SAFETY ASSESSMENT OF BRIDGE STRUCTURES EXPOSED TO EARTHQUAKE HAZARD

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Assessment of the stability of existing bridges is very significant in the process of defining the optimal structural measures for their maintenance and strengthening. To define the optimal structural measures for repair and strengthening, it is necessary to establish a complete database on existing bridge structures containing their identification data as well as monitor their conditions. This paper describes a study on the bridge infrastructure network in Republic of N. Macedonia realized as part of the INFRA-NAT project (www.infra-nat.eu). The bridge database was developed based on the data collection form and allows to establish the detailed exposure model of the entire bridge network.

By considering the general characteristics of all the structures, to develop fragility functions for bridges exposed to seismic hazard, representative samples of bridges are considered. The connectivity of the network is modelled and the entire bridge network vulnerability is considered in a more comprehensive and global manner for seismic hazard. The scope of this work is to provide practical web-based tools and databases for each country with which more informed decisions can be made related to the most vulnerable parts of the country and where resources should be invested for increased resilience.

Keywords: bridge structures, seismic hazard, data base, fragility functions, NLTHA

1. INTRODUCTION

A functioning infrastructure network during emergencies is an important aspect for every country. Bridges represent critical elements as they provide reliable modes of transportation throughout a region. The growth of traffic loads, the variability of wind, seismic and hydraulic forces, and the natural deterioration of constitutive materials of bridges tend to increase their vulnerability. Since their collapse imposes high costs for their users and the local economies, they require proper and timely maintenance. Without adequate maintenance, the risk of collapse and the costs for their repair are increasingly higher over time, especially at the end of their serviceability period. Adding that much of the bridge infrastructure in N. Macedonia was constructed prior to the 1990s, when new legislation became effective [1], it is of crucial importance to monitor and assess the existing bridge infrastructure. Due to the fact that the collapse of bridges and the risk pertaining to fatalities are undesirable for the society, bridge engineering has developed tools for achieving acceptable conditions regarding bridge safety and functionality. These tools allow integration of assessments of bridge conditions, making decisions about maintenance and planning maintenance budget allocation over time for the road network or a single bridge.

A major component in determining the vulnerability of bridge infrastructure is associated with seismic events. Ensuring bridges do not collapse and are usable during the aftermath of an earthquake is crucial for relief efforts (e.g. access to hospitals, aid to be dispatched).

2. SELECTION OF BRIDGES

For the needs of the project aim, extensive activities have been carried out to collect and harmonise the bridge inventory data, with focus on the bridge structures placed on the main transportation routes. Depending on the level of available data, categorisation of the bridges was performed. Systematisation of the bridge inventory results in proper definition of characteristic bridge typologies for which physical vulnerability is assessed.

According to data completeness, the bridges are divided into 3 levels, starting from the Level 0 (most basic data involving location and total length) up to detailed data referring to type of superstructure, dimensions of structural elements, type of abutments and central piers, materials used for construction of the super- and sub-structure, type of traffic for which a bridge is intended as well as conditions of bridge structures (Level 1 and Level 2).

Out of the total number of collected bridges, there is data for material and structural system (Level 1) for 398 bridges, accounting for 59% of the total number of bridges, while more detailed information including data about damages (Level 2) exists for 196 bridges, or 29% of the total number of bridges, presented in Figure 1.

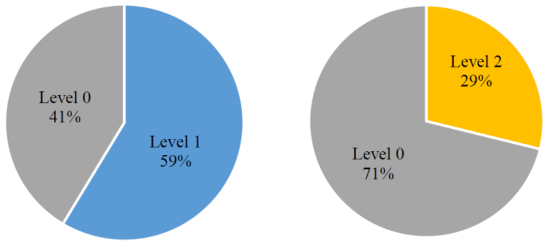

Figure 1. Percentage of bridges belonging to each information level

Additionally, several classes of bridges were identified according to the building material. The statistics show that the most numerous are the reinforced concrete bridge structures, accounting for 92% of the total number of bridges. Considerably smaller number of bridges accounting for 4% of the total are composite reinforced concrete and stone, while the remaining bridges account for 4% of the total number of bridges. Therefore, it is straightforward to state that the reinforced concrete bridges dominate the bridge stock in N. Macedonia and that their importance weighs mostly in the selection of the bridge typologies.

Regarding the deck structural system, out of the total number of bridge structures located along the main routes in N. Macedonia, the most numerous are simply supported beam bridges (57%) and continuous beam bridges (32%) shown in Figure 2. From the total number of bridge structures, 9% represent frame systems, while negligible are the arch bridges with 2% and the remaining 1% with other structural systems.

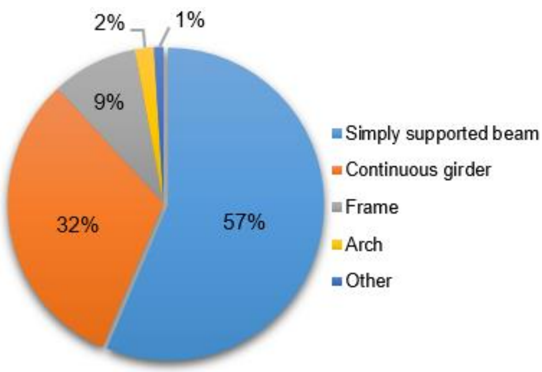

Figure 2. Percentage of bridges according to the structural system

Considering the need for classifying the bridge stock into several categories, several other characteristics of the bridges were taken into account. Namely, the number of spans, deck width, span length and pier height were the key parameters for developing the most representative bridge taxonomies and subjecting them to nonlinear time history analyses.

Thus, it was obtained that most of the bridge structures have a total deck width of around 10m. As to the number of spans, the most common are single span bridges (37%) and three-span bridges (33%). Bridges with two spans account for 11% of the total number of bridges, whereas bridges with four and more than four spans individually account for less than 10%. The mean value of the maximum span of the considered bridges amounts to 16m, i.e., most of the bridges (90%) are with a maximum span ranging between 7 to 25m.

In the end, according to the relevance of each taxonomy, 4 types of representative bridges were selected for analysis. The selection was based on the number of bridges from each typology in the total bridge stock of N. Macedonia. Figure 3 describes the selection process of the bridges and presents the most relevant bridge typologies.

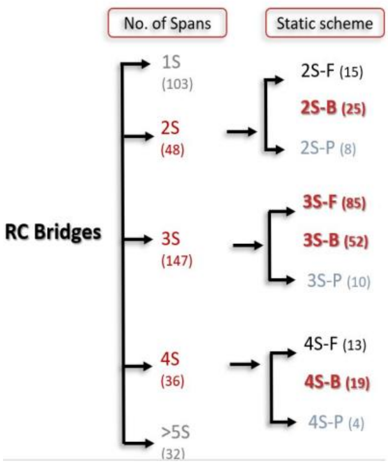

Figure 3. Bridge taxonomy definition

It is noticed from Figure 3, that even though there are many single span (1S) bridges in the bridge stock of N. Macedonia, they are not critical for the seismic resilience of the infrastructure since they behave rather well during seismic events. Therefore, 1S bridges are not included in the fragility analysis. In contrast, the bridges with 5 or more spans (>5S) were not considered in the fragility analysis due to the low number of representative specimens. Under the static scheme column, F, B and P stand for frame, beam and plate systems accordingly.

3. BRIDGE MODELING

The modelling of the bridges was performed in OpenSees software following the need for fast and reliable nonlinear time history analysis [8]. Basically, the bridges are composed of a single roadway supported on sub-structural components. Being the most critical parts for the seismic response of a bridge structure, the elements of the sub-structure are modelled in a more detailed way. For the deck and pier segments, frame elements were used. *Elastic* and *BeamWithHinges* elements were employed for the modelling of the deck and the piers, respectively following the assumption that plastic hinges might occur in the piers exclusively. The other comprising elements were mostly *zeroLength* and *twoNodeLink* elements applied for the deck connections and the bearings. Inelasticity was applied through the *BeamWithHinges* and the *zeroLength* elements using cross-sectional discretization with fibers. The mathematical model of a characteristic bridge is presented below in Figure 4.

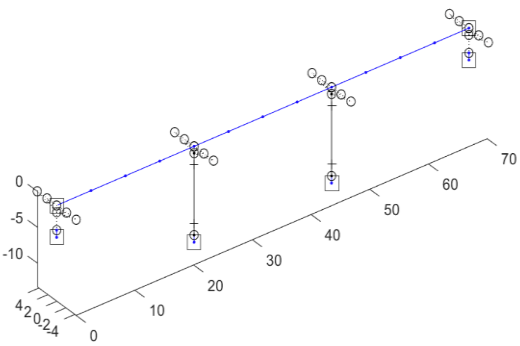

Figure 4. FE model of a characteristic 3 span simply supported beam bridge

Regarding the materials, *Concrete01* and *Steel01* materials from the OpenSees database were applied for the fiber section of inelastic elements.

The analyses were performed in a semi-automated manner. To be precise, the geometry was defined manually but the other processes were generated by an application developed specifically for the need of computing the fragility curves for bridges - BRI.T.N.E.Y (BRIdge auTomatic Nonlinear analysis based Earthquake fragilitY). BRI.T.N.E.Y performs tasks to read the bridge geometry data and creates its FE models for carrying out analysis with OpenSees [3]. The post-processing of the results is also performed by the same automatic application.

4. SEISMIC HAZARD DEFINITION

One of the basic project objectives was to select a reliable and up-to-date seismic hazard model that will provide a realistic estimate on the expected ground motion intensity, leading to achieve best vulnerability estimate on the bridge infrastructure. Reliable estimation of seismic hazard is one of the key components in selection of appropriate ground motion accelerograms that will be further used for the dynamic analysis of the specific bridge typologies.

For the purpose of the project, the most updated research, namely the EC8 National Model [9], was chosen to be used as reference seismic hazard to be implemented for further calculations in the OpenQuake engine [6].

Six sites (Figure 5, 6) were selected for further analyses. They were selected according to three main criteria: bridge locations, different hazard values considering the peak ground acceleration (PGA) for the 475 year-return period, Figure 5, and different soil categories according to the V_{S30} values of Figure 6.

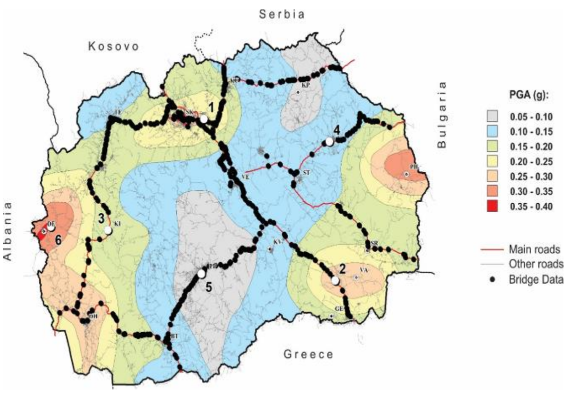

Figure 5. Selected sites with different hazard levels, superimposed on the PGA map for rigid soil conditions and the 475 year-return period

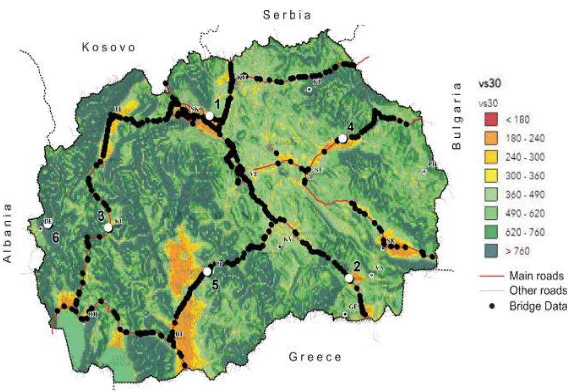

Figure 6. Selected sites with different site conditions, superimposed on the USGS VS30 map

In particular, sites numbered 3, 5 and 6 are representative of bridges located in regions characterized by stiff soil conditions, corresponding to EC8 soil class B, while sites numbered 1, 2 and 4 are representative of bridges located on soft soil conditions, corresponding to EC8 class C. Site-specific hazard analyses were performed for the 6 sites for 7 return periods (98, 224, 475, 975, 2475, 4975 and 9975 years, corresponding to probabilities of exceedance in 50 years of 40%, 20%, 10%, 5%, 2%, 1% and 0.5%) assuming a representative value of V_{S30}=600m/s for EC8 soil class B and V_{S30}=300m/s for EC8 soil class C.

The disaggregation analyses were performed both in terms of PGA and average spectral acceleration (AvgSA) [7] for the six selected sites for the most representative branch of the adopted logic tree, which was associated with the gridded source model (M1) and the GMM by Chiou and Youngs (2014) [4]. The AvgSA was computed over the range of periods 0.2s-1.0s, which was considered sufficiently wide to capture the first mode responses of most bridge structures, in addition to their associated higher mode response.

In this study, the Conditional Spectrum (CS) was used as an alternative to the more common and widely adopted Uniform Hazard Spectrum (UHS). The CS represents the expected response spectrum conditioned on the exceedance of a target spectral acceleration value at the period of interest [2].

Accelerogram selection for this study was performed by recasting of conditional spectrum record selection based on AvgSA [7]. An example of the records selection for Site 2, referred to the return period of 475 years, is shown in Figure 7 (the 30 green lines are the RotD50 response spectra of selected ground motions, while their average is represented by the blue line). The red lines represent the target conditional spectrum (average and average ±2 standard deviations).

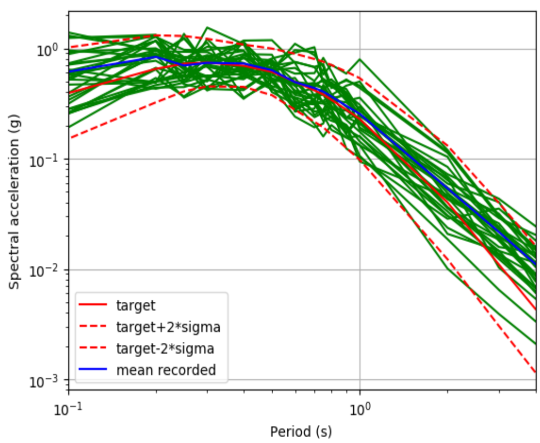

Figure 7. Conditional spectrum AvgSa-based record selection performed for Site 2, considering the 475-year return period

5. FRAGILITY CURVES

Bridge fragility curves are essential for the estimation of the road system's resilience, recovery planning, as well as pre- and post-earthquake retrofit prioritization [10]. However, it is impossible to compile a database encompassing all usual types of bridges within a single study [11]. Thus, the database presented herein may be used for a large number of bridges, with special focus on typologies commonly found in the main roads in N. Macedonia.

Methodologies for obtaining the fragility curves can be categorized based on several parameters, such as: analysis methods, seismic hazard, choice of critical components, engineering demand parameters, limit states etc.

The adopted methodology for the fragility assessment of the bridges in this study is based on inelastic response history analysis. As previously mentioned, the fragility curve is obtained point by point for 7 increasing hazard levels.

Regarding the critical components for the fragility analysis of bridges, previous research studies have been addressed in order to choose the most suitable methodology. Having in mind the extensiveness of the study and the bridge stock, the most appropriate approach was to limit the choice of critical components to the piers and bearings [5,12,13] in order to concentrate only on the structural elements that suffer greatly during seismic events.

Then, the failure mechanisms are defined for the chosen critical elements. The failure of the piers is reached either due to shear failure *V* or because the chord rotation *θ* is exceeded. Bearings, on the other hand, can fail because of exceedance of their displacement capacity. It is termed as 'unseating' and can either be manifested as a simple fall of the deck from the bearing or a full loss of support from the pier head.

In the end, two performance levels or limit states (LS) are considered in this study, both adequate for the purpose of connectivity analysis over the damaged road network and consistent with current resolution of damage predictions via numerical analysis: damage (SLD) and collapse (SLC). The methodology previously described for computing fragility curves is therefore applied twice, with different response threshold (capacity) values. Figure 8 shows the characteristic fragility curves for the pier deformation capacity and unseating of the bearings for a single bridge analysis.

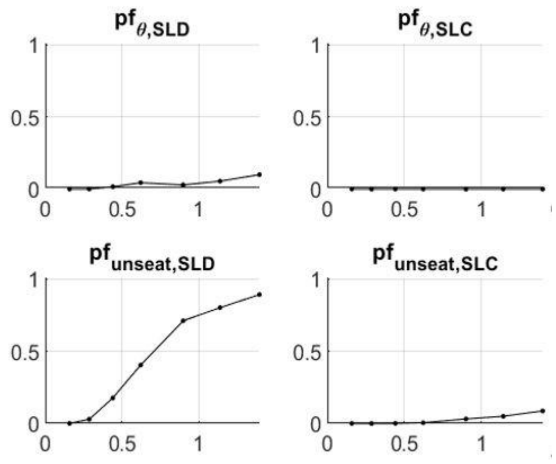

Figure 8. Characteristic fragility curves for a single bridge regarding deformation capacity *θ* and unseating

The fragility curves for each typology are defined as pairs of mean (μ_{lnY}) and standard deviation (σ_{lnY}) that define a lognormal distribution, Equation 1, which describes the probability of exceedance of a specific damage state (i.e. damage or collapse, *LS*) based on the intensity of ground motion shaking, *IM*. After the thorough application of the previously defined methodology, the results obtained for the taxonomies considering the beam bridges are presented in Figure 9.

$$p_f(LS \mid IM : \mathrm{x}) = \Phi\left(\frac{\ln(\frac{x}{\mu_{\ln Y}})}{\sigma_{\ln Y}}\right) \qquad (1)$$

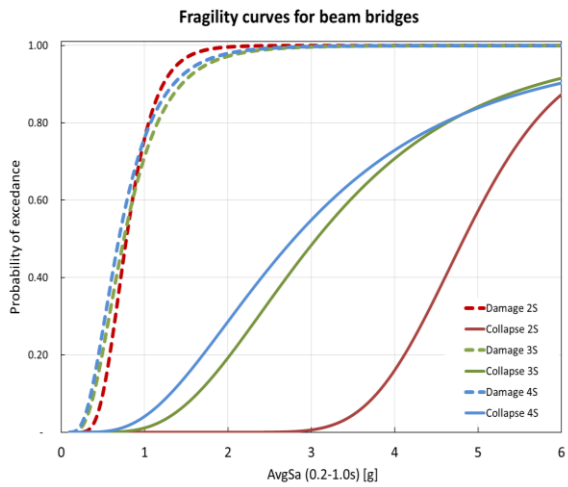

Figure 9. Fragility curves for beam bridges

6. CONCLUSIONS

The study presents the developed and implemented methodology in order to obtain taxonomy level fragility curves for representative bridge types within the context of INFRA-NAT project. Once the inventories were categorized, a numerical modelling framework was executed to produce sets of synthetic numerical models that are characteristic of a group to the taxonomies they represent, based on the necessary assumption that the behavior of the synthetic group will be equivalent to the one of the real bridges that are a part of that same taxonomy. The performance of each taxonomy was evaluated by performing an extensive number of non-linear time-history analysis of the synthetic bridge models to sets of earthquakes, consisting of 30 bi-directional ground motion records for each of the seven intensity measure levels (total of 210 records per set). The performance of each bridge-record combination was then associated to the probability of exceedance of two limit states (damage and collapse) and later processed to obtain continuous fragility functions for each. Finally, results were combined to produce taxonomy level fragility curves that will be applied to the real bridges in the inventory of N. Macedonia by implementing them in a specifically built web-based platform that will carry out risk calculations, developed as a part of the scope of INFRA-NAT.

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