic losses due to business interruption should be modeled considering the structural and non-structural losses L_{DE} and the time recovery (T_{RE}) needed to repair the structure. Obviously T_{RE} is strictly correlated with the direct economic losses because it increases with the extent of the structural damage (Miles and Chang, 2006, 2003).

The indirect casualties losses (L_{IC}) describe the number of injuries or deaths due to functionality disruption and could be evaluated as the ratio between the number of injured people N_{in} and the total number of people served by the building N_{tot}:

$$L_{IC} = \frac{N_{in}}{N_{tot}} \tag{11}$$

These types of losses could be quite important for structures like hospital where the loss of functionality can generate injuries and deaths for a long period after the occurred extreme event.
Finally L_D and L_I can be calculated, as suggested by Cimellaro et al. (2010), as follows:

$$\begin{aligned} L_D &= L_{DE}^{\alpha_{DE}} \cdot (1 + \alpha_{DC} \, L_{DC}) \\ L_I &= L_{IE}^{\alpha_{IE}} \cdot (1 + \alpha_{IC} \, L_{IC}) \end{aligned} \tag{12}$$

where α_{DE} and α_{IE} are weighting factors related to construction losses in economic term and business interruption, respectively, while α_{DC} and α_{IC} are the weighting factors related to nature of occupancy. It should be noted that casualties losses were introduced as penalty function in Equations 12.

4.2 Recovery Function and Time

Recovery time (T_{RE}) and recovery function (f_{Rec}) are essential for evaluating resilience, hence they should be evaluated accurately. These crucial points unfortunately were treated in a approximate way such as the linear trend covered in one year proposed in HAZUS (Whitman et al., 1997). Moreover, the critical structure considered could not return to the pre-disaster functionality state, but it may exceed the previous performance if during the recovery process pre-existing problem are fixed (Figure 18 - curve C) or it can be damaged permanently (Figure 18 - curve A). An example of permanent functionality loss is represented by the Port of Kobe. In 1994, prior to the earthquake (one of the most significant earthquake in the word: it destroyed 150,000 buildings, 1 km of the Hanshin Expressway, 120 of the 150 quays in the port of Kobe, and fires which raged over large portions of the city (City of Kobe, 2012)), the port was the world's sixth largest container port in terms of cargo throughput; in 1997 after the repairs had been completed, the port was ranked seventeenth (Chang and Nojima, 2001). Recovery process is complex and it is influenced by many variables, time dimensions and spatial dimension. Moreover, viewing disaster resilience and recovery process as a deliberate process

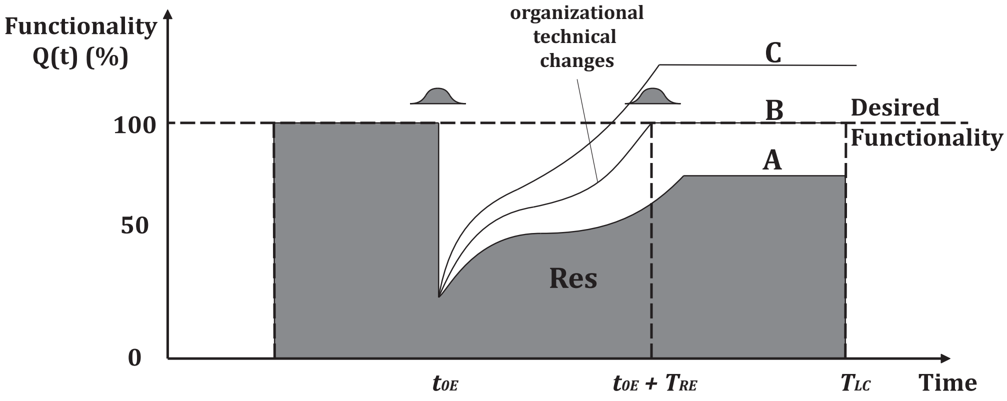
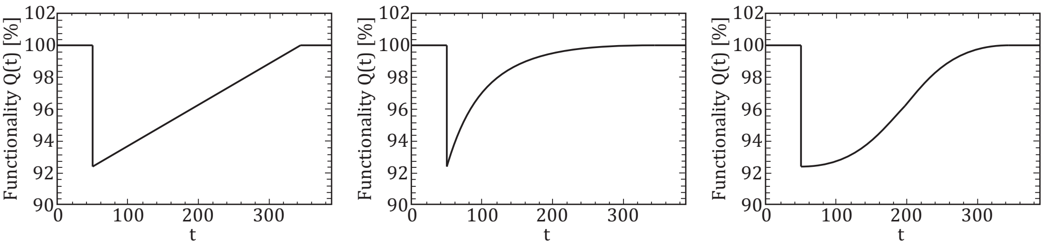


Figure 18: The influence of resourcefulness on resilience (Cimellaro et al., 2010)

that comprises a series of event, actions or changes to enhance the capacity of affected structure or system, but also community, when faced to singular, multiple or unique shocks and stresses,places emphasis on the human role. In summary, the recovery phase and time show disparities among different geographic areas in the same community or state, showing different rates and quality of recovery.This observation highlights how complex is to model recovery of single critical facility or critical systems. Different type of recovery function can be selected depending on the system and society preparedness response, for example three possible recovery functions are: linear, exponential (Kafali and Grigoriu, 2005) and trigonometric (Chang and Shinozuka, 2004).



(a) (b) (c)

Figure 19: Linear Recovery function: a) linear; b) exponential; c) trigonometric (Cimellaro et al., 2010)

$$f_{rec} = a\left(\frac{t-t_{0E}}{T_{RE}}\right) + b \qquad \text{linear} \tag{13}$$

$$f_{rec} = a\,\exp\left(-b\,\frac{t-t_{0E}}{T_{RE}}\right) \qquad \text{exponential} \tag{14}$$

$$f_{rec} = \frac{a}{2}\left\{1+\cos\left[\frac{\pi b\,(t-t_{0E})}{T_{RE}}\right]\right\} \qquad \text{trigonometric} \tag{15}$$

The simplest form is the linear one that is generally used when there is not information regarding preparedness and resources available (Figure 19(a)). The exponential recovery function could be used when the responce is driven by an initial inflow of resource, but the rapidity decreas as the process reachs the end(Figure 19(b)). The last one is the trigonomatric that is used when the recovery responce is driven by lack or limited resources (Figure 19(c)).

5 Structural fragility curves and resilience

The prediction of structural damage is critical for the evaluation of economic losses and should be carefully estimated specially for critical structures. A possible and useful representation to describe structural damage distribution is given by fragility curves. Fragility curves provide graphic information on the distribution of damage by representing the cumulative distribution of damage, which specifies the continuous probability that an indicated damage level has been reached or exceeded. Fragility curves were introduced in the framework of earthquake engineering and they can be empirical or analytical, based on the source of the and type of analysis.

Empirical fragility curves are based on test or field data interpretation and engineering judgment. They are usually based on damage data reported from past events, for example Shinozuka et al. (2000b) present empirical fragility curves from bridge damage observed in the 1995 Kobe earthquake.

Analytical fragility curves are developed from structural response data obtained through analysis of structures using simulated input data for exceptional event considered, for example ground motion for earthquake problems as Shinozuka et al. (2000a) did, exploiting non linear analysis.

Theoretically, fragility curves represent the probability that the response R of a structure exceeds a given threshold r_{lim} given a certain excitation level. It can be represented as proposed in Equation 16, as follow (Barron-Corvera, 2000; Reinhorn et al., 2001):

$$Fragility = F_Y = P\left\{R \geq r_{lim} \mid I\right\} \tag{16}$$

where R is the response parameter (deformation, displacement, force, velocity,

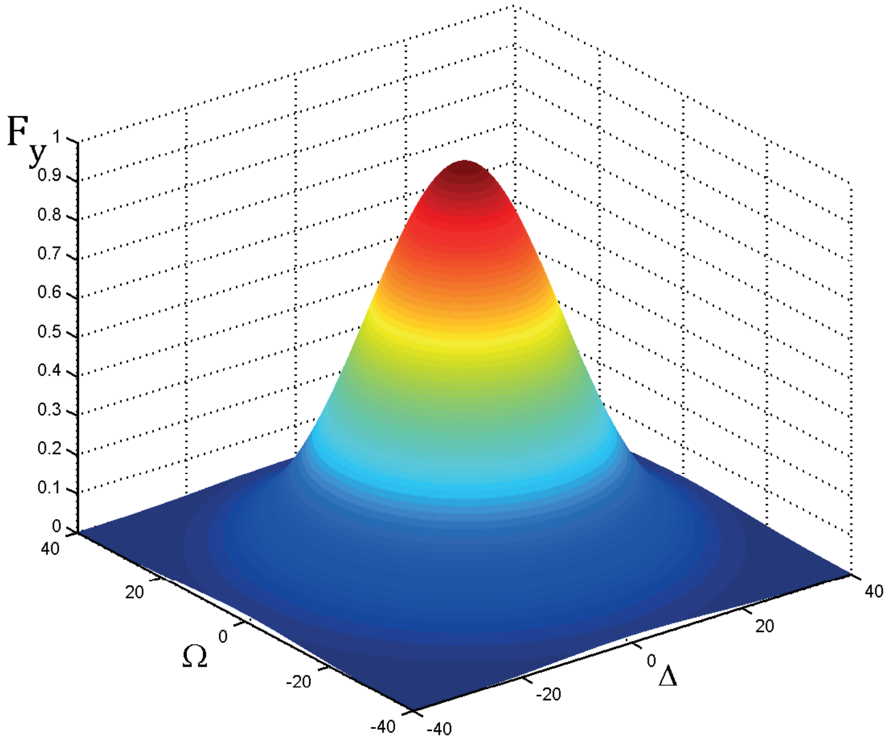


Figure 20: S.O.M.B.R.E.R.O representation of a simple bell curve

acceleration, etc.); r_{lim} is the response threshold parameter that is linked with the damage and I is the intensity of the event. This definition can be extended to the N-dimensional space when the number of parameters to be checked is N, by applying the following equation (Cimellaro et al., 2006):

$$\begin{aligned} Fragility &= F_Y = P\left\{R_1 \geq r_{lim\,1} \cup R_2 \geq r_{lim\,2} \ldots \cup R_N \geq r_{lim\,N} \mid I\right\} \\ &= P\left\{\bigcup_{i=1}^{n} R_i \geq r_{lim,\,i} \mid I\right\} \end{aligned} \tag{17}$$

where R_i is the response parameter related to a certain quantity (force, displacement, acceleration, etc.) and $r_{lim,\,i}$ is the corresponding threshold parameter correlated to damage. For example in a two dimensional case considering Δ and Ω as control parameters the fragility can be written as follow:

$$Fragility = F_Y = P\left\{\Delta \geq D_{lim} \cup \Omega \geq O_{lim} \mid I\right\} \tag{18}$$

In this case the probability distribution can be represented like a surface (i.e, 3-D "bell curve" see Figure 20) as proposed by Bruneau and Reinhorn (2007) to achieve quantification of engineering seismic resilience through the concept of Sliding an

Overlaid Multidimensional Bell-curve of Response for Engineering Resilience Operationalization (S.O.M.B.R.E.R.O) using an Orthogonal Limit-space Environment (OLE). The surface can be expressed by iso-probability contours in the OLE space as shown in Figure 21. SOMBRERO representation coupled with limit states thresholds can give useful information regarding damage state and the probability that the response exceeds a specific limit. In Figure 22 the bell surface and a plane representing a mono-parametric limit state is reported, the limit state governed by one parameter is represented by a line into the OLE plane. The probability to exceed a specific limit state can be directly calculated from the volume under the surface distribution exceeding the threshold. In figure 22 a mono-parametric limit has been introduced for simplicity, however the response of the structure can be analyzed considering one or more mono-parametric limit states and/or generalized multidimensional performance limit states, as illustrated in Figure 23. The gray area in Figure 23 represents the one where limit states have been exceeded and it is used to compute the corresponding probability.

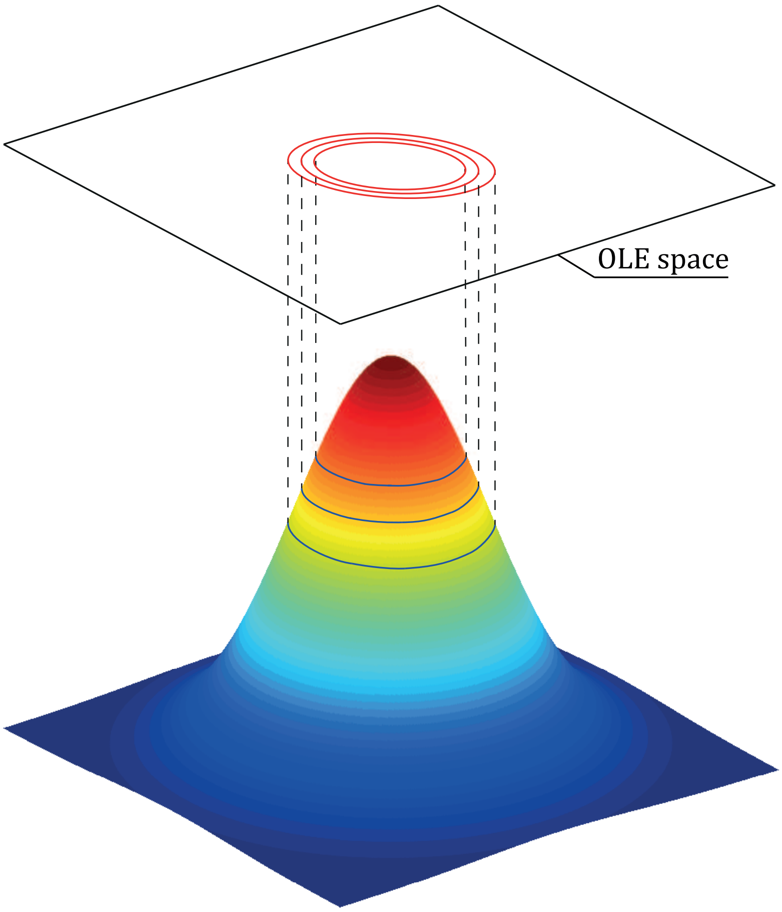


Figure 21: Iso-probability contours in OLE space

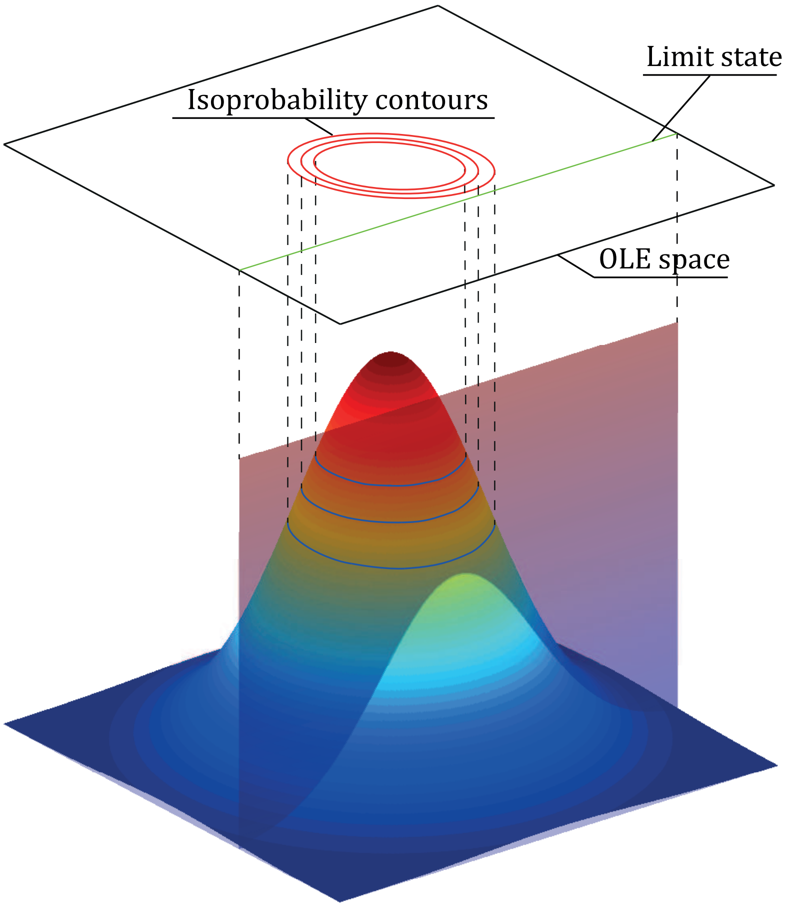


Figure 22: Bell surface, iso-probability contours and limit state in OLE space

Generalized formulation for multidimensional performance limit states have been proposed by Cimellaro et al. (2006) and it can be expressed as follows:

$$L\left(R_1, \ldots R_n\right) = \left(\frac{R_1}{r_{lim\,1}}\right)^{N_1} + \left(\frac{R_2}{r_{lim\,2}}\right)^{N_2} + \ldots + \left(\frac{R_n}{r_{lim\,n}}\right)^{N_n} - 1 = 0 \quad (19)$$

Equation 19 can be written in a more compact form:

$$L\left(R_1, \ldots R_n\right) = \sum_{i=1}^{n} \left(\frac{R_i}{r_{lim\,i}}\right)^{N_i} - 1 \quad (20)$$

where R_i is the response parameter (displacement, energy, force, acceleration, etc.); r_i is the response threshold parameter which correlated with the structural or non-structural damage and N_i is the interaction factor determining the shape of n-dimensional surface. The response threshold parameters used to define the limit states, reported for simplicity over only two response parameters in Figure

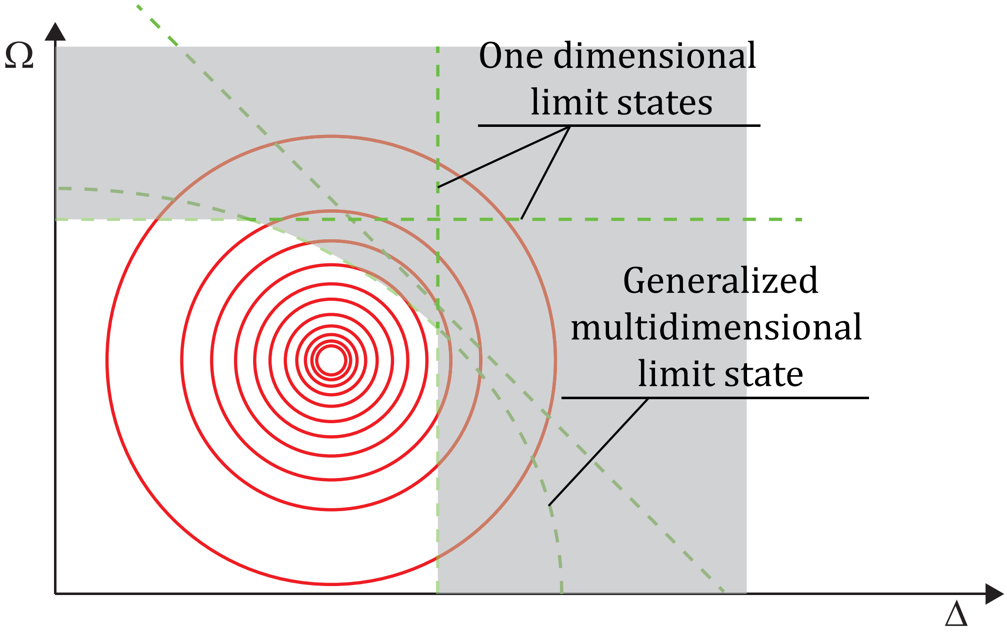


Figure 23: Multidimensional Limit states and generalized form in the OLE space

23, are deterministic, however they could be also considered as random variables. The probability of exceedance for a two dimensional limit state can be expressed as follow (Cimellaro et al., 2006; Bruneau and Reinhorn, 2007):

$$F_Y = P_{LS} = \lim_{N_{TE}\to\infty}\left\{\frac{N_R\left[\left(\frac{R_1}{r_{lim\,1}}\right)^{N_1}+\left(\frac{R_2}{r_{lim\,2}}\right)^{N_2}\geq 1\right]}{N_{TE}}\right\} \tag{21}$$

where N_R is the number of responses that exceeds the performance limit state while N_{TE} is the total number of responses. In order to reduce the probability of exceedance it is possible to design ad hoc retrofitting strategies that lead to a change in the probable structural response, which is equivalent to sliding the multidimensional bell curve within the OLE space, as schematically shown in Figure 24. On the other hand, severe events like impact or blast or effects acting during a long period like alkali-silica reaction or steel rebar corrosion can move the bell surface into the gray area in the OLE space leading to an increase of the probability of exceedance.

By applying the concepts introduced above it is possible to build proper fragility curves for the structure or infrastructure considered. Focusing the attention to the fragility curves, the influence of exceptional loading events, resourcefulness and retrofitting can be better understood considering Figures 25, 26, 27 and 28. In Figure 25(a) the functionality over time is reported, the structure results undamaged up to t_0 when an event occurs; till that time the fragility curve is represented by the blue line in Figure 25(b). Due to the exceptional event of intensity I_1 the

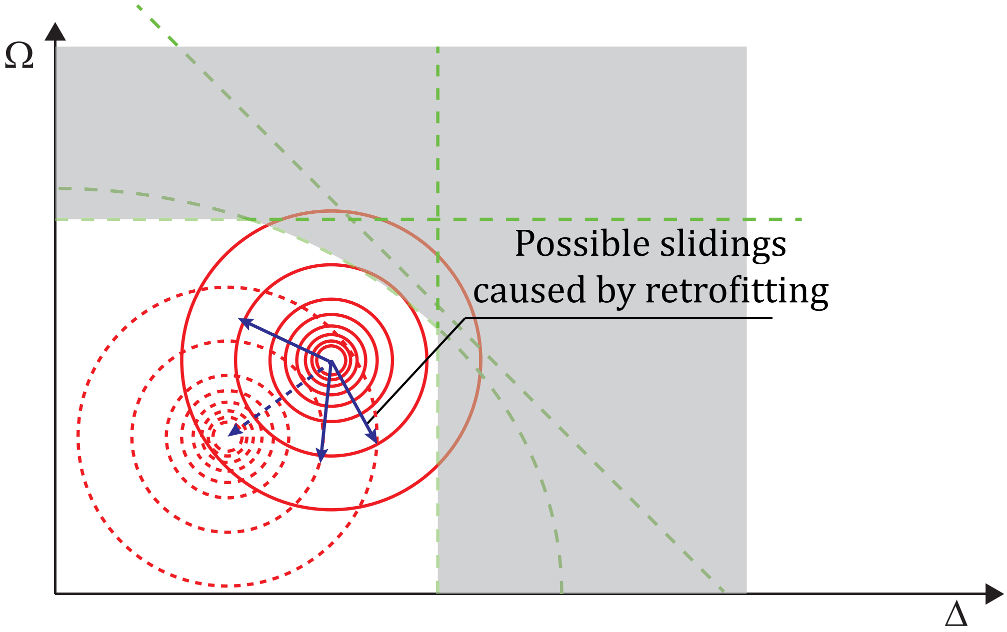


Figure 24: Effects of retrofitting on bell curve in the OLE space

structure has been damaged and the fragility curve moves up (red line in Figure 25(b)), hence if an event with intensity I_1 occurs, the probability of exceeding the limit state considered is higher than the one observed for the undamaged structure. Focusing attention on the recovery phase and considering different instants

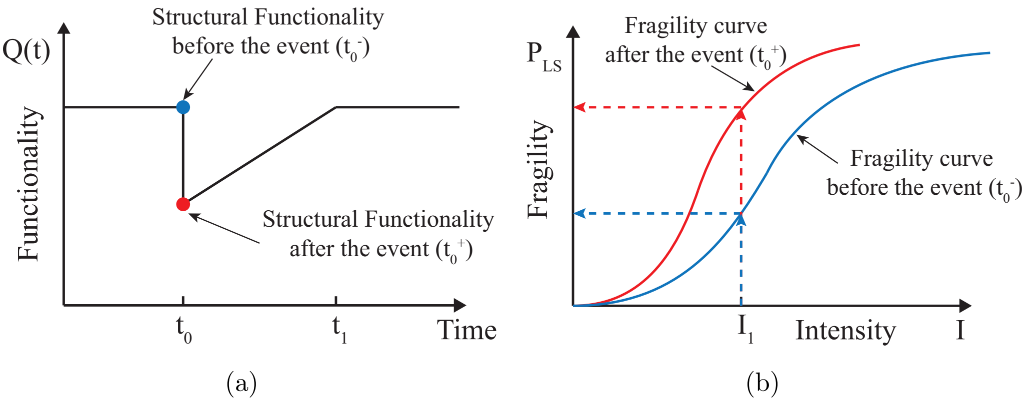
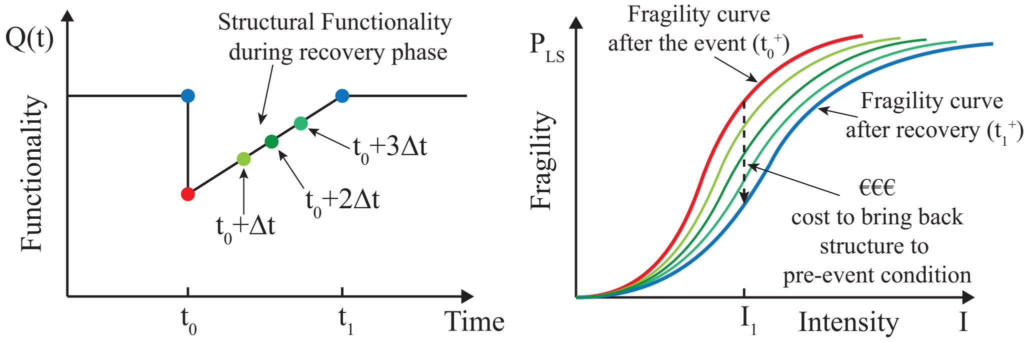


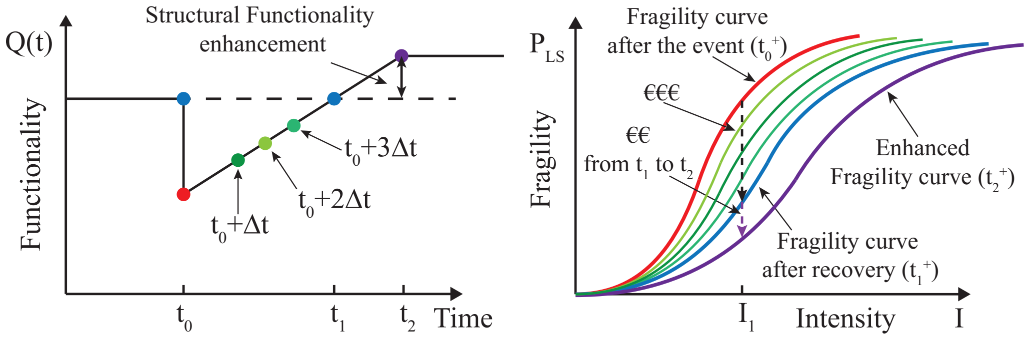
Figure 25: Effects of an event with intensity I_1 on the fragility curve: a) functionality; b) fragility curves

(see Figure 26(a)) between t_0 and t_1 (time marking the end of recovery), Figure 26(b) illustrates how structural repairs progressively shift the fragility curve back to the original condition that existed before the instant t_0, and finally attained at t_1. This requires a financial investment. Moreover, as Figures 27 shows, it is possible to increase the functionality to above the pre-event condition, this leading to enhance resilience by reducing the probability of losses in a future exceptional event.



(a) (b)

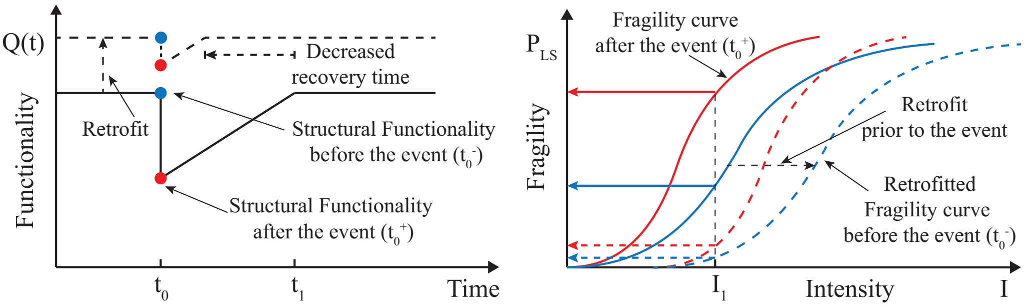
Figure 26: Effects of resourcefulness and recovery phase on the fragility curve: a) functionality; b) fragility curves



(a) (b)

Figure 27: Effects of structural performance enhancement after recovery phase on the fragility curve: a) functionality; b) fragility curves

The benefit of retrofitting prior to an exceptional event can be assessed and quantified using the fragility curves and resilience concepts presented in Figures 25. As proposed by Bruneau and Reinhorn (2007), it is assumed that the relativity of the fragility curves in Figure 25(b) for a given structure remain the same, and the retrofit prior to an event is equivalent to sliding fragility curves along the horizontal axis such that a greater, in terms of intensity, event is required after retrofit to produce the same probable loss of structural functionality (Figure 28(b)). Once the structure has been retrofitted, the functionality $Q(t)$ has been increased (Figure 28(a)). Furthermore, when an exceptional event with the same intensity occurs the probable loss of structural functionality due to damage should be also reduced as shown by the corresponding drop between time t_0^- and t_0^+ in Figure 28(a). The benefit due to retrofitting strategies can be underlined also considering the recovery time which can be drastically reduced leading to an increase of the structural resilience properties.



(a) (b)

Figure 28: Effects of retrofitting on the fragility curve and structural functionality: a) functionality; b) fragility curves

6 Concluding remarks

It is evident that the resilience concepts and framework summarized above are not in contrast with the Eurocode philosophy or any other performance-based design approach commonly used in North America. The resilience approach considered introduces the losses and loss recovery in time by applying loss functions in engineering and economical terms and functionality functions before, during and after an extreme event.

The resilience formulation presented introduces the effects of response, recovery and retrofit in the aftermath of a exceptional event as parameters of functionality losses, which influence physical and socioeconomic systems. The method summarized in the previous sections is quite capable to quantify resilience and it can be considered as a consistent and comprehensive approach useful to understand damage, response and recovery. In fact, resilience functions reported manage to explain quantitatively and qualitatively the time variation of damage as well as its link to response and recovery. Finally, the resilience concepts reported can be useful to help the decision makers in planning processes to efficiently improve and guide in response and recovery operations.

Certainly, there are still several important steps to be done for an effective adoption of resilience approaches in design. Define a uniform glossary, improve the link with developed risk assessment and mapping approaches and produce a harmonized guidelines for resilience management with a basic set of resilience management activities to assist authorities, lifeline operators and public are some of the key aspects to be developed. They are essential elements, necessary to adopt these ideas and thus needed to enhance the resilience of European critical infrastructures.

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