New Integrated 2G3 Response Modification Method for Seismic Upgrading of New and Existing Bridges

D.N. Ristic & J.D. Ristic
"Ss. Cyril and Methodius" University, Skopje,
Institute of Earthquake Engineering and Engineering Seismology (IZIIS),
Skopje, Republic of Macedonia

SUMMARY
The high seismic risk pertaining to transportation networks in South East Europe (SEE) is a serious threat to public safety, sustainable economic and social development and security in the region. Extensive experimental and analytical research in the frames of the new NATO Science for Peace Project "Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828)", focused on fundamental research and development of an innovative technology for seismic isolation and seismic protection of bridges, is presently being conducted at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje. The main objective of the innovative NATO SfP project have been focused on development (creation) and experimental validation of new, highly efficient 2G3-GOSEB bridge seismic isolation system. The new system is developed based on optimized integration of the innovative concepts of Multi-Level Multi-Directional Seismic Energy Dissipation and Globally Optimized Seismic Energy Balance.

Keywords: *Bridges, seismic isolation, hysteretic dampers, response modification*

1. FOREWORD

The high seismic risk pertaining to 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.

Figure 1. Kobe, Japan, M=7.2, 1995, Total Collapse of Hanshin Line

Figure 2. Chile earthquake, Magnitude M=8.8, Most Recent: February 27, 2010

The observed severe damages and total collapses of bridge structures in recent earthquakes in many world seismic countries (Japan, Chile, Turkey, U.S.A., China, etc.), Fig. 1. & Fig. 2, has clearly demonstrated the urgent need for adoption of an advanced technology for qualitative seismic safety improvement of classical existing and new bridge systems.

2. MODERN CHALLENGE OF WORLD-WIDE BRIDGE ENGINEERING INDUSTRY

Structural earthquake engineering that is particularly connected with bridge strategic structures is distinguished and identified as a central and very specific expert activity of the modern world-wide bridge engineering industry. World experts, in the role of principal design engineers of the most prominent structures worldwide are increasingly organized in very specialized expert teams that put concerted efforts toward realization of specific projects in the field of structural earthquake engineering. Bridges of extraordinarily large proportions are presently increasingly being constructed all over the world (Fig. 3. and Fig. 4). As prominent structures and with their appearance, these bridges reflect, in the most transparent way, the evident progress and the high achievements made in modern structural earthquake engineering.

Figure 3. Hangzhou Bay Bridge, Most L is Low-Level Viaduct, Total L=35.673 km, China, Opened in 2008.

Figure 4. Donghai Bridge ("East Sea Grand Bridge"), Total L=32.5 km, China, Opened 2005.

The development and application of successful systems for seismic protection of distinctively long and large new bridges represents the greatest challenge of the present scientists and experts in the field of structural earthquake engineering. Due to the uniqueness of the applied structural system and the possible big “surprises” regarding the intensity of seismic effects, it is necessary to carry out specific investigations for the purpose of providing efficient seismic protection of the unique systems of modern bridge structures.

3. MAIN OBJECTIVES OF THE INNOVATIVE NATO SCIENCE FOR PEACE PROJECT

The main objective of the present innovative NATO SfP project have been focused on original development (creation) and experimental validation of new, highly efficient, 2G3-GOSEB bridge seismic isolation system. The new system is developed based on optimized integration of the innovative concepts of Multi-Level (ML) Multi-Directional (MD) Seismic Energy Dissipation (2) and Globally Optimized Seismic Energy Balance (G). The new “2G3” high performance seismic isolation and seismic upgrading system for bridges actually represent very important technical innovation capable of integrating the three highly important advantages: Seismic isolation, Seismic energy dissipation and Effective displacement control (3). With the achieved advanced seismic isolation and seismic protection performances with created 2G3-system, in compliance with the current seismic input energy, complete seismic protection of bridge structures is provided, even under the strongest earthquakes. In the present paper presented are created four highly important innovative end-products (deliverables): (D1) Prototypes of new hysteretic energy dissipation components, (D2) Prototypes of new hysteretic energy dissipation devices, (D3) Prototypes of new and innovative 2G3-GOSEB system, and (D4) Advanced design procedure for application of new 2G3-GOSEB system for seismic protection of new and existing bridges. The end-result of this innovative NATO SfP project represents new technology integrating response modification and seismic isolation into efficient bridge seismic protection system. This project is clearly technologically supporting in best way all involved South East European countries in making their infrastructure compliant with the European standards.

4. PROTOTYPES OF INNOVATIVE ENERGY DISSIPATION COMPONENTS (EDC)

Generally, creation of prototypes of the innovative energy dissipation components (EDC) include organized research activities in three separate phases as follows:

Phase-1: *Development of innovative concept of ML-MD Hysteretic energy dissipation devices (EDD).* Basic studies in this domain have been performed and final design of the innovative ML-MD hysteretic energy dissipation devices (EDD) and innovative ML-MD hysteretic energy dissipation components (EDC) is completed. Manufacturing of ML-MD Hysteretic energy dissipation components (EDC) is presently being completed, as part of the experimental program-1.

Phase-2: *Testing of innovative hysteretic energy dissipation components (EDC).* Testing of the new hysteretic energy dissipation components will be completed in laboratory conditions, based on performed optimal experimental program and successful set-up of respective experimental tests.

Phase-3: *Modeling of innovative hysteretic energy dissipation components (EDC).* In the final phase, based on complete experimental evidence from conducted original experimental tests and final test results, new widely applicable and realistic theoretical models of the tested hysteretic energy dissipation components will be developed and proposed for practical implementation. The proposed new theoretical models actually represent the main and very important output from the conducted experimental program-1.

The process of creation, construction and testing of full-scale & scaled prototype models of innovative seismic energy dissipation components (EDC) represent important initial experimental program part-1. Considering the project plan, the initial study program-1 is being realized in two phases, representing two respective theoretical and experimental sub-projects as follows:

(1) Sub-Project-No. 1: Creation, construction and testing of new Energy Dissipation Components of Horizontal H-Class: Type-1 (EDC-HC-T1), Type-2 (EDC-HC-T2) and Type-3 (EDC-HC-T3); and
(2) Sub-Project-No. 2: Creation, construction and testing of new Energy Dissipation Components of Vertical V-Class: Type-1 (Standard): (EDC-SVC-T1) and Type-2 (Complex): (EDC-CVC-T2).
The created prototypes of innovative energy dissipation components (EDC) are integrated as original constituent parts in respective prototypes of innovative ML-MD energy dissipation devices (EDD).

5. PROTOTYPES OF INNOVATIVE ENERGY DISSIPATION DEVICES (EDD)

Within the frames of construction and experimental testing of large-scale models of the new ML-MD innovative 2G3-GOSEB system in IZIIS Dynamic Testing Laboratory under seismic loads, detailed and profound consideration was made regarding necessary materials, possible performers of the specific manufacturing operations as well as testing conditions for the created prototypes of innovative ML-MD hysteretic energy dissipation devices (EDD). Creation of innovative prototypes and preparation of full documentation needed for the manufacturing of the innovative ML-MD Hysteretic energy dissipation devices is completed. The programmed original process of manufacturing of all different types of ML-MD Hysteretic energy dissipation devices is under realization as part of the experimental program-2, which is briefly described bellow. The new ML-MD GOSEB system can successfully be applied for seismic upgrading of a dominant number of typical RC bridges (Fig. 8), constructed with neoprene and/or similar bearings in Macedonia and SE Europe in general.

Generally, under this research phase, the planned research activities in IZIIS, Skopje, are organized in two separate phases as follows:

Phase-1: *Testing of new ML-MD hysteretic energy dissipation devices.* Testing of new ML-MD hysteretic energy dissipation devices (EDD) is planned to be completed in laboratory conditions based on defined optimal experimental program and set-up of respective experimental tests; and

Phase-2: *Modeling of ML-MD energy dissipation and isolation devices.* Analogously, in the final phase, based on complete experimental evidence from conducted original experimental tests and final test results, new widely applicable realistic theoretical models of the tested hysteretic energy dissipation devices will be originally developed.

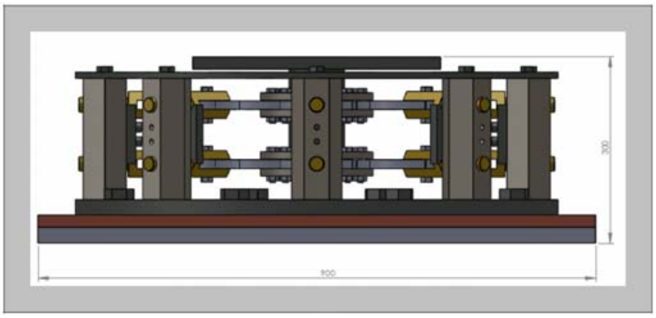


Figure 5. Design of innovative ML-MD Energy Dissipation Devices of Horizontal H-Class

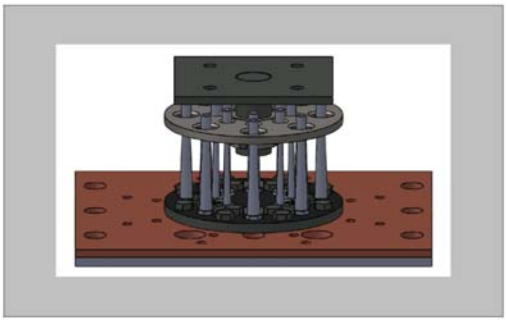


Figure 6. Design of innovative ML-MD Energy Dissipation Devices of Vertical V-Class

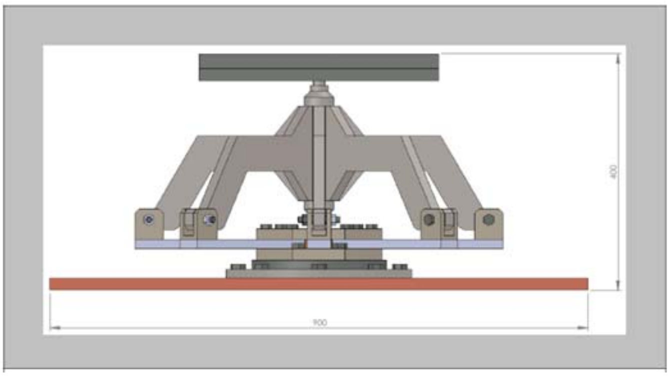


Figure 7. Design of innovative ML-MD Energy Dissipation Devices of Complex Vertical V-Class (EDD-CVC-T1).

Figure 8. Typical example of classical bridge over Vardar river (Motorway in Macedonia)

The phase of creation, construction and testing of full-scale & scaled prototype models of innovative energy dissipation devices (EDD) actually represent experimental program part-2. Considering the original project plan, the integral study program-2 is being realized in three basic phases, representing three respective theoretical and experimental sub-projects as follows:

(1) Sub-Project-No. 3: Creation, construction and testing of new ML-MD Energy Dissipation Devices of Horizontal H-Class: Type-1 (EDD-HC-T1) and Type-2 (EDD-HC-T2), (Figure 5);
(2) Sub-Project-No. 4: Creation, construction and testing of new ML-MD Energy Dissipation Devices of Upgraded Vertical V-Class: Type-1 (EDD-UVC-T1) & Type-2 (EDD-UVC-T2), (Figure 6); and
(3) Sub-Project-No. 5: Creation, construction and testing of new ML-MD Energy Dissipation Devices of Complex Vertical V-Class: Type-1 (EDD-CVC-T1), (Figure 7).

6. SHAKING TABLE TESTS OF 2G3-GOSEB BRIDGE PROTOTYPE MODEL

The planned experimental program part-3 includes creation, construction and testing of representative prototypes of bridge shaking table test models (Figure 9, Figure 10 & Figure 11) with integrated innovative 2G3-GOSEB seismic isolation systems. Considering created innovative options of constructed large-scale shaking table test models, planned is realization of various experimental shaking table tests under simulated shaking effects of the selected representative recorded real and strong earthquake ground motions. The planned experimental seismic shaking table tests will serve as realistic experimental validation of the actual response modification performances and generated efficiency of the created different options of innovative 2G3-GOSEB bridge systems for seismic upgrading of typical existing classical bridges (Figure 8) and seismic protection of new important and large bridges.

During the process of the design of Basic (Classical) Bridge Model (C-BBM), and planning of integral experimental shaking-table tests, several relevant conditions, highly important for the present experimental multi-task innovative study, have been achieved as follows:
1. With simulated strong shaking-table input in one direction, by well selected position of model set-up, bridge model excitation will be successfully realized in both, longitudinal-x and transversal-y direction. Presently are selected equal earthquake shaking components in x and y direction. This is achieved by selected diagonal position of the bridge model on IZIIS shaking table (45 degrees);
2. The developed bridge model fully integrates both end supports (left and right), as well as middle piers with different stiffness characteristics (considering different height of the piers);
3. The designed Basic Bridge Model is characterized by well manifested all three first mode shapes representing the most representative and specific case with: Mode-1, in transversal-y direction, Mode-2, in longitudinal-x direction and Mode-3 represent clear torsion mode shape;

Figure 9. Construction large-scale experimental bridge model in IZIIS, Skopje dynamic testing laboratory

Figure 10. Erected large-scale experimental bridge model in IZIIS, Skopje, laboratory (phase-1)

4. The designed Basic (Classical) Bridge Model is successfully accommodated for multi-purpose use and can assure very realistic experimental investigation of four (or even more) different bridge construction technologies: (1) Testing of classical bridge structures; (2) Testing of the innovative 2G3-GOSEB bridge systems involving rubber isolators and different types of energy dissipation devices; (3) Testing of innovative 2G3-GOSEB bridge systems involving spherical-sliding bearings, and different types of energy dissipation devices and (4) Innovative bridge systems involving UHYDE-friction controlled energy dissipation devices. Considering the project plan, this integral study phase includes realization of four test phases representing respective sub-projects as follows:

1. Sub-project-1 (G4-P1): *Construction of basic bridge model (BBM).* Construction of a scaled three-span BASIC RC BRIDGE MODEL (BBM) representing the BASIC STRUCTURE designed to assure its adoption for multi-usage and realization of the planned full program of shaking-table tests of bridge models with different innovative seismic isolation systems, System-1, System-2, and System-3.
2. Sub-project-2 (G4-P2): *Construction of Bridge model-1 (ML-GOSEB-BM1-RB).* Construction of scaled three-span innovative ML-GOSEB bridge model-1 (System-1), incorporating new scaled energy dissipation devices and basic seismic isolation system with adopted rubber bearings, denoted as ML-GOSEB-BM1-RB.
3. Sub-project-3 (G4-P3): *Construction of Bridge model-2 (ML-GOSEB-BM2-SSB).* Construction of scaled three-span innovative ML-GOSEB bridge model-2 (System-2), incorporating the new scaled

energy dissipation devices and basic seismic isolation system with adopted spherical sliding bearings, denoted as ML-GOSEB-BM2-SSB. (Test set-up and tests will be realized based on optimal test program plan for bridge model-2.

4. Sub-project-4 (G4-P4): *Construction of Bridge model-3 (UHYDE-BM3-CF).* Construction of the scaled three-span innovative ML-GOSEB bridge model-3 (System-3), incorporating seismic isolation system UHYDE based on the adopted controlled friction bearings, denoted as ML-GOSEB-BM3-FB. Test set-up and tests will be realized based on optimal test program plan for bridge model-3.

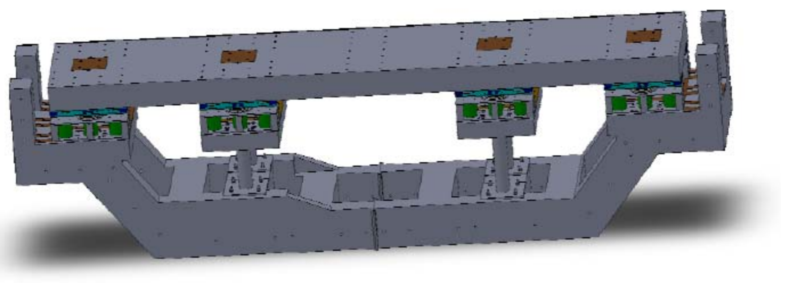
EBM1-SC Vibration Periods T_1=0.255 s (y) T_2=0.254 s (x) T_3=0.122 s (xy) **EBM1-FC** Vibration Periods T_1=0.262 s (y) T_2=0.261 s (x) T_3=0.131 s (xy)		WEIGHT OF MODEL SLAB: Q_0=83.25 kN ADDITIONAL LOAD: q=1.5 kN/m^2 Q_a=16.65 kN TOTAL WEIGHT OF MODEL SUPER - STRUCTURE: Q_S= 99.9 kN

Figure 11. Designed innovative large-scale bridge test model with superstructure and substructure elements. Optional seismic isolation systems and typical columns with different pier's stiffness.)

7. CASE STUDY: EFFICIENCY OF NEW 2G3-GOSEB SEISMIC ISOLATION SYSTEM

To obtain basic system verification and evaluation results, very extensive analytical seismic response studies have been performed considering the designed innovative laboratory bridge model prototype with incorporated an optimized 2G3-GOSEB seismic isolation system. The integral analytical study of seismic response characteristics of the designed bridge model with 2G3-GOSEB system are carried out using comparatively Experimental Bridge Model-1 with Stiff middle Columns (EBM1-SC) and Experimental Bridge Model-2 with more Flexible middle Columns (EBM2-FC). The constructed large scale experimental bridge model structure exists with three bridge spans and its total length is L=7.40+2x0.20+2x0.25=8.30m (Fig. 9, Fig. 10 and Fig. 11).

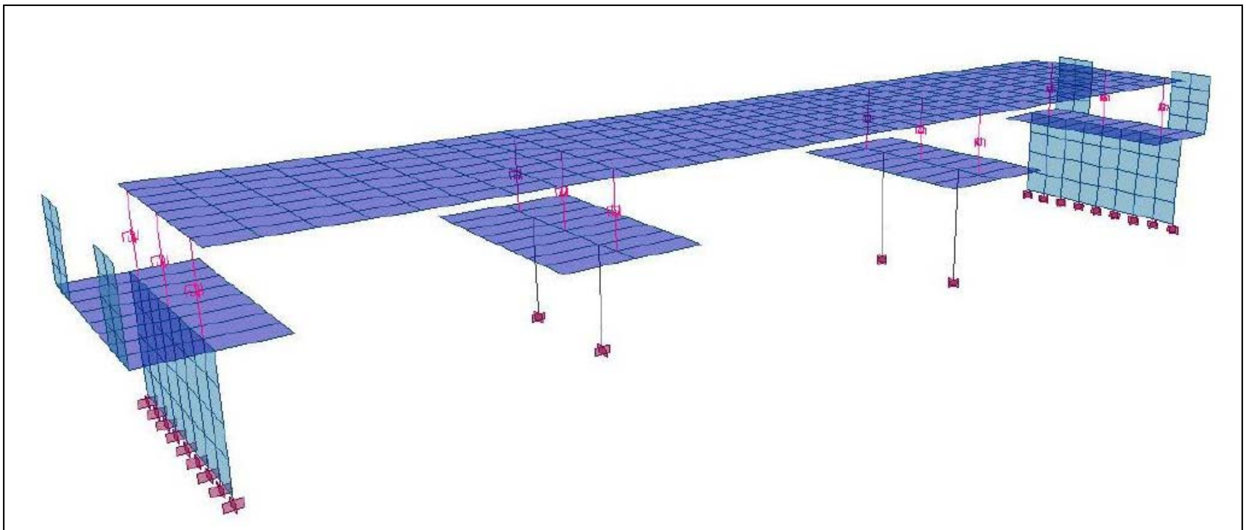


Figure 12. Formulated 3D mathematical model of large-scale seismic shaking table bridge test model with innovative 2G3-GOSEB seismic isolation systems

The superstructure is designed as a stiff continuous system composed of RC tick slab d=30cm, width b=150cm and length l=740cm. The sub-structure consists of two specially designed RC end supports (abutments) and two middle steel piers with different heights (Formed of pairs of two steel piers with D=160mm). Hight of left and right pier are h1=60cm and h2=80cm, respectively. The piers are fixed to the stiff RC footings and on the top are connected with appropriately designed RC cap beam. The RC superstructure slab is supported by eight (8) rubber seismic isolators installed at both sides on the top of four sub-structure specially designed steel supports (installed above the two abutments and two middle piers). At all the four bridge supports, innovative two level, named multi level (ML) seismic energy absorbers, active in longitudinal direction, transverse direction, or in general case active in all directions, named multi directional (MD), are considered.

7.1. Seismic Response of Experimental Bridge Model-1 With Stiff Columns (EBM1-SC)

Formulated 3D mathematical model of the constructed large-scale Experimental Bridge Model-1 with stiff middle columns (EBM1-SC) and with integrated innovative 2G3-GOSEB seismic isolation systems is presented in Figure 12. Extensive seismic response study was performed applying the formulated nonlinear mathematical model, considering as input the effects of very strong earthquake ground motions. RC superstructure slab and RC substructure elements are modeled with shell finite elements. The existing steel middle piers are modeled with 3D beam finite elements, while rubber seismic isolators, as well as energy dissipating devices are modeled with nonlinear link elements.

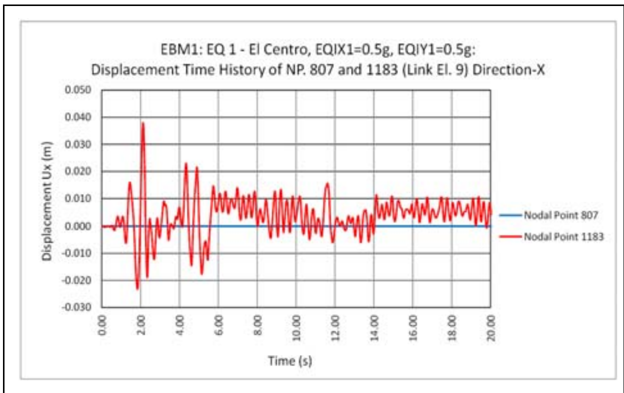


Fig. 13. EBM1-SC: Displacement response DX(m) of NP=807 & NP=1183 (LS). EQ: El-Centro, EQI-0.7g.

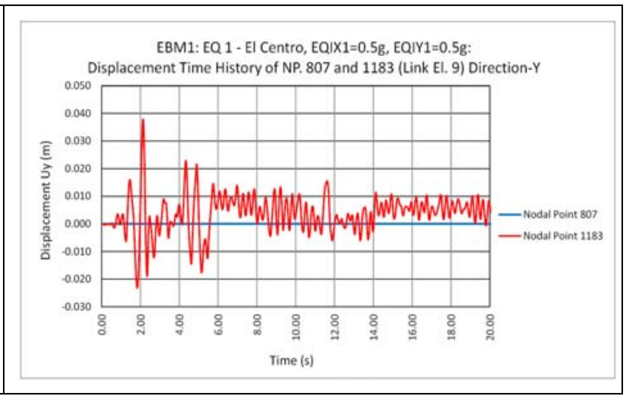


Fig. 14. EBM1-SC: Displacement response DY(m) of NP=807 & NP=1183 (LS). EQ: El-Centro, EQI-0.7g.

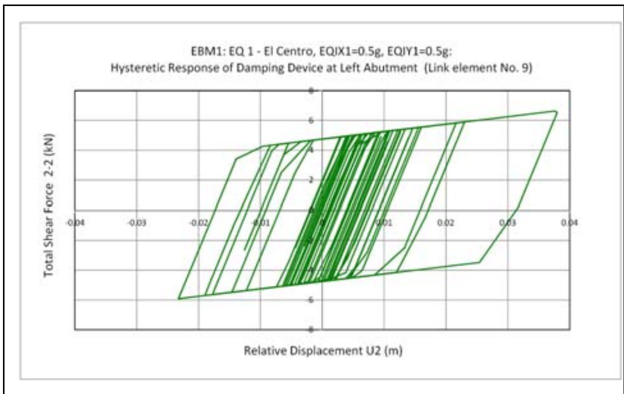


Fig. 15. EBM1-SC: Hysteretic response of EDD-1 at left end-support. DIR-X. EQ: El-Centro, EQI-0.7g.

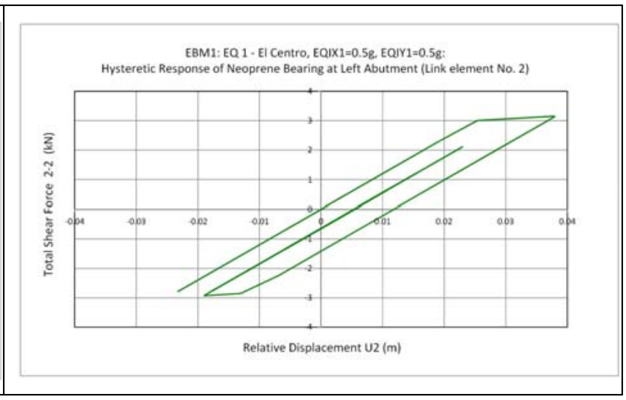


Fig. 16. EBM1-SC: Hysteretic response of SRB-1 at left end-support. DIR-X. EQ: El-Centro, EQI-0.7g.

For this considered option-1 of bridge structural system, non-linear seismic response of the modeled structure was analyzed using two different earthquake records: (1) El-Centro record and (2) Ulcinj-Albatros record. The PGA of both records were scaled to extremely high intensity level (PGA=0.7g), acting inclined for 45 degrees in respect to the bridge longitudinal axis. So, in such a case, the bridge is excited simultaneously in longitudinal direction and in transverse direction with identical seismic input components, having very high PGA=0.5g. Here are presented only selected typical response results for left bridge support, demonstrating the actual seismic performances of the system. For model EBM1-SC, displacement response DX(m) & DY(m), of nodal points NP=807 (substructure) and nodal point NP=1183 (superstructure) above left support (LS), under El-Centro earthquake are comparatively presented for x-direction and y-direction in Fig. 13 and Fig. 14. In addition, presented are hysteretic responses of energy dissipating device EDD-1 at left end-support and hysteretic response of square rubber bearing SRB-1 at left end-support, respectively in Fig. 15 and Fig. 16. From the integral and presented results, evident is very favorable behavior of the analyzed bridge system-1.

7.2. Seismic Response of Experimental Bridge Model-2 With Flexible Columns (EBM2-FC)

For the second analyzed option (option-2) of bridge structural system, non-linear seismic response of the structure was analyzed using also two different earthquake records: (1) El-Centro record and (2) Ulcinj-Albatros record. The PGA of both records were also scaled to extremely high intensity level (PGA=0.7g), acting inclined for 45 degrees in respect to the bridge longitudinal axis. Analogously, the bridge was excited simultaneously in longitudinal direction and in transverse direction with identical seismic input components, having very high PGA=0.5g. For this case presented are identical selected typical response results for left bridge support (LS) in (Fig. 17, Fig. 18, Fig. 19 and Fig. 20). To observe response differences, for this model case (FC) presented are also selected typical response results for higher bridge pier in (Fig. 21, Fig. 22, Fig, 23 and Fig. 24).

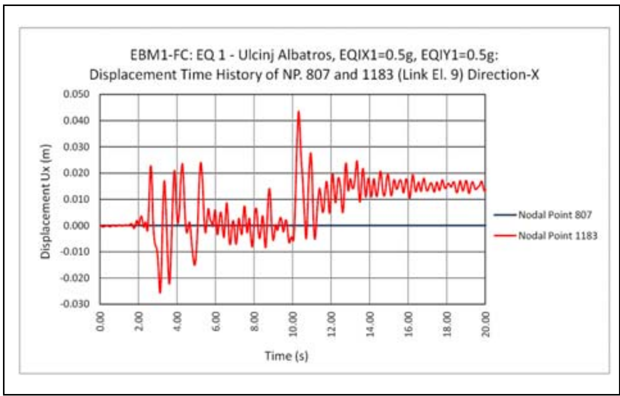


Fig. 17. EBM1-FC: Displacement response DX(m) of NP=807 & NP=1183 (LS). EQ: ULC-AL, EQI-0.7g.

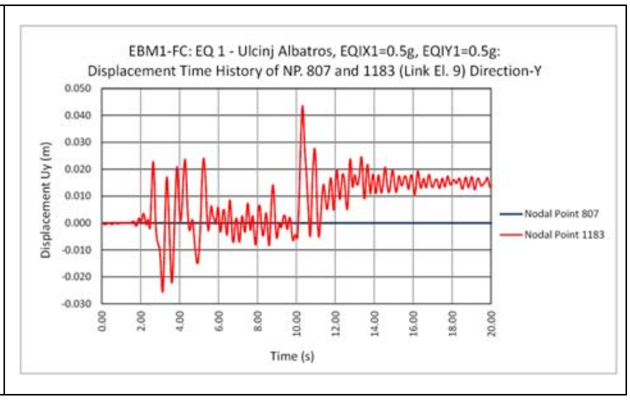


Fig. 18. EBM1-FC: Displacement response DY(m) of NP=807 & NP=1183 (LS). EQ: ULC-AL, EQI-0.7g.

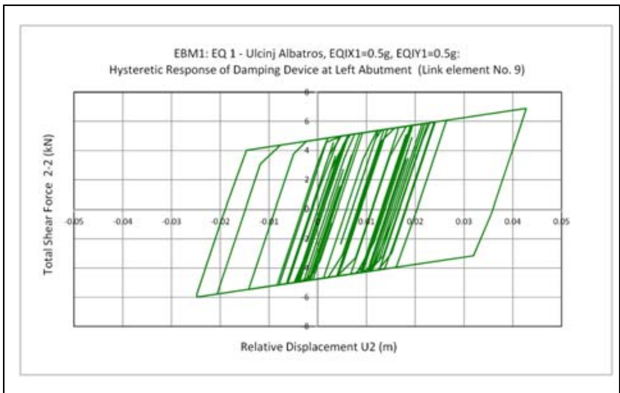


Fig. 19. EBM1-FC: Hysteretic response of EDD-1 at left end-support. DIR-X. EQ: ULC-AL, EQI-0.7g.

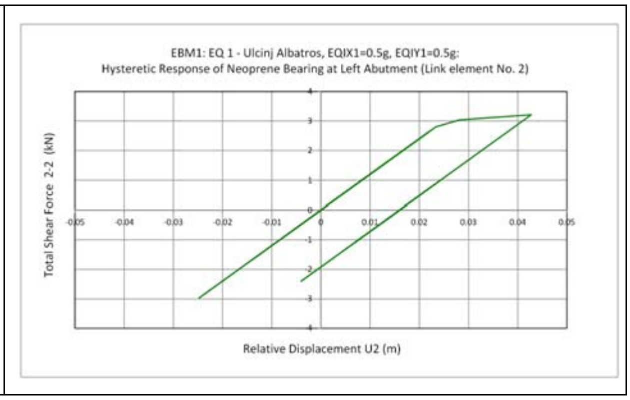


Fig. 20. EBM1-FC: Hysteretic response of SRB-1 at left end-support. DIR-X. EQ: ULC-AL, EQI-0.7g.

As in the first case, from the integral and presented results, also is confirmed very favorable behavior of the analyzed bridge system-2. With the innovative 2G3-GOSEB system, structural response modification is possible to control providing full seismic protection of bridges under the effect of the strongest earthquakes.

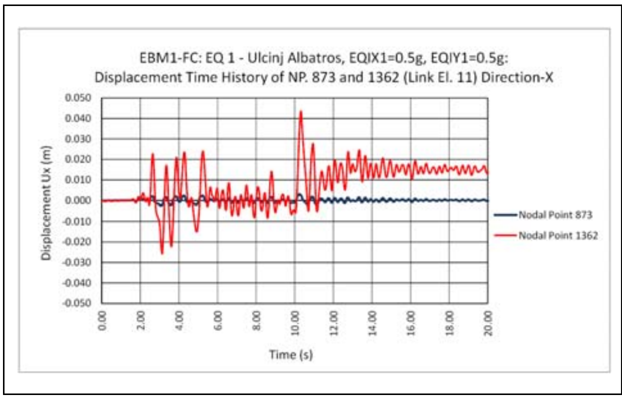


Fig. 21. EBM1-FC: Displacement response DX(m) of NP=873 & NP=1362 (LC). ULC-AL, EQI-0.7g.

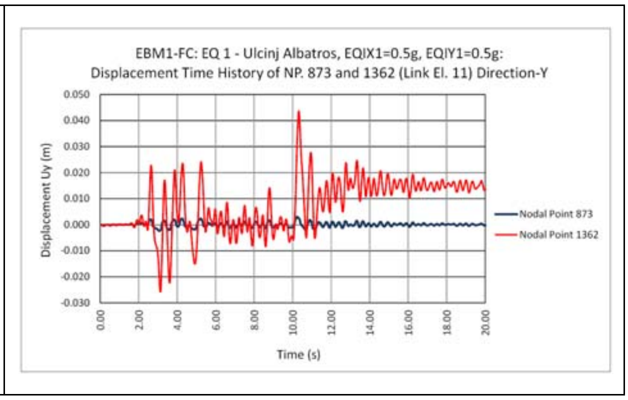


Fig. 22. EBM1-FC: Displacement response DY(m) of NP=873 & NP=1362 (LC). EQ: ULC-AL, EQI-0.7g.

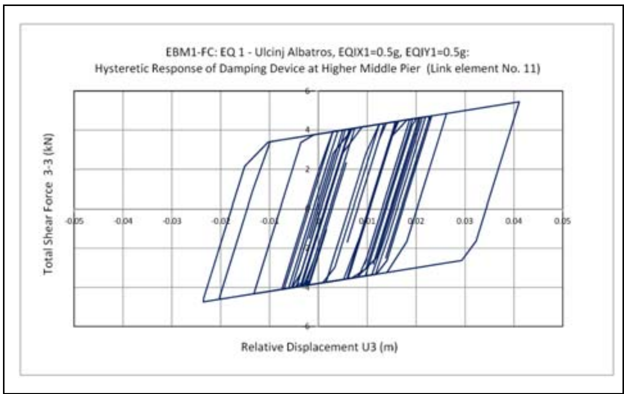


Fig. 23. EBM1-FC: Hysteretic response of EDD-1 at LC-support. DIR-Y. EQ: ULC-AL, EQI-0.7g.

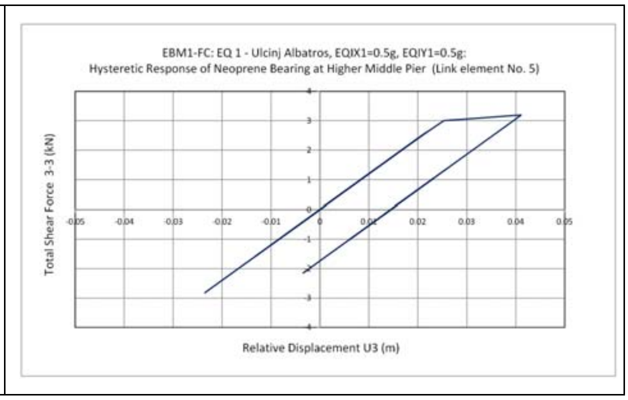


Fig. 24. EBM1-FC: Hysteretic response of SRB-1 at LC-support. DIR-Y. EQ: ULC-AL, EQI-0.7g.

8. CONCLUSIONS

Considering research results obtained from the conducted extensive theoretical study presented above, using designed innovative bridge model prototype structure, the following general conclusions are derived: (1) The optimized seismic isolators are very effective for bridge seismic vibration control. However, for any particular bridge, seismic isolators should be designed based on advanced optimization process. Applying the required expert knowledge, the designers will be able to achieve successful selection of seismic isolators; (2) The new multi-level multi-directional “2G3-GOSEB” hysteretic seismic energy absorbers possess unique energy absorption features since they are capable of adapting their behavior to the actual intensity of seismic input energy. Actually, the new “2G3-GOSEB” hysteretic energy absorbers provide the most innovative and advanced features of multi-level earthquake response in all directions; (3) The optimized displacement bound devices (rubber stoppers, etc.) are very effective for excessive displacement control of the bridge superstructure.
It is clear that the “2G3-GOSEB” rubber stoppers represent highly efficient system devices providing additional contribution to the improvement of the bridge seismic safety, particularly in the case of very strong earthquakes; (4) The new “2G3-GOSEB” high performance seismic isolation system for bridges, created based on an optimized seismic energy balance actually is very effective technical innovation capable of integrating the advantages of seismic isolation, seismic energy dissipation and effective displacement control; (5) The new “2G3-GOSEB” seismic isolation system for bridges based on multi-level seismic energy absorption and optimized seismic energy balance shows very high seismic control performances and can be used for full seismic protection of bridges in longitudinal and transversal direction under the effect of very strong earthquakes.

ReSIN: NEW INNOVATIVE RESEARCH NETWORK OF YOUNG SCIENTISTS

Based on initiated cooperation among responsible institutions in several participating countries (R. Macedonia, Germany, Albania, Bosnia and Herzegovina and Serbia), as result of this innovative project, established is new regional seismic isolation network ReSIN. It represents unique innovative chain involving young scientists focused on development of innovative seismic isolation technologies, applicable for efficient seismic protection of bridges and other infrastructure and civil engineering systems against destructive earthquakes.

ACKNOWLEDGEMENT

Presently, (at IZIIS, Skopje), extensive experimental and analytical research is continued in the frame of the approved new three year NATO Science For Peace Project: *Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies* (SFP: 983828), focused on fundamental research and development of innovative technology for seismic isolation and seismic protection of bridges *(New large-scale scientific and research activity with participation of five countries).*
The extended NATO SfP support for realization of this innovative project is highly appreciated.

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