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ВЕРОЯТНОСТЕН СЕИЗМИЧЕН АНАЛИЗ ЧРЕЗ МОНТЕ КАРЛО СИМУЛАЦИИ НА МОСТОВЕ НА МАГИСТРАЛА „ЕГНАТИЯ“ В СЕВЕРНА ГЪРЦИЯ

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PROBABILISTIC SEISMIC ANALYSIS BY MONTE CARLO SIMULATION FOR EGNATIA HIGHWAY BRIDGES IN NORTHERN GREECE

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Abstract:
The present paper deals with a simplified analytical methodology for the evaluation of vulnerability curves for bridges. The methodology combines the nonlinear static pushover procedure, the capacity spectrum method, and Monte Carlo simulation techniques for the treatment of various uncertainties. The methodology is applied for establishing fragility curves for an reinforced concrete bridge in the Kavala section of Egnatia Motorway, in the county of East Macedonia, Northern Greece. The Kavala bridge examined herein is a structurally representative one of many bridges in Egnatia Motorway, and in Greece more generally.

Keywords:
Earthquake Engineering, Computational Structural Mechanics, Egnatia Highway Bridges, Monte Carlo Techniques, Vulnerability Functions.

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1. INTRODUCTION

As well-known [1-3, 16, 24], for the seismic analysis and assessment of Civil Engineering Structures, and especially of highway bridges, a reliable estimation of the input parameters must be realized taking into account a lot of uncertainties. These mainly concern the holding properties of the building materials which had been used for reinforced concrete (RC) structures, e.g. the spatial variation of the strength and elasticity modulus of concrete and steel, as well as the cracking effects etc. [8-10, 19, 20, 24].

On the other hand, vulnerability analysis of Civil Engineering Structures, and especially for highway bridges, represents a critically important step in their seismic damage estimation and protection process [2, 3, 21]. The relevant fragility curves provide the probability that a specific damage level will be exceeded for a given intensity of a seismic event [15, 17]. In this respect, development of vulnerability relationships for both, the existing and under design Civil Engineering structures, is a key element in formulating mitigation and disaster planning strategies in Civil Earthquake Engineering for the estimation of the urban seismic risk [21]. 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.

The present paper deals with a simplified analytical methodology for the evaluation of vulnerability curves for bridges. The methodology combines the nonlinear static pushover procedure, the capacity spectrum method [4, 15, 17], and Monte Carlo simulation techniques for the treatment of various uncertainties [1, 3, 5, 13, 16]. The methodology is applied for establishing fragility curves for an reinforced concrete bridge in the Kavala section of Egnatia Motorway, in the county of East Macedonia, Northern Greece. The Kavala bridge examined herein is a structurally representative one of many bridges in Egnatia Motorway, and in Greece more generally.

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 recent (2006-2010) construction in Europe. Moreover, for the design and construction of Egnatia Motorway, a lot of Applied Science topics are involved, e.g. structural and seismic mechanics, geotechnical and transport engineering, hydraulic and environmental engineering, probabilistic methods [1, 3, 11, 23, 24], etc. The total length of Egnatia Motorway is about 1000 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 [2]. So, the construction of their fragility curves is very significant.

2. METHOD OF ANALYSIS

The probabilistic approach for the seismic analysis of the considered RC structures is herein obtained through Monte Carlo simulations. As well-known, see e.g. [1, 3, 5, 13, 16, 22, 26], Monte Carlo simulation is simply a repeated process of generating deterministic solutions to a given problem. Each solution corresponds to a set of deterministic input values of the underlying random variables. A statistical analysis of the so obtained simulated solutions is then performed. Thus the computational methodology consists of solving first the deterministic problem for each set of the random input variables and finally realizing a statistical analysis.

Details of the methodology concerning the deterministic problem and the probabilistic aspects are given in the next sections.

2.1. The deterministic procedure

As was mentioned in the Introduction, the present study focuses on the simplified practical fragility analysis of bridges. Details have been presented in [15, 17, 21, 23]. The vulnerability functions, required for the fragility curves, are expressed in terms of a Lognormal cumulative probability function in the form of next eq. (1):

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

Here $P_f\,(\cdot)$ is the probability of the damage parameter *DP* being at, or exceeding, the value *DPi* 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-Sd), Φ 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 β_{tot} is the total lognormal standard deviation. Thus, the description of the fragility curve involves the two parameters, S_{mi} and β_{to}, which must be determined.

The damage level depends on the input seismic excitation, i.e. the seismic ground acceleration. As well known from Structural Dynamics and Earthquake Engineering [4], because this input is not known for future earthquakes, the spectral approach is used according to various aseismic building codes [6, 7, 9, 10], see e.g. the Greek Aseismic Code EAK2000 [6].

According to equation (1), the description of the fragility curve involves only two parameters, S_{mi} and β_{tot}. The first parameter S_{mi} is estimated on the basis of the capacity spectrum method [4, 15, 17], 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 β_{tot}, which incorporates the various uncertainties in the seismic demand, in the response and the capacity of the bridge, and also in the definition of the damage index and damage states. So, it 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 (β_{tot}) can be estimated in the frame of Monte Carlo simulation techniques [1, 3, 5, 13], by realizing a statistical combination of the individual uncertainties, assuming these are statistically independent. Thus, on the basis of Monte Carlo simulations and empirical fragility curves obtained from actual Egnatia Highway bridges damage data in the frame of the research project ASPROGE [2], the value of β_{tot}) was optimally estimated to be equal to 0.60 according to the probabilistic procedure described in the next subsection.

2.2. The probabilistic procedure

In order to calculate the random characteristics of the response of the considered RC Egnatia Highway bridges, the Monte Carlo simulation is used [1, 3, 5, 11, 13, 14, 16]. As mentioned, the·main element of a Monte Carlo simulation procedure is the generation of random numbers from a specified distribution. Systematic and efficient methods for generating such random numbers from several common probability distributions are available. The random variable simulation is implemented using the technique of Latin Hypercube Sampling (LHS) [22, 26]. The LHS is a selective sample technique by which, for a desirable accuracy level, the number of the sample size is significantly smaller than the direct Monte Carlo simulation.

In more details, a set of values of the basic design input variables can be generated according to their corresponding probability distributions by using statistical sampling techniques. The generated basic design variables are treated as a sample of experimental observations and used for the system deterministic analysis to obtain a simulated solution as in subsection 2.1. is described As the generation of the basic design variables is repeated, more simulated solutions can be determined. Finally, statistical analysis of the simulated solutions is then performed. The results obtained from the Monte Carlo simulation method depend on the number of the generated basic design variables used. Such design variables for the herein considered RC structures are the uncertain quantities describing the plastic-hinges behavior and the spatial variation of input materials parameters.

Concerning the plastic hinges in the end sections of the frame structural elements [20], a typical normalized moment - normalized rotation backbone is shown in Figure 1, see [26]. This backbone hardens after a yield moment of a_{My} times the nominal, having a non-negative slope of a_h up to a corner normalized rotation (or rotational ductility) μ_c where the negative stifiness segment starts. The drop, at a slope of a_c, is arrested by the residual plateau appearing at normalized height r that abruptly ends at the ultimate rotational ductility μ_u. The normalized rotation is the rotational ductility $\mu=\theta/\theta^{yield}$.

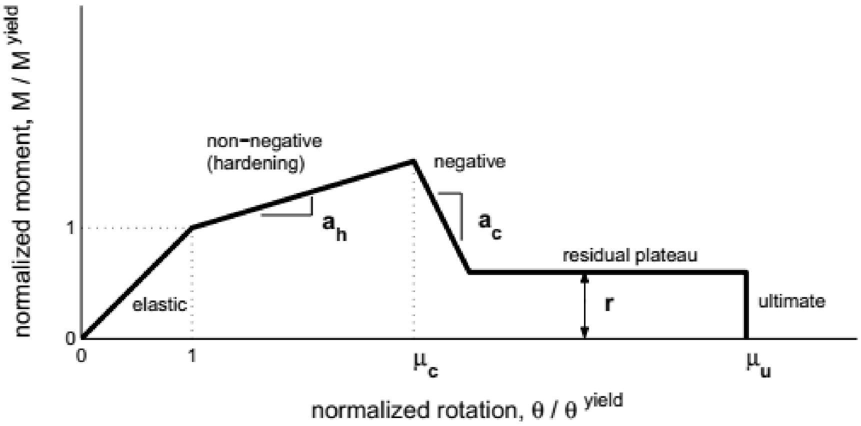

Figure 1. Representative moment-rotation backbone diagramme for plastic hinges [26].

The above six backbone parameters in Fig. 1, namely a_h, a_c, μ_c, r, μ_u and a_{My}, $= M/M_y$ are assumed to vary independently from each other according to Normal distribution [1, 13]. Typical distribution properties for these uncertain parameters concerning plastic hinges in frames according to [26] are given in Table 1. The table values concern the mean value, the coefficent of variation (COV) and the upper and lower bounds of the truncated Normal distribution.

Table 1. The distribution properties of the uncertain parameters for a typical plastic hinge [26]

	mean	COV	min	max	type
a_{My},	1.0	20%	0.70	1.30	Normal-tr.
a_h	0.1	40%	0.04	0.16	Normal-tr.
μ_c	3.0	40%	1.20	4.80	Normal-tr.
a_c	-0.5	40%	-0.80	-0.20	Normal-tr.
r	0.5	40%	0.20	0.80	Normal-tr.
μ_u	6.0	40%	2.40	9.60	Normal-tr.

Generally, following [14], by using Monte Carlo simulations, probabilistic moment-curvature curves can be developed, as shown in the Figure 2.

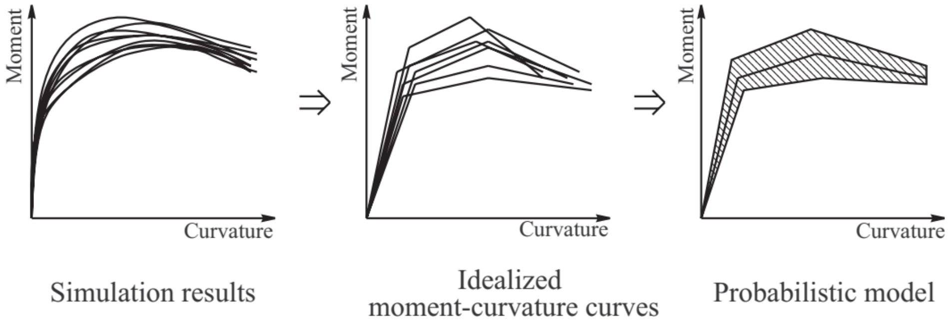

Figure 2. Process of developing a probabilistic moment-curvature curve [14].

As regards the random variation of parameters for the materials, which had been used for the building of the Egnatia Highway RC structures, their input estimations concern mainly the strength of the concrete and the steel and the elasticity modulus. According to [2] and JCSS (Joint Committee Structural Safety), see [12], concrete strength and elasticity modulus follow the Normal distribution, whereas the steel strength follows the Lognormal distribution. Finally, as concerns the treatment of strong seismic motions uncertainties, the incremental dynamic approach (IDA), see [25], can be used.

3. THE INVESTIGATED CASE OF THE KAVALA RAVINE BRIDGE IN EGNATIA MOTORWAY

As mentioned in Introduction, in order to investigate the anti-seismic security of Egnatia Motorway bridges, the research project ASPROGE [2] has been realized.

Further, a simplified methodology has been developed for the calculation of the vulnerability curves of bridges in the presence of seismic stoppers, see [15, 17.18]. 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 vulnerability analysis based on dynamic contact mechanics.

Applying the methodology proposed in the previous section, the seismic vulnerability of a structurally representative bridge of Egnatia Motorway in East Macedonia section has been assessed. This bridge is the 2nd ravine Kavala bridge shown in Fig. 3, with total length 180 m (four 45m long spans of simply supported prestressed beams). 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. Details for the geometric and elastic characteristics of the bridge elements are given in (ASPROGE, 2007), see [2].

The obtained relative vulnerability curves are shown in Figures 4 and 5.

Figure 3: The Kavala bridge on Egnatia Motorway, East Macedonia.

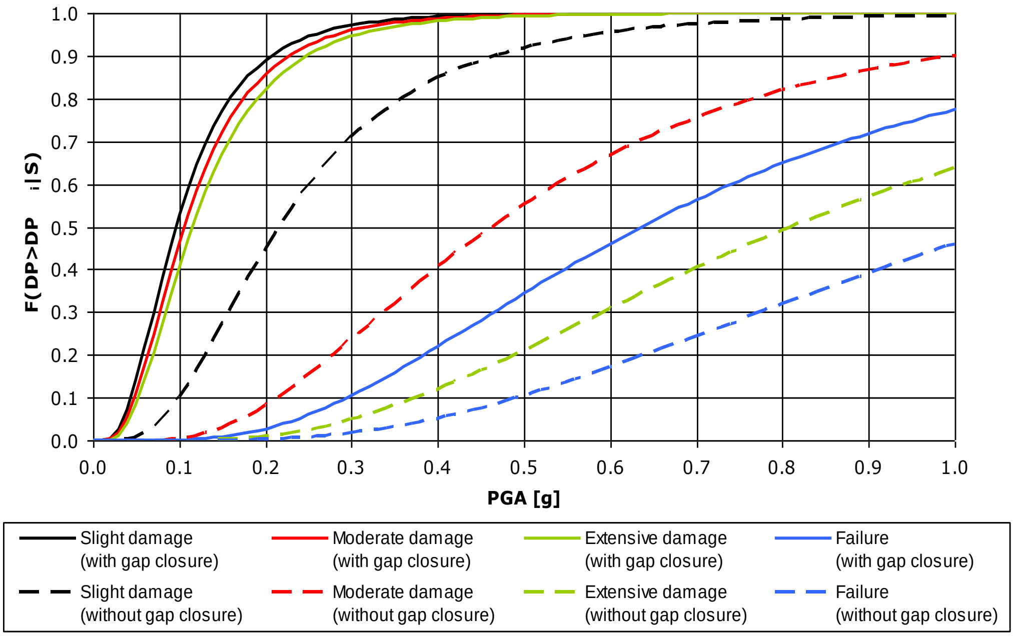

Figure 4. Fragility curves of the Kavala Ravine bridge: Longitudinal direction.

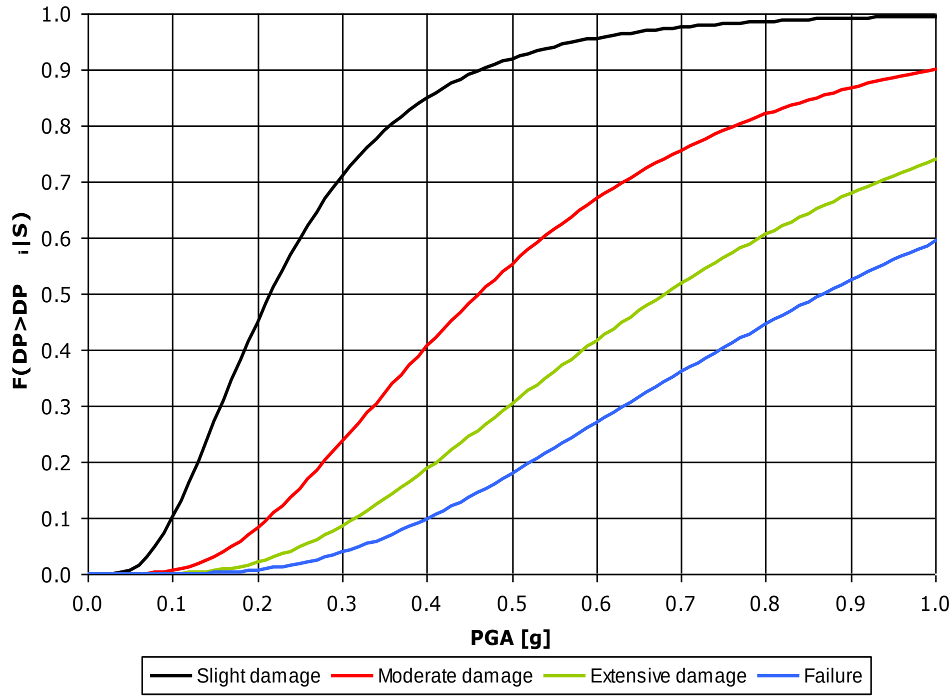

Figure 5. Fragility curves of the Kavala Ravine bridge: Transverse direction.

4. CONCLUDING REMARKS

Vulnerability curves for bridges can be computed by the herein presented simplified analytical methodology. This methodology combines the nonlinear static pushover procedure, the capacity spectrum method and probabilistic methods. The Monte Carlo simulation technique for the treatment of various uncertainties is used. Application of the proposed methodology has been realized for establishing fragility curves for an reinforced concrete bridge in the Kavala section of Egnatia Motorway, in the county of East Macedonia, Northern Greece.

REFERENCES

[1] Ang, A. H., & Tang, W. H. (1984). Probability concepts in engineering planning and design, vol. 2: Decision, risk, and reliability. New York: Wiley.
[2] ASPROGE: Research Project for the ASeismic PROtection of Bridges. Egnatia Odos S.A., Thessaloniki, Greece (2007).
[3] Casciati, F., Augusti, G., & Baratta, A. (2014). Probabilistic methods in structural engineering. CRC Press.
[4] Chopra, A.K. (2007): Dynamics of Structures. Theory and Applications to Earthquake Engineering. Pearson Prentice Hall, New Jersey.
[5] Dimov, I. T. (2008). Monte Carlo methods for applied scientists. World Scientific.
[6] EAK 2000: Greek Aseismic Code, Organization of Seismic Protection (OASP), Athens.
[7] EC8, EN 1998-1 (2005). “Eurocode 8 - Design of structures for earthquake resistance”, European Committee for Standardization, Brussels.
[8] Fardis, M.N., (2009). “Seismic design, assessment and retrofitting of concrete buildings: based on EN-Eurocode 8”. Springer, Berlin.
[9] FEMA P440A (2009). “Effects of Strength and Stiffness Degradation on the Seismic Response of Structural Systems.” U. S. Department of Homeland Security, Federal Emergency Management Agency.
[10] Greek Retrofitting Code-(KANEPE) (2017). Greek Organization for Seismic Planning and Protection (OASP), Athens, Greece, 2013. (In Greek).
[11] Hwang H.H.M and Jaw J.W. (1990): Probabilistic damage analysis of structures. J. Struct. Enging. ASCE, 116(7), 1992-2007.
[12] JCSS. Probabilistic Model Code-Part 1: Basis of Design (12th draft). Joint Committee on Structural Safety, March 2001. Available from: http://www.jcss.ethz.ch/.
[13] Kottegoda, N., & Rosso, R. (2000). Statistics, probability and reliability for civil and environmental engineers. McGraw-Hill, London.
[14] Lee, T. H., & Mosalam, K. M. (2006). Probabilistic seismic evaluation of reinforced concrete structural components and systems. Report 2006/04, Pacific Earthquake Engineering Research Center. University of California, Berkeley, USA Google Scholar.
[15] Liolios Ast., Panetsos P. and Liolios Ang. (2011), Egnatia Motorway, Northern Greece: Seismic Risk Assessment of Bridges. In: Folic, R. & Radonjanin V. (eds.), Contemporary Civil Engineering Practice 2011, Proc. Intern. Conf., Andrevlje, 19-20 May 2011, Serbia.
[16] Melchers R.E. & Beck, A.T. (2018), Structural Reliability Analysis and Prediction, 3rd Edition, Wiley: New York.
[17] Moschonas, I.F., Kappos, A.J., Panetsos, P., Papadopoulos, V., Makarios, T., Thanopoulos, P. (2009). "Seismic fragility curves for greek bridges: Methodology and case studies". Bulletin of Earthquake Engineering, 7(2), pp. 439-468.
[18] Panetsos, P. & Liolios, A. (2010). “Seismic vulnerability functions for a bridge case of Egnatia motorway”. In: Kappos, A.J. (editor), “Aseismic design and constructions in EGNATIA ODOS, the highway connecting Epirus through Macedonia to Thrace and eastern border of Greece”, Hellenic Society for Earthquake Engineering, Thessaloniki, 2010.
[19] Penelis G. Gr., & Penelis Gr. G. (2014). “Concrete Buildings in Seismic Regions”. CRC Press.
[20] Priestley, M.J.N., Seible, F.C. and Calvi, G.M. (1996). “Seismic Design and Retrofit of Bridges”. John Wiley & Sons, Inc..
[21] Rossetto, T., & Elnashai, A. (2003). Derivation of vulnerability functions for European-type RC structures based on observational data. Engineering Structures, 25(10), 1241-1263.

[22] Thomos, G.C. & Trezos C.G. 2006. Examination of the probabilistic response of reinforced concrete structures under static non-linear analysis, Engineering Structures, Vol. 28, 120–133
[23] Shinozuka, M., Feng, M.Q., Lee, J., and Naganuma, T. (2000): Statistical Analysis of Fragility Curves. Journal of Engineering Mechanics, ASCE, 126, No. 12, 1224-1231.
[24] Strauss A., Frangopol D.M., Bergmeister, K.. (2010). "Assessment of Existing Structures based on Identification", Jnl Struct. Eng. ASCE, 136(1), 86-97.
[25] Vamvatsikos, D. and C.A. Cornell, (2002). "Incremental dynamic analysis". Earthquake Engineering and Structural Dynamics, vol. 31, 491–514.
[26] Vamvatsikos, D., & Fragiadakis, M. (2010). Incremental dynamic analysis for estimating seismic performance sensitivity and uncertainty. Earthquake engineering & structural dynamics, 39(2), 141-163.