ANALYTICAL FRAGILITY CURVES FOR TYPICAL BRIDGES IN REPUBLIC OF MACEDONIA

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Summary: *Presented in this paper is the vulnerability of road bridges typical for the Republic of Macedonia through analytical vulnerability curves. The typical bridges were selected on the basis of the performed inventory study within which statistic analysis of in situ collected data on all vital structures along the national roads and high-ways in the territory of RM was carried out. The results from the performed statistic analysis show that most of the bridge structures represent reinforced concrete girder bridges. To define their vulnerability, there were selected representative examples with variable geometrical characteristics whose values were adopted in combination with the values obtained from the statistic analysis. The vulnerability curves were obtained analytically, applying the multiple stripe analysis method. Numerous nonlinear analyses were performed with real time histories. PGA was used as a measure of intensity. Based on the nonlinear behaviour of the bridge and the development of displacements in the bearings, four levels of damage were defined.*

Keywords: *Reinforced concrete girder bridge, fragility curve, vulnerability assessment*

1. INTRODUCTION

Seismic risk assessment represents a key element in the formulation and development of strategies for mitigation and planning of earthquake consequences. In that respect, definition of vulnerability of existing bridge structures and bridge structures in the phase of design and construction, represents a critically important step in the process of vulnerability assessment.

To assess the seismic vulnerability of bridge structures in a certain region, in the ideal case, one should develop vulnerability curves for each structure taken separately based on its design parameters. This approach is very costly and hence practically inapplicable. Considering the fact that, within a certain region, many of the bridge structures are similar according to their characteristics, bridges can be generalized, i.e., they can be

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classified such that each bridge is classified into a certain group or type. In that case, seismic vulnerability is evaluated, i.e., vulnerability curves are generated for each type of bridge structues taken separately instead of each individual bridge.

2. CLASSIFICATION SYSTEM FOR ROAD BRIDGES IN THE TERRITORY OF RM

Republic of Macedonia is characterized by a well developed road network which, according to the Public Enterprize for National Roads runs to a length of 14 182km and includes high-ways, national roads, regional and local roads. Within these investigations, bridge structures along national road sections including Corridor 10 (north – south) were analyzed. A total of 7 road sections (M-1, M-2, M-3, M-5, M-5, M5-arm and M-6 (Fig. 1)) with a total number of 459 bridges (bridges, underpasses, overpasses, viaducts and pipelines) were analyzed.

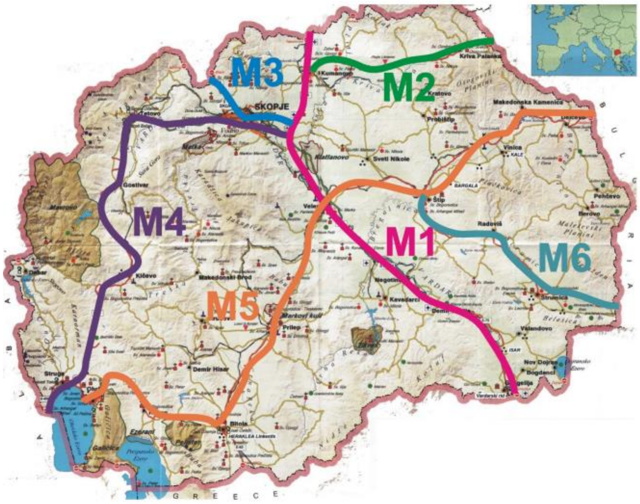

Figure 1. National road network in the territory of the Republic of Macedonia

An inventory study was performed including in situ collected data on all vital structures along the national road directions and highways in the territory of RM. For each of these bridges, more than 80 data were collected among which: number of spans, type of material, structural system, type of superstructure, length of middle span, height of central piers, type of abutments, width of deck structure, position of the bridge in respect to the barrier, conditions of the superstructure, conditions of the substructure, etc.. These data are part of the database resulting from the long year cooperation beteween the Fund for National and Regional Roads, Skopje and the Institute for Earthquake Engineering and Engineering Seismology through the project “Information System for Inventory and Monitoring of the Conditions of Bridge Structures Along the Road Network of the Republic of Macedonia” ([1], [2], [3], [4], [5], [6]). Within the frames of this project, in accordance with the recommendations given by the World Bank, the database on bridges also included all structures with a bridge structural system, meaning that overpasses and underpasses as well as viaducts were included in addition to bridges. The information system contains two different types of data, namely data of a time invariable and data of a time variable character.

The data from the base that are of a time invariable character mainly represent administrative and technical data on each registered structure and are entered in a previously prepared inventory form on each structure taken separately. The filled out inventory form provides a high quality insight into the structure and represents the so called “identity card of the structure”. The data in the database that are of a time variable character are entered in the prepared forms for general main inspection, i.e., through in situ inspection of their components. The general main inspection is carried out at previously defined time periods.

The methodology used in the realization of this project complied with the then known world experience in the domain of monitoring of conditions prevailing along transportation systems, including structures that represent their constituent part. In the realization of the project, the instructions given by the International Bank for Reconstruction and Development were observed.

Some of the results obtaind from the analysis of the data from the database are shown in Fig. 2 and Fig. 3.

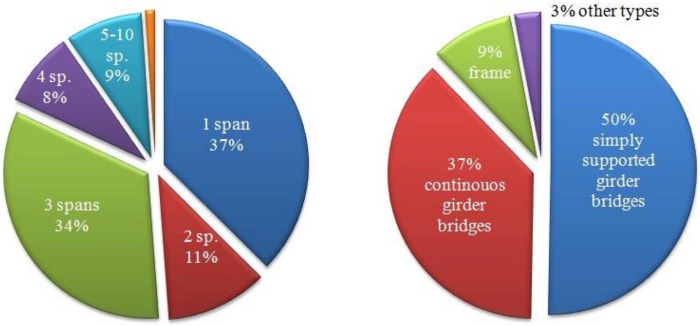

Figure 2. Classification of bridge structures according to number of spans and structural system

Fig. 2 shows a review of the number of bridges according to the number of spans (to the left) and structural system (to the right). On the left presentation, one can see that most of the bridges have one, i.e., three spans, i.e., over 70% of all bridges are with a single or three spans. As to the structural system, according to Fig. 2 (to the right), each second bridge in RM represents a simply supported girder bridge.

In accordance with the presented reviews, a three span simply supported girder bridge was selected as a typical bridge.

To define the vulnerability of the selected bridge encompassing the characteristics of all bridges of this group, four representative bridges were selected. The geometrical characteristics of these bridges were selected in accordance with the results from the performed statistic analysis of all individual data from the database. Some of the results obtained for this type of bridges are given further in the text, while details on the performed statistic analysis of all types of bridges taken separately are given in [7].

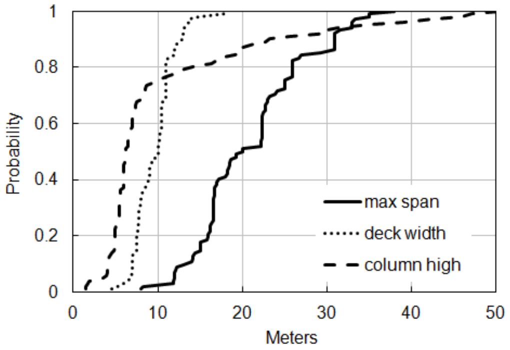

Figure 3. Empirical cumulative distribution functions for the geometrical characteristics of MSSSCGB

Fig. 3 shows the empirical cummulative distribution functions for the maximum span, width of the deck structure and height of the central pier developed on the basis of the mean value and the standard deviation obtained by analysis of the collected data on all bridges taken separately. Combining the mean value plus/minus one standard deviation for the maximum span and height of each pier, 9 bridges were obtained. Out of these, only 4 were selected, accounting for more than 5% of the total number of bridges of this type. The value of the deck structure width was taken as constant.

The analytical models generated in this investigation are quite precize wherefore many data were necessary to model the different components of the bridge. The models were generated in the FELISA/3M, [11] computer programme, which is verified and developed at the Institute of Earthquake Engineering and Engineering Seismology, Ss. Cyril and Methodius University in Skopje. For each representative bridge, nonlinear analyses with time histories were carried out.

3. ANALYSIS OF REPRESENTATIVE BRIDGES

A typical reinforced concrete bridge with three spans consists of a superstructure (prestressed main girders, cross girders and a deck) that rests upon the substructure consisting of central piers – walls through elastomeric bearings placed upon single beams. The length of the spans is 14.5m, 21.0m and 27.5m, the height of the central columns is 3.5m and 10.6m, whereas the width of the deck structure of all representative bridges is the same and amounts to 9.7m. The cross-section of the central column has a width of 6.0m and a height of 1.0m and it is reinforced with a reinforcement whose area, in accordance with the valid standards and norms, amounts to 1% of the total area of the pier cross-section.

Under the effect of the seismic load applied in both horizontal directions simultaneously in the analysis, the superstructure (the main girders, the cross girders and the deck) was expected to behave in the linear range. Therefore, the main girders were modelled with un-cracked cross-sections, i.e., elastic linear FRAME 3D beam elements (6 degrees of freedom at each point). The elastomeric bearings were modeled by LINK3N and elastic idealy plastic material, whose initial elastic stiffness in both horizontal directions amounted to 3380kN/m in accordance with the selected dimensions and the corresponding catalogue. The reinforced concrete piers were modeled by nonlinear 3D SOLID20N finite elements with 20 integration points. The value of the elasticity modulus was adopted to be 33000MPa, which is the corresponding concrete class for the construction of this type of bridges. For the reinforcement, TRUSS3N elements with elastic material model with elasticity modulus of 20000MPA and yielding stress of 400 MPa were used. The mode of modeling of the reinforced concrete elements by use of finite elements is shown in details in [8] and [9]. The finite element model of one of the representative bridges is presented in Fig. 5.

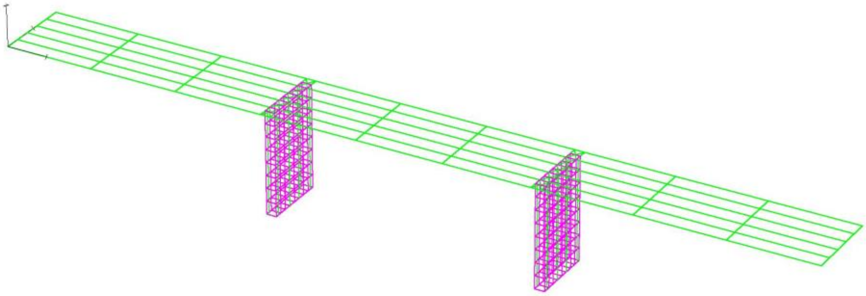

Fig. 5 FEM model of concrete girder bridge

Considered in the analysis was the soil-structure interaction defined on the basis of the theory of elastic half-space developed by Beredugo, Y.O. and Novak, M. [10]. The stiffness coefficients were obtained by an iterative procedure and they are frequency dependent.

3.1. SELECTION OF INPUT TIME HISTORIES

For the territory of the Republic of Macedonia, there are no recorded time histories of strong earthquakes, wherefore to achieve the seismic hazard level in the region, the real time histories from the database of the Pacific Earthquake Engineering Centre (PEER) in Berkeley, California were selected as an input for the nonlinear analysis. To obtain as reliable results as possible from the nonlinear dynamic analysis, the characteristics of the selected earthquakes corresponded to the seismic hazard defined for the territory of the Republic of Macedonia. In this way, a total of 9 earthquakes were selected. Eight (8) were from the database of the Pacific Earthquake Engineering Centre and the last one was the local earthquake recorded in Ulcinj, Montenegro in 1979. The selection of real time histories from the database was done according to three factors: magnitude, distance and soil type. They were selected according to the local site conditions. The spectra of the selected earthquakes (according to the number in the RSN database) are given in Fig. 4.

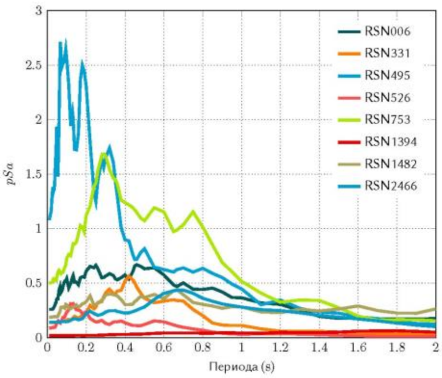

Figure 5. Spectra of time histories selected from the database of the Pacific Earthquake Engineering Centre PEER, Berkeley

Each structure was analyzed for the nine time histories scaled to 7 intensities (0.20g, 0.25g, 0.30g, 0.35g, 0.40g, 0.45g and 0:50g). Most of the analyses were done with a time step of 0.002 seconds. For this type of bridges, a total of 252 analyses were carried out.

4. DEFINITION OF DAMAGE INDEX AND DAMAGE LIMIT STATE

The discrete conditions of damage were defined based on the response of the structures obtained from the performed nonlinear static analyses during which, monitoring of the development of material nonlinearities at different loading phases was enabled. Nonlinear static analyses were conducted for all representative examples.

Based on the obtained results, the relationship between the maximum displacement of the superstructure obtained from the nonlinear analysis U and the ultimate displacement of the bridge superstructure U_u (Eq.1) were used to define the model of damage.

$$DI = \frac{U}{U_u} \tag{1}$$

This criterion was defined based on the main relationship: seismic demand – capacity of the bridge structure consisting of a superstructure, central piers and bearings in which the soil – structure interaction was included. The ultimate displacement from equation (1) represents a sum of ultimate displacement of the pier that includes the effect of the soil-structure interaction and the ultimate displacement of the bearing.

Due to the fact that all four representative bridges have different capacity, this index was normalized according to the index of displacement at the yielding moment DI_y for each bridge in accordance with its capacity. In this way, normalized indices of damage were obtained (Eq. 2).

$$I = \frac{DI}{DI_y} \tag{2}$$

In accordance with the obtained results on response of the structures, three limits of displacement, i.e.,damage were defined. The first indicates the yielding moment. Until the reaching of displacement U_y, minor deformations occur and the structure does not suffer any damage. The second limit is the moment when the structure achieves displacements $2U_y$, while the third limit is reaching displacements of $3.5\ U_y$. It is concluded that the structure experiences failure under all displacements exceeding U_u. The ultimate values for all damage levels are given in Table 1.

Table 1. Defined damage levels

	Level	Damages	Index
1	Negligible deformations	No damage	<1
2	Moderate deformations	Minor damage	1-2
3	Large deformations	Extensive damage	2-3.5
4	Failure	Failure	>3.5

5. FRAGILITY CURVES

From the performed 252 nonlinear analyses of all four representative bridges, there were obtained damage indices represented by probability distribution functions. To present the obtained indices, there was used the normal distribution of probability whose density function is represented by expression (3):

$$f_x(x)=\frac{1}{\sigma\sqrt{(2\pi)}}exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \tag{3}$$

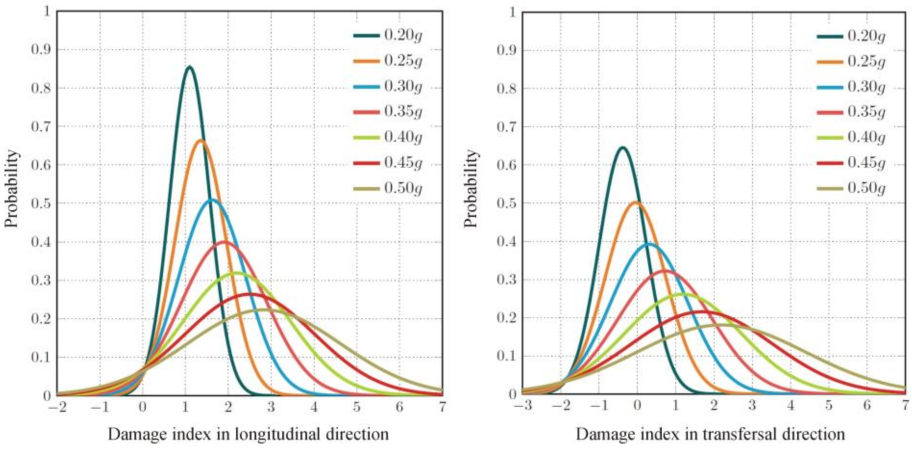

Figure 6. Probability density functions of girder bridges in longitudinal direction (left) and transverse direction (right)

where μ represents the mean value, while σ represents the standard deviation, i.e., dispersion of the obtained values. Fig. 6 shows the obtained probability density functions of the girder bridges in longitudinal (left) and transverse direction (right). The diagrams clearly show that the probability of achievement of a lower level of damage, i.e., area encompassed by the corresponding curve with the abscissa and ordinate axis, is greater under lower intensity levels. With the increase of the intensity level, the probability for occurrence of more extensive damage increases. It can also be concluded that there is a difference between the probability for damage in longitudinal and transverse direction of the girder bridge structures, i.e., girder bridges are more vulnerable in longitudinal direction.

Using the methodology of multiplied analyses by application of the approach involving maximization of the probabilistic function based on the number of analyses at which structures with corresponding level of damage were obtained, there were defined the parameters that characterize the vulnerability functions for all damage levels. The vulnerability curves are shown in Fig. 7, through the values of the damage probability matrix given in Table 2.

Table 2. Damage probability matrix

	Index	0.20g	0.25g	0.30g	0.35g	0.40g	0.45g	0.50g
Slight	<1	10.3	26.8	46.4	63.9	77.1	86.1	91.8
Moderate	1-2	6.8	16.8	29.8	43.5	56.1	66.8	75.3
Extensive	2-3.5	0.4	1.8	5.2	10.7	18.2	27.0	36.3
Failure	>3.5	0.0	0.0	0.3	0.9	2.5	5.2	9.3

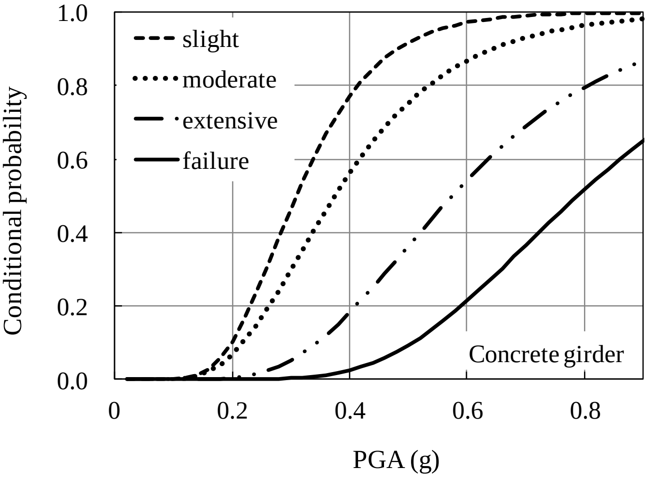

Figure 7.Vulnerability curves for reinforced concrete girder bridges in the Republic of Macedonia

From the obtained vulnerability curves, it can be concluded that the existing girder bridges (as designed) exhibit a satisfactory behaviour under the effect of an earthquake that may happen in this area. For a certain level of PGA(g), the probability of occurrence of minor or moderate displacements is similar, unlike the remaining levels. The vulnerability curves show that 50% of the structures will experience slight damage under an intensity level of 0.34g, whereas they will experience a moderate damage level under an intensity level of 0.37g. Under an earthquake of intensity of 0.57g, 50% of the girder bridges will experience extensive damage, while collapse will take place at 0.75 g. Namely, under an earthquake with intensity of 0.30 g, more than 46% of the girder bridges will experience slight damage, while less than 1% of the total number o bridges will experience failure.

6. CONCLUSION

This paper shows the results from the multi-disciplinary investigation that involved selection of typical bridges in the Republic of Macedonia through development of numerical mathematical models for which numerous nonlinear analyses were performed to finally develop vulnerability curves by using the approach involving multidisiplinary analyses. The obtained vulnerability curves show that the existing structures are characterized by an acceptable level of vulnerability, i.e., for the designed level of intensity, there is a 46% probability that the bridges will suffer minor damage, 30% that they will suffer moderate damage and 5% that they will suffer extensive damage. There is almost no probability for failure of any of these structures.

The vulnerability curves for the typical bridges in the Republic of Macedonia developed during the presented investigation are of a particular importance for assessment of the vulnerability that may affect risk reduction in disaster management. The conditions of the key elements of the transportation network of the Republic of Macedonia have a considerable effect upon the total post-earthquake scenario for the region.

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АНАЛИТИЧКЕ КРИВЕ ПОВРЕДЉИВОСТИ ЗА ТИПИЧНЕ МОСТОВЕ У РЕПУБЛИЦИ МАКЕДОНИЈИ

Резиме: *У овом раду, помоћу аналитичких крива повредљивости претстављена је повредљивост друмских мостова типичних за Републику Македонију. Типични мостови, изабрани су на основу направљене инвентарске студије, у чијем оквиру је извршена статистичка анализа података за све виталне објекте на магистралним путним правцима и аутопутевима на територији Републике Македоније, сакупљених на лице место. Резултати направљене статистичке анализе су показали да највећи број су гредни армиранобетонски мостови. За дефиницање њихове повредљивости изабрани су репрезентативни примерци са варијабилним геометријским карактеристикама, чије вредности су усвојене комбинацијом вредности добијених статистичком анализом. Криве повредљивости аналитички су добијене применом методе* multiple stripe *анализе. Направљене су бројне нелинеарне анализе за временским истојријама. Као мера интензитета употребљена је PGA. На основу реалног понашања моста и развоја померања у лежиштима дефинисана су четири нивоа оштећења.*

Кључне речи: *Армиранобетонски гредни мост, крива повредљивости.*