A New Paradigm in Urban Road Network Seismic Vulnerability: From a Link-by-link Structural Approach to an Integrated Functional Assessment

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ABSTRACT

Other than the direct exposure of a seismic event, the interruption of the transportation network causes an indirect exposure of the population living in stricken areas. In spite of such evidences, current planning practices rarely address road network seismic risk concerns beyond the typical structural link-by-link approach.

The underlying hypothesis of the current research work is that, when facing a major earthquake, the impacts on road networks performance for emergency response functions can be minimized namely by the introduction of measures, not only in terms of infra-structural reinforcement but also in terms of network connectivity and activities location.

Potential applications of this work include urban planning micro and macro scale solutions to be included in specific instruments (such as urban master plans or emergency plans). Additionally, the proposed method may be integrated in loss estimation models, which still do not include earthquake losses due to inaccessibility.

Keywords

Road network, seismic vulnerability, blockage situations.

INTRODUCTION

The underlying hypothesis of the current research work is that the impacts on the performance of road transport infra-structures for emergency response functions can be minimized when facing a major earthquake, namely by redundancy. Basically, it should be critical to reduce the blockage probability of a link which, not having alternative routes, has the potential to isolate a street or a small city quarter. Secondly, the land-use dimension refers to critical functions accessibility in earthquake scenarios (such as hospitals, schools, fire-departments, etc.). In this sense, it should be urgent to strengthen a link which, for example, allows access to a major hospital. Finally, demand patterns refer to specific patterns which are induced by a large quake (such as emergency vehicles using wrong way streets due to road closures). Therefore, it is important to analyse network performance from a critical origin-destination paths operability perspective (instead of a conventional volume/ capacity perspective) taking into account the induced specific demand patterns and network operability.

CONTEXT

This work was built on the basis of the existing knowledge in each of the following related domains: **i)** seismic risk management and urban planning; **ii)** risk assessment and loss estimation, and; **iii)** road network vulnerability studies and applications.

Seismic Risk Management and Urban Planning

Even though land-use techniques and other planning related measures should be included in a strategy to cope with disaster risk mitigation in urban areas, in practice, they are still neglected in many local planning processes and management procedures of cities around the world.

For example, a common argument in post disaster studies is the establishment of a high correlation between population density and both human and material losses caused by disasters. When cross analyzing the deadliest recorded earthquakes with its magnitude, McDonald (2003, pp 28 - 29) affirms that loss of life is linked to the density of population on the particular location more than the magnitude of the earthquake.

Moreover, the broad implications of controlling population densities, unavoidably invoke the wider discussion regarding urban form and structures. In what concerns mobility, the concept of the compact city has been argued as more efficient. However - and although the issue of disaster risk mitigation has not yet been included in the urban form debate - it is also obvious that a transport network in a compact city operates closer to its capacity, therefore has greater difficulty to cope with unscheduled events.

Risk Assessment and Loss Estimation

Belonging to the United States Department of Homeland Security, the Federal Emergency Management Agency (FEMA) has developed a risk assessment software program (HAZUS) for analyzing potential losses from floods, hurricane winds and earthquakes, before, or after, a disaster occurs. However, in the case of earthquakes, interdependence of components on overall system functionality is not addressed by the methodology. According to the source (FEMA 2003, pp 7-3), such considerations require a network system analysis that would be performed separately by a highway system expert.

Road Network Vulnerability Studies and Applications

Since the Hanshin-Awaji earthquake in 1995, transport network vulnerability has emerged as a new research topic (Murray 2007, pp 10 – 12) and “subsequent research was directed at degraded networks, usually urban

Road Links Vulnerability Assessment

As a reasonable balance between reality representation and model applicability only two sources of road closures are proposed to be modelled: **i)** caused by debris from collapsed buildings, and; **ii)** due to damages to bridges. The following sections briefly introduce the necessary steps to model network vulnerability based on the above mentioned sources of road closures: seismic hazard representation; building damage assessment, and; bridges damage assessment.

The application of the seismic hazard disaggregation method reveals itself as the most adequate procedure for the Seismic Hazard Representation - the mathematical formulation of this method will not be discussed in this paper; however it can be found in Sotto-Mayor (2005, pp 25 - 28).

In what concerns building damage assessment several methods can be found in the literature, belonging to two major categories: **i)** analytical, or; **ii)** empirical. Notwithstanding the recognition of advantages and disadvantages in both methods, the precise choice will depend on local conditions for particular studies, namely the available data.

Concerning Bridges Damage Assessment, it is proposed to adapt the decision model proposed by Vieira (1997). Basically, this model suggests a multicriteria value model enabling the prioritization of bridges and tunnels for the implementation of civil protection policies.

It is important to note that this work focuses more on network analysis rather than seismic risk analysis methods; however existing methods in such domain have to be deployed in order to establish a relation between general earthquake effects and road network closures.

Blockage Scenarios Risk Computation

This section will further detail how the road links vulnerability assessment can be used to compute the blockage scenarios risk. Thus, the first step in this process is network modelling. For such purpose the conventional network modelling design is extremely limiting so a new design is proposed (see Figure 1.). This detailed design allows capturing, in a more realistic manner, the effects of building collapses in road closures.

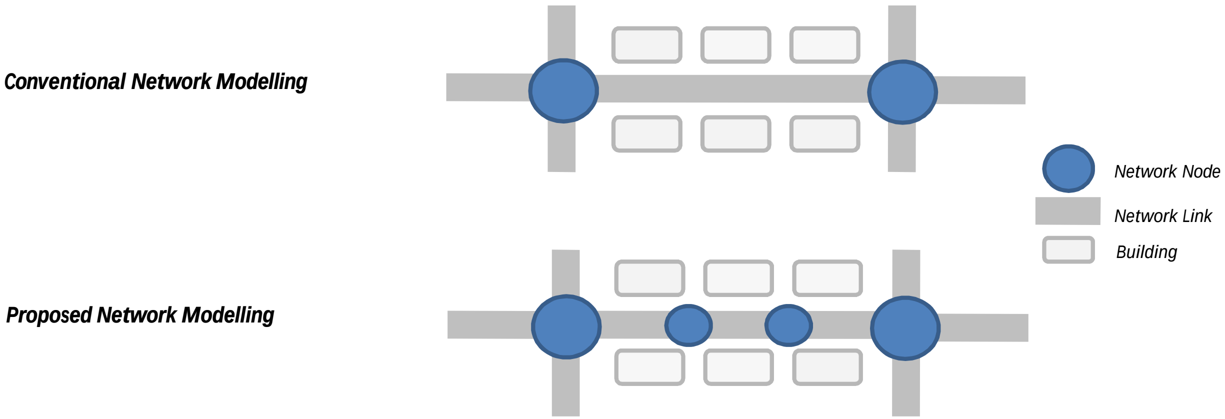

Figure 1. Conventional and proposed network modelling
(Source: elaborated by the authors)

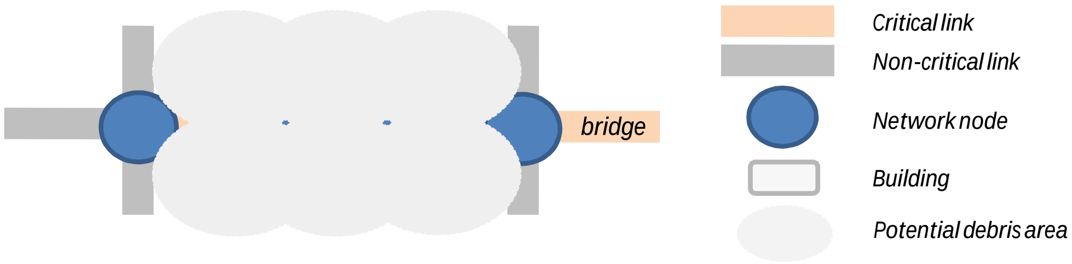

Figure 2 – Spatial relations between buildings potential debris area and critical links (Source: elaborated by the authors)

At this point, although it is possible to identify individual links which can be closed after an earthquake, their broader implications in terms of inaccessibility potential (i.e. parts of the network - such as streets or small quarters - which can be inaccessible) remain unknown. For such purpose, based on the critical links identification, a network analysis should be conducted in order to identify all possible blockage scenarios. Since a high number of combinations are expected, particularly in densely build-up areas, this step would require the development of an automated procedure through programming on a GIS environment. Basically, this step attempts to introduce the connectivity dimension explained earlier.

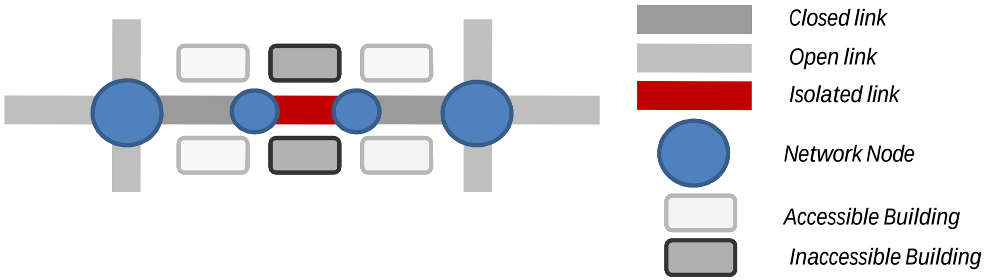

Figure 3 – Example of a blockage scenario (two closed links) (Source: elaborated by the authors)

Although at this stage the model allows identifying all blockage scenarios which can occur after a major earthquake, their broader implications in terms of emergency response are not known. For such purpose, it is crucial to quantify the potential seriousness of those blockage scenarios, either in terms of people concentration (e.g.: schools) or critical functions (e.g.: hospitals). It is important to note that these concerns are related exclusively with emergency response; therefore other issues - such as: i) public safety (risk of human losses using road infrastructures during earthquake); ii) long term economic effects, and; iii) interactions with other lifelines - are not captured in this method. Thus, an index - based on variables which reflect the previously mentioned seriousness - will have to be developed and quantified for each building. In this sense, several variables concerning both the potential demand of emergency response services (such as inhabitants, visitors - students, workers, shoppers, etc.) as well as the supply of such services (existence of critical functions such as hospitals, fire departments, civil protection facilities, police headquarters, etc.), will have to be considered.

urban road networks, seismic risk concerns have typically been tackled exclusively through a structural link-by-link approach.

In this context, the objective of the current work is to develop a method to assess urban road network seismic vulnerability for emergency response functions. Therefore it focuses on strengthening urban network resiliency in seismic scenarios based on three main dimensions: **i)** network connectivity; **ii)** land use, and; **iii)** demand pattern. Therefore this methodology addresses network vulnerability not only by its structural characteristics but also by its functional role. Moreover, it adapts and deploys several existing vulnerability assessment methods, for different sub-systems of the built environment, in order to carry out a network analysis enabling the identification and characterization of potentially dangerous blockage scenarios.

ACKNOWLEDGMENTS

We are very grateful to all authors, colleagues and professionals who contribute to this ongoing research. The authors acknowledge the financial support provided by FCT.

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