REGIONAL PERFORMANCE-BASED ASSESSMENT OF TRANSPORTATION NETWORKS

B. Cetiner¹, E. Taciroglu²

ABSTRACT

Recent advances in performance-based seismic engineering and existing information technologies provide opportunities to develop extremely granular inventories of the built environment and assess its vulnerabilities to earthquakes and other hazards. The present study focuses on bridges—which arguably are the most critical elements of a transportation network—and delineates the ingredients needed to bring a regional seismic assessment tool to fruition. These ingredients range from site-specific ground motion estimation to automated development of models using harvested data from repositories to damage and economic loss assessment. After identifying the ingredients, an overall framework is articulated for regional risk assessment of transportation networks. Several application examples are provided to demonstrate the viability and the utility of the envisioned approach.

¹Ph.D. Candidate, Dept. of Civil and Environmental Engineering, University of California, Los Angeles, Los Angeles, CA 90095 (email: bacetiner@ucla.edu)
²Professor, Dept. of Civil and Environmental Engineering, University of California, Los Angeles, Los Angeles, CA 90095 (email: etacir@ucla.edu)
Regional Performance-Based Seismic Assessment of Transportation Networks

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ABSTRACT

Recent advances in performance-based seismic engineering and existing information technologies provide opportunities to develop extremely granular inventories of the built environment and assess its vulnerabilities to earthquakes and other hazards. The present study focuses on bridges—which arguably are the most critical elements of a transportation network—and delineates the ingredients needed to bring a regional seismic assessment tool to fruition. These ingredients range from site-specific ground motion estimation to automated development of models using harvested data from repositories to damage and economic loss assessment. After identifying the ingredients, an overall framework is articulated for regional risk assessment of transportation networks. Several application examples are provided to demonstrate the viability and the utility of the envisioned approach.

Introduction

The most effective way to prevent loss of life and damage due to earthquakes is (i) to identify facilities at risk; (ii) to quantify exposure; and finally (iii) to improve resiliency through retrofit, insurance, post-event emergency planning, and design/code improvements. Significant improvements in resiliency cannot be attained without data and knowledge from the first two steps. Current regional seismic assessment tools for bridges (and other structures alike) are very rudimentary and do not rely on up-to-date or updateable inventories, which means that their utility is limited.

Civil engineers routinely design structures (including bridges)—almost invariably one at a time—and in these design processes, the performance and behavior of other structures in the region are hardly considered. Nevertheless, hazards affect entire regions, and the proverbial “big picture” is needed for developing actuarial plans, for urban planning and public policy decisions, and for emergency service planning. For each of these three items, the respective consumers of the big picture are insurance companies, government agencies, and first responders. Moreover, the built environment is highly interconnected. It comprises residential neighborhoods and business centers, transportation networks, and lifelines. These components interact with each other in significant ways and effect each other’s performance—not only during extreme events, but also under service conditions.

Consider a scenario that highlights the issue at hand: imagine that a hospital building is designed for the most extreme event; such an event has happened; and the hospital indeed remained operable. However, also imagine that several key bridges in the region have collapsed and a great

¹Ph.D. Candidate, Dept. of Civil and Environmental Engineering, University of California, Los Angeles, Los Angeles, CA 90095 (email: bacetiner@ucla.edu)
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majority of the hospital personnel couldn’t get to work that day. Clearly, the performance of this emergency response facility can not be gauged though an analysis that ignores network effects.

**Challenges**

Having established the need for regional assessment, let us identify the challenges. The *first* class of challenges involve harvesting of data and the conversion of data to metadata and eventually into analysis models. This is a challenging task because sample population is diverse (in other words, not all bridges and buildings are the same), and this diversity requires the use of sophisticated—and until recently non-existent—data harvesting tools. Another challenge in this area is that access to detailed data may be not be possible (this would then require estimation missing data, through techniques such as *machine learning*). Finally, processing of harvested data and analyzing the resulting models require large computational resources—it is fair to state that regional assessment studies will break computational records among civil engineering applications.

The *second* class of challenges involves transforming the models into *decision variables*, such as economic loss estimates, downtime and repair costs, insurance premiums. The challenges in this area include the necessity to use heterogeneous analysis tools and to link them to obtain the decision variables. New methodologies need to be brought in—including data analytics and Bayesian inference methods [5]—to organize and make sense of the output of the analyses over the extremely large metadata sets.

Given the motivation and challenges cited before, the overarching objective of the present effort is to develop a (semi-) automated interactive platform that can evaluate seismic vulnerability of transportation networks as a whole so that financial losses their disruptions will cause can be accurately understood and countered.

There are three distinct threads of features that such a platform should have: (*i*) it has to be able to harvest data and metadata and use them to generate structural models as well as freight traffic information, (*ii*) it has to be able to carry out site- and structure- specific seismic analyses, and (*iii*) and finally it has to be able to evaluating the consequent economic losses at the network-level. Details of the proposed work, some preliminary results are provided in the following sections.

**Methodology**

The ingredients of the proposed bridge database and regional assessment tool—henceforth referred to as BridgeR, which is currently under development—are graphically illustrated in Figure 1. BridgeR will contain a module that harvests raw data (including images) from public databases and users, and converts them into metadata. These metadata will then be stored and organized in a relational database. Using the metadata, it is possible to create analysis models. The analysis will be carried out using several publicly available tools. Namely, OpenSHA [4] will be used to compile site-specific ground motions from databases such PEER NGA West 2 [1]. OpenSees [7] will be used for carrying out the nonlinear time-history analyses, which yield fragilities. Subsequently, a loss assessment tool, such as FEMA PACT [3], will be used to estimate financial losses and repair downtimes.
Once the site- and structure specific results are computed, they will be committed back to the relational database so that they can be accessed by users, and also they can be used to learn about the common behavior of sub-classes of bridges and components. This learning process will be used to eliminate unrealistic/non-physical results and also the devise automated metadata for yet-to-be modeled new bridges for which only a few pieces of information are known (such as structure type, number of spans, and year-built).

The final component of BridgeR will be its user interface, which will allow users to contribute data and to visualize the models and the analysis results. At the present time we are configuring BridgeR to interface with Google SketchUp and Google Earth for visualization, both of which have public Application Programming Interfaces (API) and are free to general public.

A graphical illustration of the envisioned work-flow for the aforementioned data harvesting and regional assessment analyses for each individual bridge is provided in Figure 2. Assessment will begin by developing an analysis model of the specimen bridge using images, for example, and other sources (these sources of data are discussed later in a subsection below. A suite of representative ground motions for the specific site of the bridge will be compiled using OpenSHA. The analysis model and the selected ground motions will then be used in nonlinear time-history analyses in order to develop a statistical picture of the potential performance outcomes in the form of fragility curves. Fragility curves provide the probabilities of exceedance of selected—holistic as well as component—performance states such as, collapse, serviceability, etc.

These fragility curves embody the *aleatoric* uncertainties in the selected ground motions, and the *epistemic* uncertainties in the generated models. Harvested data will naturally contain
epistemic uncertainties, and as more information is gathered for each bridge in the database, these uncertainties will be reduced over time. The fragility curves will ultimately be used to estimate the decision variables for assessment, such as economic losses, downtime, and repair/retrofit costs and prioritization metrics.

Source of Data

A significant portion of the data required to devise bridge models for analysis will come from various existing databases. One such major database is the National Bridge Inventory (NBI) compiled by the Federal Highway Administration (FHWA). NBI provides metadata on all bridges and tunnels in the U.S., and its primary intent has been to book-keep bridge conditions—it provides a 0-9 scale rating on components (superstructure, deck, culvert, etc.). We already created computer codes that extract all available information from the NBI database, which include YearBuilt, MatType, Length, NumLanes, AvgDailyTraffic, etc. The BridgeR database now hosts the entire NBI dataset (Figure 3), and offers metadata as well as a GoogleEarth-based visualization.

Figure 2. BridgeR workflow for an individual bridge specimen.
Another major database is the *Caltrans Bridge Inventory (CBI)*, which is compiled and maintained by the California Department of Transportation (Caltrans). It provides *all* details of bridges, including site conditions and foundation configurations. However, CBI cannot be interrogated online—access is only granted by special permission from Caltrans. We will use the CBI primarily to *validate* the bridge models developed from image data and other public databases for a limited set of representative bridges (of types: toll, ordinary, curved, suspension, etc.).

A third source will be the California Strong Motion Instrumentation Program (CSMIP) Database, which is maintained by the California Geological Survey (CGS). It provides most of the details of 72 bridges in CA (including site conditions and foundation configurations). CSMIP database can be interrogated online and it contains bridge response data from past earthquakes, which can be also used for *model validation* [6].

The final source of data harvesting and model creation will be GoogleEarth/Maps. In recent work [2], we developed codes that automatically extract high-quality images of a bridge, given its longitude-latitude information. To date, we have validated these image-to-model conversion capabilities on several sample bridges using both CSMIP collected seismic data A validation study carried out on the San Bernardino I-10/I-215 Interchange Bridge, which is shown on Figure 4. The validation study comprised the comparisons of image-extracted column dimensions (diameters, and heights), bent locations, in-span hinge locations, deck elevations, deck dimensions as well as mode shapes and natural frequencies with those that are obtained from Caltrans structural drawings. The accuracy of image-based model is remarkable, with highly accurate matches on both geometry dimensions and modal characteristics. For brevity, details of the image-to-model module are omitted here, but a few examples of automatically generated models using this tool are shown on Figure 5.
Figure 4. A validation study of the image-to-model toolbox on I-10/I-215 Interchange Bridge: (a) image-based model; comparison of as-built and image based (a) column diameters, and (b) deck elevations along the bridge; (d) comparison on modal frequencies.

<table>
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<th>Mode</th>
<th>$T_{Image-Based}$ (sec)</th>
<th>$T_{As-Built}$ (sec)</th>
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<td>Mode 8</td>
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</tbody>
</table>

Figure 6. Image-to-model toolbox applied to the (a) Los Angeles Wilshire/I-405N On-Ramp, (b) Los Angeles I10/I405N Interchange, and (c) Coronado Bridge in San Diego.
Future Work Beyond Development of Basic Capabilities

Upon the development of basic capabilities of BridgeR, we plan to couple it with another database that we will harvest on freight tonnage and cargo value by regions of origin and destination, and associated routing information. This coupling will enable direct case studies on potential interruptions to movement of goods and services in a given region due to seismic events and the resulting economic losses at a very high level of granularity. By modeling all bridge structures comprising a regional transportation network, structure-specific fragility curves for each structure can be established. Once component-level fragility information is paired with site-specific seismic hazard data, the effect of seismic events on a series of bridges and their critical components can be quantified and translated into post-event traffic capacity measures.

Acknowledgments

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References