

Estimation of Seismic Resilience of Road Infrastructures: An Integrated Approach



A. Del Grosso, M. Cademartori, S. Osmani, and D. Pastorelli

Abstract The asset management of road infrastructures in zones prone to seismic hazard requires the estimation of the seismic resilience of the network. This involves implications of both structural and transport engineering methods in order to correlate the possible damage of a given structure to the consequence on the entire network. The paper aims at developing a simplified, but still reliable method, for the estimation of the seismic resilience of a road network considering different structures and including a transport module. First, the seismic vulnerability of the structures is defined by means of fragility curves developed with different methods depending on the level of knowledge of the structures. Second, the consequence of the structural damage on the road capacity has been estimated. The different scenarios of road capacity after the seismic event are then included in the traffic module in order to estimate the post earthquake response of the road network.

Keywords Seismic vulnerability · Seismic resilience · Road infrastructures

1 Introduction

Nowadays, the resilience concept of a network has become primary in the infrastructure management environment, to evaluate losses suffered by the community.

This paper aims at connecting the structural and seismic fields to transport engineering as these disciplines are strongly correlated within the management of a road network.

This approach has been developed within the FORESEE Project [1] in order to link structural and transport engineering parameters.

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In road networks, bridges and tunnels are vulnerable elements when a disruptive event occurs. A key element for road managers is the best allocation of budgets in order to improve network resilience through corrective actions.

The main objective of this study is to define an integrated and practical procedure, able to link seismic vulnerability of bridges and tunnels within the network, to the overall system behavior in terms of transport parameters for different hazard scenarios.

The resilience assessment requires the evaluation of the difference between the Level of Service provided by the network in a baseline scenario (i.e., in the absence of seismic events) and the same in case of hazard scenarios. Moreover, it requires knowledge about service restoration time and service restoration path.

In order to define losses and resilience of a network, several steps are necessary:

- Definition of suitable methodologies for seismic fragility and vulnerability analysis and risk evaluation about assets located in the network
- Multiple traffic analysis, in order to link structural characteristics to transport quantities
- Traffic analysis outputs interpretation in order to evaluate Resilience Key Performance Indicators.

2 Fragility and Vulnerability Analysis

The Fragility and Vulnerability Analysis tool, which is under development as part of FORESEE project [1], is the starting step for the Infrastructures resilience assessment: it contains the main inputs of the entire process and the knowledge level affects the analysis detail level.

Whatever the knowledge level is, full or simplified knowledge, it is important to describe the Transport System, including assets and components.

The fragility and vulnerability of an asset against a specific hazard requires the knowledge about the hazard characteristics and the asset's structural capacity.

In the following, a description of the main analyses carried out is shown.

2.1 Fragility Analysis

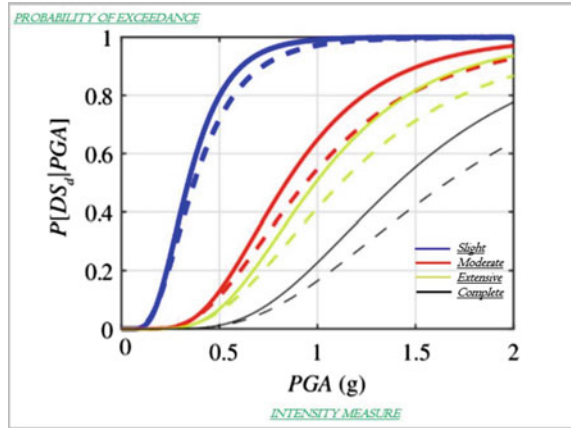
The fragility of an asset is defined through fragility functions.

A fragility function is a curve as a log-normal cumulative probability distribution that defines the probability of exceedance of a certain limit state or level of damage, for a given or a smaller hazard intensity measure (IM) (Fig. 1).

The fragility functions can be derived from several kinds of analysis:

- Literature or databases sources;
- Simplified Displacement-Based Assessment [2, 3];

Fig. 1 Example of seismic fragility curves for a given asset



- Non-Linear Static Analysis [4];
- Non-Linear Dynamic Analysis or Incremental Dynamic Analysis (IDA);

The literature method consists of a collection of fragility curves based on the study of different authors and guidelines. The user will select the most applicable fragility curve set for the different bridges or tunnels within a road segment. This method is applicable for a first step analysis in case of a large portfolio of structures and when the level of knowledge does not permit a more refined method. For this method, fragility functions parameters from different approaches have been implemented (e.g. Hazus method [5], fragility functions parameters contained in the Syner-G Project [6]).

The simplified Displacement Based Assessment and the Non-linear static method are approaches useful when an accurate level of knowledge is achieved and when the structures, in particular bridges can be included in regular typologies.

The IDA method is the most accurate, it requires a significant computational effort and a high level of knowledge of the structures. This method is applicable for specific and strategic structures of high importance.

2.2 Vulnerability Analysis

Once the fragility functions are selected, the vulnerability analysis should be performed, in order to evaluate the operativity losses for different levels of damage in the assets.

The first step of the procedure is the definition of the percentage of operativity loss for different limit states. This is achieved through discretized or detailed restoration functions, which are the tool able to provide the operativity loss for a limit state occurred in an asset, related to the elapsed time after a disruptive event.

An example of discretized restoration function for the bridge, from Hazus method [5], is shown in Table 1.

Table 1 Discretized restoration functions for bridges

Restoration period	Functional percentage for damage levels			
	Slight	Moderate	Extensive	Complete
1 day	70	30	2	0
3 days	100	60	5	2
7 days	100	95	6	2
30 days	100	100	15	4
90 days	100	100	65	10

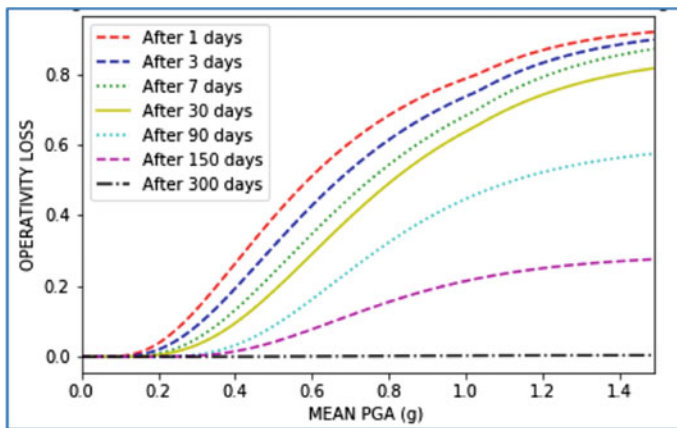


Fig. 2 Example of seismic vulnerability curves for a given asset

Thus, it is possible to have a knowledge of the recovery time for the assets.

Combining fragility and restoration functions, it is possible to obtain a set of curves able to link the values of intensity measure to the respective expected operational losses: the vulnerability curves. Each curve expresses the relation between losses and intensity measure for an asset and for a specific elapsed time starting from an event (Fig. 2).

3 Traffic Module

Fragility and vulnerability analysis and the definition of the resilience of a system, performed by the Decision Support Module are correlated through the Traffic Module.

This tool is used to perform traffic analysis in the initial situation and repeat them in the operativity loss scenarios in order to evaluate the Resilience Indicators. The idea is to investigate the change in the behavior of the system during the recovery

phase and to evaluate the Level of Service (LoS) in different scenarios. It leads to the evaluation of the Transport System recovery time and path, then the Resilience of the system. The main inputs for the transportation model are the capacity of the lanes for each arc of the road (i.e. the number of vehicles that cross the arc per unit of time) and the maximum allowed speed for the vehicles in each arc. These quantities shall be provided for the baseline scenario for the first simulation. In order to assess the change in transport parameters due to a disruptive event, it is important to correlate the loss of operability, derived from vulnerability analysis, for each asset to the modified values of capacity and speed for the arcs in the different selected scenarios after the event.

4 Decision Support Module (DSM)

The main objective of the DSM is to guarantee an instrument able to help Infrastructure Managers through the connection between of structural vulnerability and the corresponding transport flows modifications. The Traffic Module outputs (e.g. travel times, flow speeds, flow rates, flow densities, etc.) should be interpreted, in order to make an efficient decision-making process.

Starting from these outputs, it is possible to evaluate the variation of LoS in different scenarios.

Moreover, from the Traffic Module outputs, it is possible to evaluate Resilience Indicators about the infrastructure seen as a system.

Considering the recovery phase and the operativity losses of the assets, for different time intervals after an event, the description of the Resilience curves at either asset or system level is performed. At the system level, these analyses may be developed in deterministic or probabilistic terms (Fig. 3).

As consequence of the application of this framework, some Resilience Indicator are obtained.

These are associated to the “4 R” (i.e. Rapidity, Robustness, Redundancy, Resources).

The main Key Performance Indicators (KPIs) are:

- *Risk Quantification* (not necessary connected to one of the 4 “R” but affecting all of them being the probability to have an event. Especially the robustness determining the hazard input to be absorbed by the system);
- *Direct Losses* (directly connected to the robustness of the resilience);
- *Indirect Losses* (mainly connected to the redundancy and resources);
- *Resilience Assessment at the asset Level* (connected mainly to the rapidity and robustness of the infrastructure’s assets);
- *Resilience Assessment at the system Level* (connected to all the contributions).

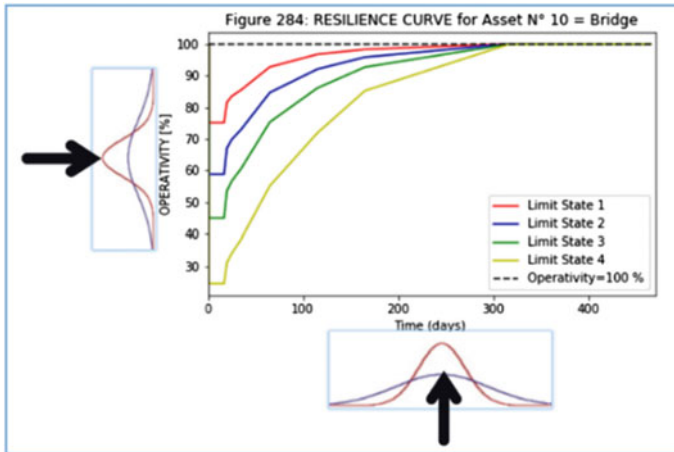


Fig. 3 Probabilistic resilience indicators at the system level

5 Conclusions

Because of the importance of transport infrastructures (i.e. typically facilities and networks that enable mobility of persons, goods and services), the need of decision support processes and methods to help managers and owners in the decision making are essential.

The approach presented in this paper tries to generate an integrated and flexible instrument that gives an overview of the infrastructure condition in terms of risk, possible losses and resilience assessment. It is still being applicate to several case studies as part of the FORESEE Project [1] and the result will soon be available.

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References

1. European Union: FORESEE Project, Horizon 2020
2. Cademartori M, Sullivan TJ, Osmani S (2020) Displacement-based assessment of typical Italian RC bridges. *Bull Earthq Eng* 18:4299–4329
3. Del Grosso A, Cademartori M, Basso P, Osmani S (2018) A simplified displacement based seismic Loss Assessment method for reinforced concrete bridges. In: IABSE conference, engineering the past, to meet the needs of the future, Copenhagen, Denmark
4. Fajfar P (2000) A nonlinear analysis method for performance—based seismic design. *Earthquake Spectra* 16(3):573–592

5. HAZUS MR4 (2003) Multi-hazard loss estimation methodology. Earthquake model. Department of Homeland Security Emergency Preparedness and response Directorate. FEMA, Mitigation Division. Washington D.C.
6. Syner-G: D3.6 Systemic seismic vulnerability and risk analysis for building, lifeline networks and infrastructures safety gain