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CRITICAL NEAR RESONANCE SHAKING TABLE TESTS OF CONSTRUCTED LARGE-SCALE UPGRADED ISOLATED USI-V-MG BRIDGE PROTOTYPE MODEL

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Abstract

Construction of modern, seismically safe bridge structures represents a permanent activity of the highest importance because bridge structures are important key elements responsible for providing continuous functioning of integral highway infrastructure systems. An extensive experimental and analytical research led by the third author was performed in the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Ss. Cyril and Methodius University in Skopje, lasting three and a half years, in the frames of the innovative NATO Science for Peace Project "Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828)", involving five countries. The specific project part included development of the innovative upgraded seismically isolated system USI with vertical multi gap V-MG representing an advanced technology for seismic isolation and seismic protection of bridges. By integrating the new uniform, vertical multi-gap (V-MG) energy dissipation devices, qualitative advances of the USI-V-MG system were achieved. The original observations resulting from the conducted complex, unique and critical near resonance shaking table tests of the constructed large-scale bridge model are presented and discussed in this paper. The extensive experimental research program was realized on a bridge model constructed by using the seismically isolated system upgraded with uniform vertical multi-gap energy dissipation devices (USI-V-MG). The installed adaptive system for seismic protection of bridges utilizes originally produced double spherical rolling seismic bearings (DSRSB) as seismic isolators, while qualitative improvement of the seismic performances is achieved through the use of novel, uniform vertical multi-gap energy dissipation (V-MG-ED) devices.

Keywords: Shaking table, bridge model, seismic test, seismic isolation, energy dissipation

1. Introduction

In the past, extensive studies in the field of seismic isolation of bridges have been mostly performed in the world's renowned research centres in Japan, USA, Italy, and New Zealand. However, in the recent years, contributions from many other countries are increased and have resulted in proposing of many new ideas and concepts. The intolerable severe impacts to modern bridge systems during strong recent earthquakes [1, 2], have been observed. It has given rise to strong arguments about the further needs for development and practical implementation of seismic isolation systems in seismic protection of bridges, [3-7]. This paper shows the obtained important results from the realized creative research part of the innovative long-term study devoted to development of a new, experimentally verified, advanced USI-V-MG system that can provide qualitative seismic upgrading of isolated bridges by using of innovative V-MG-ED energy dissipation devices [8]. The conducted initial experimental part of the study included realization of original nonlinear quasi-static tests of the created individual energy dissipation components. Unique original experimental data have been obtained, enabling development of an advanced, experimentally validated, nonlinear micro-model for hysteretic behaviour study of the complete new vertical multi-gap energy dissipation (V-MG-ED) devices with possibility of optionally different arrangement of ED components. Following some recent author's developments [8], conditions for realization of the final original study were created, involving shaking table tests of the constructed

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large-scale bridge prototype model with the applied new USI-V-MG system. The tested uniform upgrading system for seismic protection of bridges, USI-V-MG system, utilizes originally produced double spherical rolling seismic bearings (DSRSB) as seismic isolation system, while qualitative improvement of seismic performances is achieved through the use of novel uniform vertical multi-gap energy dissipation (V-MG-ED) devices.

2. Concept of New USI-V-MG Bridge System

The upgraded seismically isolated (USI) system with vertical multi gap (V-MG) energy dissipation (ED) devices represent newly created advanced technical concept providing harmonized modification and improvement of structural seismic response, Fig. 6. The USI-V-MG system is advanced alternative method for qualitative improvement of seismic protection of bridge structures through introduced concept of global optimization of seismic energy balance. The USI-V-MG system is created through obligatory incorporation of the following three complementary systems: ***(1) Incorporation of seismic isolation (SI) system:*** The applied system for seismic isolation of bridge superstructure should contain adequately selected seismic isolators that will provide very low stiffness in horizontal direction and will be capable of sustaining safely the total weight of the entire superstructure. In that way, it is enabled for an appropriately designed seismic isolation (SI) device to be installed at each supporting point of bridge superstructure whereas the total isolated weight will be directly transferred to the supporting middle piers and/or to the rigid supporting abutments of the bridge. Under such conditions, a wide range of possibilities of selecting the proper system for seismic isolation of bridge superstructure is given, including application of any newly developed advanced solutions for seismic isolation; ***(2) Incorporation of seismic energy dissipation (ED) system:*** *S*eismic isolators are characterized by insufficient damping for seismic energy dissipation, so additional seismic energy dissipaters have been introduced. For this reason, the ED devices should possess optimal stiffness, optimal bearing capacity and high ductility in relation to the seismic performances of implemented seismic isolators. Considered very large stiffness of the ED devices leads to undesired impact and impulsive transfer of inertial forces. To avoid such problem, it is favourable to reduce the initial stiffness of ED devices to an optimal level. In addition, if bearing capacity of ED devices is considered very high, large or critical forces will be transferred to the piers. To avoid related problem, bearing capacity of energy dissipation devices should be reduced to a design limit. Finally, the ductility capacity of ED devices should be sufficiently large. In the case of generated large inertial forces, relative displacements in full scale bridges can become quite large, of the order of 25-30 cm or larger. Therefore, the ED devices should possess the ability of sustaining large deformations without damage. Generally, it is necessary to introduce ED devices with greater capacity of seismic energy dissipation through nonlinear deformations and creation of pronounced hysteresis curves. In the frameworks of this study, very significant advances of the three above specified properties are achieved by formulation of the proposed advanced V-MG multi-directional energy dissipation devices, and ***(3) Incorporation of displacement limiting (DL) system:*** In the course of very strong earthquake large relative displacements may occur and sometimes they are not successfully controlled in a reliable engineering mode. By introducing specific displacement limiting devices (DLD), strong impact and negative effects will be reduced or avoided.

3. Creation and Testing of Prototypes of V-MG Energy Dissipation Devices

Within the frames of the conducted study, special attention has been paid to the formulation of integrated compact unit providing highly ductile response, as well as, structurally to represent innovative multi-gap (MG) and multi-directional (MD) energy dissipation (ED) device of a unique and large seismic energy dissipation capacity. Here, briefly are described the main creation steps, original structure and testing of prototypes of new V-MG-MD-ED energy dissipation devices:

1) Structure of multi-directional V-MG-ED devices: The structure of V-MG-ED device generally consists of: (1) base metal plate for fixation of the vertical cantilever components; (2) radial distributed in equidistance vertical energy dissipation components (EDC); and (3) upper metal plate with openings through which the energy dissipation components are activated based on gaps in different phases.

Characteristic activation modes include very frequent weak earthquakes, reduced number of moderately strong earthquakes and rare, but possible, very strong and destructive earthquakes. The prototype model of the proposed V-MG-MD-ED device, Figure 1, has been created considering several constituent parts that form a compact ED unit, including:

(a) Base plate: The base plate of the V-MG-MD-ED device is manufactured in the form of a base circular metal plate with thickness d = 25 mm and diameter of D = 450 mm. In the base metal plate, in each of the two concentric circles, eight regularly spaced equal openings with windings are made. The openings with windings are used to fix the vertical components by screwing. In the outer concentric circle with a diameter of d_1 = 340 mm, eight openings with windings are made for the fixation of the external eight vertical (V) energy dissipation components. In the internal concentric circle with a diameter of d_2 = 190 mm, spaced are other eight openings with windings for the fixation of the internal eight vertical (V) energy dissipation components.

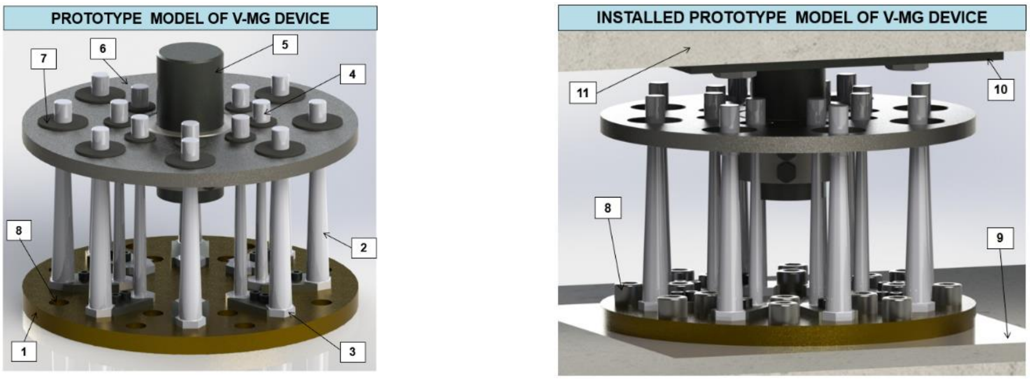

Figure 1. Prototype model of V-MG-ED device with installed V-MG-ED components: 1. Bottom fixing plate; 2. Outer V-MG components; 3. Bottom common fixing part; 4. Inner V-MG components; 5. Stiff central body; 6. Upper activating plate; 7. Gaps with distance protector; 8. Fixing bolts of base plate to substructure; 9. Substructure; 10. Upper plate fixed to superstructure; 11. Superstructure of prototype bridge.

(b) Vertical ED components: The vertical energy dissipation components are made of a ductile metal in the form of a moderately steep cut cone. According to the diameter of the cone base (Db), there have been adopted a total of four options from which there have arisen four prototype types of energy dissipation devices, Fig. 2. For each type of energy dissipation device, there have been designed vertical elements with two alternative variants of cones, regarding the considered different diameters of the top (Dt), whereat the diameter of the element at the base has been kept the same. In that way, four base-type prototypes of energy dissipation devices have been formed, each type with two variants of cones of vertical energy dissipation components as follows: *(1) Base type-1* with options: a) prototype model T11 with base and top diameters Db/Dt=32.0/25.6 mm and b) prototype model T12 with base and top diameters Db/Dt=32.0/19.2 mm; *(2) Base type-2* with options: a) prototype model T21 with base and top diameters Db/Dt=28.0/22.4 mm and b) prototype model T22 with base and top diameters Db/Dt=28.0/16.0 mm; *(3) Base type-3* with options: a) prototype model T31 with base and top diameters Db/Dt=24.0/19.2 mm and b) prototype model T32 with base and top diameters Db/Dt=24.0/14.4 mm; *(3) Base type-4* with options: a) prototype model T41 with base and top diameters Db/Dt=20.0/16.0 mm and b) prototype model T42 with base and top diameters Db/Dt=20.0/12.0 mm. All vertical components have the same height of the cone body of h1 = 190 mm and end with an identical cylinder with a diameter d = 24.0 mm with a constant height of h2 = 60.0 mm. With the adapted geometry of V-MG components, provided were equivalent conditions for fixation into the base plate, while the standard cylinder at the top provided equivalent gap-G1 and gap-G2 conditions for gap-based excitation (alternatively repeated contact and activation).

(c) Activating plate with holes: On the upper side of V-MG device, metal plate with thickness d=20.0 mm is constructed with openings with different diameters distributed along two concentric circles. The inner 8 openings are constructed with diameter d3=34.0 mm. Having standard top cylinders with diameter of d=24.0 mm, a gap of G1=5.0 mm was provided in all directions. However, the external 8 openings are constructed with diameter d4=60.0 mm. Having top cylinders with diameter of do=24.0 mm, a gap of G2=18.0 mm was obtained in all directions. The upper metal plate is fixed to the central stiff body for which is assured strong connection to the superstructure of the large-scale bridge model. With presented original structure of V-MG device, activation of the inner ED components will start after relative displacement becomes larger than 5 mm in all directions. If relative displacement exceeds 18.0 mm, then activation of all ED components located on the external concentric circle takes place.

Figure 2. Cyclic testing of V-MG-ED devices (left) and Performance of EDC with simulated gap-G2 (right)

2) Testing of prototype models under cyclic loads: Within the frames of experimental testing of produced model prototypes of V-MG energy dissipation components, an experimental program has been carried out. Each individual V-MG component has been tested twice. First test-1, representing original test, was conducted to define hysteretic response of V-MG component under the initial conditions. Second test-2, representing repeated test was performed to get an insight into the hysteretic response of the model that has already been tested.

For testing of 8 prototypes of the V-MG components under cyclic loads, simulating gap-G1 in the first case and gap-G2 in the second case, a total of 16 components of type-V have been produced. With the anticipated realization of the original and the repeated tests of each component, a total of 32 nonlinear cyclic tests have been done, Fig. 2.

4. Refined Modelling of V-MG-ED Devices and Components

An important research part included refined modelling and hysteretic response simulation of V-MG-ED devices, Fig. 3. Nonlinear numerical analysis has been carried out using the formulated refined or micro-models of the created and tested model prototypes. Commonly, cyclic displacement of up to ±45mm in X direction has been simulated through the upper plate, with a step of 5mm increase in each cycle. The mathematical model represented refined 3D finite element mesh of installed EDD-s. Modelling and analysis of the hysteretic response and energy dissipation capacity of V-MG-ED devices has been done by the use of ABAQUS CAE software. With setting the real material characteristics, the element geometry, the contour and contact conditions, the imposed displacements and other required information, appropriate conditions were created to compute results as accurately as possible.

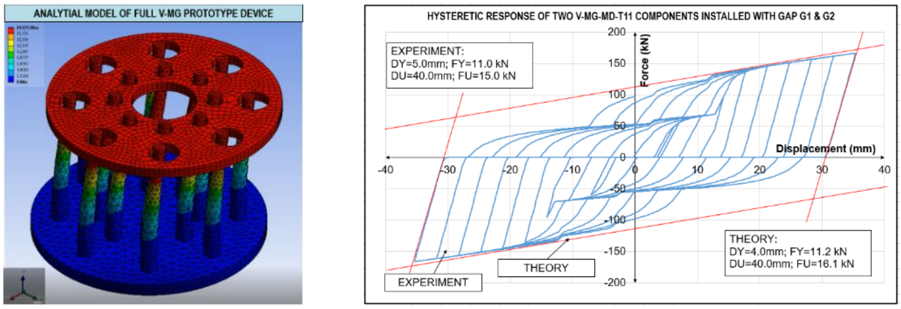

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Figure 3. Formulated refined 3D ABAQUS model of full V-MG-MD-ED device (left) and computed hysteretic response of two V-MG-MD-T11 components installed with gaps G1 & G2 (right)

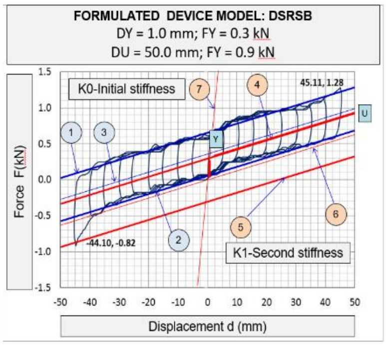
The calculations have been performed successfully, without shown any error during the step-by-step analysis process. Following the process of nonlinear micro-model formulation, considered and analysed was the specific example of partial device, assembled with two identical V-MG-MD-T11 components with different gaps G1 & G2. The resulting original and characteristic gap-based hysteretic response of the system was successfully computed, Fig. 3, right.

5. Prototype Testing of DSRSB Seismic Isolation Devices

The seismic isolation (SI) system used within the USI-V-MG bridge model was assembled by the use of prototype models of double spherical rolling seismic bearing (DSRSB) devices having two large-radius spherical surfaces (Fig. 4), which were originally designed for the purposes of the planned various experimental investigation phases [5].

Figure 4. Prototype of designed, constructed and tested DSRSB devices: (1) Cross-section with geometrical properties and (2) Device view with characteristic cross-section (*Commonly re-used prototype*)

The design of such device was conditioned by several requirements: to provide the sufficient bearing capacity for vertical loads; to provide the sufficient displacement capacity; to have radii of curvatures of the spherical surfaces adequate to achieve the targeted period of vibration; to have a sliding surface generating minimal friction and to have a central rolling part providing minimum reactive friction force. The resulting device is shown in Fig. 4. The lower (2) and upper (4) spherical plates were constructed of a hard inox polished to a mirror shine, providing durability and very low friction. Its diameter was 250mm, while the radii of the spherical surfaces were 1000mm. Both plates were fixed to the lower (1) and upper (3) steel end plates with diameter of 310mm. The inserted central rolling part (5) was constructed in the form of a ring of twelve balls with a diameter of 18mm, distributed uniformly along the circle around cylindrical slider and spaced with their opposite centres at 74mm. From the response, it is clear that the device has a sufficient capacity for horizontal deformation, amounting to over 45mm and that the shape of the hysteretic loops forms a skewed rectangle, which leads to its representation with bilinear model, Fig. 5.



EXPERIMENTAL RECORDS:

(1) upper envelope curve (EC)

(2) lower EC

(3) symmetric line

(4) shifted upper EC

(5) shifted lower EC

(6) shifted symmetric line

(7) recorded initial stiffness

Quasi-static tests of isolation devices were carried out by the use of four DSRSB devices mounted at their original locations, two at each abutment. The RC slab, weighting 85kN, brought a vertical force of 21.25kN to each one. The representative hysteretic response for a single device is shown in Fig. 5.

Figure 5. Hysteretic response of tested DSRSB prototype [5]

6. Seismic Shaking Table Tests of Large-Scale USI-V-MG Bridge Model

Due to the size of the seismic shaking table (5.0mx5.0m) and payload capacity, the originally designed USI-V-MG bridge prototype model had to be geometrically reduced in respect to the selected prototype. From those reasons, adopted was geometrical scale factor of 1:9, which verified the referred constraints in this case, but with adopted specific model design concept. As a consequence of the scale reduction, the relevant properties involved in the dynamic (seismic) tests were scaled according to a similitude law. Considering the main related factors, an adequate combined true replica-artificial mass simulation model was adopted. For simulation of the stiff RC superstructure, the stiff slab with added mass was adopted using the same material as that of the prototype structure. For simulation of the middle piers, steel material was used.

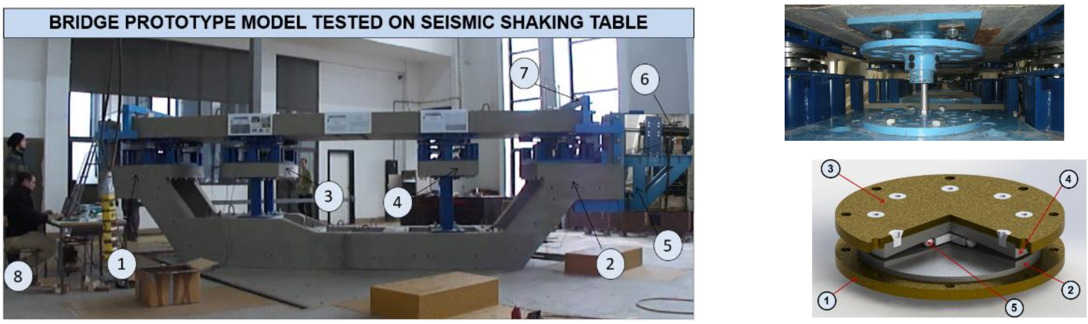


Figure 6. USI-V-MG (BM-V) bridge prototype model on IZIIS seismic shaking table: Left end support (1); right end support (2); support above shorter piers (3); support above longer piers (4); actuator supporting structure (5); actuator (6); DL devices (7); computer controlling cyclic tests (8), (Left); and Right: Disposition of DSRSB devices (superstructure supports) and partially between set new V-MG-ED device.

The seismic isolation and energy dissipation devices were designed and produced in reduced scale. The similitude law implies the adopted relations for the different parameters, all given in terms of the geometrical scale factor (*lr)*. Concrete material type C25/30 has been used for construction of RC segments of bridge model, while for construction of steel V-MG devices, steel material type S355 was selected and applied. Considering final proportions at the top level, the total length of the entire experimental bridge model is $L = 740.0$ cm $+ 2 * 20.0$ cm $+ 2 * 25.0$ cm $= 830.0$ cm. The RC deck is placed at a height distance of $h_d = 40.0$ cm from the highest RC substructure surfaces. This space (seismic gap) is used to install both, originally produced DSRSB devices, as well as the new V-MG-MD-ED devices, Fig. 6 and Fig. 7. After fabrication of all model segments and specific SI, ED and DL devices, as well as, after preparing the other testing connections and instrumentation devices, the large-scale USI-V-MG bridge prototype model was assembled and tested in the Dynamic testing laboratory of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje. With adopted 20 active recording channels, approximately 5.000.000 numerical values were recorded in each single test. Realizing four original and four repeated tests, large experimental data volume, containing about 40 million numerical values, have been recorded, integrally processed and analysed. In Fig. 7, as example, presented are time history responses of displacements and accelerations recorded during seismic test under simulated real strong El-Centro earthquake scaled to PGA=0.78g. The conducted seismic shaking table tests have shown that upgrading of seismically isolated bridges with vertical multi gap energy dissipation devices represent a highly efficient and practical engineering option.

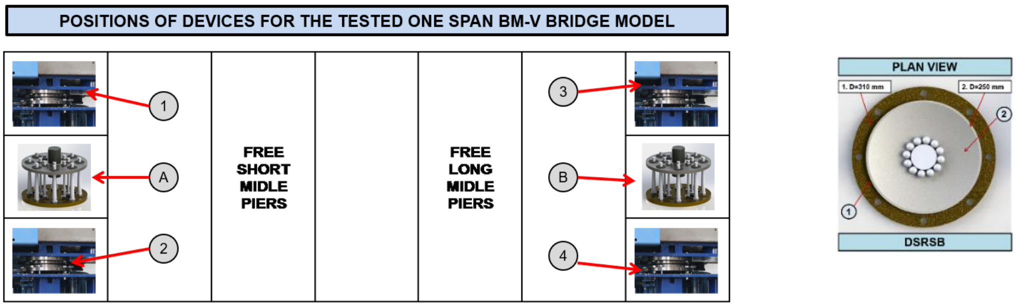


Figure 7. Defined positions of DSRSB devices (1 to 4, with details right) and V-MG-ED devices (A and B) of the tested one-span large-scale USI-V-MG (BM-V) bridge prototype model on seismic shaking table

7. Critical Seismic Shaking Table Tests near Resonance of USI-V-MG Model

The ultimate goal of the present research includes development of advanced technology for seismic protection of bridge structures under extreme seismic loading. To realize the planed unique and scientifically important and specific experimental analysis of actual seismic response characteristics of innovatively assembled large-scale bridge model, with DSRSB isolation and new V-MG energy dissipation devices, under simulated the most critical near-resonance earthquake excitations, extensive well-focused shaking table tests have been planned and realized in study phase-III. However, to provide highly valuable comparative experimental data and full evidence in differences in seismic responses of innovative bridge model tested with different test options, two additional series of shaking table tests have been planned and conducted.

The first test series included initial shaking table tests of assembled bridge model with seismic isolation only, item 7.1 (phase-I). Initial tests actually represent the first basic experimental study, devoted to experimental testing of seismic response of assembled isolated-bridge prototype model, without installed energy dissipation (ED) devices, under simulated strong earthquakes. The second test series included shaking table tests of innovatively-upgraded isolated bridge model, item 7.2 (phase-II). The conducted tests actually represent experimental study of real seismic response characteristics of constructed innovatively-upgraded isolated bridge prototype model, existing with seismic isolation (SI) and new energy dissipation (ED) devices, under simulated strong earthquakes. Finally, regarding the obtained large set of experimental results, the effects of critical near resonance (NR) earthquake input on innovatively-upgraded isolated bridge model was made possible, item 7.4 (phase-IV. Actually, the study phase-IV was devoted to processing and comparative presentation of extreme seismic responses of innovatively-upgraded isolated bridge model considering the obtained results from conducted shaking table test under simulated two series of seismic input: (1) seismic input representing critical near resonance (NR) earthquake excitations of Phase-III and (2) seismic input representing selected location representative (LR) strong earthquake excitations of Phase-II. As stated above, approximately 5 million numerical values were recorded in each single test. With newly realized four original tests of phase-I and four original tests of phase-IV, additional large experimental data volume, containing about 40 million numerical values, have been recorded, processed and analysed. Regarding the conducted very extensive experimental study program, including successfully realized full set of 16 original experimental tests, recorded were and processed about 80.000.000 numerical data values.

7.1. Phase-I: Initial shaking table tests of bridge model with isolation only

Study phase-I represent conducted initial experimental study devoted to experimental seismic response testing of constructed isolated bridge prototype model without ED devices under simulated strong earthquakes.

Table 1. Recorded difference in peak relative displacements during shaking table test of BM2-V1 model with ED devices [1c] and BM2 model without ED devices [1c*], under simulated ***compressed*** El-Centro earthquake

Tests	Test with ED devices [1c]	Test without ED devices [1c*]

	[1c] O-T1: C-El-Centro, PGA=0.78G			[1c*] O-T1: C-El-Centro, PGA=0.78G		
[1c&1c*]	Channel	MaxD [mm]	MaxD [%]	Channel	MaxD [mm]	MaxD [%]
diff.	LVDT-03	26.03	100.00	LVDT-03	40.77	**+56.62**

For the purposes of getting insight into contribution of the EDDs to the structural response, bridge model setup which involved only four DSRSB isolators (no SB dissipaters) has been tested on the shaking platform under compressed El Centro excitation scaled to PGA 0.78g. The relative displacements recorded by LVDT-03 for the system with and without SB energy dissipaters are shown in Table. 2. By comparing two responses, it may be noticed that use of dissipaters reduced maximum displacement from 40.77 mm to 26.03 mm, or 56.62%. Such favourable contribution of EDD, adequately designed in their mechanical properties, gain in importance for much stronger earthquakes.

7.2. Phase-II: Shaking table tests of innovatively-upgraded isolated bridge model

Study phase-II represent experimental study devoted to seismic response testing of constructed innovatively-upgraded isolated bridge prototype model with seismic isolation (SI) and energy dissipation (ED) devices under simulated strong earthquakes.

Regarding the stated objectives, conducted were extreme-loading experimental tests of innovatively-upgraded isolated bridge with new V-MG ED devices, simulating the following four representative and strong compressed earthquakes: [1c] El-Centro, PGA=0.78G, [2c] Petrovac, PGA=0.72G, [3c] Landers, PGA=0.76G, and [4c] Northridge, PGA=0.89G, earthquake Table 3. The peak relative displacements recorded by LVDT-03 of the system upgraded with SB energy dissipaters are well controlled in all cases. Regarding peak responses, it may be noticed that use of dissipaters reduced maximum displacements to 26.03mm, 26.61mm, 20.35mm and 31.61mm, respectively.

Table 2. Recorded peak relative displacements by LVDT sensors during conducted original shaking table tests of BM2-V1 model simulating ***compressed:*** [1] El-Centro, [2] Petrovac, [3] Landers and [4] Northridge eq.

Tests	**[1c]** O-T1: **C**-El-Centro, **PGA=0.78G**			**[2c]** O-T2: **C**-Petrovac, **PGA=0.72G**		
[1c&2c]	Channel	MaxD (-) [mm]	MaxD (+) [mm]	Channel	MaxD (-) [mm]	MaxD (+) [mm]
recorded	LVDT-03	-17.96	**26.03**	LVDT-03	**-26.61**	15.21
Tests	**[3c]** O-T1: **C**-Landers, **PGA=0.76G**			**[4c]** O-T2: **C**-Northridge, **PGA=0.89G**		
[3c&4c]	Channel	MaxD (-) [mm]	[1c&2c]	Channel	MaxD (-) [mm]	[1c&2c]
recorded	LVDT-03	**-20.35**	11.76	LVDT-03	-29.93	**31.61**

The observed favourable contribution of energy dissipation devices, provided reduction of maximum displacement bellow designed displacement limit of seismic isolators, amounting to 40.00mm. This reduction is gaining even higher importance for the case of bridge structures exposed to much stronger earthquakes.

7.3. Phase-III: Critical shaking table tests of innovatively-upgraded isolated bridge model

Study phase-III represent experimental study devoted to seismic response testing of constructed innovatively-upgraded isolated bridge prototype model with seismic isolation (SI) and ED devices under simulated critical near resonance (NR) earthquake input.

Realized model testing with compressed real earthquakes actually represent simulation of real seismic input regarding actual properties of designed and constructed scaled-model of bridge prototype, directly resulting from model similarity conditions. Frequency content of input records was accordingly changed. It is well demonstrated by presented acceleration response spectra for *compressed* Petrovac earthquake record with new frequency content used for testing, Figure 9. Dominant frequency domain includes periods less than 0.32s, while for periods T ≥ 0.32s, frequency domain is not significant.

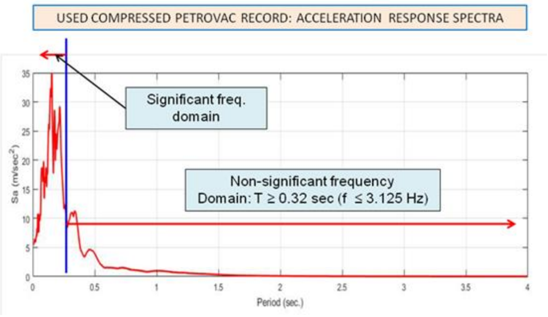


Figure 9. Acceleration response spectra of ***compressed*** Petrovac record with new frequency content used for testing

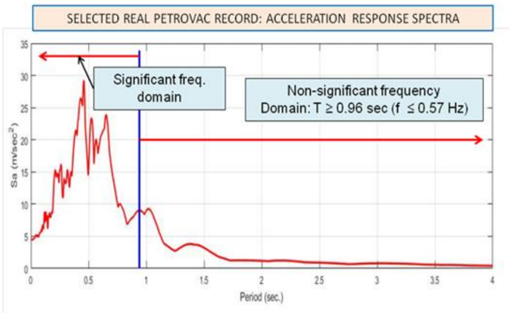


Figure 10. Acceleration response spectra of ***real*** (*not time compressed*) Petrovac record

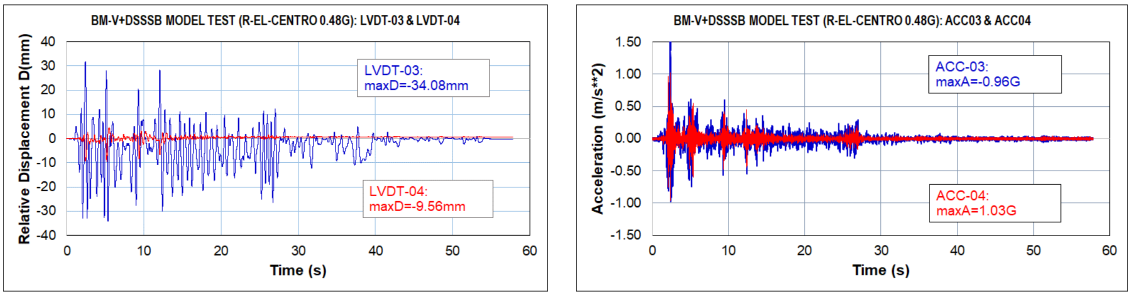


Figure 11. Relative superstructure displacement responses recorded by LVDT-03 & LVDT-04 (left) and acceleration responses recorded by ACC-03 & ACC-04 (right) during USI-V-MG (BM-V) shaking table bridge model test conducted with simulated ***real*** El-Centro earthquake.

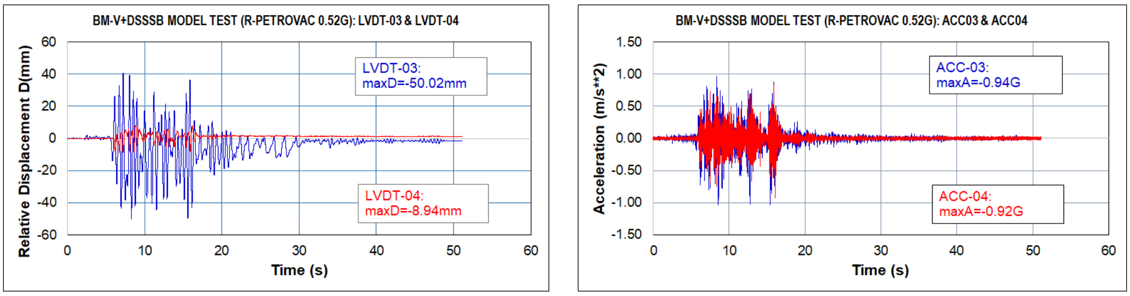


Figure 12. Relative superstructure displacement responses recorded by LVDT-03 & LVDT-04 (left) and acceleration responses recorded by ACC-03 & ACC-04 (right) during USI-V-MG (BM-V) shaking table bridge model test conducted with simulated ***real*** Petrovac earthquake.

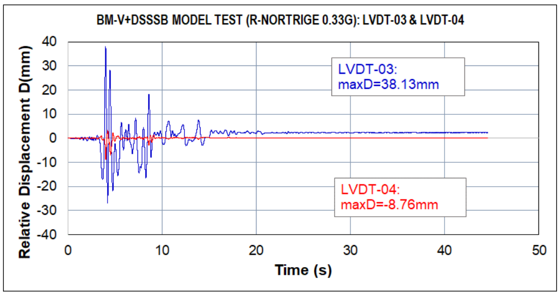


Figure 13. Relative displacement response recorded by LVDT-03 & LVDT-04 during shaking table bridge model test with simulated ***real*** Petrovac earthquake

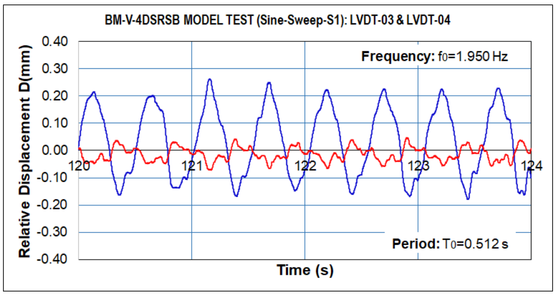


Figure 14. Vibration period of bridge model ***with seismic isolation only*** defined using recorded relative displacement during shaking table sine-sweep test

Figure 14 shows much larger initial vibration period of bridge model, T=0.512s, showing that dominant frequency content of seismic input was very well and significantly avoided. Initial vibration period was defined based on recorded time history of relative displacement during conducted initial sine-sweep shaking table test. Due to very small vibration amplitudes and present initial gaps, the excited model vibration actually corresponds to initial state with activated seismic isolation only.

The final experimental study included specific near resonance (NR) testing of constructed innovatively-upgraded isolated bridge prototype model with seismic isolation (SI) and energy dissipation (ED) devices, characterized by initial vibration period T=0.512s. Selection of applicable critical near resonance (NR) input was made after analysing acceleration response spectra of used *real* (*not time compressed*) earthquakes. Regarding, for example, acceleration response spectra of real Petrovac record, Figure 10, dominant frequency content is mainly distributed near fundamental period of the system. Due to similar observations for other earthquakes, the same four real earthquake records were accepted to be actual critical near resonance (NR) seismic input for shaking table tests.

Table 3. Recorded peak relative displacements by LVDT sensors during conducted four original shaking table tests of BM2-V1 bridge prototype model simulating ***real*** [1] El-Centro, [2] Petrovac, [3] Landers and [4] Northridge earthquake

Tests	**[1r]** O-T1: **R**-El-Centro, **PGA=0.48G**			**[2r]** O-T2: **R**-Petrovac, **PGA=0.52G**		
[1c&2c]	Channel	MaxD (-) [mm]	MaxD (+) [mm]	Channel	MaxD (-) [mm]	MaxD (+) [mm]
recorded	LVDT-03	**-34.08**	31.92	LVDT-03	**-50.02**	40.69
Tests	**[3r]** O-T1: **R**-Landers, **PGA=0.76G**			**[4r]** O-T2: **R**-Northridge, **PGA=0.33G**		
[3c&4c]	Channel	MaxD (-) [mm]	[1c&2c]	Channel	MaxD (-) [mm]	[1c&2c]
recorded	LVDT-03	**-40.55**	40.11	LVDT-03	-26.90	**38.13**

Considering the stated critical test conditions, conducted were critical NR loading experimental tests of innovatively-upgraded isolated bridge with new V-MG energy dissipation (ED) devices, simulating the following four representative and strong real earthquakes: [1r] El-Centro, PGA=0.48G, [2r] Petrovac, PGA=0.52G, [3r] Landers, PGA=0.76G, and [4r] Northridge, PGA=0.33G, earthquake Table 4. The peak relative displacements recorded by LVDT-03 of the system upgraded with SB energy dissipaters are considerably larger in all cases due to NR earthquake input. Regarding peak responses, it may be noticed that with present dissipaters maximum displacements are 34.08mm, 50.02mm, 40.55mm and 38.13mm, respectively.

Fig. 11. and Fig. 12. present relative superstructure displacement responses recorded by LVDT-03 & LVDT-04 (left) and acceleration responses recorded by ACC-03 & ACC-04 (right) during USI-V-MG (BM-V) shaking table bridge model test conducted with simulated ***real*** El-Centro and Petrovac earthquake, respectively.

Fig. 13 presentsrelative displacement response recorded by LVDT-03 & LVDT-04 during shaking table bridge model test with simulated ***real*** Petrovac earthquake.

7.4. Phase-IV: Effects of critical near resonance (NR) earthquake input on innovatively-upgraded isolated bridge model

Study phase-IV was devoted to processing and comparative presentation of extreme seismic responses of innovatively-upgraded isolated bridge model considering the obtained results from conducted shaking table test under simulated two series of seismic input: (1) considered critical near resonance (NR) earthquake input of Phase-III and (2) selected location representative (LR) strong earthquakes of Phase-II.

Table 5. comparatively presents recorded peak relative displacements by LVDT sensors during conducted original shaking table tests of BM2-V1 bridge prototype model simulating both, *real and compressed* [1] El-Centro, [2] Petrovac, [3] Landers and [4] Northridge earthquake. To show actual

effects of frequency content of NR earthquake input, comparative values of peak relative displacements for the case of seismic tests with compressed earthquakes are shown for the same PGA levels.

In all four comparative test cases, much larger peak values of relative displacements were recorded during realized tests with simulated critical NR earthquake input. The recorded increase of peak response reached amounts of +112.86% for El-Centro, +160.38% for Petrovac, +99.26% for Landers and +225.34% for Northridge earthquake, Table. 5.

The presented results clearly pointed out the following highly important observations: (1) Seismic isolation only may be regarded as unsafe solution for bridges exposed to strong earthquakes; (2) The new V-MG energy dissipation device represent very efficient solution for seismic upgrading of isolated bridges exposed to very strong earthquakes and (3) The possible negative effects of critical NR seismic input should be avoided through application of effective design process of seismically upgraded isolated bridges with new V-MG-ED devices.

Table 4. Recorded peak relative displacements by LVDT sensors during conducted original shaking table tests of BM2-V1 bridge prototype model simulating ***real and compressed*** [1] El-Centro, [2] Petrovac, [3] Landers and [4] Northridge earthquake

No. 1	[1r] O-T1: **R**-El-Centro, **PGA=0.48G**			[1c] O-T1: **C**-El-Centro, **PGA=0.48G**		
[1r&1c]	Channel	MaxD [mm]	MaxD [%]	Channel	MaxD [mm]	MaxD [%]
diff.	LVDT-03	34.08	**+112.86**	LVDT-03	16.01	100.00
No. 2	[2r] O-T2: **R**-Petrovac, **PGA=0.52G**			[2c] O-T2: **C**-Petrovac, **PGA=0.52G**		
[2r&2c]	Channel	MaxD [mm]	MaxD [%]	Channel	MaxD [mm]	MaxD [%]
diff.	LVDT-03	50.02	**+160.38**	LVDT-03	19.21	100.00
No. 3	[3r] O-T3: **R**-Landers, **PGA=0.76G**			[3c] O-T3: **C**-Landers, **PGA=0.76G**		
[3r&3c]	Channel	MaxD [mm]	MaxD [%]	Channel	MaxD [mm]	MaxD [%]
diff.	LVDT-03	40.55	**+99.26**	LVDT-03	20.35	100.00
No. 4	[4r] O-T4: **R**-Northridge, **PGA=0.33G**			[4c] O-T4: **C**-Northridge, **PGA=0.33G**		
[4r&4c]	Channel	MaxD [mm]	MaxD [%]	Channel	MaxD [mm]	MaxD [%]
diff.	LVDT-03	38.13	**+225.34**	LVDT-03	11.72	100.00

8. Conclusions

Based on research results obtained from the conducted extensive experimental and theoretical studies using designed innovative USI-V-MG bridge model prototype, the following main conclusions are derived:

(1) The constructed and investigated novel DSRSB seismic isolation devices are very attractive and effective passive devices for seismic vibration isolation of bridges in arbitrary direction;

(2) The new vertical multi-gap multi-directional hysteretic V-MG energy dissipation devices possess unique energy absorption features since they are capable of adapting their stable behaviour to the arbitrary earthquake direction and to the actual level of seismic input energy. The new V-MG energy dissipation devices provided innovative, very stable and advanced 3D hysteretic response in the most critical cases of repeated strong earthquake effects in all directions;

(3) The displacement limiting devices, DLD, represent very effective obligatory measure in function of the last line of defence from excessive displacements of the bridge superstructure. DLD actually represent efficient passive system providing improvement of the bridge seismic safety with eventual activation only in critical cases of very strong earthquakes;

(4) With the results from the conducted experimental tests confirmed is that the new USI-V-MG system represents the upgraded high performance seismic isolation option for bridges. The system is created based on optimized seismic energy balance and represents effective technical innovation capable of integrating the advantages of seismic isolation, seismic energy dissipation

and effective displacement control. The developed and tested USI-V-MG system shows very high seismic response modification performances and could be used for efficient seismic protection of bridges in all directions under the effect of very strong repeated earthquakes; and

(5) During the further study phases, creative analytical research and simulation activities will be carried out, specifically directed to development of practical design rules of the developed new seismically safe USI-V-MG bridge system.

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