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Planning and management of actions on transportation system to address extraordinary events in post-emergency situations. A multidisciplinary approach

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Abstract

The main aim of the work is the design and implementation of an integrated procedure for the identification of optimum action plans (satisfying expenditure constraints) on a road transportation system to minimize the impact produced on it by extraordinary events, in particular earthquakes. The attention is focused particularly on post-emergency situations related to effects on transportation networks caused by extraordinary events; the effects are considered with reference to bridges. Addressing the transition from physical effects to functional effects (relating to mobility) on the single infrastructure element calls for a commitment which has appeared challenging in view of the strongly innovative content involved. The analysis process consists in different steps. At the first step an effort must be made in order to acquire knowledge about the characteristics of the set of infrastructures (bridges) and about a set of possible seismic scenarios. By using fragility curves of bridges, the damage state of the network links (in which bridges are included) can be obtained. By making a series of hypotheses on how a bridge damage state can influence links' functionality, a set of "damaged" (lower capacity) road network models has been carried out. At the next step of the process, interaction between transportation supply and demand, by way of static or dynamic traffic assignment models, allows to measure the performance of the system, or rather, its overall response to extraordinary events using suitable performance indexes. Then, the network risk curve (probability of the seismic action vs. transportation system performance indexes) is derived. At the end of the process a cost-effective retrofit strategy has been identified. The procedure has been applied to a test network at regional scale in the north-east of Italy.

Keywords: Earthquake; Road network capacity; Vulnerability; Fragility curves; Bridges.

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1. Introduction – Related works

The efficiency and reliability of a transportation system have a significant influence on the economy of a territory; in effect, the system must be able to guarantee accessibility and allow the safe and smooth “movement” of people and goods.

Despite its relevance, the analysis of the reliability of transportation networks has received little attention, and tended to concentrate essentially on two aspects: journey times and networks connectivity. These measurements in themselves do not provide a basis on which to establish whether or not the capacity of the system is sufficient to meet mobility demand (Pas and Principio, 1997).

The analysis and modelling of capacity provided by a transportation network should constitute essential activities in transportation systems planning (Chen and al., 1999; Chen and al., 2002; Wong, 1996; Yang and Bell, 1998; Yang and al., 2000). Determining the maximum level of demand that can be served by a network, i.e. the network capacity, provides useful information for managing the mobility demand and identifying efficient strategies for controlling traffic flows.

In addition, the analysis of the transportation system capacity can be useful to assess how increases or changes in the mobility demand, for example due to new land-use development plans or emergency situations induced by natural and man-made events, can be absorbed by the system and consequently to identify action plans and suitable measures to improve system performance (Chan and Nojima, 2001).

Accordingly, the first requirement is for a thorough basic knowledge of the effects that can be produced on infrastructures by abnormal events (in particular earthquakes), whereupon an attempt can be made to identify the connections between these physical and mechanical impacts and the functional characteristics (as regards mobility) both of single components and of the network as a whole.

Under a spread natural or man-made disaster (e.g., earthquake, flood, etc.), it is critically important that the transportation system remains operational or that its functionality be repaired or restored as soon as possible (Nicholson and Du, 1997, Franchin and al., 2006). In particular, past experience has shown too often that earthquake damage to road network components (e.g., bridges, tunnels, retaining walls, etc.) can severely disrupt traffic flow, thus negatively impacting on the economic activity of a region as well as on post-earthquake emergency response and recovery activities (Franchin and al., 2006a; Franchin and al., 2006b; Lupoi and al., 2006; Schotanus and al., 2004). Furthermore, the extent of these impacts will depend not only on the seismic damage in the individual components, but also on the mode of functional impairment of the road system resulting from physical damage of its components. Road transportation systems comprise numerous structural components. Among the engineered components, bridges are potentially the most vulnerable under earthquake conditions (Auza et al., 2010; Banerjee and Shinozuka, 2007; Pellegrino and Modena, 2010; Zanardo and al., 2004), as demonstrated as vividly in the San Fernando, Loma Prieta, Northridge and Kobe earthquakes. The other components, such as roadway and retaining walls, are usually less vulnerable than bridge structures. Though many researchers have focused on seismic performance assessment of individual components of road network (Banerjee and Shinozuka, 2007; Banerjee and Shinozuka, 2008; Choi et al. 2004; Padgett 2007; Nielson 2005), even considering the whole life-cycle cost (Padgett et al. 2010) or studying the effect of retrofitting measures on fragility reduction

(Padgett and DesRoches, 2008; Karim and Yamazaki, 2007), only few have paid attention to seismic network system performance assessment and therefore to the optimal economic allocation in the network before the earthquake to improve/retrofit the components (Banerjee and Shinozuka, 2007; Bocchini and Frangopol, 2011; Carturan and al., 2010a; Carturan and al., 2010b; Chang et al., 2010; Nilsson, 2008; Pellegrino and Modena, 2010; Zanardo and al., 2004).

In this paper, attention will be focused particularly on critical situations connected with effects on transportation networks (roads in particular) caused by extraordinary events, for identifying an integrated procedure able to predict the effects of such events and their implications on the land-use/transportation system. The final objective of the work is the design and implementation of an integrated procedure for the identification of optimum action plans (satisfying expenditure constraints) for a road transportation system (with particular reference to bridge strengthening) and minimize the impact produced on a land use/transportation system by extraordinary events occurring across wider areas, in particular earthquakes.

The attention is focused on post-emergency situations.

The paper is organized as follows. In Section 2 a description of the integrated procedure with some details about its components is provided. Section 3 describes the application of the procedure to a case study. Concluding remarks are presented in Section 4.

2. Characteristics of the integrated procedure

2.1 Procedure architecture

The architecture of the integrated procedure is drawn by the diagram shown in Figure 1. There are three primary components:

- the bridge information system (BIS);
- the seismic information system (SIS);
- the transportation information system (TIS).

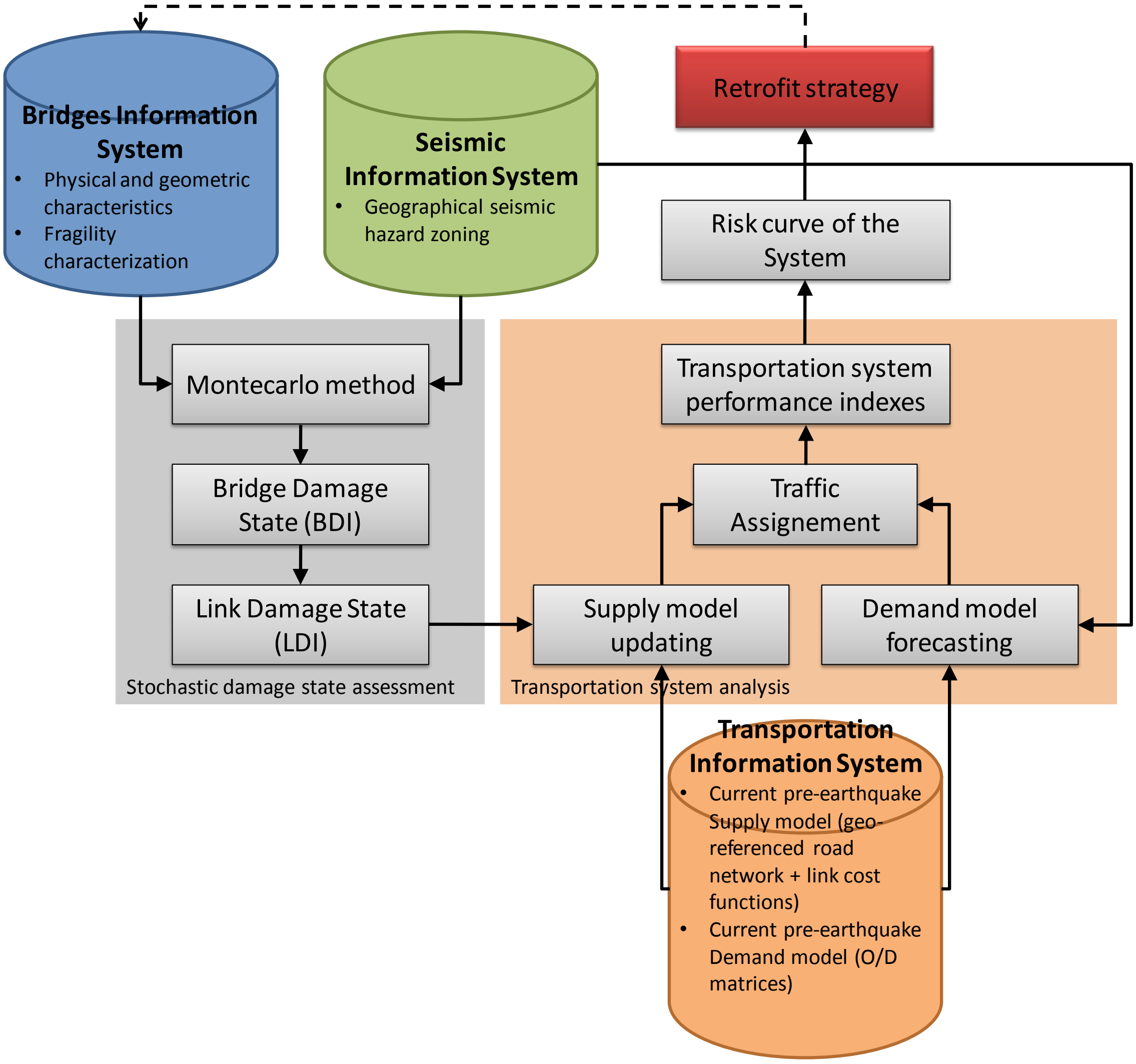


Fig. 1: Architecture of the integrated procedure.

Data archived in the information systems are used in two sequential processes:
the first, named "stochastic damage state assessment", concerns the assessment of how bridge damage state (and consequently link damage state) affects link functionality as a consequence of earthquake events.
The second process (named "transportation system analysis") refers to the tasks aimed to the assessment of transportation system performance indexes.

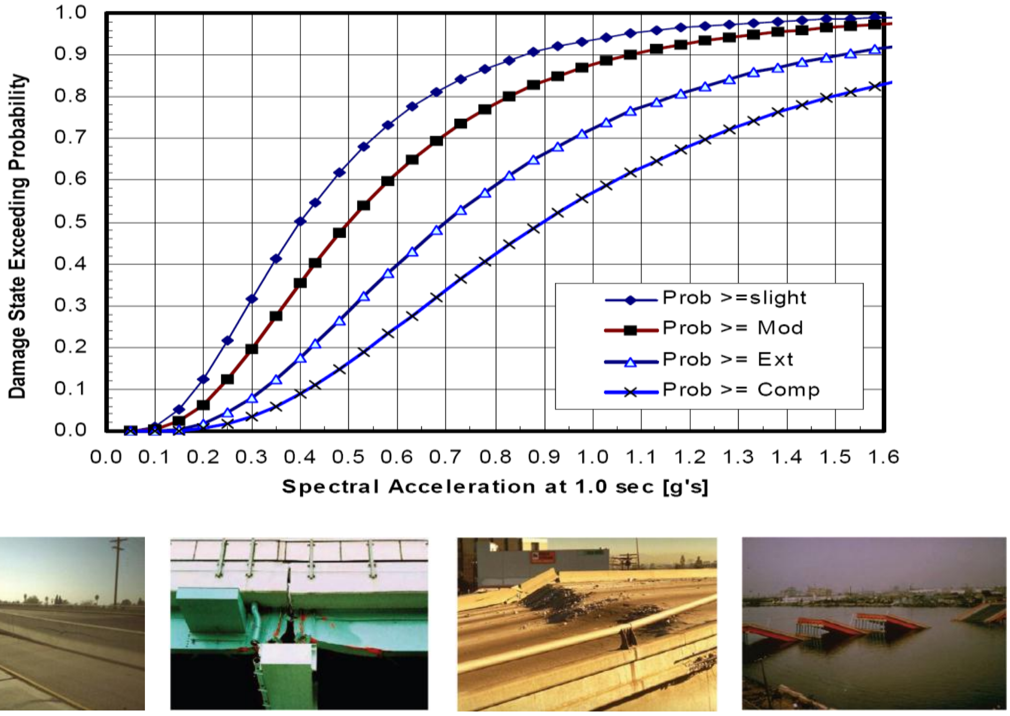
2.2 Bridges Information System

System components potentially subjected to risk, in road network risk assessment, are bridges, tunnels, slopes, retaining walls and roadways. In this analysis only bridges were taken into account since they have been considered as the most critical elements of the network. Nevertheless, the process can be generalized to include information about other facilities.

Each bridge is surveyed, its fragility[1] parameters are evaluated, and stored into an information system (a Geographic Information System). Usually, different information sources are available: historical data stored in database system, data provided by network managers, ad-hoc surveys.

Typically, bridge information relates to span length, span width, number of spans, materials, foundation soil, foundation type, skew angle, year of built, design code, etc.

A piece of information of the BIS refers to bridge fragility (a measure of bridge seismic vulnerability): the HAZUS classification (HAZUS-MH MR4, 2009), based on four possible damage states, can be used to estimate bridge fragility on the basis of bridge geometrical and physical characteristics. In Figure 2 an example of bridge fragility curve and qualitative descriptions of damage states are shown.



Slight Moderate Extensive Complete

Fig. 2: Example of a bridge fragility curve and qualitative description of "damage state".

2.3 Seismic Information System

The seismic information system contains data regarding the seismogenetic sources and their parameters to build seismic hazard map; examples of this information are:

- Geo-localized area of seismogenetic source
- Focal mechanism
- Seismic source depth

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[1] Probability of exceedance of certain damage state versus measure of seismic action.

- Annual occurrence ratio

These data can be archived and managed in a Geographic Information System (GIS); an example is represented by Information System carried out by national seismic hazard program, available in many countries.

Given the information about the seismic sources, a PSHA (Probabilistic Seismic Hazard Analysis) can be carried out following the method developed by Cornell (1968).

2.4 Transportation Information System

The design and implementation of an information system, allowing the organized collection of information relating to transportation networks (supply subsystem), mobility demand subsystem and territorial system (current and future) referable to a specific territorial entity (for instance regional scale), are central in the process of developing an integrated system for supporting the planning/management of measures to deal with extraordinary events.

With reference to supply subsystem (its topological and functional components) we referred to commercial/open source hierarchical networks. The decision to use these sources of information is justified by the fact that they are widely available and regularly updated by the makers. The first phase of the work has required a deep analysis of the information stored in these hierarchical networks, highlighting their strengths and weakness points (in fact, these networks are set up for specific purposes, such as satellite navigation, which do not always coincide with transportation planning and control requirements). The shortcomings observed in the use of these geographical databases are both structural in nature (there is no provision for storing certain items of information, e.g. traffic lights at nodes), and due to the incomplete and inaccurate information (certain items of information are handled but not always available and not all elements of the actual road network are represented correctly, e.g. inexact topological indication of nodes). These deficiencies can be identified and adjusted using other available sources of information, such as the roads registry and direct observation of the territory.

The use of such hierarchical networks together with procedures for integrating and updating the other available sources of information, represents one of the central features of the implemented information system.

Data related to demand subsystem (passengers and freights) usually refer to surveys carried out from national statistics institutes (ISTAT in Italy), surveys finalized to specific intervention on the land-use/transportation system, etc. These data, represented by O/D matrices, are commonly stored in database system. Moreover, a traffic monitoring system able to carry out information about road traffic volumes represents an important component of the transportation information system. These data are even useful for O/D matrices updating along the time.

Interesting references about Transportation Information System are available in literature (CEN, 2001; FHWA, 2001; ASTM, 2003; INSPIRE, 2010).

Transportation Planning Departments usually adopts these Transportation Information Systems to support transportation system planning and monitoring with reference to their spatial dimension of interest (urban, rural, etc.).

2.5 Stochastic damage state assessment

The level of vulnerability of an infrastructure reflects its attitude in the face of physical damage (physical vulnerability) and/or loss of functionality (functional vulnerability) occurring as the effects of abnormal external/internal events — depending also on its geometrical and structural characteristics and on the type and intensity of the event.
With reference to physical vulnerability, it will be necessary to define “sensitivity” functions for the single infrastructure, or for classes of infrastructures having similar typological and structural characteristics.
For a generic critical infrastructure element, in simplified terms, it will be:

$RFi_i = St_i \times VuFi_i$

where,

> RFi_i is the physical response of infrastructure element #i (consequence of the event);
>
> St_i represents the stimulus (in the case of an earthquake, this may depend on the magnitude of the quake and the distance of the infrastructure site from the epicentre) to which the element is subjected;
>
> $VuFi_i$ is the physical sensitivity of infrastructure element #i, which measures its likelihood to be affected by the abnormal event (physical vulnerability).

The sensitivity functions can be achieved, adopting two approaches:

- in the first instance, sensitivity are deduced from elements of qualitative and/or quantitative evidence;
- in the second, the functions are identified using suitable computation models.

The use of appropriate computation tools for modelling the physical/mechanical characteristics of the infrastructure element and its different components (referring specifically to bridges, viaducts, underpasses and tunnels), constitutes a fundamental step of the integrated procedure. For example, the availability of numerical models for an infrastructure element allow the analyst to estimate the values of suitable indicators for the response of the infrastructure to external stresses, according to the intensity and type of stress (stimulus), and the element structural characteristics (sensitivity).

In our case, bridge damage states (Fig. 2) are identified according to bridge fragility curves with the Montecarlo random number generation. Figure 3 represents the generation of the bridge damage state given a certain IM (Intensity Measure of the seismic event) value (in this case a spectral acceleration S_a equal to 1.0s). A random number is generated for an IM value: this number can identify five bridge damage states according to the position between the four curves. The circles in Figure 3 are possible bridge damage states; the black circle is the one determined by the random number produced by Montecarlo method.

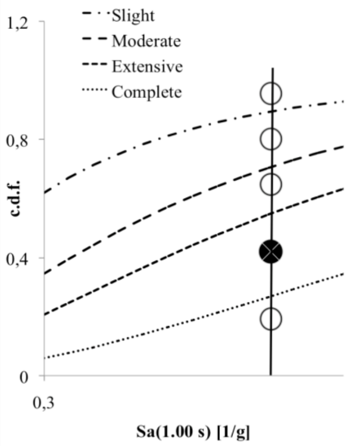


Fig. 3: Montecarlo random variables, in relation to the bridge damage state.

2.6 Transportation system analysis

The transportation system analysis process has the following inputs:

- pre-earthquake supply model (current network)
- pre-earthquake demand model (current O/D matrices),

for describing the road transportation system performance with reference to the current (pre-earthquake) scenario, and

- post-earthquake supply model (post-earthquake network)
- post-earthquake demand model (post-earthquake O/D matrices)

for describing the road transportation system performance with reference to the post-earthquake scenarios.

With regard to post-earthquake condition of the system, two main problems arise:

1 – to estimate the travel demand characteristics as a function of the modification of land-use/transportation system (as a consequence of the earthquake).

A classical four-step model (generation, distribution, modal split, assignment) can be used to forecast the travel demand (O/D matrices related to road network) characteristics with reference to post-earthquake scenarios. In this assessment the variation in generation and attraction indexes appears hard; this variation is strictly connected with the characteristics of the land-use system after the earthquake and, it is related to the vulnerability of the whole land-use system and reconstruction plans. In this sense, knowledge of the building fragility curve associated to each traffic zone of the system (available from a building information system) can be used to forecast the corresponding level of damage of the buildings and the level of reduction of human activities.

2 – to evaluate the supply system (road network) functional deterioration as a function of the damage state of the infrastructure:

the physical response (consequence) of the critical element of the network (link or node) must be related, by means of suitable functional forms, to its capacity (but in similar way to other parameters as, for instance, allowed speed, vehicle weight, etc.) defined as the maximum number of vehicles served per unit of time by this same element. A variation in capacity is therefore defined as the functional response of the infrastructure element to a change in its physical characteristics. The functionality of an element is likely to change as the consequence of a certain event (by which the physical response is induced), and this represents the functional vulnerability of the element.

The shift from stimulus (event) to functional response (translated in terms of capacity) occurs according to the following simplified scheme:

$$C_i=RFu_i=VuFu_i\times RFi_i=VuFu_i\times(St_i\times VuFi_i)$$

where,

C_i is the capacity function of element #i, (functional “response” of the element);

$VuFu_i$ is the functional sensitivity of infrastructure element #i, measuring its likelihood to undergo the effects of the stimulus (functional vulnerability of the element).

In this situation, the functional conditions of the single element are evaluated according to a suitably defined capacity function and the physical response of the infrastructure assumes the role of input.

One of the challenges of the research is the identification of these capacity functions, which will be defined on the basis of suitable mathematical structures (compatible with the nature of the input variables, whether quantitative or qualitative).

Finally, system performance is assessed by traffic assignment model. The interaction between demand and supply depends on the level of detail of the analysis: static or dynamic traffic assignment models. In the latter situation travel demand characteristics must be considered with a higher level of detail considering the within-day demand variation (Cascetta, 2009).

The process described is very general and it is possible to adopt different level of sophistication both in supply and demand modelling as consequence of the scenarios that need to be analysed.

2.7 System risk curve

The result of the main part of this work is the system risk curve i.e. the relation between the severity of the seismic action (given in terms of probability of occurrence of a seismic action) and a parameter that represents the increase of generalized cost of road network users (economic losses).

2.8 Retrofit strategy

In general terms retrofit is an activity that improves the performance of a bridge and consequently modify its fragility curve.

The proposed retrofit strategy starts from the results of the assessment proceduredescribed in the previous sections. The proposed method does not classify each bridge (link) according to the economic loss (e.g. in terms of wasted time or delay) caused by its impairment (Sgaravato et al. 2008) since this approach does not consider the effect of interaction between bridges (links) damages. This method groups bridges (links) according to a certain characteristic (i.e. the links' owner, the links' importance, or a criterion suggested by the Authority), then each group is considered as retrofitted. For each configuration with only one group retrofitted, transportation system performance indexes are computed. The group that gives the best performance is the first to be retrofitted. In the next step of this iterative procedure the first group is maintained retrofitted and each of the other groups are considered as retrofitted. Again, the group with the best performance is the second to be retrofitted. This search algorithm, called "step-wise", continues until all groups are retrofitted.

3. Case study

A test area has been identified with the aim to verify the applicative effectiveness of the proposed procedure. The attention has been focused on a regional area in the northeastern part of Italy between the cities of Venice and Treviso; this area was chosen for its significant seismic hazard. Moreover, Transportation Information System (Province of Venice), Bridges Information System (Italian Bridge Interactive Database) and Seismic Information System (Italian Project for seismic hazard assessment of the GNDT, National Group for the Protection against Earthquakes) are available for this area. In this test area there are forty bridges with various typologies: single span, multi span, steel, composite and masonry bridges, straight or skewed.

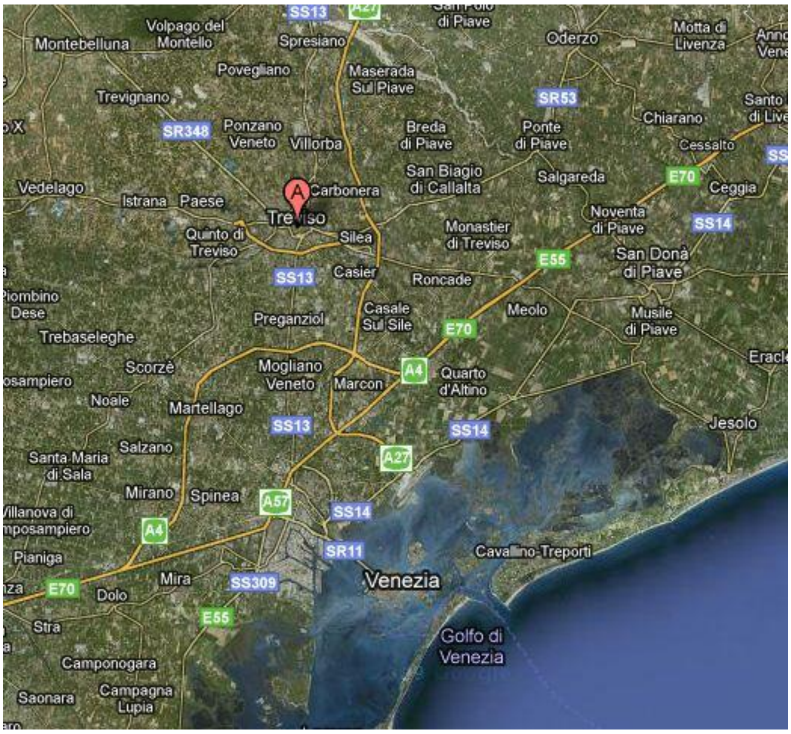


Fig. 4: Map of the test area.
Source: Google Maps.

3.1 Bridge Information System

Data used to build the Bridge Information System were retrieved from in-land surveys, from historical research (road owner archive) and from maps. Data were stored in a database called I.Br.I.D. (database can be consulted on line at the project web site <http://ibrid.dic.unipd.it/>, see Figure 5). The information used to build fragility curves are:

- Span length
- Span width
- Number of spans
- Materials
- Foundation soils
- Foundation type
- Skew angle
- Year of building
- Design code

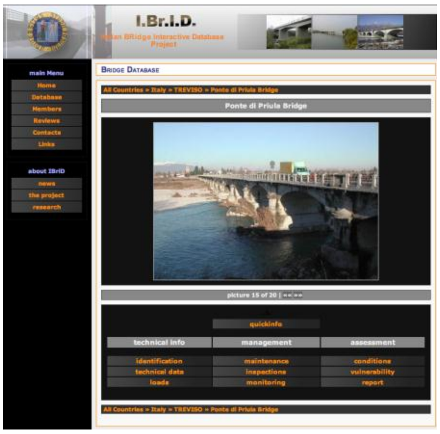


Fig. 5: Bridge Information System I.Br.I.D. Web Graphical User Interface.

In this case study curves were built using the procedure described in Hazus Manual (HAZUS®MH MR4, 2009) and RiskUe (RiskUe, 2004).
An example of a bridge fragility curve is presented in Figure 6.

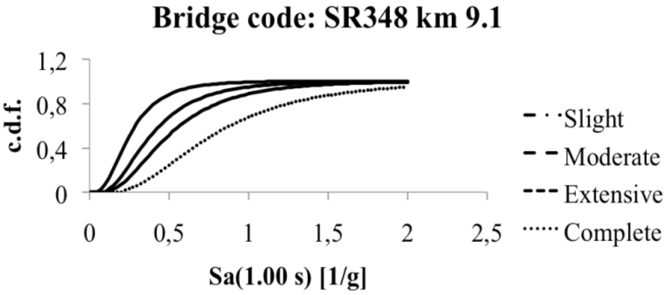


Fig. 6: Fragility curve of a bridge belonging to SR348 in the test area road network.

3.2 Seismic Information System

Seismic scenarios were built using data retrieved from Italian risk hazard analysis carried out by INGV (INGV, 2007) ("Istituto Italiano di Geofisica e Vulcanologia" – "Italian Institute for Geophysics and Volcanology"). This is an approximate way of proceeding, since these are not actual seismic scenarios, but envelops of scenarios. These data can be retrieved on line at <http://zonesismiche.mi.ingv.it/> (reference year: 2004).

With reference to a certain geographical point, the seismic action is characterized both by intensity and probability of occurrence (Fig. 7).

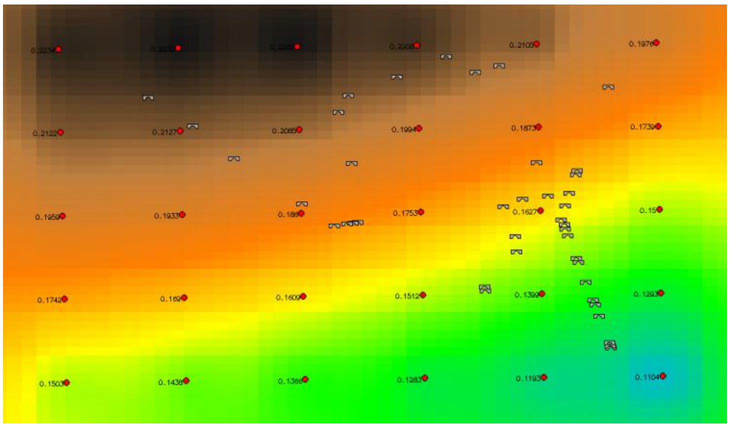


Fig. 7: Example of data re-sampling for actual seismic action calculation.
Source: INGV, 2007.

3.3 Transportation Information System

Transportation Laboratory of Padova University in agreement with Venice Province Administration has been dealing with the design and development of an Information System (Rossi and al., 2008) which supports transportation system planning and monitoring, with reference to the Province territory.

The research topics relate to the method of design of the information system, meant as a whole of human resources, instruments and procedures (both manual and automatic) for acquiring, storing and exchanging information. The main goal of the information system is to integrate different modelling tools and databases available to the Administration. The new integrated information system uses an Oracle® DBMS to store heterogeneous data sources and to provide and receive data used and produced by various modelling tools.

In the development of system architecture particular attention has been paid to the study of procedures specifically dedicated to both the growth and the updating of the information system, in order to guarantee both the capability of responding to new analysis requirements, and the consistency of the information collected in the course of time.

The system collects information related to:

- the current supply subsystem (road network schematization) characterized by 7.500 one-way links and 2.800 nodes covering an area of interest of around 7.080 square kilometres (around 2.674.000 inhabitants). The supply model is completed by link travel time functions assigned to the network links using a functional road classification; in this application several BPR type functions have been estimated using experimental data;

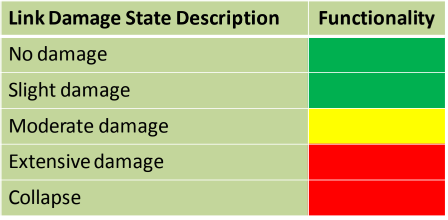
- the current demand subsystem, that is represented by 623×623 O-D matrices (passenger cars and freight vehicles matrices).

3.4 Stochastic damage state assessment and transportation system analysis

The random number generated by the Montecarlo method determines the Bridge Damage Index (BDI). A correlation has been made to relate the BDI to the link damage state (by way of a so called Link Damage Index, LDI); according to Shinozuka et al. (2006) the following relation has been used:

$$LDI = \sqrt{\sum_{bridge \in link} BDI^2}$$

The link damage indexes were grouped into three levels to determine which functionality reduction has to be applied to those links that include damaged bridges (Figure 9).



Link Damage State Description	Functionality
No damage	🟩
Slight damage	🟩
Moderate damage	🟨
Extensive damage	🟥
Collapse	🟥

Fig. 9: Link levels of functionality related to Link Damage State.

The link functionality has been translated into operational terms using three simple rules:

- no traffic restriction was applied for the highest level (no damage or slight damage);
- speed was reduced to 50% with respect to the original one and the transit of trucks was forbidden for the intermediate level (moderate damage);
- the link was closed for the worst level (extensive damage or collapse).

Nine seismic scenarios have been analysed; per each seismic scenario 30 iterations of the Montecarlo method have been played, giving a total of 270 damaged networks.

A Deterministic User Equilibrium traffic assignment has been carried out to analyse transportation system performance, with reference to the current state and each damage scenario,.

In this case study it is assumed that any change in demand (numbers of travels generated and attracted by each zone and traffic distribution) occurs between the "no damage" scenario (current state) and the "damaged" scenarios. The analysis is done with reference to post-emergency situation (some months later the event).

The difference between the total travel time for the current condition ("no damage") and that for the "damaged" scenario was used as global performance index (named total delay); the total network travel time for the current situation and for each seismic scenario has been estimated using Citilabs Cube®.

As an example, with reference to the seismic scenario functional effects shown in Figure 9, in Figure 10 the corresponding traffic assignment results are shown: the green bars represent traffic flow increase with regard to the current situation (no-damage network assignment); the red bars represent traffic flow decrease with regard to the current situation.

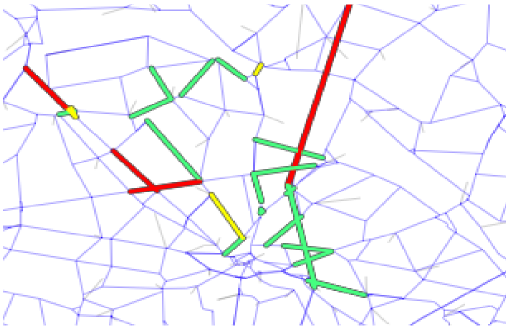


Fig. 10: Link damage state produced by a certain seismic scenario and corresponding functionality assessment:
Green line: no traffic restriction
Yellow line: intermediate functionality (speed limit reduced by 50% and trucks not admitted)
Red line: closed links

It is interesting to observe (Fig. 11) how the traffic flows change over an area larger than the one hit by the earthquake (black line perimeter).

Fig. 11: Traffic assignment results with reference to a seismic scenario.

3.5 System risk curve and results of retrofit strategy

The system risk curve was plotted for the case without retrofitting considering nine seismic scenarios (see section 3.4). The economic loss is given in terms of total delay as a function of annual occurrence ratio of seismic scenario.

In Fig. 12 the risk curves for the system without and with retrofitting (i.e. in the hypothesis of retrofitting all the existing bridges in the test area) are plotted for nine seismic scenarios.

As a consequence a retrofit priority has to be defined to move from the dark curve to the light one.

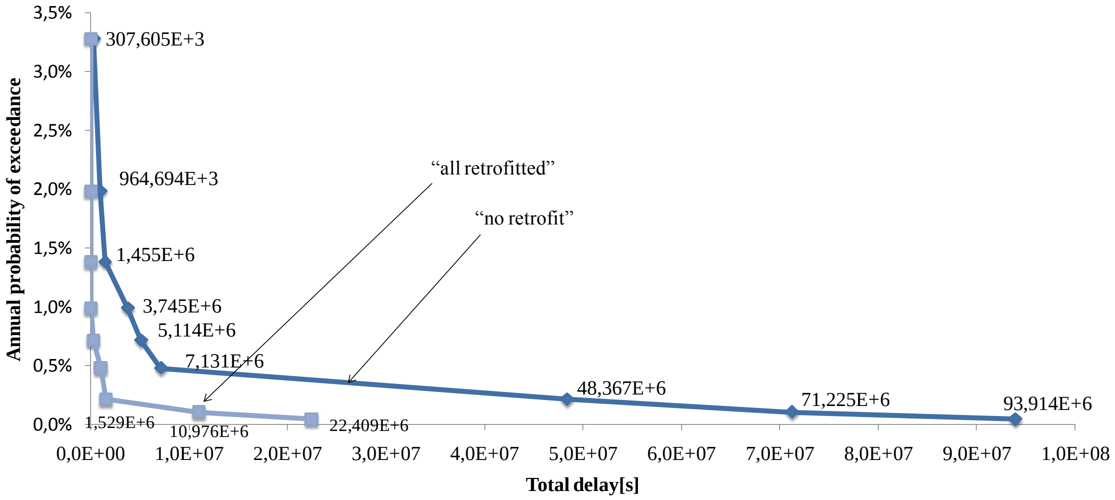


Fig. 12: System risk curves with reference to the “no retrofit” and the “all retrofitted” cases.

In this work, as an example, the optimal resource allocation research method for retrofitting was applied for the seismic scenario with return time of 475 years.

Forty bridges have been grouped into 5 groups according to the road to which they belong:

- Highway A27
- Provincial road SP102
- State road SS13
- Provincial road SP248
- Regional road SR348.

During each step of the procedure a road network configuration with only one retrofitted group has been considered and the total delay with regard to the current condition (no damage) has been computed. At each step, the group with the lowest total delay has been chosen as the best solution.

Keeping the “best retrofitted group” from the last step of procedure the simulation was developed for the remaining groups. The scheme was repeated until all groups of bridges were retrofitted.

The result of the retrofit strategy process is plotted in Fig. 13 and the corresponding numerical results are reported in Table 1.

For each step of the procedure the plotted data are the difference between the total delay associated to a certain configuration with only one retrofitted group and the “all retrofitted” case.

In detail, the group of bridges allowing the maximum benefit when retrofitted is the “highway A27” one, hence this will be the first to be retrofitted. The second group is the “SR348” one, hence this will be retrofitted as second. The last group of bridges to retrofit is the “SP248” one (fourth step).

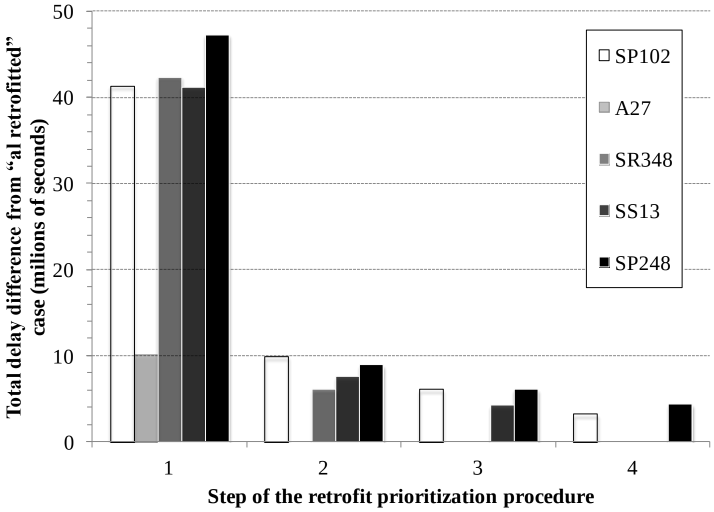


Fig. 13: results of the retrofit prioritization procedure.

Table 1: computational results of the retrofit prioritization procedure. In grey the best bridges group (minimum total delay difference from “all retrofitted” case) for each step.

First step		Second step		Third step		Forth step	
Group	Total delay difference from “all retrofitted” case (seconds)	Group	Total delay difference from “all retrofitted” case (seconds)	Group	Total delay difference from “all retrofitted” case (seconds)	Group	Total delay difference from “all retrofitted” case (seconds)
SP102	4.12E+07	SP102	9.82E+06	SP102	6.00E+06	SP102	3.12E+06
A27	1.01E+07	SR348	6.06E+06	SS13	4.20E+06	SP248	4.32E+06
SR348	4.23E+07	SS13	7.51E+06	SP248	6.06E+06		
SS13	4.11E+07	SP248	8.85E+06				
SP248	4.72E+07						

This results have been compared with those using the common criteria based only on traffic volumes (Administration often firstly retrofits bridges having highest traffic volumes). The difference appears significant (Table 2).

Table 2: comparison between two retrofit sequences on groups of bridges (based on the proposed retrofit strategy and “highest flows” strategy).

Strategy	1st group	2nd group	3rd group	4th group	5th group
proposed	A27 →	SR348 →	SS13 →	SP102 →	SP248
higher flows	A27 →	SP102 →	SS13 →	SR348 →	SP248

4. Conclusion and future works

In this paper an integrated procedure for infrastructures (in particular bridges) retrofitting based on a multi-disciplinary approach (Structural Engineering, Transportation Engineering and Operational Research) has been proposed.

The main objective of the work is the design and implementation of an integrated procedure for the identification of optimum action plans (satisfying expenditure constraints) on a road transportation system to minimize the impact produced by extraordinary events, in particular earthquakes. The procedure allows assessing consequences of a seismic event in terms of economic losses (time, cost opportunity, etc.) and uses these assessments to identify a priority retrofit order over infrastructures (or groups of them) not based simply on the “highest traffic volumes”.

A test area has been identified with the aim to verify the effectiveness of the proposed procedure. The attention has been focused on a regional area in northeastern Italy between the cities of Venice and Treviso; this area was chosen for its significant seismic hazard.

In order to analyse the transportation system performance, with reference to the current state and each damage scenario, a Deterministic User Equilibrium traffic assignment has been carried out.

In this case study it was assumed no variation in mobility demand between the “no damage” scenario (current state) and the “damaged” scenarios. The analysis was done with reference to post emergency situation (some months later the event)

The proposed procedure, even though simplified and afoot of future improvements, implements an efficient retrofitting strategy.

Future research should focus on the following issues:

- to improve the simulation of the seismic scenario;
- to improve the procedure for obtaining fragility curves, particularly for retrofitted bridges (a procedure to build fragility curved from parameters via Finite Element Method non linear analysis could be considered);
- to identify improved relations between bridge and link damage indexes;
- to identify link capacity functions defined on the basis of suitable mathematical structures;
- to embed other vulnerable elements in the analysis (slopes, tunnels, etc.);
- to consider the demand variability as a consequence of the seismic event in the post emergency situation;
- to consider other performance indicators of the transportation system.

The post-earthquake traffic patterns are characterized by uncertainty and high variability, hence it is difficult to collect them with traditional techniques. Efforts should be made in future researches in order to calibrate/validate the proposed procedure, also using emerging technologies (mobile phones, GPS, etc.) to collect post-earthquake travel demand data.

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