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Abstract

The disruption or destruction of critical infrastructures (CIs) due to natural hazard events may have effects not only on the surrounding structures and environment, but also on the public health and safety, the economy, and the national security. Therefore, it is important for local and national governments to identify or develop efficient and strategic tools to manage and mitigate the risk and improve the resilience of these systems. The ST@STREST framework proposed in Deliverable 5.1 may represent the basis for the development of a new stress test concept that will support decision makers in the evaluation of strategies to not only reduce the risk but also to enhance the resilience of CIs against natural hazards. The time-evolution of community needs and the ability of the CIs to fulfill these needs are best represented and modelled using the concept of resilience rather than that of risk. In fact, the instantaneous loss by itself does not reveal how a community or society responds to a disaster. In this report the main aspects of a resilience-based stress test concept aimed at integrating the evolution in time of the performance of the CI in ST@STREST is introduced and discussed.

Keywords: resilience, critical infrastructures, stress test

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Table of Contents

Abstract	i
Acknowledgments	iii
Deliverable Contributors	v
Table of Contents	vii
List of Figures	ix
List of Tables	xi
1 Introduction	1
2 Modelling resilience of critical infrastructures against natural hazards ..	3
3 Resilience-based stress test for critical non-nuclear infrastructures	6
3.1 CLOSING THE LOOP	6
3.1.1 Future research and discussions	8
4 Conclusions	10
References	11

List of Figures

Fig. 2.1 Representation of the network supply and demand curves after a disastrous event (adapted from Sun et al. 2015).....	5
Fig. 3.1 Workflow of the ST@STREST methodology (Deliverable 5.1, Esposito et al., 2016).	6
Fig. 3.2 Resilience metrics defined for a gas network, from Bellagamba (2015).....	9

List of Tables

No table of figures entries found.

1 Introduction

Critical infrastructures (CIs) are societal systems characterized by a high degree of interconnections and complex performance capability. The complexity stems from different aspects such as the spatial scale, the interactions with other infrastructure systems of the same or different types, and the dynamic and non-linear interactions with the community needs for the services provided by the CIs. When CIs are affected by extreme natural events, such as earthquakes, floods, tsunamis, etc., they are more and more often unable to quickly recover their functionality, either back to the pre-disaster original state, or just to a level sufficient to satisfy the post-disaster demand. With the increasing density and interconnectedness of the communities today, the demand on and the importance of the CIs is growing; thus, the consequences of CI failure (to meet the demands) can be devastating both from the standpoint of human life endangerment and from the economic standpoint. The post-disaster performance of CIs has a high impact on the coordination and the execution of emergency actions, and at the same time it influences both the long-lasting post-disaster recovery process of the community, and the eventual post-disaster resumption of community functions.

Today, after decades of development of probabilistic risk assessment techniques, there are solid probabilistic engineering risk assessment methods and tools that provide practical estimates of instantaneous CI performance (service) loss due to direct and indirect disaster-induced damage. However, the instantaneous loss by itself does not reveal how a community served by the CIs responds to a disaster. The *time dimension* represents a key aspect: the time-evolution of community needs and the ability of the CIs to fulfill these needs (e.g. water, gas, and electricity) is best represented and modelled using the concept of resilience rather than of risk.

Conducting a stress test to assess only the risk of a civil infrastructure system, i.e. to relate the losses with the total probability of their occurrence due to one or more hazards, does not provide enough information on the ability of the CI system to function and recover after a disaster. The system, and systems of systems that form the built environment of our society, are non-linear.

The ST@STREST framework proposed in Deliverable 5.1 (Esposito et al., 2016) aims at evaluating the CI system risk from natural hazards. However, this framework was designed to also serve as a basis for the development of a new stress test concept that may support decision makers in the evaluation of strategies to not only decrease the risk exposure, but also to enhance the resilience of CIs against natural hazards.

It is clear that a new *resilience-oriented stress test methodology and framework* for civil infrastructure systems must include the recovery process and, furthermore, include models of how the systems function and deliver their service to the community, and how the community recovers its needs for such services. The ST@STREST framework was developed while keeping in mind such an extension, to make it possible to test the resilience of CIs to extreme events, i.e. to verify the capacity of CIs to anticipate, absorb and adapt to events disruptive to its function, and recover either back to its original state or another state consistent with the needs of the community during, and at the end of the post-disaster recovery process.

The extension of the proposed framework requires mainly the pursuit of two main goals:

- Identification of resilience metrics and standardized methodologies to model the resilience of CIs; and
- Understanding how stakeholders' needs depend on CIs, defining resilience-based acceptance criteria.

The term resilience has increasingly been seen in the research literature in many fields, from psychology, biology, economy, social studies, and also engineering. Definition and modelling or disaster resilience of engineered systems is the topic of an increasing amount of recent research work. Nevertheless, there is still a substantial diversity among the definitions and the modelling of resilience. In particular, there is no standardized approach that suggests how to quantify the natural disaster resilience of CIs in the context of natural hazard (Bruneau et al., 2003).

Regarding the identification of resilience-based acceptance criteria, understanding how the different stakeholders' needs depend on the functionality of the CIs represents the key issue. Business activities need suitable facilities and their supply chains and delivery networks; everyone needs a transportation network, electricity, water, gas, and communication networks but, in the aftermath of a disastrous event, some of these services (e.g. water) are more needed than others. There are also different, and competing priorities for services to critical facilities (e.g. hospitals). Reconciling these factors to develop CI resilience acceptance criteria, taking into account not only the instantaneous losses but also the time evolution of the CIs and the community systems during the recovery process, is not trivial.

In this report these aspects will be argued in more details. An overview of a possible approach to integrate the evolution of the CI performance in time in the ST@STREST framework is introduced and discussed.

2 Modelling resilience of critical infrastructures against natural hazards

The probabilistic resilience assessment of CIs is gaining increasing importance in a research effort toward assessing the risk and resilience of communities to natural hazards because the CIs are essential to the functioning of a community.

Several definitions of resilience have been offered in various disciplines. Many of them are similar and they overlap with existing concepts as robustness, flexibility, agility, etc. The concept of resilience has been also approached across application domains, including psychology, ecology, enterprises, and engineering, among others. In the engineering domain, in particular in the subdomain of infrastructure systems, the National Infrastructure Advisory Council (NIAC, 2009) defined the resilience of infrastructure systems as “the ability to predict, absorb, adapt and/or quickly recover from a disruptive event such as natural disasters”. Infrastructure systems are also considered as subdomain of social science, in which lack of CI resilience can lead to huge consequences on communities.

In the civil infrastructure domain, in a field-defining paper, Bruneau et al. (2003) conceptualized the resilience as a metric that “can be understood as the ability of the system to reduce the chances of a shock, to absorb a shock if it occurs, and to recover quickly after a shock”. The authors defined four dimensions of resilience in the well-known resilience triangle model: 1) robustness, the strength of the system, 2) rapidity, i.e. the speed at which the system could return to its original state or at an acceptable level of functionality, 3) resourcefulness, the level of capability in applying material and human resources to respond to a disruptive event, and 4) redundancy, the extent to which carries by a system to minimize the likelihood and the impact of disruption.

Bruneau et al. (2003) proposed a deterministic static metric of the resilience loss of a community with respect to a specific event, as the expected degradation in quality (probability of failure), over time (that is, time to recovery), R , formulated in the following equation.

$$R = \int_{t_0}^{t_1} [100 - Q(t)] dt \quad (2.1)$$

where $Q(T)$ represents the quality of the system, t_0 the time when the specific damaging event occurs and t_1 is the time when the restoration of the system is completed (indicated by a quality of 100%). The notion of system quality was left open to interpretation, but is often understood as the ability of the system to perform, which, in the case of CIs, may mean the quantity of delivered service.

Following the Bruneau et al. (2003) pioneering study, considerable attention has been focused towards developing frameworks to assess the resilience of civil facilities or infrastructures; among these, notable works are: Chang and Shinouzuka (2004), Franchin and Cavalieri (2015), Bocchini et al. (2014), Francis and Bekera, (2014), Broccardo et al. (2015), Iervolino and Giorgio (2015), Sun et al. (2015).

Among them, the most innovative are Francis and Bekera, (2014) and Broccardo et al. (2015).

Francis and Bekera (2014) proposed a resilience factor as quantitative metric of an infrastructure system's resilience. This factor depends on a speed recovery factor, the original stable system performance level (pre-disaster performance of the system), the performance level immediately post-disruption (before recovery starts), and the performance at a new stable state level (after recovery efforts have been exhausted). The speed recovery factor is defined as a function of the time that is acceptable to elapse after a disaster before recovery starts, the time to complete initial recovery actions and the time to final recovery.

Broccardo et al. (2015) investigated all the statistical assumptions and limitations to integrate the quantification of seismic resilience of a given civil facility or system in a stochastic Markovian framework. In particular, the study revisited the PEER framework formula by imposing the resilience of a facility as a final decision variable, analyzing then the limitations and the range of applicability evaluating the probability of interaction between the recovery time and the inter-arrival time of seismic events.

However, despite the increasing importance of the role of system resilience in various disciplines of system engineering, and the recent efforts by many authors, there is a substantial diversity among the definitions and the modelling of resilience (Hosseini et al., 2016, Henry and Ramirez-Marquez, 2012, , Ouyang and Duenas-Osorio 2012, Bruneau et al., 2003).

As also reported by Bruneau et al. (2003) "there is no explicit set of procedures that suggests how to quantify resilience in the context of earthquake hazard, how to compare communities with one another in terms of resilience, or how to determine whether individual communities are moving in the direction of becoming more resilient in the face of earthquake hazards."

Communities and infrastructure systems are complex systems of systems. Modelling their resilience against natural hazards in a probabilistic way and with a single metric is not quite straightforward. Further, most of the resilience quantification frameworks proposed in literature impose the point of view of the infrastructure owner, i.e. to recover the initial functionality of the system as fast as possible. However, CIs are built to deliver a service to a community, then the resilience assessment should also take into account the ability of a CI to supply the time-varying community demand for the services provided by the assessed CI (Mieler et al., 2015). A CI resilience quantification framework needs to explicitly account for the evolution of the supply (i.e. the service supply capacity of the system) and for the evolution of the demand of the community and other CIs for its services in the aftermath of a disaster (Dider et al., 2015; Sun et al. 2015a, 2015b; Didier et al., *in prep*).

To this aim, Didier et al. (2015) and Sun et al. (2015a, 2015b) proposed a compositional demand/supply resilience quantification framework adapting the Bruneau et al. (2003) definition to compare the post-earthquake evolution of the supply provided by a CI (an electric power network in these cases) and the demand generated by the customers in the community. Given this definition, the resilience becomes dependent not only on the performance and ability of the CI to recover but also on the ability of the community to recover the demand, as also shown in Fig. 2.1. More recently, Didier et al. (*in prep*) proposed a framework to evaluate the post-disaster resilience of CIs that allows to account explicitly for the evolution of the demand of a community and the demand of other CIs during the post-disaster recovery process.

A more detailed discussion on the aforementioned frameworks can be found in Deliverable 4.5 (Stojadinovic and Esposito, 2016).

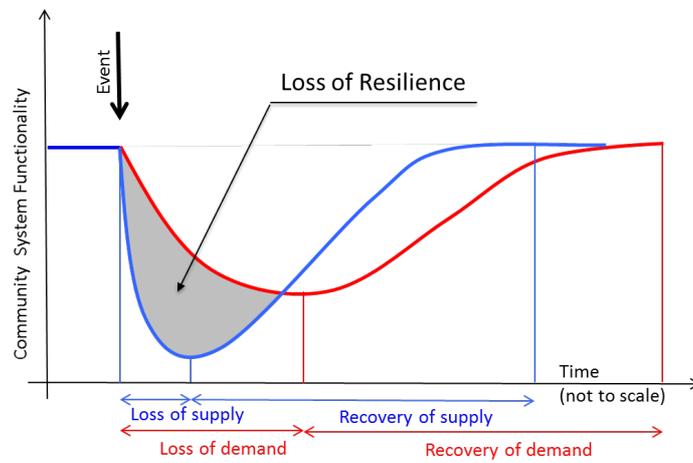


Fig. 2.1 Representation of the network supply and demand curves after a natural disaster event (adapted from Sun et al. 2015b).

3 Resilience-based stress test for critical non-nuclear infrastructures

3.1 CLOSING THE LOOP

In this section the ST@STREST framework proposed in Deliverable 5.1 (Esposito et al., 2016), and shown in Fig. 3.1, is analyzed to define a new concept of stress test aimed at testing the resilience (and not only the risk) of CIs to extreme events and comparing the probability of loss of resilience (not just the probability of instantaneous losses) to acceptable levels.

A resilience-based stress test concept may support decision makers in the evaluation of strategies to improve the capacity of CIs to anticipate, absorb and adapt and/or quickly recover from a disruptive event.

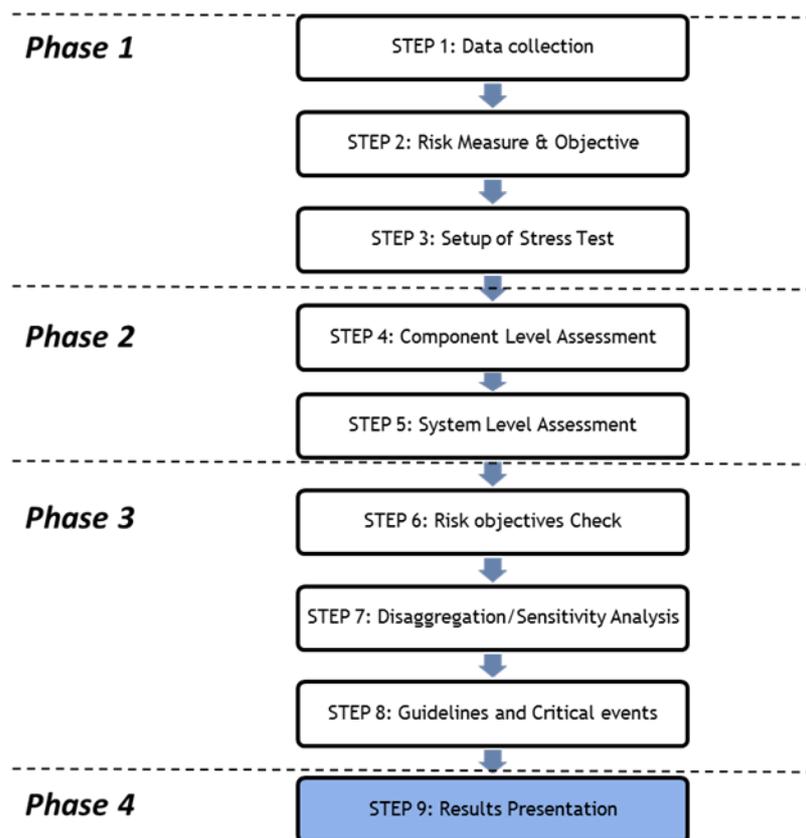


Fig. 3.1 Workflow of the ST@STREST methodology (Deliverable 5.1, Esposito et al., 2016).

The ST@STREST framework is composed of four main phases and nine steps to be conducted sequentially. In the Pre-Assessment phase (Phase 1) all the data available on the

CI and on the phenomena of interest (hazard context) are collected. Then, the goal (i.e. the risk measures and objectives), the time frame, the total costs of the stress test and the most appropriate Stress Test Level to apply to test the CI are defined. In the Assessment phase (Phase 2), the stress test is performed at Component and System Levels. The performance of each component of the CI and of the whole system is checked according to the Stress Test Level selected in Phase 1. In the Decision Phase, the stress test outcomes are determined i.e. the results of risk assessment are compared with the risk objectives defined in Phase 1. In particular, a stress test grade is assigned and the global outcome is determined by employing a grading system. Further, a penalty system is also proposed to define how reliable the results of the stress test are, and in case it is needed, to penalize simplistic approaches that cannot guarantee an accurate analysis. Then, critical events, i.e. events that most likely cause a given level of loss value are identified through a disaggregation analysis. Finally, risk mitigation strategies and guidelines are formulated based on the identified critical events. In the Reporting Phase the results are presented to CI authorities and regulators.

In order to define a new concept of stress test aimed at verifying and mitigating the resilience of CIs, some aspects of the four-phase ST@STREST workflow have to be reviewed and the scope of each phase of the methodology modified, in particular:

- Pre-Assessment phase (Phase 1)

The collection of all data available on the CI also has to include all the information required for the estimation of the resilience metrics selected for the assessment, e.g. the information on the rate of recovery, conditioned on the incurred damage state (the recovery curves, a counterpart to vulnerability curves), the funds, materials and manpower availability for the recovery and restoration process, the pre- and post-event demand patterns for the service of the investigated CI, the characterization of the community the CI serves, and the operation models of the CI in both normal and emergency conditions.

Further, resilience-based objectives/acceptance criteria have to be defined for each resilience metric and according to the specific perspective considered, i.e. the network operator and/or the community the CI serves. Here, the competing interests of the network operator (e.g. maximizing profit) and the community (e.g. minimizing disruption to the population) need to be reconciled in an aggregate acceptance criterion.

- Assessment phase (Phase 2)

In the Assessment phase, the resilience (and not only the performance) of each component of the CI (Component analysis) and the whole system (System Analysis) should be evaluated according to the ST-Level selected. One possible way to perform this task is to use the compositional demand/supply resilience quantification framework (Didier et al., *in prep*).

More efforts should be devoted to develop standardized methodologies aimed at verifying the resilience of CIs in the natural hazard context, both at component and system level (see Section 3.1.1).

- Decision Phase (Phase 3)

The results of the resilience assessment are compared with the objectives defined in the pre-assessment phase and resilience mitigation strategies and guidelines are formulated. An effort to disaggregate the resilience of a CI-Community system to find which elements and systems and which events cause the largest amount of impact.

- *Report phase (Phase 4)*

Results of the resilience analysis and mitigation strategies are presented to CI authorities, regulators and representatives of the community. An effort to communicate resilience (and its probabilistic nature), building on the ongoing work on communication or risk, should be undertaken.

3.1.1 Future research and discussions

The extension of the proposed framework requires mainly the pursuit of two main goals:

- Identification of resilience metrics and development of standardized methodologies to model the resilience of CIs; and
- Definition of resilience-based acceptance criteria, understanding how community's needs depend on critical infrastructures.

Definition and modelling of disaster resilience of engineered systems is the topic of an increasing amount of recent research. Nevertheless, there is still a substantial diversity among the definitions and the modelling of resilience. In particular, there is no standardized approach that suggests how to quantify the natural disaster resilience of CIs in the context of natural hazard. As future research, we foresee the need of defining a taxonomy of resilience metrics mainly based on the following aspects:

- The identification of quantifiable time-dependent system delivery functions that specify the system functionality of the infrastructure system under study, such as the flow, the connectivity, the time delay, etc.
- The modelling of interdependencies between networks within a community.
- Including the social perspective in the definition of resilience metrics accounting for time-varying community demand for the services provided by the assessed CI.

The definition of resilience metrics requires a deep understanding of the CI's functionality and the parameters that are important for both the operator and the society the CI serves.

An example of possible resilience metrics for a gas distribution network (Bellagamba, 2015) is provided in Fig. 3.2. In this case, the system functionality is expressed in terms of daily gas flow. The resilience metrics are identified comparing the required system functionality by the community (demand, red line) to the effective capacity of the network after an earthquake (blue line), in particular:

- The non-supplied demand $S_{Nonsupplied}$, defined as the area between the capacity and the demand curves when the demand curve is above the capacity curve.
- The recovery time of the gas distribution network $T_{Recovery}$, defined as the time needed for the gas distribution network to recover its full functionality.
- The time needed for the capacity to be equal or greater than the demand, called resilience time, $T_{Resilience}$.

Further, according to the different possible metrics, standardized approaches aimed at modelling the resilience of non-nuclear CIs should be identified and/or developed. This implies, first a review of the existing approaches in the field of quantitative risk analysis and a classification based on, for example, the use of analytic or simulation-based approaches for the quantification of the aleatory uncertainties, the inclusion of inter-dependencies with other infrastructure systems and the interaction with the community the CI serves, etc.

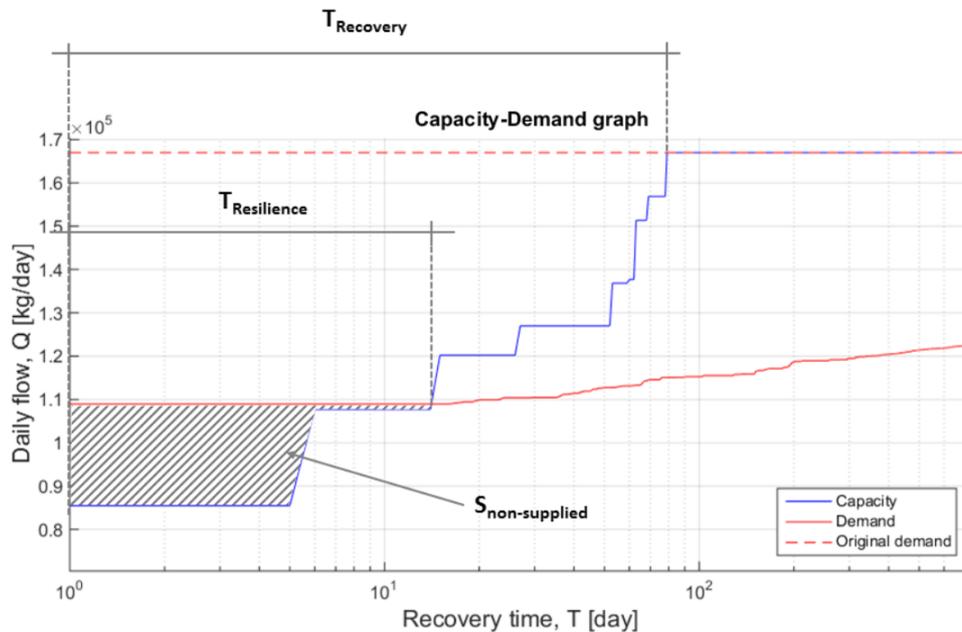


Fig. 3.2 Resilience metrics defined for a gas network, from Bellagamba (2015).

Another important aspect for the development of a resilience-based stress test concept is represented by the definition of acceptance resilience-based criteria to be identified in the Phase 1 of the workflow. The key question to be answered is:

- When and how do the CI systems need to be restored before adversely affecting the different stakeholders, (e.g. community, the infrastructure operator)?

Understanding how community's needs depend on the functionality of the CIs (now and in the future) is the key. Business activities need suitable facilities and their supply chains and delivery networks; everyone needs a transportation network, electricity, water, gas, and communication networks but, in the aftermath of a disastrous event, some of these services (e.g. water) are more needed than others.

A first attempt toward this direction is represented by the report published in April 2015 by the National Institute of Standards and Technology (NIST, 2015): "Community Resilience Planning Guide for Buildings and Infrastructure Systems". The Guide provides a methodology for a local government, as the logical convener, to bring together the relevant stakeholders and incorporate resilience into the long-term community development planning processes. In particular, it identifies the ways social organizations depend on buildings and infrastructure systems to help support community recovery by establishing recovery sequencing and the degree of functionality needed in the built environment at different points in time after a hazardous event. The guide also provides examples of resilience goals that communities might set for their social institutions.

4 Conclusions

Conducting a stress test to assess only the risk of a civil infrastructure system does not provide enough information on the ability of this system to function and recover after a disaster. The system, and systems of systems that form the built environment of our society, are non-linear. Thus, the response of such systems to a shock (an impulse triggering loss of functionality due to instantaneous vulnerability) cannot be investigated by simply summing up the response to individual components in much the same way that unit pulse response functions cannot be used to evaluate the response of a non-linear dynamic system.

It is now clear that stress tests on civil infrastructure systems must include the recovery process and, furthermore, include models of how the systems function and deliver their services to the community, and how the community recovers its needs for such services. Tracking the evolving balance of such supply and demand is key to modelling and engineering resilience. The ST@STREST framework proposed in Deliverable 5.1 may represent the basis for the development of a new resilience-based stress test concept that will support the decision makers in the evaluation of strategies to not only reduce the risk but to also improve the resilience of CIs and the community they serve against natural hazards. To this aim, the main aspects to be analyzed to integrate the evolution in time of the performance of the CI in the ST@STREST framework were introduced and discussed in this report.

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