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ADVANCED SEISMIC UPGRADING OF EXISTING BRIDGES WITH NEW ADAPTIVE IMSO-SYSTEM FOR SEISMIC RESPONSE MODIFICATION

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Abstract

The high seismic risk of transportation networks in South East Europe (SEE) is a serious threat to public safety, sustainable economic and social development and security in the region. This risk has not been quantified to this date and sound seismic risk mitigation concepts are not available. Most of the existing bridges are constructed as non-aseismic and are older than 40 years, so that they are highly vulnerable to seismic loads and require immediate, reliable and cost-effective seismic upgrading. Therefore, leaded by the third author, specific large-scale international NATO Science for Peace Project "Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828)", was directed to realization of fundamental research and development of an innovative technology for seismic isolation and seismic protection of bridges. Extensive experimental tests have been conducted at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje, Macedonia. The extensive research activity of this innovative NATO SfP project has been focused on development, creation and experimental validation of new, highly efficient, seismic response modification system for bridges. The proposed adaptive IMSO-system was developed based on optimized integration of the innovative concepts of Multi-Level Multi-Directional Seismic Energy Dissipation and Globally Optimized Seismic Energy Balance (GOSEB-System).

The newly created adaptive IMSO-system for seismic protection of bridges represents important technical innovation capable of integrating the advantages of seismic isolation, seismic energy dissipation and effective displacement control. With the achieved advanced seismic isolation and seismic protection performances, in compliance with the actual seismic input energy, complete seismic protection of bridge structures is provided, even under the strongest earthquakes.

In this paper presented are the original results obtained from recently conducted extensive experimental and analytical research devoted to development and validation of the created new method for advanced seismic upgrading of new and existing bridges including application of advanced adaptive IMSO-system for structural seismic response modification. The existing prototype bridge considered herein for innovative upgrading represents typical classical system commonly used in south-east Europe during middle years of the 20th century, mostly designed without consideration of seismic loads. It was confirmed that, with installation of optimally designed new adaptive IMSO-system, the selected specific non-seismic existing structure can be efficiently upgraded and converted to seismically resistant structure for expected seismic effects in its location. The specific nonlinear behavior features of all integrated components in the original IMSO-system have been successfully considered in the formulated advanced phenomenological analytical model.

Keywords: Bridges, nonlinear response, seismic isolation, response modification, passive control

1. Introduction

With conducted harmonized project research and management activities, the following principal end products of the innovative long-term NATO SfP research project have been successfully achieved: (1) Developed i.e. created is a new highly efficient bridge seismic isolation system (ML-MD GOSEB-System) with efficient 56 technological options, based on innovative integration of concepts of Multi-Level Multi-Directional Seismic Energy Dissipation and Globally Optimized Seismic Energy Balance; (2) Mobilized is scientific potential in the region for advanced solving of NATO and society policy related complex safety problems including the principal topic of seismic upgrading of existing bridges; (3) Created is improved Cross-Border cooperation and regional approach for realization of development projects; (4) Promoted is application of the advanced technologies for seismic protection of bridges; (5) Achieved is reduction of the necessary financial resources; (6) Promoted is harmonization of safety and security level; (7) Promoted is concept for successful and harmonized application of European standards; (8) Provided is own innovative scientific contribution to seismic isolation of bridges; (9) Contributed is to motivation of end users toward application of innovative technologies; (10) Provided is a general impetus to scientific staff and young researchers toward development and application of advanced technologies through successful international cooperation.

Following brief presentation of the basic concept of the newly developed adaptive seismic response modification IMSO-system, in this paper are included representative results obtained from conducted extensive study devoted to general demonstration of potential wide practical applicability of the developed IMSO-system for seismic upgrading of new and existing bridges constructed without proper consideration of seismic effects.

Beside the original study results, in the paper are also described the implemented innovative components and devices of the applied suitable technological option of IMSO-system: (1) Seismic isolation devices; (2) Hysteretic energy dissipation devices; (3) Displacement limiting devices, as well as (4) The developed advanced phenomenological model applicable for future modeling, analysis and design of bridges with new IMSO-system efficient for seismic protection of new and existing bridges.

2. Concept of adaptive seismic response modification IMSO-system

The basic concept of the adaptive seismic response modification IMSO-system, Fig. 1, for improved seismic protection of bridges, Fig. 2, is based on general globally optimized seismic energy balance (GOSEB-approach) including optimal integration of advantages of three basic devices: (1) Seismic isolation (SID); (2) Seismic energy dissipation (EDD) and (3) Displacement limitation devices (DLD).

The first variation of seismic isolation (SI) device (Fig. 1) represents common laminated seismic rubber bearing. The second variation of SI device (Fig 3a) represents seismic isolator composed of two parallel inox steel plates with inner spherical surfaces. Between the surfaces installed is special roller composed of twelve steel balls arranged in ring type single module. The displacement control (DC) device (Fig. 3c) is made of soft rubber, providing limitation of large displacements with its stiffening capacity. The energy dissipation (ED) device (Fig 3b) is composed of radially spaced C-type components in two levels (eight in each level), providing energy dissipation through induced hysteretic response.

First, the optimized seismic isolation devices (SID) are used to achieve effective bridge isolation and essential seismic response modification. Seismic isolator models are constructed and experimentally studied with four different optional types (circular and square laminated rubber seismic isolators, double spherical sliding seismic isolators and double spherical rolling seismic isolators) and each type should be designed based on advanced optimization process. Applying expert knowledge, the designers will be able to achieve successful selection of the appropriate types and characteristics of seismic isolators (considered type is shown in Fig. 3a1 and Fig 3a2).

Second, models of the new multi-level multi-directional energy dissipation devices (EDD) are constructed and experimentally studied with seven optional types (HC-EDD, HS-EDD, V-EDD, VM-EDD, C-EDD, SF-EDD and SB-EDD) and they are basically invented to achieve unique energy absorption features since they are capable of adapting their behavior to the actual intensity of input seismic energy.

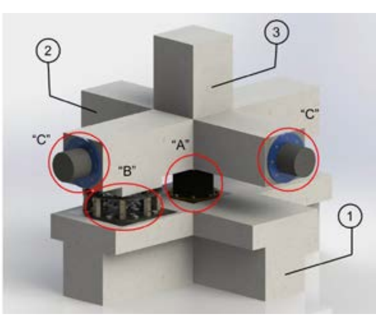

Fig. 1. Concept of new IMSO-system with 56 technological options

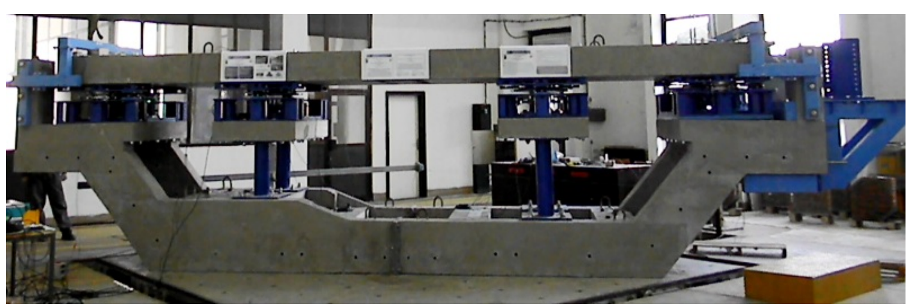

Fig. 2. Constructed and tested innovative large-scale bridge models on seismic shaking table with seven different technological options of the new IMSO-system

Actually, the new hysteretic energy dissipation devices are able to provide the most innovative and advanced features of multi-level earthquake response in all directions considering adopted variable gap concept. (considered type is shown in Fig. 3b1 and Fig 3b2). Third, the models of optimized displacement limitation devices (DLD) are constructed and experimentally studied with two optional types (hysteretic, H-DLD & rubber, R-DLD), and with their application proved is very effective and efficient limitation of excessive displacement of bridge superstructure under very strong earthquakes (considered type is shown in Fig. 3c1 and Fig 3c2).

Fig. 3a1. Tested (DSRSI) double spherical rolling seismic isolator

Fig. 3b1. Tested innovative energy dissipation devices (HC-EDD) of horizontal HC-type

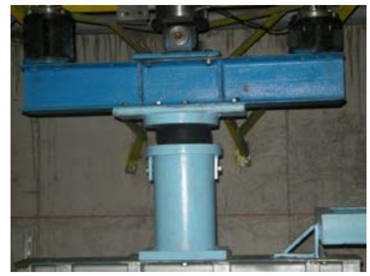

Fig. 3c1. Tested displacement limitation devices (R-DLD)

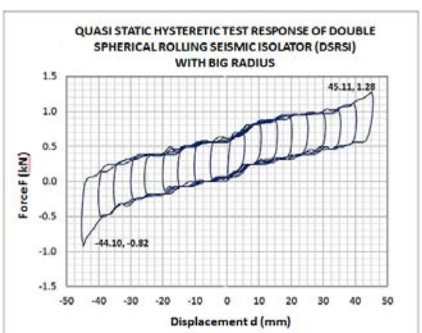

Fig. 3a2. Typical force-deformation hysteretic response of DSRSI-Device

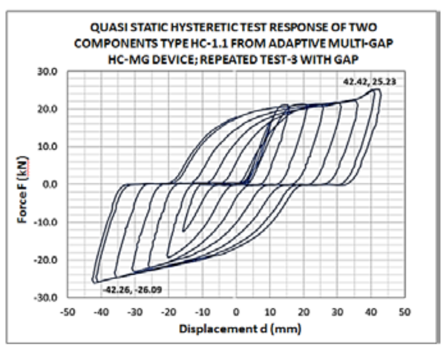

Fig. 3b2. Typical hysteretic response of the tested HC-ED devices with gap

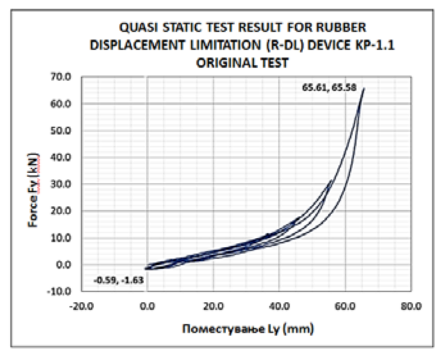

Fig. 3c2. Typical hysteretic response of the tested R-DL devices

3. Seismic evaluation of existing prototype bridge

3.1 Description of the bridge structure

The chosen representative structure is a reinforced concrete viaduct with five spans and total length of L = 2*16.9 + 3*21.1m = 97.1m. The viaduct is located at km 10+524.85 of the M-26 road, section Gostivar-Kicevo, Fig. 4a, 4b and 4c. According to the project documentation, the bridge is designed as a classical frame structural system cast in place. The superstructure of the bridge consists of two main longitudinal girders with height h=1.40 m constructed at a distance of e=6.10 m, secondary transverse girders (located at every support and also three or four along spans) and reinforced concrete slab with width b=9.6 m and thickness of d_p=0.18 m. The longitudinal section of the bridge is shown on Fig. 5a, while in Fig. 5b is given animated 3D bridge view.

The bridge substructure includes box type abutments cast in place Fig. 4c and middle supports each consisting of two RC piers with circular cross section (D=1.0 m) founded with single footings, Fig. 4b, Fig. 5a and Fig. 5b. The pier heights vary between 10.1m and 17.9m. Both end supports of the bridge are movable bearings in longitudinal direction, while middle piers at both ends are with fixed connection. In plane, the bridge forms a horizontal curve with small radius of R=70.0 m, Fig. 5b. The transverse slope of the bridge deck is 6.4%. The vertical alignment of the bridge deck has a small gradient also. The piers and the abutments of the bridge are founded on stiff rock foundation with bearing capacity of σ_0 = 3.5 MPa.

The RC structure is constructed with concrete grade MB30, except for the wing walls which are built with concrete grade MB45 and the footings which are built with concrete grades MB10 and MB22. The reinforcement steel used for the structure is of grade C 240/360. The selected existing viaduct considered in this study is about 40 years old and presently is in regular traffic function.

Fig. 4a. Road view above existing bridge with classical system

Fig, 4b. View of substructure of selected classical bridge structure

Fig. 4c. View of abutment of the selected prototype bridge

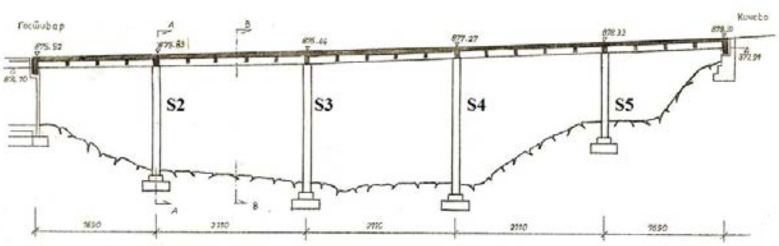

Fig. 5a. Longitudinal section of horizontally curved existing RC bridge

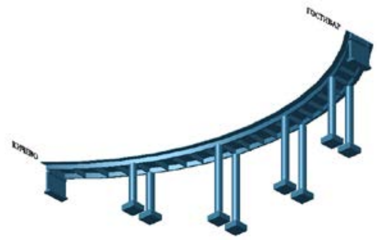

Fig. 5b. Animated 3D view of bridge

3.1 Modeling and seismic evaluation of selected prototype bridge

To achieve advanced seismic safety evaluation of the existing structure formulated was 3D nonlinear mathematical model incorporating the real geometrical, physical and material characteristics of the bridge.

The RC deck was modeled with shell finite elements while for the bridge girders, beams and columns were used 3D beam finite elements. The connection between the super and sub-structure was modeled as fixed while end supports were considered as movable bearings. Potential plastic hinges were modeled as non-linear at both ends of middle piers (two cross-sections, one at the foundation level and one at contact with longitudinal and transverse beams of the superstructure). Nonlinear behavior of the cross-sections representing potential plastic hinges was modeled based on specified family of moment-curvature (M-φ) relations, Fig. 6b, defined for several levels of axial forces in order to include variation effect of axial forces and also based on computed axial force-moment (N-M) interaction diagrams, Fig. 6a.

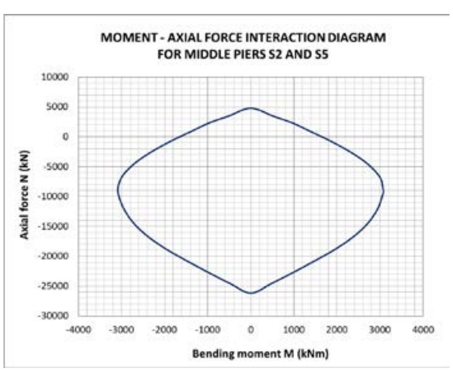

Fig. 6a. Computed interaction relation moment-axial force (M-N) for piers S2 and S5

Fig. 6b. Moment-curvature (M-φ) relations for piers S2 and S5 under different axial (N) forces

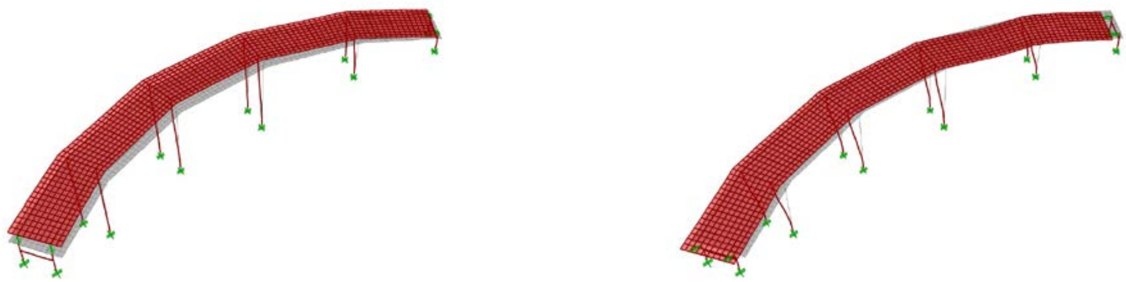

Fig. 7. Dynamic characteristics of the bridge structure: a) Mode shape 1 and b) Mode shape 2

Boundary conditions of middle piers and abutments were considered fixed due to high bearing capacity of the foundation soil, while the end supports of the superstructure upon abutments was modeled by springs realistically simulating behavior of the RC movable bearings. The main objective of the analysis was realistic evaluation of seismic resistance of the structure, defining the minimal seismic intensity expressed by PGA level, at which total failure of the structure occurs. From the analysis of the dynamic characteristics defined are periods and mode shapes of the bridge. Mode shape-1 with period T_1=0.850 sec has vibrations dominantly expressed in transverse direction of the bridge, Fig. 7a. Mode shape-2 with period T_2=0.778 sec, has vibrations dominantly expressed in longitudinal direction, Fig. 7b. Mode shape-3 with period T_3=0.517 sec, has vibrations dominantly expressed as torsional representing rotation of the bridge superstructure. In the second phase, conducted was respective study of seismic resistance capacity of the structure by implementation of several earthquake records and iterative nonlinear analysis procedures. For each earthquake record, defined was maximum level of peak ground acceleration (PGA) for which the structure remains non-collapsed, i.e., defined was structural state just before total failure.

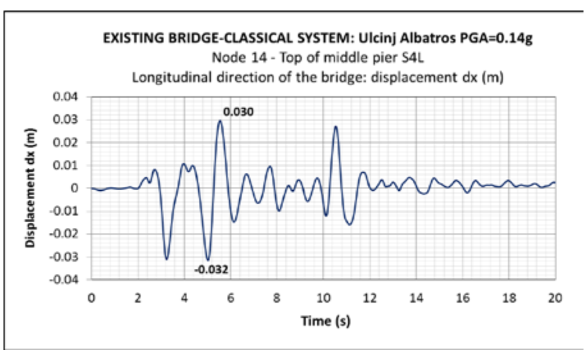

Fig. 8. Time history response of displacement dx (m) at the top of pier S4L in longitudinal direction

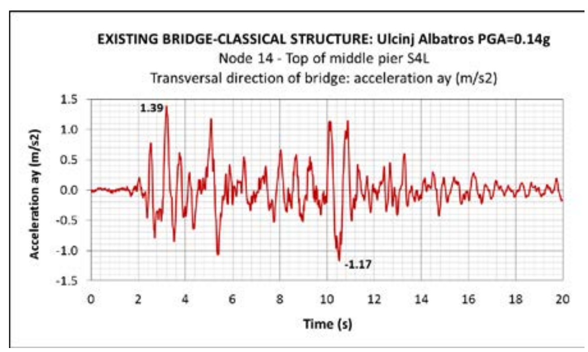

Fig. 9. Time history response of acceleration ay (m/sec^2) at the top of pier S4L in transversal direction

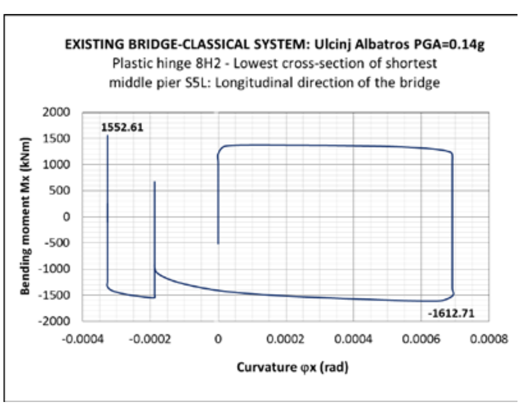

Fig. 10. Hysteretic response MX-φX of bottom plastic hinge of pier S5L in T-direction (no failure)

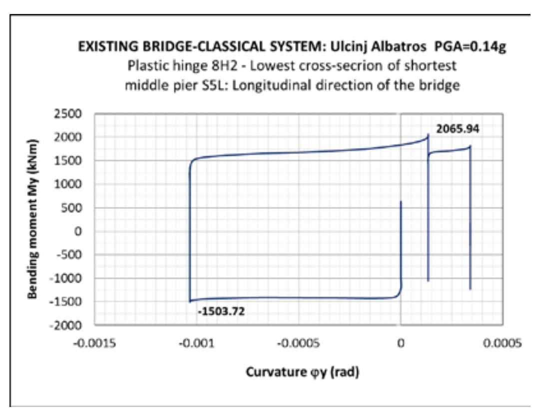

Fig. 11. Hysteretic response MY-φY of bottom plastic hinge of pier S5L in L-direction (no failure)

In this paper are included only selected characteristic results obtained from the performed iterative nonlinear analysis of the bridge under real Ulcinj-Albatros earthquake record recorded during the Montenegro earthquake of 1979. This earthquake record represents design earthquake relevant for the specific bridge site, proposed based on seismological and geophysical studies.

In this case, obtained are the following main findings: (1) Complete failure of the structure occurs only if maximum acceleration level in global direction is PGAgl>0.14g, (2) If maximum acceleration level is PGAgl<0.14g, failure of the structure does not occur, and (3) For PGA=0.14g reached is stage just prior to total failure. Such seismic intensity was simulated by simultaneous application of two scaled identical acceleration records in transversal x-direction and longitudinal y-direction of the bridge, as projections from global direction considered at angle 45°. It means that the stage just prior to failure is reached for applied seismic input with PGAx = PGAy = 0.10 g, simultaneously in longitudinal (x) and transversal (y) direction.

In Fig. 8 shown is the time history response of displacement dx(m) at the top of the longest pier S4L in longitudinal direction of the bridge for Ulcinj-Albatros earthquake input with PGAgl=0.14g. The obtained maximum displacement is dx,max=0.032m. In Fig. 9 shown is the time history response of acceleration ay (m/sec^2) at the top of pier S4L in the transverse direction of the bridge, also under Ulcinj-Albatros earthquake with PGAgl=0.14g, stage just prior to failure. The obtained maximum acceleration is ay,max=1.39 m/s^2.

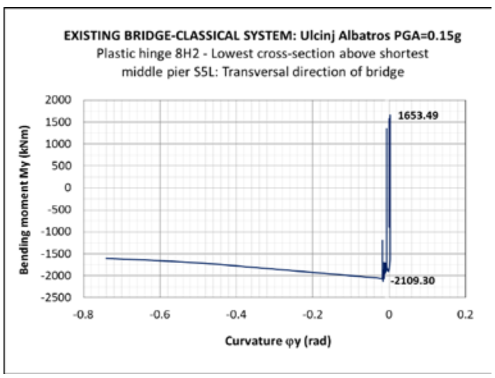

Fig. 12. Hysteretic response MX-φX of bottom plastic hinge of pier S5L in T-direction (failure)

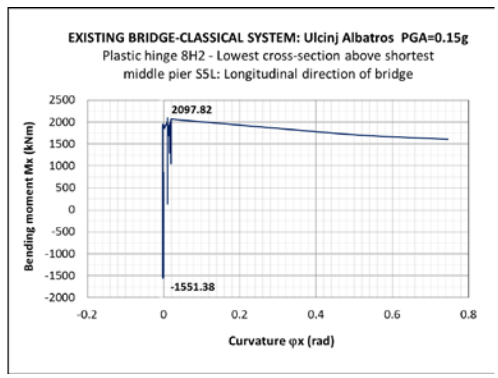

Fig. 13. Hysteretic response MY-φY of bottom plastic hinge of pier S5L in L-direction (no failure)

In Fig. 10 and Fig. 11, respectively are shown hysteretic responses of the bottom cross-section of the shortest middle pier S5L in T-direction and S5L in L-direction just prior to failure due to the effect of the Ulcinj-Albatros earthquake record scaled to PGAgl=0.14g, demonstrating that total collapse does not occur. Comparatively, in Fig. 12 and Fig. 13, respectively are shown hysteretic responses of the bottom cross-section of the shortest middle pier S5L in T-direction and S5L in L-direction due to the effect of the Ulcinj-Albatros earthquake record scaled to PGAgl=0.15g, demonstrating in this case total collapse of the middle pier and most probably the whole structure.

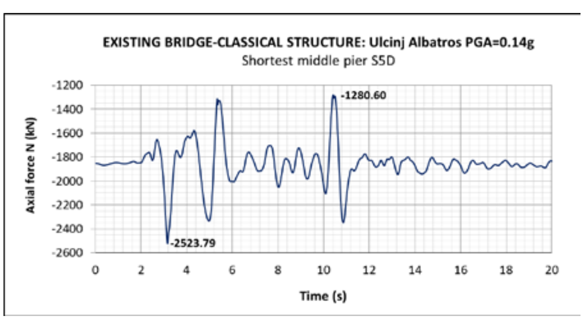

Fig. 14. Time history response of axial force N (kN) at the bottom of shortest middle pier S5D

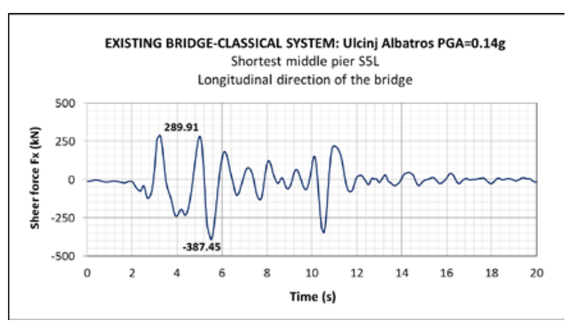

Fig. 15. Time history response of shear force FX (kN) at the bottom of middle pier S5L: L-direction

In Fig. 14 is shown the time history response of the axial force N (kN) at the base of the shortest middle pier S5D, under the effect of the Ulcinj-Albatros earthquake with PGAgl=0.14g. The values of the axial force range from N_{min}=-1280.60kN to N_{max}=-2523.79kN. In Fig. 15 shown is the time history response of the shear force FX (kN) at the base of shortest middle pier S5L in L-direction, ranging from FX_{min}=-387.45kN to FX_{max}=289.91kN, for the same earthquake input.

4. Seismic evaluation of upgraded bridge with new adaptive IMSO-system

4.1 Concept of seismic upgrading of the bridge with IMSO-system

Modification of the structural system begins with separation of the bridge superstructure and substructure and formation of a seismic joint in which seismic isolation and seismic energy dissipation devices are built-in. With the separation of the superstructure and the substructure of the bridge, the boundary conditions of the middle piers are changed from a double fixed to a single fixed, i.e. cantilever system.

To get an insight into the effects of the new IMSO-system for seismic upgrading of the "non-aseismic" structural system of the previously analyzed existing bridge, an optimal concept for defining an adequate IMSO-system was implemented. Taking in consideration the real characteristics of the existing bridge, the IMSO-system adapted to the specific case was formulated as follows:

(1) Basic seismic isolation system was formed by installation of two seismic isolators over each of the six supports. This system consists of seismic sliding bearings with two spherical surfaces with large radius and minimal friction for the purpose of minimizing the friction force and protect the weak middle piers that are characterized by quite low (limited) moment bearing capacity of the fixed to support critical cross-sections;

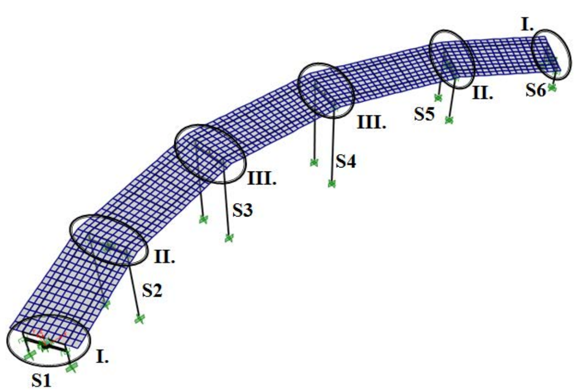

Fig. 16. Nonlinear model of upgraded bridge structure with new response modification IMSO-System

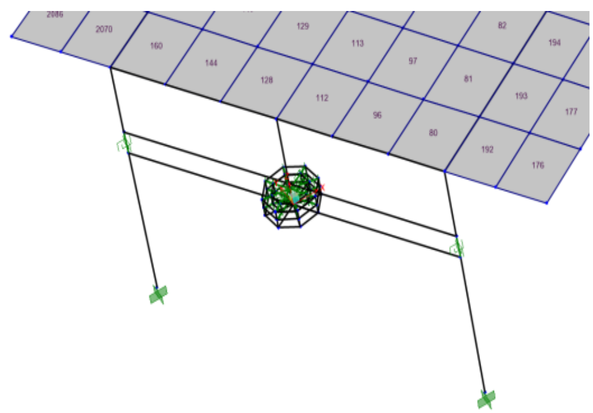

Fig. 17. Detail of abutment model with seismic isolation and ED-device of horizontal HC-type

(2) Seismic energy dissipation system was incorporated with special treatment of the supports considering real and different characteristics of the middle piers and the end supports, (Fig. 16), as follows:

I. "Strong" seismic energy dissipation devices of HC-type with higher yielding capacity with two levels of activation were used above the bridge abutments S1 and S6. The seismic energy dissipation components at both levels were appropriately designed to safely receive the generated horizontal forces and to provide required level of seismic energy dissipation in accordance with the earthquake intensity;

II. "Weaker" seismic energy dissipation devices of HC-type with lower yielding capacity, with two levels of activation were used above the shortest middle piers S2 and S5. The seismic energy dissipation components at both levels were appropriately designed to sustain large generated horizontal forces that could cause failure of the short middle piers;

III. No seismic energy dissipation devices were used above the longest middle piers S3 and S4 in order to prevent increase of the horizontal forces transferred to the central piers in which case present is only the low friction force that will not cause failure of the longest and the most flexible piers.

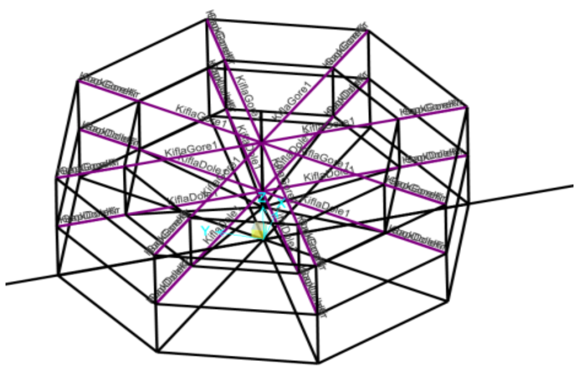

Fig. 18. Full nonlinear model of seismic energy dissipation (ED) device of horizontal HC-type

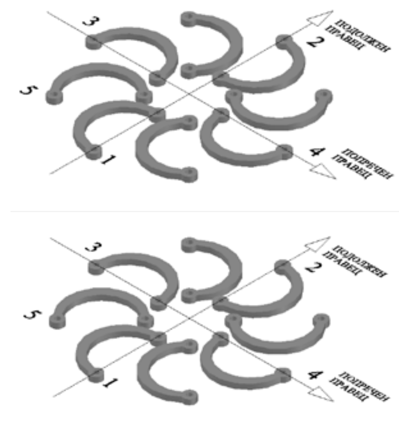

Fig. 19. Orientation of energy dissipation components of level-1 and level-2 of HC-EDD

(3) Displacement control system was not herein introduced explicitly, but its role was given to the stronger energy dissipation components from the second level of the energy dissipation devices installed along the axis above the abutments S1 and S6.

4.2 Modeling and seismic evaluation of upgraded bridge with IMSO-system

The nonlinear behavior of cross-sections representing potential plastic hinges was modeled in the same way as previously, using the same specified moment-curvature (M-φ) relations for different levels of axial forces in order to include variation effect of axial forces, Fig. 6b and the same axial force-moment (N-M) interaction diagrams, Fig. 6a. The only difference in this case was the location of the potential plastic hinges, actually they were considered only at the bottom critical cross-sections of the middle piers. From the new analysis of the dynamic characteristics defined are periods and mode shapes of the modified bridge structure. Mode shape-1 with period T_1=0.914 s has dominant vibrations in transverse direction of the bridge, Fig. 20a. Mode shape-2 with period T_2=0.773 s, has dominant vibrations in longitudinal direction, Fig. 20b. Mode shape-3 with period T_3=0.546 s, has dominant vibrations expressed as torsion representing rotation of the bridge superstructure.

Fig. 20. Dynamic characteristics of the IMSO-bridge structure: a) Mode shape 1 and b) Mode shape 2

With the performed analytical research implementing the formulated phenomenological nonlinear analytical model, it was derived that the new modified bridge system could sustain the increased Ulcinj Albatros earthquake intensity, i.e., it remained stable under the defined earthquake level reaching the value of even

PGAgl=0.42g. In this way, the modified structural system with the built-in IMSO-system becomes seismically resistant to a satisfying level, without any need for strengthening of its substructure.
The actual state of the modified structural system of the bridge defined with the performed nonlinear analysis of the seismic response to the Ulcinj Albatros earthquake with peak acceleration of PGAgl= 0.42g is presented further in the text through the selected characteristic results.

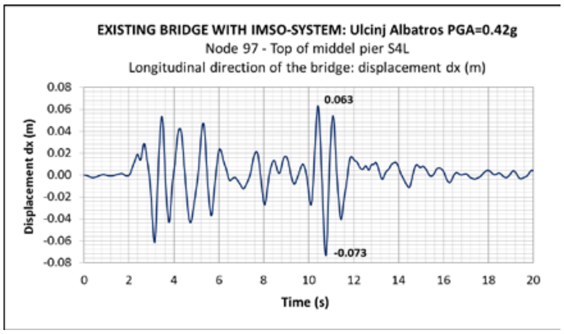

Fig. 21. Time history response of displacement dx (m) at the top of longest pier S4L in longitudinal direction

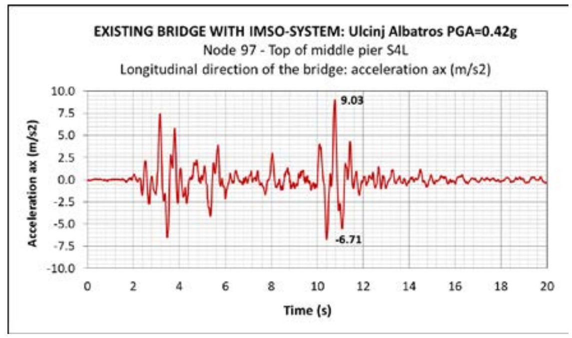

Fig. 22. Time history response of acceleration ay (m/sec^2) at the top of pier S4L in longitudinal direction

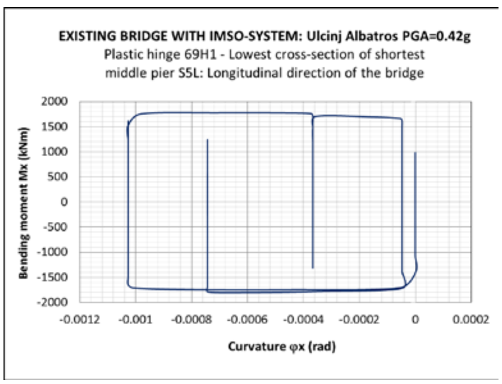

Fig. 23. Hysteretic response MX-φX of bottom plastic hinge of shortest pier S5L in L-direction (no failure)

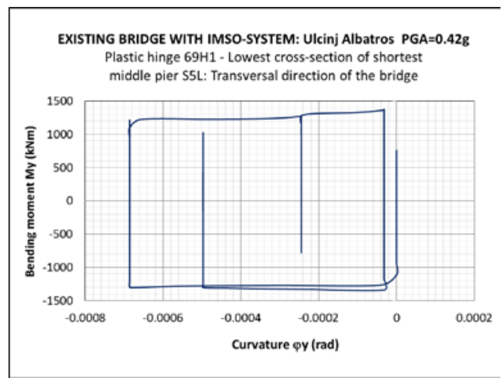

Fig. 24. Hysteretic response MX-φX of bottom plastic hinge of shortest pier S5L in T-direction (no failure)

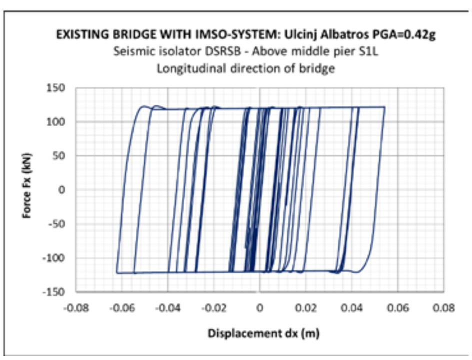

Fig. 25 Hysteretic response of seismic isolator above abutment: FXmax=120 kN, Dmax =5.4 cm

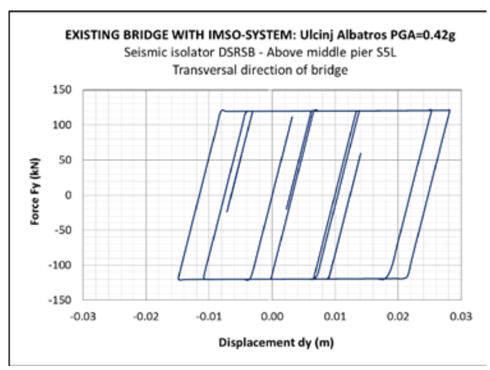

Fig. 26. Hysteretic response of seismic isolator above shortest pier S5L: FXmax=120 kN, Dmax=2.8 cm

In Fig. 21 shown is the time history response of displacement dx(m) at the top of the longest middle pier S4L in longitudinal direction of the bridge for Ulcinj-Albatros earthquake input with PGAgl=0.42g. The obtained maximum displacement is dx,max=0.073m. In Fig. 22 shown is the time history response of acceleration ay (m/sec^2) at the top of longest pier S4L in the longitudinal direction of the bridge, also under Ulcinj-Albatros earthquake with PGAgl=0.42g. The obtained maximum acceleration is ax,max=9.03 m/s^2.

In Fig. 23 and Fig. 24, respectively are shown hysteretic responses of the bottom cross-section of the shortest middle pier S5L in longitudinal direction and S5L in transversal direction due to the effect of the Ulcinj-Albatros earthquake record scaled to PGAgl=0.42g, demonstrating that collapse does not occur.

In Fig. 25 is shown hysteretic response of seismic isolator above abutment S1L in longitudinal direction of the bridge due to the effect of the Ulcinj-Albatros earthquake record scaled to PGAgl=0.42g. The obtained maximal force equals to FXmax=120 kN, and the maximal value of the displacement is Dmax=5.4 cm. In Fig. 26 is shown hysteretic response of seismic isolator above shortest middle pier S5L in transversal direction of the bridge due to the effect of the Ulcinj-Albatros earthquake record scaled to PGAgl=0.42g. The obtained maximal force equals to FXmax=120 kN, and the maximal value of the displacement is Dmax=2.8 cm.

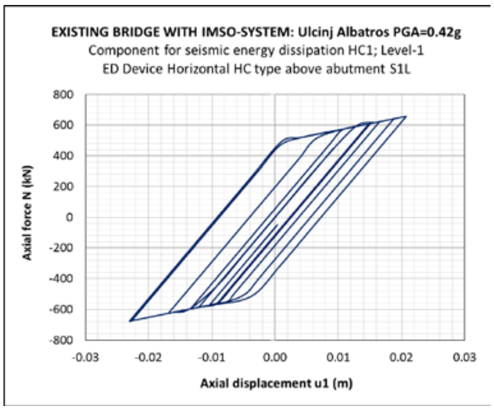

Fig. 27. Hysteretic response of energy dissipation component HC1 from level-1 of ED device above abutment: Nmax = 676.7 kN, Dmax = 2.3 cm

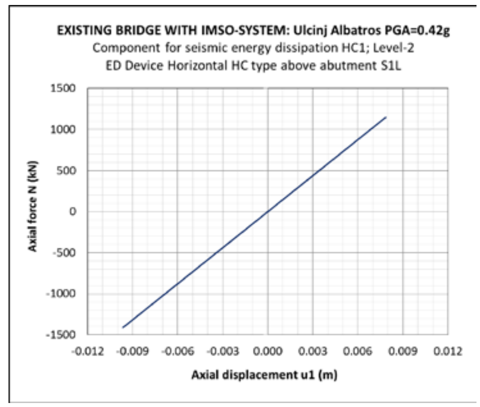

Fig. 28. Hysteretic response of energy dissipation component HC1 from level-2 of ED device above abutment: Nmax = 1411.6 kN, Dmax = 0.97 cm

In Fig. 27 and Fig. 28 respectively are shown hysteretic responses of seismic energy dissipation component HC1 at level-1 and component HC1 at level-2 of the ED device above abutment S1 of the bridge due to the effect of the Ulcinj-Albatros earthquake record scaled to PGAgl=0.42g. The obtained maximal axial force for the component HC1 from level-1 equals to Nmax=676.7 kN, with maximal value of the displacement of Dmax=2.3 cm.

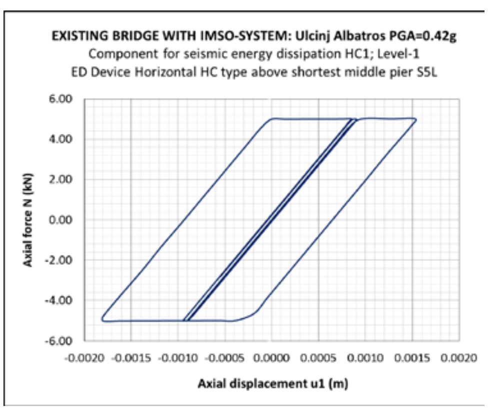

Fig. 29. Hysteretic response of energy dissipation component HC1 at level-1 of ED device above shortest pier S5: Nmax = 5.0 kN, Dmax = 0.18 cm

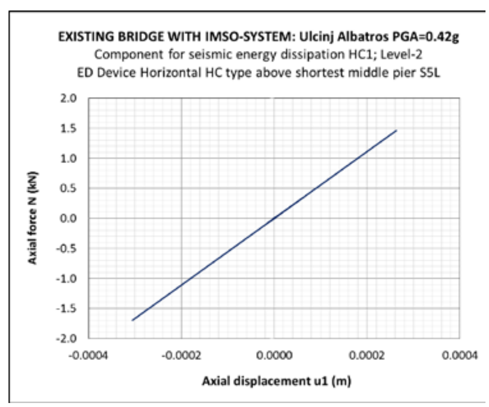

Fig. 30. Hysteretic response of energy dissipation component HC1 at level-2 of ED device above shortest pier S5: Nmax = 1.7 kN, Dmax= 0.026 cm

The obtained maximal axial force for the component HC1 from level-2 equals to Nmax=1411.6 kN, with maximal value of the displacement of Dmax=0.97 cm. In Fig. 29 and Fig. 30 respectively are shown hysteretic responses of seismic energy dissipation component HC1 at level-1 and component HC1 at level-2 of the ED device above shortest middle pier S5 of the bridge due to the effect of the Ulcinj-Albatros earthquake record scaled to PGAgl=0.42g. The obtained maximal axial force for the component HC1 from level-1 equals to Nmax=5.0 kN, with maximal value of the displacement of Dmax=0.18 cm. The obtained maximal axial force for the component HC1 from level-2 equals to Nmax=1.7 kN, with maximal value of the displacement of Dmax=0.026 cm.

In Fig. 31 and Fig. 32 respectively are shown gap-hook responses for seismic energy dissipation component HC1 at level-1 and component HC1 at level-2 of the ED device above the abutment S1 of the bridge due to the effect of the Ulcinj-Albatros earthquake record scaled to PGAgl=0.42g. The obtained maximal axial force for the gap-hook element for component HC1 from level-1 equals to Nmax=7535.4 kN, with maximal value of the gap designed to equal Dmax=1.5 cm. The obtained maximal axial force for the gap-hook element for component HC1 from level-2 equals to Nmax=2785.9 kN, with maximal value of the gap designed to equal Dmax=3.0 cm.

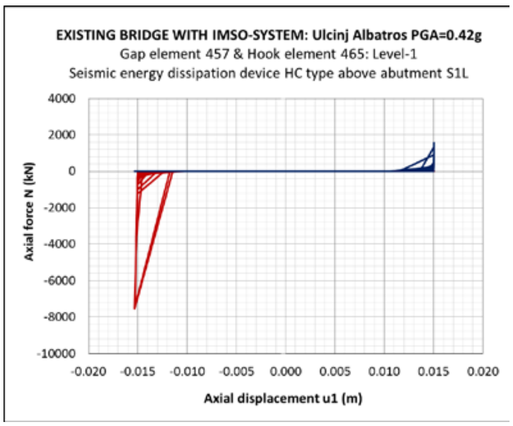

Fig. 31. Gap – Hook response of ED component HC1 at level-1 of ED device above abutment: Nmax = 7535.4 kN, Dmax = 1.5 cm

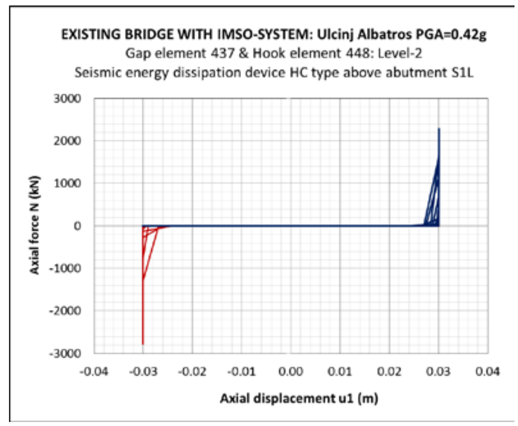

Fig. 32. Gap – Hook response of ED component HC1 at level-2 of ED device above abutment: Nmax = 2785.9 kN, Dmax = 3.0 cm

5. Conclusions

Classical bridge: From the performed detailed nonlinear analyses of the existing bridge designed as a classical structural system, several important remarks and conclusions can be drawn:

1) The classical structural system of the analyzed existing bridge is characterized by very low seismic resistance, or more precisely, it shows a very high and economically unacceptable seismic risk due to the high level of vulnerability to earthquake effects;

2) Under the effect of the Ulcinj-Albatros earthquake, the classical structural system experiences total failure at unacceptably small PGAs. More precisely, under all levels higher than PGAgl>0.14g, i.e., PGAx>0.10g and PGAy>0.10g, the structure experiences failure in the shortest pair of middle piers, as presented on Fig. 12 and Fig. 13. The failure occurs when the PGA of the Ulcinj-Albatros earthquake is PGAgl=0.15g, i.e., PGAx=PGAy=0.106g. The maximal value of the bending moment at the bottom critical cross-section at the moment of failure is M_{max}=2097.8 kNm.

3) With such realistic insights, it can be concluded that many infrastructure networks in the Balkan region and Southeast Europe are characterized with high to very high seismic risk since most of the existing bridges are designed as classical structural systems and do not possess a satisfying level of seismic safety;

4) To reduce the high seismic risk of existing bridge structures, it is necessary to perform detailed reevaluation of their seismic resistance levels in order to define optimal measures for their extremely necessary seismic revitalization and upgrade.

IMSO-bridge: Based on the derived and presented results from the carried out extensive analytical research, one could get a clear insight into the seismic response characteristics of the modified existing bridge by installation of the new IMSO-system. The most important conclusions can be summarized as follows:

1) The installation of the new IMSO-system into the existing traditional structural system enables a very important modification of the seismic response of the new system in a positive and desired way;
2) The existing structural system of the bridge characterized by very low seismic resistance was successfully seismically upgraded by installation of the optimal IMSO-system to the extent that it can remain seismically safe even under the effect of strong earthquakes with peak accelerations of up to PGAgl=0.42 g;
4) The optimal design of the seismic isolation and seismic energy dissipation devices and their adequate distribution over the structural system enabled their adaptable activation and generation of several lines of defense leading to improvement of the seismic safety of the integral structural system; and,
5) The application of the new IMSO-system in the design procedure of new bridge structures will enable extraordinarily qualitative success. Actually, it will highly increase the level of bridge seismic protection since all the components of the system can be optimally designed.

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