USE OF PASSIVE CONTROL SYSTEMS FOR THE RETROFITTING OF MASONRY ARCH BRIDGES

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Abstract

In this paper, the use of passive control devices and especially dampers is investigated for the retrofitting of historical masonry structures. The investigation is made through the presentation of a case study, an existing masonry bridge, which consists part of the secondary railway network of Greece. Structural requirements resulting from high-level functional specifications for the new type of trains' circulation impose the need of structural strengthening. At the same time, due to the high seismicity of the area under consideration, measures for the earthquake protection of the historical structure should be taken. The introduction of passive control dampers into adequate locations of the load-bearing system of the structure is proposed. Their efficiency is investigated either in terms of displacements or in terms of energy dissipation. In this framework, an integrated methodology for the evaluation of the response of structures retrofitted with dampers is presented.

Introduction

The Mediterranean basin is characterized by cultural heritage masonry structures of great architectural and historical importance. For the protection, restoration or rehabilitation of these structures, the need of intervention to their structural system is imperative, whether in order to encounter the problem of past damage and general deterioration in time, or even in order to meet additional specifications imposed by rehabilitation requirements. Alongside, the high seismicity of the area under consideration poses a continuous threat to masonry structures, which due to their low tensile strength are highly vulnerable to dynamic loadings such as earthquake.

Special demands related to the respect of the originality of historical structures, differentiate the process of their retrofitting from modern structures' repair and strengthening. Interventions should be orientated to be reversible, compatible and the less intrusive possible. For this purpose, conventional techniques are often unable to copy with historical structures reinforcement and modern methods have to be investigated.

A modern approach of retrofitting of historical structures involves the control of the structural response through the increase of the structure's capacity to dissipate energy. This is achieved by the incorporation of dampers into the load-bearing system (Casciati and Faravelli, 2001). In this way, during a dynamic event, an amount of the input energy is removed from the structural vibration and is converted into heat. The benefits of such a transformation of energy are interpreted either into diminution of failure or, in the long run, into reduction of the structural fatigue and increase of the structural life. Furthermore, this method complies with the basic rules of restoration and retrofitting, as mentioned above.

In this paper, the response of the special category of masonry arch bridges is investigated. A case study of an existing bridge, consisting part of the second railway network of Greece is presented. The evaluation of the actual structure is made, through stress and failure analysis. For this purpose, an analytical model is developed using the three-dimensional solid element. Failure analysis, following stress analysis is performed, providing an indication of failure that occurs under a seismic ground excitation, as defined by the Greek Aseismic regulation. In the following, a system of dampers is properly introduced into the load-bearing system to protect it against earthquake actions.

Time-history analysis is performed for the evaluation of the effect of damper systems, throughout a full seismic event. Results are presented in terms of structure's displacements and seismic energy dissipation.

The Manari bridge

The Manari bridge is a curved arch masonry bridge, situated in Peloponnese, Greece. It was built in 19th century, by the French company "Societé Anonyme Internationale de Construction et d' Enterprises des Travaux Publics", in order to serve the area train circulation. Its actual state is illustrated in Fig.1.

The bridge's total curve span is equal to 116,00 m, its height is 20,00 m and its width is 4,25 m. It consists of 8 semicircular arches, the spans and the radius of which are 12,50 m and 5,75 m long, respectively. Under the train circulation deck, there is a 2-meter infill of stones. The bridge is made of ashlar masonry of optimum construction quality. The average dimensions of the blocks are 60 x 40 x 40 cm^3.

During the last decades, the circulation of the bridge is limited to old type of trains. In order to permit circulation of new type of trains, the bridge has to be reinforced so as to be able to withstand applied loadings.

Figure 1. The Manari bridge

Structural identification

The analytical model

For the structural identification of the bridge an analytical model has been developed using three-dimensional isoparametric solid finite elements, activating three translational degrees of freedom on each node. This kind of simulation has been considered adequate in order to describe accurately the geometry of the structure and the function of its load-bearing system. The stones infill under the deck of the bridge has been simulated using frame elements of high stiffness, so as to express efficiently its load-bearing function. In Fig.2, the analytical model is presented.

For the masonry it has been considered: modulus of elasticity E=3.000MPa, strength in tension f_{wt}=0,70MPa, strength in compression f_{wc}=6,00MPa.

Dead and live loads, soil pressure at both ends of the bridge, earthquake loads and railway function loads have been taken into account.

The train circulation actions include:

a) train weight loading along the track way axis

b) centrifugal force vertically to the track way axis

c) lateral train loading vertically to the track way axis

d) actions due to start/braking

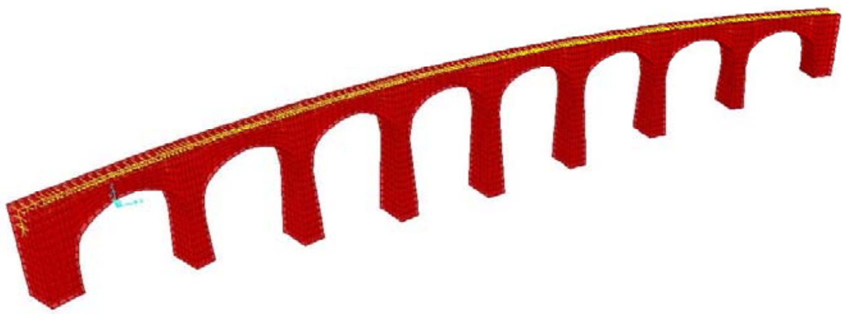

Figure 2. The finite element model

Stress and failure analysis

Response spectrum analysis has been performed using the SAP V.9 software. The first three eigen-periods are T_1=0,64 sec, T_2=0,56 sec and T_3=0,45 sec. For the failure analysis of the structure, the methodology developed by Syrmakezis, Antonopoulos and Mavrouli (2005) has been followed. Basic steps included in this procedure are the transformation of the three-dimensional stress state into its two-dimensional equivalent one and the elaboration of the acquired data, using the modified Von-Mises failure criterion (Syrmakezis and Asteris, 2001). The FAILURE software has been employed. In Fig.3 the areas that have failed for seismic ground acceleration equal to 0,24g and applied railway loads are presented. Graphical failure results are illustrated for a longitudinal section on the mid-level of the curved masonry bridge and they show the location of failure on the wall surface but not the plane on which it occurs. Red areas represent failure under biaxial tension, while green areas represent failure under biaxial tension-compression.

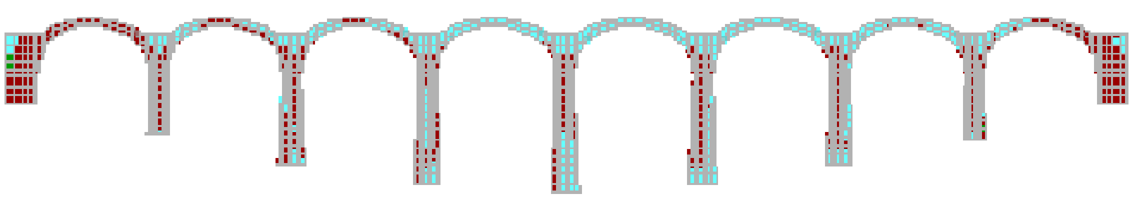

Figure 3. Failure evaluation

Results revealed the incapacity of the bridge to withstand applied loads. Resulting damage is mainly owed to seismic loading rather than operational actions. As a result, immediate strengthening is required.

Structural retrofitting

Dampers placement

During the design procedure, it should be taken into account that the dissipation of seismic energy is closely related to the specifications of the damper elements (Sedlachek and Pong, 2003). The seismic energy dissipation and the limitation of deformations depend on the structure properties as well as the damping and stiffness properties of the incorporated dampers. The interaction of all these characteristics is also important for the final response of the structure.

For the retrofitting of the masonry arch bridge, incorporation of dampers into the load-bearing system has been proposed. Proper placement and number of dampers is crucial for the determination of the response of the retrofitted structure. For the seismic risk mitigation of the bridge, damper braces have been incorporated into the load-bearing system of the structure, along the bridge axis, at the upper part of each arch. The selected location is seen in Fig.4.

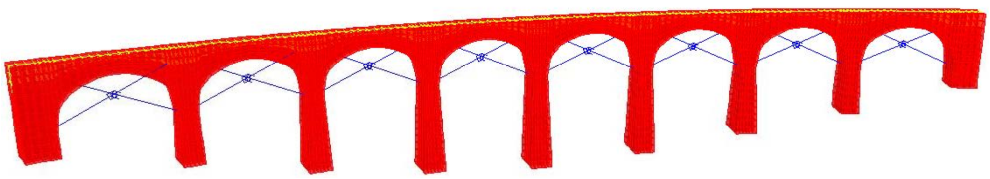

Figure 4. Location of damper braces

Simulation of damper elements

Damper elements simulation is based on the Maxwell model of viscoelasticity, having a nonlinear damper in series with a spring (Sun and Lu, 2005). The nonlinear force-deformation relationship is expressed by Equation (1):

$$f = kd_k = c\dot{d}_c^{\,cexp} \tag{1}$$

where k: spring constant, c: damping coefficient, $cexp$: damping exponent, d_k: deformation across the spring and $\dot{d}_c$: deformation rate across the damper.

Damper elements have been simulated as non-linear link elements.

Seismic loading assumptions

For the demonstration of the dampers effect on the response of the structure, time-history analysis has been performed, in order to obtain the amount of the dissipated energy throughout the seismic event. The accelerogram used is the one of the earthquake of Athens in 1999 and it is seen in Figure 5.

The seismic loading in terms of ground acceleration has been applied in two horizontal directions.

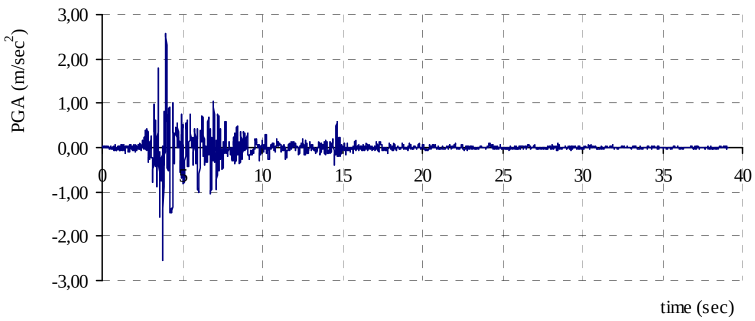

Figure 5. Athens (1999) earthquake accelerogram

Time-history analysis results

In order to evaluate the efficiency of dampers for the dissipation of seismic energy, the results are reported in terms of energy and displacements. For the graphical presentation of results, a time period from 0 to 10 sec has been included, since within this period the seismic event reaches its peak and the energy dissipation is concluded.

In Fig.6, the amount of the energy that is dissipated by dampers, in relation to the total input energy and the modal damping energy, representing inherent energy dissipation, is presented for the retrofitted structure. For the time-history analysis, a modal damping equal to 3% has been considered for all modes.

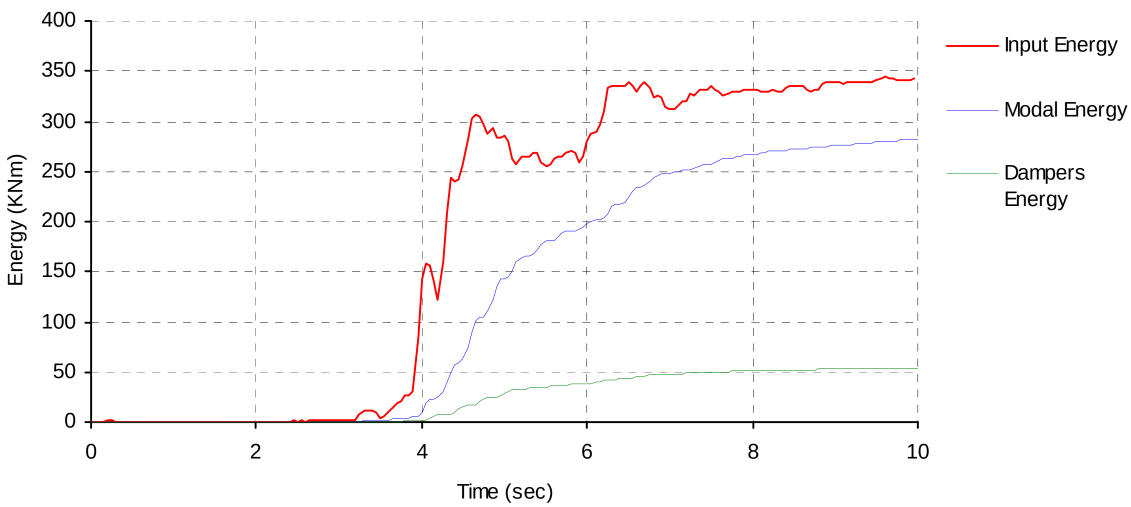

Figure 6. Energy balance for the retrofitted structure

In Figs.7a-7b, the kinetic and potential energy developed, due to earthquake loading and other imposed loads on the structure, is presented, before and after retrofitting.

In Figs.8a-8b, the displacements of an indicative joint at the top of the bridge, along its vertical axis of symmetry, are shown before and after retrofitting.

The results revealed that for the retrofitted structure, the dampers energy dissipation reaches the rate of 85% of the input energy, while the inherent energy dissipation rate equals to 15%. The diminution of kinetic and potential energy is apparent for the use of damper braces, thus resulting in smaller values of stresses and subsequent diminution of the seismic risk.

Displacements of the afore-mentioned indicative joint are diminished from 0,08 m to 0,05 m.

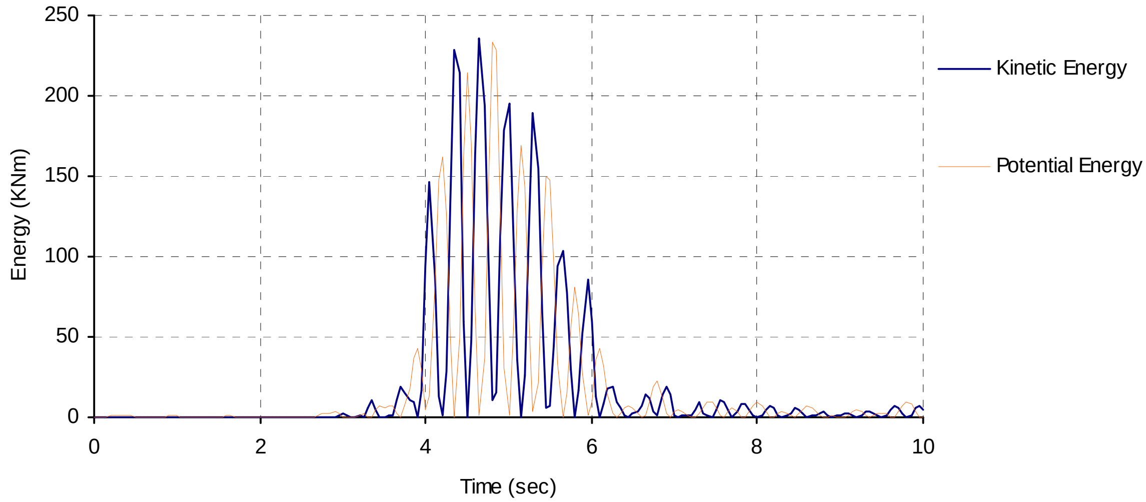

Figure 7a. Kinetic and Potential Energy for the non-retrofitted structure

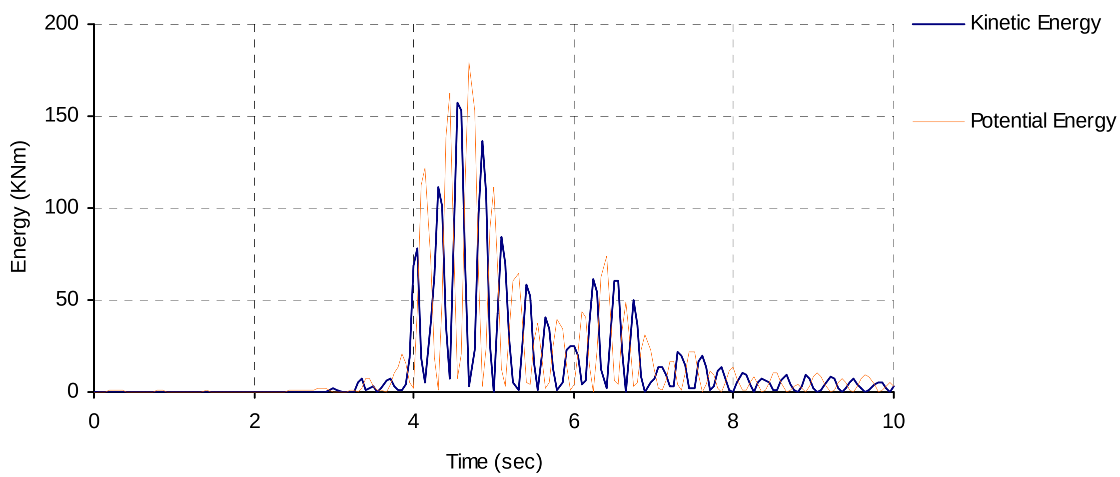

Figure 7b. Kinetic and Potential Energy for the retrofitted structure

Conclusions

In this paper an integrated approach for the structural retrofitting of historical masonry arch bridges has been presented, through a case study: the railway bridge Manari, located in Peloponnese, Greece.

Model assumptions for the analytical simulation of the structure have been shown, during the phase of the structural identification. Stress and failure analysis have been performed using a procedure especially adapted to masonry structures. Graphical failure results have been presented.

Retrofitting of the masonry arch bridge has been proposed using damper braces. Proper placement of dampers has been investigated and time-history analysis has been performed in order to achieve seismic energy dissipation results.

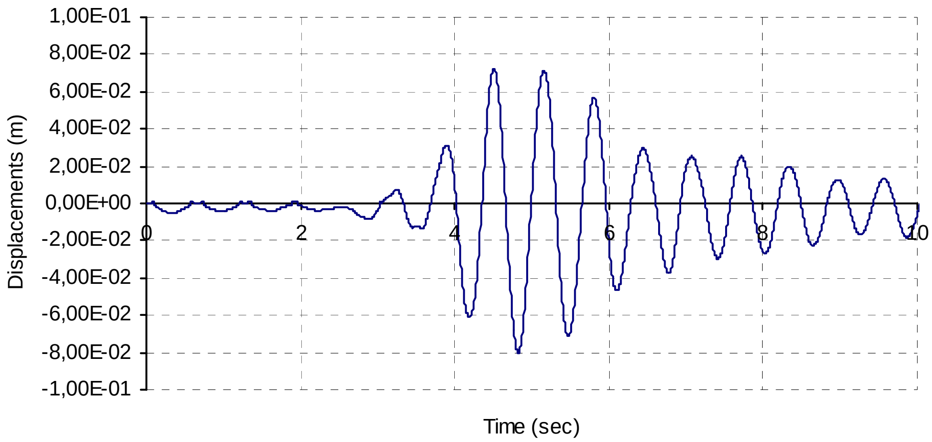

Figure 8a. Displacement of an indicative joint of the non-retrofitted structure

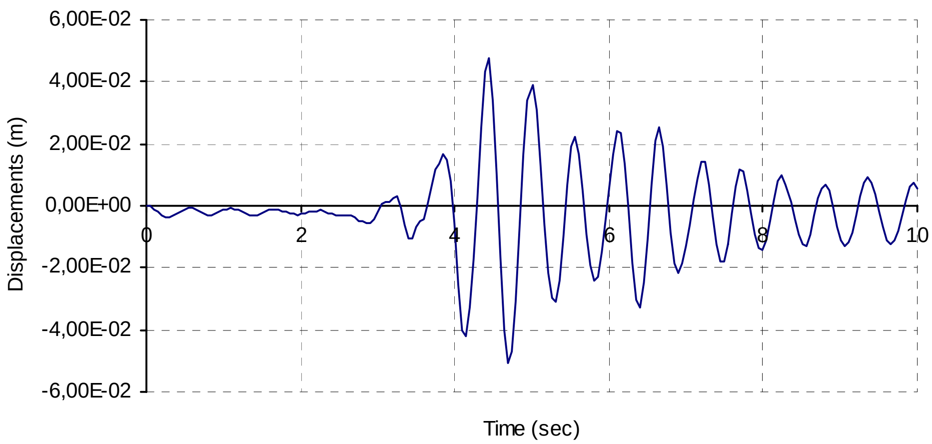

Figure 8b. Displacement of an indicative joint of the retrofitted structure

Results have been reported in terms of dampers and modal energy dissipation, in relation to total input energy, resulting for seismic and all other applied actions. Dampers have been proven to be very efficient in limiting stresses and deformation values. The benefits from this effect have also long-term aspects, as far as it concerns the reduction of the structural fatigue and the increase of the structural life.

Acknowledgements

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