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Near- and far-field earthquake damage study of the Konitsa stone arch bridge

Nikolaos Simos[a,*], George C. Manos[b], Evaggelos Kozikopoulos[b]

[a] Brookhaven National Laboratory, USA
[b] Laboratory of Experimental Strength of Materials and Structures, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece

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ABSTRACT

This paper reports on the sensitivity of earthquake response and damage of long span masonry stone bridges to near field (impulsive type) and far field earthquakes. Towards that objective, the Konitsa Bridge is used as a case study. The particular bridge was selected for offering certain unique features such as long span, built right on an active fault, survived a recent pair of near-filed type earthquakes with minimal damage and finally, construction material mechanical properties and strength could be deduced from a recently collapsed similar bridge in the area. The multifaceted study integrated in-situ measurements of dynamic characteristics, laboratory tests on representative stone and mortar materials and a series of finite-element analyses based on non-linear modelling using a combination of discontinuous and continuous representations to capture the behavior of bridge structural component interface and interaction as well as mortar-stone interaction and failure. In addition to the ground motion records of the recent seismic activity at the Konitsa Bridge location, four additional earthquake records representing near-field and far-field families were utilized to assess the stone bridge sensitivity. The study revealed that far-field earthquakes are far more destructive than near-field counterparts, a finding in full agreement with studies on near field earthquake effects on nuclear structures. The applicability of earthquake damage indicators such as CAV, Arias intensity and energy rate, typically used for conventional and nuclear structures, was evaluated based on the numerical analysis results.

1. Introduction

Masonry arch bridges are an integral component of the heritage of cultures worldwide reflecting unique engineering techniques developed over the centuries characterizing the region where they are located. Typically, masonry stone bridges were constructed to serve local communities by utilizing construction materials from the vicinity and therefore allowing the construction techniques to evolve and adopt to the quality of the available raw materials. Due to ageing, neglect and compounded with often poor-quality restoration works that were performed on these structures over the years there is an urgent need to evaluate their current structural health state, identify structural degradation and locations of distress and perform appropriate restoration based on sound engineering assessment. The unique engineering techniques used in the construction of these bridges poses a challenging engineering problem and an intriguing numerical case for predicting their dynamic response and seismic vulnerability.

In the last couple of decades experimental and numerical studies on masonry stone bridges have been performed to address both the ageing as well as the impact of vehicle or rail traffic both of which were not accounted for in the original construction. T. Akoi and co-workers [1] studied the Rakanji Bridge in Japan. Most relevant in this study is the fact that study conducted both stone and mortar tests establishing a good basis of analysis and material properties. Both micro-tremor measurement by ambient vibrations and acceleration by traffic vibrations were measured. Laboratory tests on similar materials to those of the bridge were conducted to establish the Young's modulus and compressive strength of the stone and the mortar. A number of historic stone arched bridges around Japan were studied by J. Kiyono and his co-workers [2]. In their all numerical study the dynamic behavior of several stone arched bridges were simulated using the 3-dimentional Distinct Element Method. Actual earthquake ground motions observed during the 1995 Hyogo-ken Nanbu earthquake were used in their study in conjunction with impulse waves to determine the modal characteristics and their collapse potential. G. Castellazzi and co-workers [3] conducted 3D finite element modelling and in situ experimental testing. To deduce both the material properties of the masonry constituting and the structural behavior of a masonry case study bridge subjected to

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[*] Corresponding author.
E-mail address: simos@bnl.gov (N. Simos).

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increased rail traffic. L. Pelà et al. [5] studied the seismic performance of existing masonry arch bridges using non-linear techniques and following procedures and standards including pushover analyses and response spectrum approaches. Laboratory tests were also conducted to aid the calibration of their model. Seismic assessment and retrofitting measures of a historic stone masonry bridge that experienced a M7.2 earthquake in1953 and recent M6.1 and M6.0 earthquakes in 2014 was studied in [6] in a parametric study to reverse poorly-designed and implemented restorations. B. Sevim and co-workers [7,8] conducted studies of arch bridges in Turkey where ambient vibration data were utilized to calibrate numerical models which subsequently were used to conduct earthquake analyses of stone arch bridges by representing the stone/mortar elements as a linear elastic homogeneous continuum. In [8] the response of bridges under near and far fault ground motions have been calculated using linear finite element analysis and, according to the authors [8], near fault ground motions impose higher seismic demand on the arch, an assessment derived from calculated higher displacements and stresses. Findings in [8] are contrary to a wealth of reported experimental and analytical data on nuclear-type structures [29–31] as well as experience data from sitting of nuclear reactor installations where near-field earthquakes of magnitude $M \leq 5.5$ have been treated as low damageability potential earthquakes [29], It should be emphasized, however, that the linear-elastic treatment of the arch bridge structures in [8] may very well produce higher displacements and subsequently stresses when subjected to a near-field earthquake signal due to the presence of a dominant velocity pulse that characterizes near-field earthquakes.

A large body of research work has been reported in recent years [4,9–14] aiming to characterize the complex mechanical behavior of the two-material system (stone and mortar) and deduce constitutive relations as well as failure behavior. Objective of this body of research was the combining the properties of the "unit block" (stone) exhibiting high compressive strength with the mortar which exhibits brittle behavior in tension and governed by friction in shear. Computational strategies for masonry structures were addressed in a PhD Thesis [4] by J. B. Lourenço. The anisotropy of the material is such that a complete description is impossible and therefore simplifications must be made. In [14] Drosopoulos and co-workers studied the ultimate failure load of stone arch bridges based on 2-D, plane strain finite element analysis which included interfaces, simulation of cracks, unilateral friction contacts and the implementation of a path-following technique to estimate the ultimate load. Comparison to relevant experimental results was also presented. Numerical techniques addressing the interaction of mortar and stone blocks or block-block non-linear contact were also explored. Specifically, B. O. Caglayan and co-workers [15] integrated a 3-D finite element analysis with in-situ acceleration measurements to study a long concrete arch bridge located in an earthquake-prone region. Structural analysis of masonry historical constructions were conducted in [16] based on limit analysis, simplified methods, FEM macro- or micro-modeling and discrete element methods (DEM). Numerical analyses [17–20] based on 3D non-linear finite elements were used to study masonry structures and in particular stone bridges. Results of a comprehensive assessment of the case study (Konitsa Bridge) are presented in [21]. Seismic hazards associated with the region and practices are presented in [22–28]. The effects of near-field and far field earthquakes on nuclear structures based on shake table experiments and confirmatory numerical studies are presented in [29–31]. Damage indicators of earthquakes used in seismic vulnerability assessment and field observations, including correlation with observed damage, are discussed in [32,33]. Observations and studies of masonry structures under seismic loads are reported in [34–39,41–43].

In the present study a 3D, non-linear analysis of a large arch stone bridge was performed as a case study for assessing the damageability of different type of earthquakes, i.e. near-field and far-field, on these structures. The selection of the Konitsa Bridge as the reference structure was prompted by the fact that it is situated on a known fault, its performance/survivability to a pair of recent near field earthquakes was assessed plus the fact that actual seismic ground motions were recorded in the proximity of the bridge. Furthermore, the recent collapse of a similar large stone arch bridge in the general area, built at the same period (1870) with similar material and techniques provided access to actual aged structural materials (mortar in particular) for laboratory testing and eventual use of the test data in the case study bridge. Using the non-linear capabilities of the LS-DYNA finite element code a numerical representation of the bridge was deduced as combination of discontinuous model (between distinct structural sections such as primary arch and secondary arch or mandrel wall) and continuous model (within each structural section). Specifically, interface conditions and failure between structural segments are governed by the mortar failure behavior. In the "continuous model" the governing constitutive relations and failure characteristics of a "unit" or element representing the stone-mortar materials and their interaction are those of a Winfrith type concrete with two-phase material where the mortar is smeared within the unit or element. Tension cracking is assumed to be controlled by mortar while crushing by the stone material. Properties from the laboratory tests were used in the adopted constitutive relations and failure. Two independent campaigns were conducted on the case bridge to deduce modal and damping characteristics and help fine-tune the numerical model. Sought in the main body of the current research reported within, is the structural damage sensitivity of this case study structure (and others like it) to the nature or type of near-field and far-filed earthquake motions. Actual earthquakes recorded around the world were utilized and the predicted damage, as well as the applicability of metrics of earthquake damage potential used in modern earthquake engineering (i.e. CAV, Arias Intensity) are assessed. The studies revealed, that the damageability of far-field earthquakes is more severe than that of near-field counterparts of same peak ground acceleration, in agreement with findings of experimental studies on nuclear-type structures [30].

2. Case study bridge location and structural characteristics

2.1. Location and structural details

The case study Konitsa Bridge shown in Fig. 1 was built in 1870 and is located at the mouth of the Aoos River Gorge near the city of Konitsa, northwestern Greece. It is in close proximity to the Konitsa fault (Fig. 2) and, following the recent collapse of the Plaka Bridge [19], is the largest of its kind single arch stone bridge in Greece. Approximately twenty (20) single arch stone bridges with arch opening > 12 m are found in north-western Greece. It is of significant cultural heritage value as it represents the stone building art of the wider region. It is a single span structure made from natural, local stone with a primary (lower) and secondary (upper) arches. It has an opening of 39.8 m, height of 20 m. The primary arch has a thickness of 1.30 m and the secondary arch a thickness of 0.59 m. The deck width is 3 m with a protective parapet. It is not clear, however, as to width and thus weight of the original construction parapet and whether the one currently in place represents the original construction (poor quality restoration work was performed between 1988 and 1992). It also evident that during this structural intervention "restoration" was also performed in critical elements of the bridge (sections of the lower and upper arches near the crown as shown in Fig. 1) where concrete replaced the stone work and a steel mesh was introduced in part of the intrados. Important structural features to note are (a) the "periodical" tie keys which have been used in long span stone bridges of the region and (b) the geometric configuration of the abutment stone layers receiving the normal load from the ends of two arches that they support (Fig. 1c; d). As shown in Fig. 1 the LHS abutment foundation is supported on rock base while the RHS abutment on foundation that is embedded in what appears to be "weathered" rock. Details on the depth of the RHS foundation are not readily available and therefore uncertainties of whether a competent