Chapter 2
Resilience-Based Design (RBD)

Abstract This chapter introduces the concepts of Resilience-Based Design (RBD) as an extension of Performance-Based Design (PBD) starting from the MCEER definition of Resilience. The four attributes of resilience are introduced: Rapidity, Robustness, Redundancy and Resoucefulness. A state of art of the different methodologies to assess resilience is provided clarifying the differences among Resilience, Vulnerability, Sustainability and Risk. Some considerations on how to communicate risk on RBD are also provided.

2.1 Resilience-Based Design in Structures

A disaster resilient community is a society that can withstand an extreme event, natural or man made, with a tolerable level of losses, and is able to take mitigation actions consistent with achieving that level of protection (Mileti 1999). In the last decade, earthquake engineers have given more attention to deformations during their analysis and to life safety, while less attention has been given to socio-economic parameters. Nowadays, attention is shifting towards the necessity to develop a damage-free structure using risk assessment tools, which should develop more robust structures against uncertainties. Shorter recovery processes are possible at the building level if the structure has little or no damage; otherwise it might take months to recover. In order to reduce the losses, the emphasis has shifted to mitigations and preventive actions before the earthquake events. One of the options for achieving more resilient structures in face of an earthquake is to provide them with advanced technologies such as self-centering capabilities with minimum residual deformations, which will allow for a faster recovery process (Christopoulos and Filiatrault 2006). Mitigation actions can reduce the vulnerability of such facilities. However, in case of insufficient mitigation actions, or in case that the events exceed expectations, damage occurs and a recovery process is necessary in order to continue to have a functional community. Seismic resilience describes the loss and loss recovery required to maintain the function of the system with minimal disruption. While mitigation may emphasize use of technologies and implementation of policies to reduce losses, resilience also considers the recovery process including the behavior of individuals and organizations in the post disaster

G.P. Cimellaro, *Urban Resilience for Emergency Response and Recovery*,
Geotechnical, Geological and Earthquake Engineering 41,
DOI 10.1007/978-3-319-30656-8_2

phase. A wealth of information is available on specific actions, policies or scenarios that can be adopted to reduce the direct and indirect economic losses due to earthquakes, but there is little information on procedures on how to quantify these actions and policies. Seismic resilience can compare losses and different pre and post event measures verifying if these strategies and actions can reduce or eliminate disruptions in presence of earthquake events.

2.2 MCEER Pioneer Definition of Unidimensional Resilience

There is a broader debate in literature on how resilience is defined. An extensive description of the state-of-the art in the definition of resilience can be found in Cimellaro et al. (2009). After a careful analysis of the literature, the authors decided to follow the definition provided by Bruneau et al. (2003) which has been clarified and extended in Cimellaro et al. (2010a). Disaster resilience, as MCEER's resilience framework defines it, is the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters, and carry out recovery activities in ways that will minimize social disruption, while also mitigating the effects of future disasters (Bruneau et al. 2003). Consequently, strength, flexibility, and the ability to cope with and overcome extreme challenges are the hallmarks of disaster-resilient communities. According to MCEER, Resilience (R) is defined as a function indicating the capability to sustain a level of functionality or performance of a given building, bridge, lifeline networks, or community, over a period defined as the control time T_{LC}. Analytically, Resilience is defined as

$$R(\mathbf{r}) = \int_{t_{OE}}^{t_{OE}+T_{LC}} Q_{TOT}(t)/T_{LC} dt \tag{2.1}$$

where $Q_{TOT}(t)$ is the global performance function of the region considered; T_{LC} is the control time of the period of interest that is usually decided by owners, or society (usually is the life cycle, life span of the system etc.); t_{0E} is the time instant when the event happens; is a vector defining the position within the selected region where the resilience index is evaluated Cimellaro et al. (2009, 2010a,b). The time T_{LC} includes the building recovery time, T_{RE} and the business interruption time that is usually smaller compared to the other one. The performance function is the combination of all functionalities related to different facilities, lifelines, etc. for the case when physical infrastructures, resources and services are considered, which will be described in the following paragraphs. In MCEER's terminology, the seismic performance of the system is measured through a unique decision variable (DV) defined as "Resilience" that combines other variables (economic losses, casualties, recovery time, etc.), which are usually employed to judge seismic performance. This

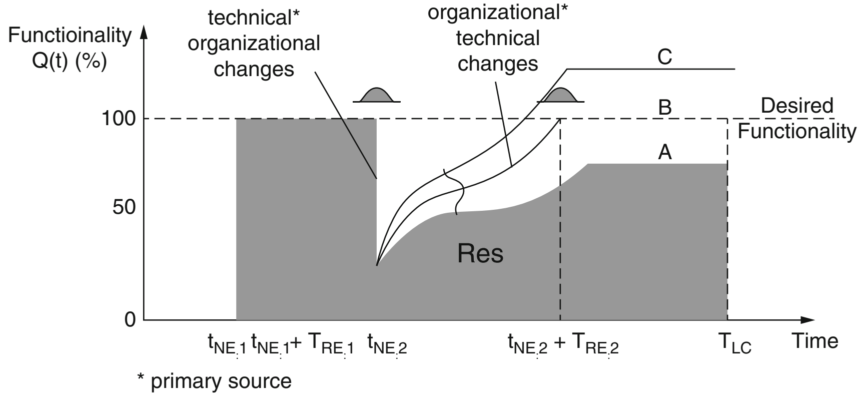

Fig. 2.1 Schematic representation of disaster resilience

Resilience is defined graphically as the normalized area underneath the performance function of a system defined as $Q(t)$. $Q(t)$ is a non-stationary stochastic process and each ensemble is a piecewise continuous function as the one shown in Fig. 2.1, where the functionality $Q(t)$ is measured as a dimensionless (percentage) function of time. For a single event, Resilience is given by the following equation (Cimellaro et al. 2005; Bruneau and Reinhorn 2007)

$$R = \int_{t_{OE}}^{t_{OE}+T_{LC}} Q\,(t)/T_{LC}dt \tag{2.2}$$

where

$$Q\,(t) = [1 - \mathrm{L}\,(\mathrm{I},\mathrm{T}_{\mathrm{RE}})]\,[H\,(\mathrm{t} - \mathrm{t}_{0\mathrm{E}}) - H\,(\mathrm{t} - \ (\mathrm{t}_{0\mathrm{E}} + T_{RE}))]f_{\mathrm{Re}\,c}\,(t, t_{0E}, T_{RE}) \tag{2.3}$$

where $L(I, T_{RE})$ is the loss function; f_{REC} $(t,t_{0E},$ $T_{RE})$ is the recovery function; $H(t_0)$ is the Heaviside step function, T_{LC} is the control time of the system, T_{RE} is the recovery time from event E and; t_{NE} is the time of occurrence of event E. The recovery time and the recovery path are two key components for evaluating resilience, so they should be estimated accurately. Unfortunately in most common loss estimation models, such as HAZUS (2014), the recovery time is evaluated in simple terms and it assumed that within one year, everything returns back to normality. In reality, it should be taken into account that the system may not always return to the pre-disaster baseline performance (Fig. 2.1). Perhaps, it may exceed the initial performance (Fig. 2.1-curve C), particularly when the system can use the opportunity to fix pre-existing problems inside the system itself, or on the other hand the system may suffer permanent losses and equilibrate below the baseline performance (Fig. 2.1-curve A). A clear example of the condition shown in Fig. 2.1-curve A is represented by Kobe earthquake that clearly demonstrates that certain kinds of long-term impacts losses do occur, at least in catastrophic disasters. In 1994, prior to the earthquake, the Port of Kobe was the world's sixth largest container port in terms of cargo throughput; in 1997, after repairs had been completed, it ranked seventeenth (Chang and Nojima 2001). In fact, performance and recovery of transportation systems often requires longer repair times than other lifeline systems and in the case of Kobe port, it appeared to play a major role in the development of long-term impacts. Transportation losses served to accentuate existing social and economic conditions of vulnerability, and they lead to permanent loss in business and therefore the port never came back to its pre-earthquake ranking. In general, the resilience index can be applied to different fields (e.g. engineering, economic, social science) and it can be used at various temporal and spatial scales. A Resilience Framework requires the combination of qualitative and quantitative data sources at various *temporal and spatial scales*, and as a consequence, information needs to be aggregated or disaggregated to match the scales of the resilience model and the scales of interest for the model output. Following sections present a description of each scale.

2.2.1 Spatial Distribution

Resilience can be considered as a dynamic quantity that changes over time and across space. It can be applied to engineering, economic, social, and institutional infrastructures, and can use various geographic scales. The first in quantifying the resilience performance index (R) is to define the *spatial scale* (e.g. building, structure, community, city, region, etc.) of the problem of interest. It is also important to mention that the entire recovery process is affected by the *spatial scale* of the disaster. Huge disasters will have longer recovery processes (Fig. 2.2). The *spatial scale* will also be used for defining the performance measures that will be considered in defining the global functionality of the system.

2.2.2 Temporal Distribution

The second step is to define the temporal scale (short term emergency response, long term reconstruction phase, midterm reconstruction phase, etc.) of the problem of interest (Fig. 2.2). The selection of the control period T_{LC} will affect the resilience performance index. Therefore when comparing different scenarios, the same control period should be considered. Figure 2.2 shows the spatial and temporal dimension of Resilience-Based design (RBD).

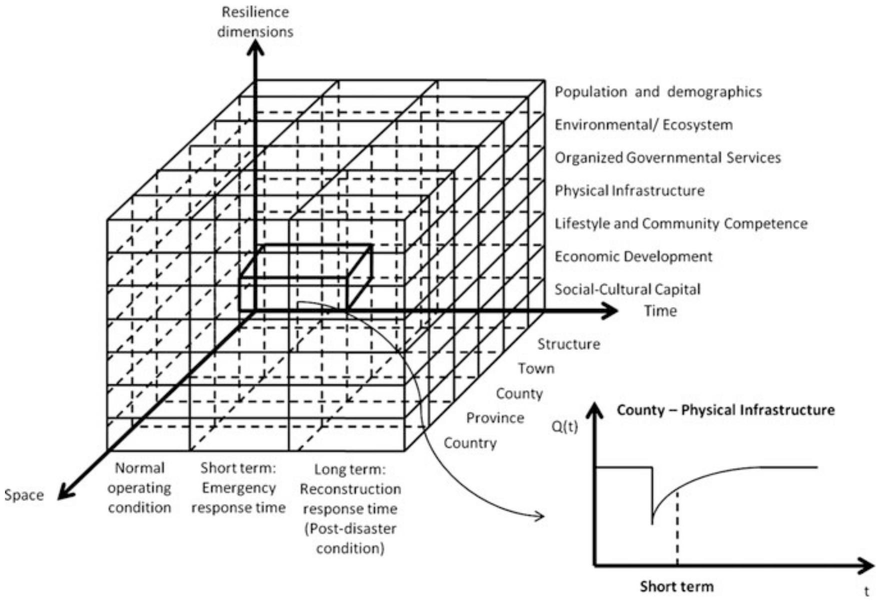

Fig. 2.2 Schematic representation of disaster resilience

2.3 The Four Rs for Resilience

While defining Resilience clearly presents a challenge, identifying the features of organizations and other social units that make them resilient is even more difficult. Resilience is an important concept for disaster management in complex systems. The objectives of enhanced Disaster Resilience are to minimize loss of life, injuries, disruption of important services, and economic losses; in short, to minimize any reduction in quality of life due to disaster. Inherent in the definition of disaster resilience are a number of characteristics that help to make it more tangible and measurable. Specifically, disaster resilience is characterized by:

- – *Reduced failure probabilities* – i.e., the reduced likelihood of damage and failures to critical infrastructure, systems and components;
- – *Reduced consequences from failures* – in terms of injuries, lives lost, damage and negative economic and social impacts; and
- – *Reduced time to recovery* – the time required to restore a specific system or set of systems to normal or pre-disaster level of functionality.

Based on these characteristics, resilience can be enhanced by reducing the likelihood of failure of critical infrastructure (thereby, reducing their impacts) and speeding up the time it takes to make a full recovery. In an effort to enhance these disaster resilience characteristics, researchers at the MCEER (Bruneau et al. 2003;

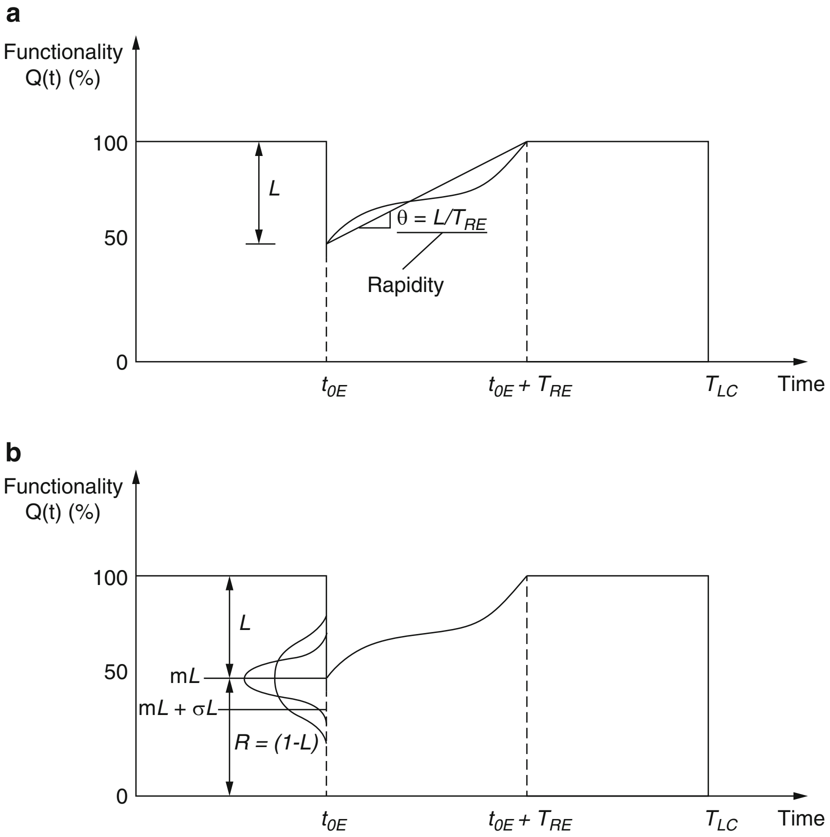

Fig. 2.3 Dimensions of resilience: rapidity (**a**) and robustness (**b**)

Bruneau and Reinhorn 2007) have identified four fundamental properties. These are *robustness*, *resourcefulness*, *redundancy*, and *rapidity*. These dimensions can better be understood by looking at the functionality curve shown in Fig. 2.3.

2.3.1 Rapidity

Rapidity is the "capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption" (Bruneau et al. 2003). According to the NIST report (2015), rapidity is defined as "the speed with which disruption can be overcome and safety, services, and financial stability restored". Mathematically, it represents the slope of the functionality curve (Fig. 2.3a) during the recovery-time and it can be expressed by the following equation

$$Rapidity = \frac{dQ(t)}{dt}; \ (t_{0E} \leq t \leq t_{0E} + T_{RE}) \tag{2.4}$$

An average estimation of rapidity can be defined by knowing the total losses and the total recovery time to regain 100 % of functionality, as follows

$$Rapidity = \frac{L}{T_{RE}} \tag{2.5}$$

where L is the loss, or drop of functionality, right after the extreme event.

2.3.2 Robustness

Robustness in the realm of to engineering systems is, "strength, or the ability of elements, systems or other units of analysis to withstand a given level of stress, or demand without suffering degradation or loss of function" (Bruneau et al. 2003). With respect to infrastructural qualities, NIST defines the robustness as "the inherent strength or resistance in a system to withstand external demands without degradation or loss of functionality". It is therefore the residual functionality right after the extreme event (Fig. 2.3b) and can be represented by the following relation

$$Robustness = 1 - \tilde{L}(m_L, \sigma_L); \tag{2.6}$$

where $\tilde{L}$ is a random variable expressed as function of the mean m_L and the standard deviation σ_L. A more explicit definition of robustness is obtained when the dispersion of the losses is expressed directly as follows

$$Robustness = 1 - \tilde{L}(m_L + a\sigma_L); \tag{2.7}$$

where a is a multiplier of the standard deviation corresponding to a specific level of losses. A possible way to decrease the uncertainty in the robustness of a system is to reduce the dispersion in the losses represented by σ_L. In this definition, robustness reliability is therefore the capacity of keeping the variability of losses within a narrow band, independently of the event itself (Fig. 2.3b). Two examples of systems with and without robustness, respectively, are the Emergency Operation Center (EOC) and the Office of Emergency Management (OEM) organization during the World Trade Center disaster in 2001 (Kendra and Wachtendorf 2003). The EOC facility, part of OEM, was not sufficiently robust to survive the September 11, attack (being located in the 23rd floor of the 7 World Trade Center). However, by the strength of its resourcefulness, OEM exhibited considerable robustness as an organization, demonstrating an ability to continue to function even after losing the WTC facility and a great part of its communications and information technology infrastructure. When the latter was restored, it contributed to the resilience of the OEM as a functional and effective organizational network.

2.3.3 Redundancy

According to the earthquake engineering field, *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” (FEMA 2000). In other words, it describes the availability of alternative resources in the recovery process of a system. In order to have a complete overview of the resilience problems, the definition of redundancy in the structural field is also referenced: “Structural redundancy refers to the multiple availabilities 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 “the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e. capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality” (Bruneau et al. 2003). Simply, it describes the availability of alternative resources in the loss or recovery process. Redundancy, as NIST defines it, is “system properties that allow for alternate options, choices, and substitutions when the system is under stress”. Redundancy is a key attribute of resilience, since it represents the capability of using alternative resources, when the principal ones are either insufficient or missing. If the system is resilient there will always be at least one scenario allowing recovery, regardless of the extreme event. If this condition is not fulfilled by the system, then changes to the system can be made, such as duplication of components to provide alternative paths in case of failure. An example of a system without redundancy is well illustrated in the World Trade Center terrorist attack mentioned above, when the EOC facility was destroyed and there was no other office that could immediately, or instantaneously, replace the main facility. Redundancy should be developed in the system in advance, and it should exist in a latent form as a set of possibilities to be enacted through the creative efforts of responders, as indicated below.

2.3.4 Resourcefulness

Resourcefulness is “the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis; resourcefulness can be further conceptualized as consisting of the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources to meet established priorities and achieve goals” (Bruneau et al. 2003). This is a property that is difficult to quantify, since it mainly depends on human skills and improvisation during the extreme event. Referring to infrastructural qualities, NIST defines resourcefulness as “the capacity

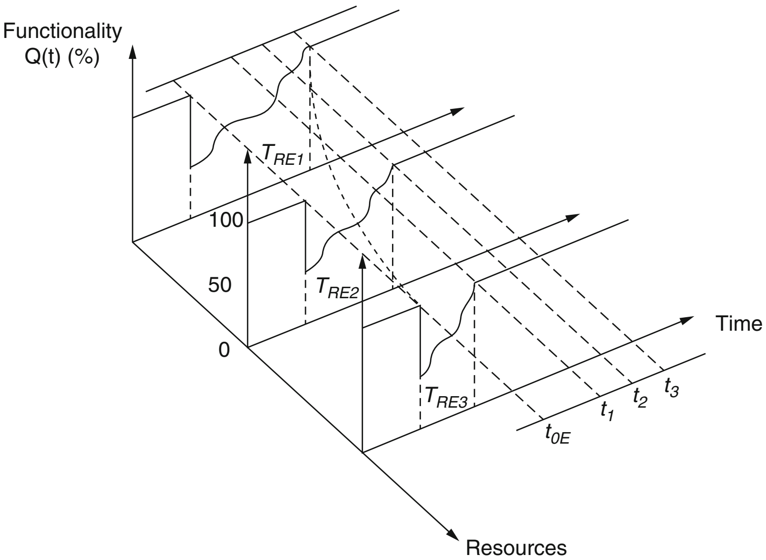

Fig. 2.4 The influence of resourcefulness on resilience (Bruneau and Reinhorn 2007)

to mobilize needed resources and services in emergencies". Resourcefulness and Redundancy are strongly interrelated. For example, resources, and resourcefulness, can create redundancies that did not exist previously. In fact, one of the major concerns with the increasingly intensive use of technology in emergency management is the tendency to over-rely on these tools, so that if technology fails, or is destroyed, the response falters. To forestall this possibility, many planners advocate Redundancy. Changes in Resourcefulness and Redundancy will affect the shape and the slope of the recovery curve and the recovery time T_{RE}. As illustrated in Fig. 2.4, 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. 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, and a reported bonus cost of over 14 million of dollars was paid to the contractor for early completion. Likewise in less advanced societies where resources are scarce, time recovery could approach infinity. However, in resourceful societies the recovery time could be also 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 benefit to both axes.

Resourcefulness also affects Rapidity and Robustness. It is through Redundancy and Resourcefulness (as means of resilience) that the Rapidity and Robustness (the ends of resilience) of an entire system can be improved.

2.4 Inherent vs. Adaptive Resilience

Inherent resilience means that the resilience analyzed is preexisting within a community or infrastructure (usually used as the baseline for measuring outcomes and change over time), while *adaptive* resilience is the ability to learn from an event and respond to changes (is a process involving social learning, but it can also have a measurable outcome). However, it is important to highlight that the disaster resilience can be considered as a dynamic process, so it may move from a pre-event inherent resilience to a post-event adaptive resilience, with both process and outcome measures (Norris et al. 2008; Rose 2007). This dynamic process feeds back into alterations in the inherent resilience of the community as suggested by the disaster resilience of place model (Cutter et al. 2008). However, at this stage the relationship between these two definitions of resilience is still at the theoretical level as the concept has not been empirically tested yet.

2.5 Resilience vs. Vulnerability

The difference between these two concepts is that resilience approach focuses on the quality of life of the people at risk and developing opportunities to generate a better outcome. In contrast, the vulnerability approach places stress on the production of nature (Smith and O'Keefe 1996) to resist the natural hazard. Engineers, guided by legislation, play a leading role in the quantification of vulnerability. Moreover, the concept of vulnerability has to be related with the definition of fragility. In order to better understand the relationship between these two concepts, it is useful to focus on the field of seismic engineering and provide two different methods of evaluating vulnerability and fragility. Given a certain control parameter (for example the shaking intensity), vulnerability (and in particular a vulnerability function) defines the loss, while fragility (more precisely a fragility function) gives the probability of some undesirable event (e.g. collapse). Thus the fragility function may assess the probability that a building will collapse as well as the probability that a factory may release hazardous materials into the atmosphere, given a certain seismic intensity. On the other hand, vulnerability functions would provide, as a function of the same control parameter, the damage factor for the building (e.g. valuated as repair cost divided by replacement cost) or the quantity of hazardous materials released. Resilience defines the capacity of a system to bounce back for a disruption. A distinction between the different terms is provided by Manyena in 2006 that also highlighted the necessity to develop a complementary "map of

Table 2.1 Difference between vulnerability and resilience (Manyena 2006)

N.	Vulnerability	Resilience
1	Resistance	Recovery
2	Force bound	Time bound
3	Safety	Bounce back
4	Mitigation	Adaptation
5	Institutional	Community – based
6	System	Network
7	Engineering	Culture
8	Risk assessment	Vulnerability
9	Outcome	Process
10	Standards	Institution

resilience and vulnerability" to create and increase the conscious role of the entire society in the restoration process. Furthermore, defining and mapping resilience has become an important tool in the decision-making process both for the engineering profession and the policy makers (Table. 2.1).

2.6 Resilience vs. Sustainability

The term sustainability appeared in the early 1970s as the rapid growth of the human race and the environmental degradation associated with increased consumption of resources raised concerns. Finding a way for consent between environment, advancement, and well-being of the world's poor was discussed in the United Nation's 1972 Stockholm Conference. "Sustainable development" was presented by Ward and Dubos (1972). The concept is not necessarily modern: (Gibson et al. 2010) imply that the concept of sustainability, as an old wisdom, has been around since the dawn of time in most communities. The definition of sustainability given by the Brundtland Commission, formally known as the World Commission on Environment and Development (WCED), was a turning point for government policy makers, scientists, politicians, sociologists, and economists. "The development that meet the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987) is a definition for sustainability that challenged the traditional ways of doing business, changed the interpretation of the word development, and helped scientists and practitioners to understand not only the environmental impacts but also the social and economic effects of projects as the human race interacts with its surroundings.

Since, Among all definitions of resilience, according to Walker and Salt (2006) resilient systems are "sustaining ecosystems and people in a changing world" the resilience is intertwined with sustainability. Sometimes resilience is considered as one the indicators of sustainability. However the correlation between these two, is more complicated. Moreover, being resilient is essential to be really sustainable and they cannot be taken into account separately. According to David Maddox, the future cities must have three inevitable characteristics. They must be **Sustainable**, **resilient** and **livable**.

It is possible to have sustainable cities which can reduce resource and energy consumption, optimize waste management and be economically efficient but not necessarily operative in case of shocks and major turbulence so that they are not resilient. Such cities are not truly sustainable. It is possible to have resilient cities that are not sustainable according to energy consumption, social equity, economical efficiency, and so on. They are not even resilient, but rather resistant, in the sense that they resist the hazardous situations. It is possible to have livable cities that are neither resilient nor sustainable. It is possible to have resilient and sustainable cities that are not livable, and so are not truly sustainable.

Although both sustainability and resilience are essential for future cities, the might work against each other in some cases.

Density is a good example. Usually dense and compact cities are considered sustainable cities, as they can reduce the energy consumption. For instance Public transportation requires a certain population density to be economically viable, but dense urban systems can make cities more vulnerable to extreme events. So, defining a limit of the for population density in a city might be the solution to have cities that are both sustainable and resilient. Resilience planning and management efforts needs to be linked with sustainability in order to move towards desired future sustainable systems.

For example, after the Superstorm Sandy hit New York City and the New Jersey coastline, there have been a lot of discussions about large technical infrastructure solutions for dealing with unexpected future storm surge and coastal flooding. One proposal was to build sea gates at the narrow section of the New York harbor entrance. However if the dam would have built, it would have caused serious economically unsustainable long-term maintenance costs with severe ecological side effects.

2.7 Resilience vs. Durability

Durability is the ability to endure for a system. A durable structure is a system which lasts longer, so less resources are required to bring back the system to the initial conditions.

In order to explain the correlation between durability and resilience let's consider two projects shown in Fig. 2.5.

Project 1 reaches the specific level of functionality in which the fundamental maintenance is required, before project 2, so it is less durable, so it will require more resources to go back to the initial conditions and it will be less resilient. On the other end project 2 is more durable, so it will require less maintenance and it will be faster to recover when an extreme event occurs. So this dimension has a positive effect on resilience.

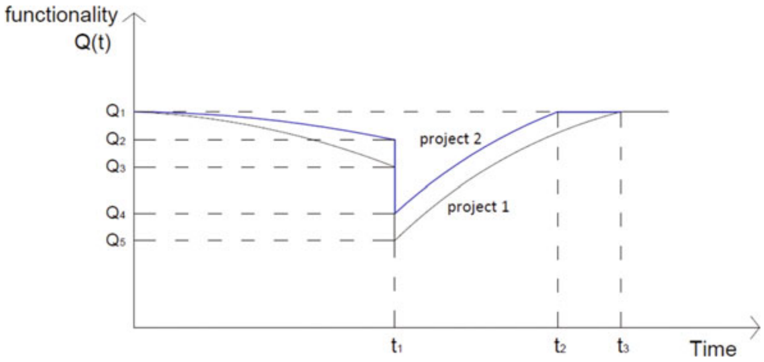

Fig. 2.5 Durability vs. resilience

2.8 Resilience vs. Risk

Risk analysis is an important tool for informed decision making and it is typically defined in terms of the probabilities of occurrence and the associated consequences of hazardous scenarios. Risk analysis is usually divided in:

1. *Risk assessment*, which means identifying, evaluating and measuring the probability and severity of risks
2. *Risk management* which means what to do about risk;

Risk analysis can be also divided in:

1. *Qualitative risk analysis* which uses words or colors to identify and evaluate risks or presents a written description of the risk
2. *Quantitative risk analysis* **(QRA)** which calculates numerical probabilities over the possible consequences;

QRA seeks assessing numerically probabilities for the potential consequences of risk, and is often called probabilistic risk analysis or probabilistic risk assessment (PRA). The analysis often seeks to describe the consequences in numerical units such as dollars, time, or lives lost.

Resilience analysis can be used to quantify the capacity to "bounce back" from extreme events of civil engineering assets. In certain sense is complementary to *Risk analysis*, which is used to quantify the safety of civil engineering assets, but they are also dependent each other as shown in Fig. 2.6. Both approaches are important for informed decision making.

1. **Risk analysis** is used to prioritize the **mitigation strategies** when running on limited budget.
2. **Resilience analysis** is used to prioritize the **restoration strategies** when running on limited budget.

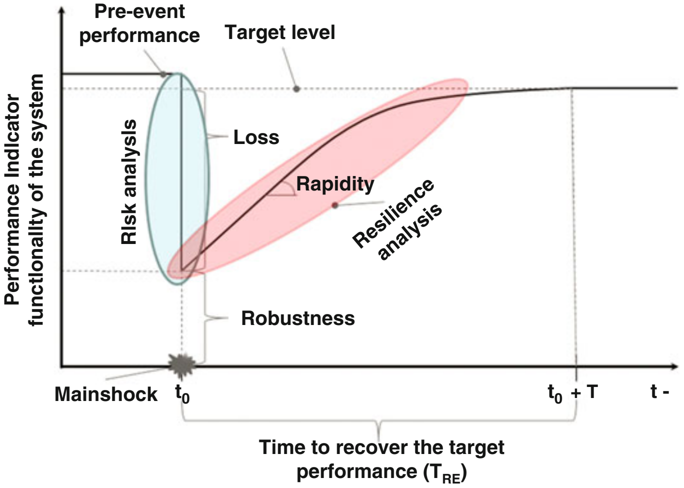

Fig. 2.6 Risk analysis vs. Resilience analysis

2.9 The Risk Management of Complex Infrastructural Systems

The first real problem to accomplish the administration of an articulated system is establishing the degree of risk exposure, and finding a method to numerically evaluate its percentage. Once this is done, the second step is to establish a procedure to lower the risks. The first method proposed in literature is a probabilistic methodology which has many inherent problems. A critical infrastructure is defined as a system including all elements necessary to provide sustainable services within the nation’s power, transportation, waste management, water, telecommunication sectors, etc. Traditional risk assessment tools do not explicitly capture the influence of unpredictable factors on the system performance. Moreover, a significant of recent high consequence failures can be attributed directly to number cognitive uncertainties, at both the individual and organizational level (Watkins and Bazerman 2003). This means that neither civilians nor decision making administration know exactly how to behave in front of catastrophic events, also due to the fact that the models in their possession are not accurate enough to represent accurately the reality. The models’ uncertainty includes both *unknown-knowable* (information exists, but it is not possible to properly utilize it; often rejected or not believed) and *unknown-unknowable* (information or knowledge does not exist). The first requirement is to evaluate how reliable the model is. This is possible through three different parameters:

1. **Face validity**: the degree to which a method appears to be appropriate for doing what it intends to do. It is based on justifications provided by the state-of-art and knowledge and experience;

2. **Content validity**: addresses the degree to which the method addresses the problem (issue) it is intended to address;
3. **Construct validity**: addresses the degree to which the results of the method can be accounted for by the explanatory constructs of a sound theory. Construct validity is demonstrated when measures that are theoretically predicted to be highly interrelated are shown in practice to be highly interrelated.

The *Probabilistic Approach* is defined as the "mathematical framework aimed at enhancing our understanding of the future", and it is considered to be a good method to prevent disasters and organize prevention works. The probability theory does not provide a correct and sure answer to a problem, but rather it provides the "most probable" answer identified with a certain probability to be true. Due to real world complexity, when a model is made to perform tests, a series of uncertainties should be taken into account. In the late 1990s the risk analysis community actively adopted the aleatory and epistemic taxonomy to characterize uncertainty which are briefly described in Sects. 2.9.1 and 2.9.2.

2.9.1 Aleatory Uncertainties

Many phenomena or processes of concern to engineers contain randomness which means that the expected outcomes are unpredictable. Such phenomena are characterized by field or experimental data that contain significant variability, i.e., the observed measurements are different from one observation to another. Within a range of certain values may occur more frequently than others. The variability inherent in such data or information is statistical in nature, and the realization of a specific value involves probability.

2.9.2 Epistemic Uncertainties

Epistemic uncertainty is a representation of the analyst's knowledge and ability to formulate a model that can predict the behavior of the system under consideration. As understanding is improved, perhaps as a function of research or observation, epistemic uncertainty can potentially be reduced (if not eliminated) via Bayesian updating according to the Bayes Rule. Examples of epistemic uncertainties are easy to find. They include: hurricane surge models, corroded pipeline burst models, earthquake attenuation relationships, "climate change" models etc. Epistemic uncertainties also include the strength for grades of structural steel and concrete, as well as soils under dynamic and pseudo-static loadings. In complex engineering systems it is often impossible and impractical to distinguish uncertainties in aleatory and epistemic categories, and this is why the *Amalgamatic (aka type III or mixed) uncertainty* was created. It is defined as having both aleatory and epistemic components.

2.10 Uncertainties in RBD

The RBD methodology can be used on a scenario basis (deterministic approach) or include uncertainties (probabilistic approach) when a particular level of confidence of achieving performance objective is of interest. In general, five types of random variables can be included in the probabilistic description of the resilience index. In this case, the joint probability density function is given by the following expressions

$$f_{R,T_{RE},Q,X,I}\left(r,t_{RE},q,x,i\right)=f_{R,T_{RE},Q,X,I}\left(r\,|\,t_{RE},q,x,i\right)\cdot f_{T_{RE},Q,X,I}\left(t_{RE}\,|\,q,x,i\right)\cdot f_{Q,X,I}\left(q\,|\,x,i\right)\cdot f_{X,I}\left(x\,|\,i\right)\cdot f_{I}\left(i\right) \tag{2.8}$$

The marginal probability density function (PDF) of the resilience index is given by

$$f_R\left(r\right)=\int_{t_{RE}}\int_{q}\int_{x}\int_{i} f_{R,T_{RE},Q,X,I}\left(r,t_{RE},q,x,i\right)dt_{RE}\cdot dq\cdot dx\cdot di \tag{2.9}$$

Therefore the expected value of the resilience index, which is a random variable, is given by

$$m_r=E\left\{R\right\}=\int_{-\infty}^{\infty} r\cdot f_{R,T_{RE},Q,X,I}\left(r,t_{RE},q,x,i\right)\cdot dr \tag{2.10}$$

where $I=$ intensity measures; $X=$ response measures; $Q=$ performance measures; $T_{RE}=$ recovery time measures; $R=$ resilience index; $m_r=$ mean resilience index.

2.11 Communicating Risk in RBD

Engineers need to know which measures of risk are most meaningful or relevant to decision makers, and then be able to communicate those risks, and the costs and benefits of mitigation, in concise, credible and meaningful terms. Keller and Blodgett (2006) have shown that when the problems are formulated in terms of frequencies rather than probabilities, the perceived threat of the risk is increased. The *probabilistic approach* described in Sect. 2.10 is more comprehensive and general, but the information provided to the public (e.g. decision makers, politicians, etc.) should be deterministic (scenario or event based), because it is simpler and easier to understand. In communicating risk effectively, the public has difficulty thinking in probabilistic terms (Patt and Schrag 2003). In fact, according to Kahneman and Tversky (2000), small probabilities (which are frequently associated with natural hazard events) are often underestimated. According to Samant's personal communication 2011, “By eliminating probability, which is a confusing concept for a lot of people, the [risk] becomes way more impactful for the average person”. Many authors believe the scenario approach may also impact the emotions associated with an event.

2.12 Summary and Remarks

Disaster resilience combines information from technical and organizational fields, from seismology and earthquake engineering to social science and economics. The final goal is to integrate the information from these different fields into a unique function leading to results that are unbiased by uninformed intuition or preconceived notions of risk. Resilience is defined as the capability to sustain a level of functionality or performance over a period defined as the control time; in the plane of functionality versus time, it is represented by the area underneath the function. Furthermore, resilience can be considered as a dynamic quantity that changes over time and across space. The resilience of a system can be improved through four attributes:

- *Rapidity*, which is the capacity to contain losses and avoid future disruption. It represents the slope of the functionality curve during the recovery time;
- *Robustness*, which indicates the ability of a system to withstand a given level of stress maintaining its functionality;
- *Redundancy*, which refers to alternative resources in the recovery process when the principal ones are insufficient;
- *Resourcefulness*, which accounts for the human factor and, in particular, the capability to forecast dangerous events without over-relying on technological devices.

Comparison between Resilience and Vulnerability, Sustainability, Durability and Risk are provided to clarify confusion between these different concepts which are interdependent with the resilience dimension. Either a deterministic or a probabilistic approach can be used to study this characteristic of the system; however the first one is preferred over the second one for providing information to the public because it is easier to understand.

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