VULNERABILITY FUNCTIONS FOR BRIDGES IN SEISMIC REGIONS OF EGNA TIA MOTORWAY IN NORTHERN GREECE

Asterios LIOLIOS¹, Panagiotis PANETSOS² & Angelos LIOLIOS³

¹,³Democritus University of Thrace, Xanthi, Greece
²Egnatia Odos S.A., Thessaloniki, Greece

Abstract: The paper considers the problem of computing analytically the vulnerability curves, and so constructing the fragility curves to estimate the vulnerability of Civil Engineering Structures, such as buildings and especially bridges. Emphasis is given here for a special bridge of the motorway Eg natia Odos, Northern Greece. The methodology applied in this paper involves the use of the Finite Element Method (FEM) and of pushover analysis for the computation of the capacity curve of the bridge in combination with inelastic demand spectra for the estimation of the degree of damage for a given peak ground acceleration (PGA).

Key words: Earthquake Structural Engineering, Bridge Vulnerability Functions

1. Introduction.

Vulnerability functions for Civil Engineering structures represent a critically important step in seismic damage estimation process. Estimating urban seismic risk in Earthquake Engineering is the key element in formulating mitigation and disaster planning strategies [1]. In this respect, development of vulnerability relationships for both, the existing and under design Civil Engineering structures, represents a critically important step in damage estimation process.

Scope of the vulnerability analysis is the creation of the so-called fragility curves [1-4,9-11], through which the probability that a specific damage level will be exceeded for a given intensity of a seismic event may be quickly estimated, supporting significantly the decision-making procedures. So, fragility curves for Civil Engineering Structures, such as buildings and especially bridges, are a useful tool for the assessment of the damage they may sustain for a certain level of earthquake shaking. In combination with seismic hazard analysis at the bridge sites, they can lead to a reliable assessment of the seismic risk of highways. Furthermore, they can even be used by the authorities in charge to prioritize the on site aftershock inspections, in order to check the structural integrity of the bridges subjected to a severe seismic event.

Several methodologies dealing with the assessment of fragility curves for bridges can be found in recent literature, based on either empirical or analytical procedures [2-3,9-11]. Also, methodologies originally proposed for buildings can sometimes be extended for use in the case of bridges [2-4,14].

¹ Professor, Democritus University of Thrace, Dept. Civil Engineering, Inst. Structural Mechanics and Earthquake Engineering, GR-671 00 Xanthi, Greece. (e-mail: liolios@civil.duth.gr)
² PhD, Bridge Maintenance Department, Egnatia Odos S.A., Thessaloniki, Greece, (e-mail: ppane@egnatia.gr)
³ PhD Candidate, Democritus University of Thrace, Dept. Civil Engineering, Inst. Structural Mechanics and Earthquake Engineering, GR-671 00 Xanthi, Greece. (e-mail: angelosliolios@gmail.com)
In the present article, a simplified analytical methodology for the evaluation of vulnerability curves for bridges having deck on precast beams, seating through elastomeric bearings on the piers and with seismic stoppers is presented. The methodology combines the nonlinear static pushover procedure and the capacity spectrum method [1-4, 9-11], and in connection to the details of [4] is applied for establishing fragility curves for an existing reinforced concrete bridge crossing a steep slope in the Kristallopigi – Psilorahi section of Egnatia Motorway, in the county of Epirus, Northern Greece.

Egnatia Odos is a new motorway that crosses Northern Greece in an E-W direction. It is currently the largest and technically the most demanding highway project in Greece, and one of the biggest ones under current (2008-2009) construction in Europe. Moreover, for the design and construction of Egnatia Motorway, a lot of Applied Mechanics topics are involved, e.g. structural and seismic mechanics, geotechnical and transport engineering, hydraulic and environmental engineering, etc. So, Egnatia Motorway can be considered as an active field of Applied Mechanics. Its main axis has a length of 670 km and includes about 1900 special structures (bridges, tunnels and culverts). These structures are expected to withstand several minor or moderate earthquakes during their life, and may be damaged if they are subjected to a major (catastrophic) earthquake. So, the construction of their fragility curves is very significant. The bridge examined herein is a structurally representative one of many bridges in Egnatia Motorway, and in Greece more generally.

2. Method of Analysis

The vulnerability functions, required for the fragility curves, are expressed [2-4, 9-11] in terms of a Lognormal cumulative probability function in the form of next eq. (1):

\[
P_f(DP \geq DP_i \mid S) = \Phi \left( \frac{1}{\beta_{tot}} \ln \left( \frac{S}{S_{mi}} \right) \right)
\]

Here \( P_f(\cdot) \) is the probability of the damage parameter \( DP \) being at, or exceeding, the value \( DP_i \) for the \( i \)-th damage state for a given seismic intensity level defined by the earthquake parameter \( S \) (here the Peak Ground Acceleration-PGA or Spectral Displacement-\( S_d \)), \( \Phi \) is the standard cumulative probability function, \( S_{mi} \) is the median threshold value of the earthquake parameter \( S \) required to cause the \( i \)-th damage state, and \( \beta_{tot} \) is the total lognormal standard deviation. Thus, the description of the fragility curve involves the two parameters, \( S_{mi} \) and \( \beta_{tot} \), which must be determined.

Now we consider briefly the problem of computing the vulnerability functions (2.1) for Civil Engineering Structures, such as buildings and especially bridges. For the latter ones, the case of reinforced concrete bridges with seismic stoppers is herein investigated. This case is a Contact Mechanics problem. So, such bridges can be considered as nonlinear elastic and inelastic systems with impacts which arise in mechanical and civil engineering applications. In Civil Engineering applications, such systems arise also, besides in the above analysis of bridges with seismic stoppers, in the analysis of pounding of adjacent buildings.

Next it is briefly described the general problem of the seismic pounding of adjacent structures. This problem belongs to the so-called Dynamic Inequality Problems of Mechanics, for which a strict mathematical treatment can be obtained by using the variational or hemivariational inequality concept. As well known, the latter one has been introduced in Mechanics by P.D. Panagiotopoulos [5]. As concerns their numerical treatment, many significant contributions are already available, see e.g. [5,6]. So, for the case of two interacting structures (A) and (B), following e.g. the procedure of [7,8], the problem is first formulated as an inequality one by using concepts of Non-Convex Analysis. Next, double discretization, in space by the Finite Element Method and in time by a direct-time integration scheme (e.g. the central
difference method), and optimization methods are used. Thus, by piecewise linearization of the interface unilateral contact laws, at each time-step a nonconvex linear complementarity problem of the following matrix form with reduced number of unknowns is finally solved:

\[(2.2) \quad v \geq 0, \quad A v + a \leq 0, \quad v^T (A v + a) = 0.\]

So, the nonlinear Response Time-History (RTH) for a given seismic ground excitation can be computed.

As was mentioned in the Introduction, the present study focuses on the simplified practical fragility analysis of bridges, that involve impacts due to the seismic stoppers designed to effectively withstand earthquake loads and reduce the size of the piers. For such a practical simplified analysis, these systems are represented by single and multi degree of freedom models with piecewise linear elastic stiffness elements that often involve strong inelastic behavior in parts of the system. So, the previous general approach for pounding of adjacent structures is simplified by considering the simple bridge with seismic stoppers shown in Figure 1a. The bridge deck is connected to the piers by elastomeric bearings and seismic stoppers are added on the pier caps that have a small gap with the deck structure so that the elastomeric bearings are free to move under ambient or traffic loads, while they impact on the stoppers only under moderate or strong earthquake loads. Activation of the stoppers due to impact results in sudden increase of the stiffness of the structure. The gaps between the stoppers and the bearings are usually selected such that the impact with the stoppers occurs before the pier yielding.

\[\text{Fig. 1: Schematic diagram of (a) single span bridge and (b) multi span bridge.}\]
From the previous analysis is obvious that the damage level depends on the input seismic excitation, i.e. the seismic ground acceleration. As well known from Structural Dynamics and Earthquake Engineering [1], because this input is not known for future earthquakes, the *spectral approach* is used according to various aseismic building codes, e.g. the Greek Aseismic Code EAK2000 [12]. So here, instead of a non-linear dynamic analysis, which is time consuming [1], the approach of [4,14] is followed. According to equation (1), the description of the fragility curve involves only two parameters, $S_{mi}$ and $\beta_{tot}$. The first parameter $S_{mi}$ is estimated on the basis of the capacity spectrum method [1], wherein the demand spectrum is plotted for a range of values of the earthquake parameter $S$ (in spectral acceleration vs. spectral displacement format) and it is superimposed on the same plot with the capacity curve of the bridge. The earthquake parameter used in this study is the peak ground acceleration (PGA). The second parameter of Eq. (1) is the total lognormal standard deviation $\beta_{tot}$, which takes into account the uncertainties in seismic input motion (demand), in the response and resistance of the bridge (capacity), and in the definition of damage states. This parameter ($\beta_{tot}$) can be estimated by a statistical combination of the individual uncertainties (in demand, capacity, and damage state definition) assuming these are statistically independent. On the basis of empirical fragility curves obtained from actual bridge damage data, the value of $\beta_{tot}$ was set [4,14] equal to 0.6; due to the lack of a more accurate estimation of uncertainties in capacity, demand and damage states.

Due to limited space here, for details for the main steps of the proposed methodology see [4, 14-16].

3. **The case of an Egnatia Motorway bridge with seismic stoppers**

The bridge considered herein is the G2 valley-bridge near Kristallopigi, Epirus, built on the west sector of the Egnatia Motorway, in northern Greece.

![Fig. 2 (Photos 1,2): The G2/Kristallopigi bridge on Egnatia Motorway, Northern Greece.](image-url)
The 100m long bridge is carrying the right branch of the motorway over a steep mountainy slope near Kristallopigi. The bridge consists of three equal spans, each constructed using six 33m long prestressed – precast concrete beams that rest on two piers and two abutments via elastomeric bearings, as shown in Photos 1,2 of Fig.2. The reinforced concrete piers are twin square columns, 20m high, framed by an orthogonal beam that supports the precast beams through 6 type NB4 rectangular elastomeric bearings with dimensions 600x700x255 (135) in (mm). A 25cm thick in situ reinforced concrete slab, on the top of the beams, continues over the piers. It is acting as a diaphragm along the total length of the bridge, which is separated by the abutment ballast walls through elastometallic anchored joints, by gaps of 20 cm. Stoppers on the pier’s beams were designed to be distant from the superstructure such as to be activated after the exceeding of the maximum spectral displacement. Due to limited space here, details for the geometric and elastic characteristics of the bridge elements are given in [14-16], where also the computation steps for obtaining the fragility curves shown in Fig. 3 are given in details.

![Fragility curves of the G2 Kristallopigi bridge, Egnatia Odos motorway, Northern Greece.](image)
Conclusions
A simplified methodology has been presented for the calculation of the vulnerability curves of bridges in the presence of seismic stoppers. This methodology, using the Finite Element Method (FEM), is based on a modal pushover nonlinear static analysis and on a capacity demand spectrum approach, instead of a time consuming non-linear dynamic based vulnerability analysis. Using the aforementioned approach, fragility curves were developed for the G2 Kristallopiogigi valley bridge of Egnatia Odos motorway, in Northern Greece.

REFERENCES