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Upgrading of isolated bridges with vertical fixed energy dissipation devices: shaking table seismic tests

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Abstract

In the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Ss. Cyril and Methodius University in Skopje, extensive experimental and analytical research have been performed led by the third author, in the frame of the innovative NATO Science for Peace Project "Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828)". The specific project part included development of the innovative USI-VF system representing advanced technology for seismic isolation and seismic protection of bridges. By integrating the newly uniform VF energy dissipation devices, important advances of the USI-VF system have been achieved. The response of the isolated segment of the structure becomes controlled by simultaneous effects of the present isolation system and the new advanced added damping system. Initially, in the paper are presented the original research idea, device creation process, production of the first model prototypes, as well as, the original experimental laboratory tests of the main components of the integral prototypes of the developed new uniform VF energy dissipation devices. The innovative concept of the adaptive vertical energy dissipation device, VF device, has created important improvements and advanced seismic response features. The new VF devices provide added "adaptive" damping to the common seismically isolated system which generally does not possess sufficient damping capacity. In the second part of the paper, briefly are discussed unique and original observations resulting from conducted complex shaking table tests of large-scale bridge model. The extensive experimental research program is realized on a bridge model constructed by using the seismically isolated system upgraded with vertical fixed energy dissipation devices (USI-VF). The installed adaptable system for seismic protection of bridges utilizes double spherical rolling seismic bearings (DSRSB) as seismic isolators, while the qualitative improvement of seismic performances is achieved through the use of novel adjustable multi-directional vertical fixed energy dissipation (VF-ED) devices.

Key words: Shaking table, bridge model, seismic test, passive control, seismic isolation, energy dissipation

1 Introduction

Extensive studies in the field of seismic isolation of bridges have been mostly performed in the world's renowned research centers 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-VF system that can provide qualitative seismic upgrading of isolated bridges by using of innovative VF energy dissipation devices [8]. The tested uniform upgrading system for seismic protection of bridges, USI-VF 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-fixed (VF) energy dissipation devices.

2 Concept of new USI-VF bridge system

The upgraded seismically isolated (USI) system with vertical-fixed (VF) energy dissipation (ED) devices represent newly created advanced technical concept providing harmonized modification and improvement of structural seismic response, Fig. 9. The USI-VF 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-VF 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 favorable 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 transfer 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 real 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 VF 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 VF 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 VF energy dissipation devices:

1) Structure of multi-directional VF-ED devices: The structure of multi-directional VF-ED device generally consists of: (1) base metal plate for fixation of the vertical cantilever or fixed components; (2) adequately distributed vertical energy dissipation components (EDC); and (3) upper metal plate with openings through which the V-type energy dissipation components are activated based on gaps in different phases. Characteristic activation phases 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 VF-MD energy dissipation 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 VF-MD energy dissipation device is manufactured in the form of a base circular metal plate (d = 25 mm) with a 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 d1 =

340 mm, eight openings with windings are made for the fixation of the external eight, vertical-cantilever (V) or vertical-fixed (VF) or combined set, energy dissipation components. In the internal concentric circle with a diameter of d2 = 190 mm, spaced are other eight openings with windings for the fixation of the internal eight vertical (V) energy dissipation components. The diameter of the opening with winding is considered standard and provides the possibility of assembling different combinations of produced different types of vertical energy dissipation components, Table 1.

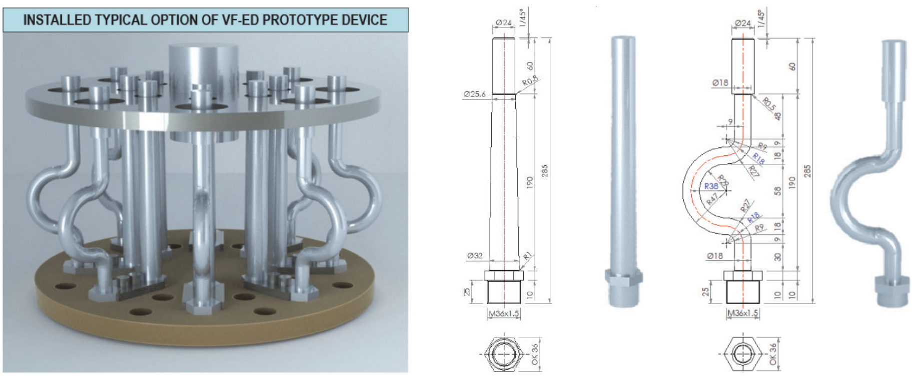


Figure 1. Prototype of VF-MD energy dissipation device with 8V-MG-ED & 8VF ED components (left) and prototypes of V-MG-ED and VF-ED components (right)

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, Table 1a, Table 1b and Fig. 1.

Table 1a. Prototype models of V-MG-ED components

Prototype base-type	Prototype Notation	Geometry form	Geometry of gaps	Activation direction	Base-Db [mm]	Top-Dt [mm]
1	V-MG-MD-T11	T11	G1 & G2	MD	32.0	25.6
	V-MG-MD-T12	T12	G1 & G2	MD	32.0	19.2
2	V-MG-MD-T21	T21	G1 & G2	MD	28.0	22.4
	V-MG-MD-T22	T22	G1 & G2	MD	28.0	16.0
3	V-MG-MD-T31	T31	G1 & G2	MD	24.0	19.2
	V-MG-MD-T32	T32	G1 & G2	MD	24.0	14.4
4	V-MG-MD-T41	T41	G1 & G2	MD	20.0	16.0
	V-MG-MD-T42	T42	G1 & G2	MD	20.0	12.0

Table 1b. Prototype models of VF-ED components

Prototype model	Prototype notation	Geometry form	Geometry of gap	Activation direction	Body-Dc [mm]
1	VF-MG-MD-D22	D22	*no/ optional*	MD	22.0
2	VF-MG-MD-D20	D20	*no/ optional*	MD	20.0
3	VF-MG-MD-D18	D18	*no/ optional*	MD	18.0
4	VF-MG-MD-D16	D16	*no/ optional*	MD	16.0

For each single energy dissipation device can be designed actual combined installation option using gap-based vertical elements of V-type, curved vertical-fixed elements of VF-type and possibly curved gap-based vertical elements of CV-type, Table 1a and Table 1b. For V-prototypes, two alternative variants of cones are used regarding the considered different cone diameters at the top (Dt), whereat the diameter of the element at the base, (Db), has been kept the same. All V-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 VF 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 do=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 m m. 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. The original structure of VF device consists of eight external vertical-fixed VF-components, but optionally, four can be used as vertical-fixed VF, and four as gap-based CV-components.
2) Testing of prototype models under cyclic loads: Regarding the experimental testing of produced model prototypes of V-MG and VF-MG energy dissipation components, an ample experimental program has been realized. Each individual component has been tested twice. First test-1, representing original test, was conducted to define hysteretic response of ED 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.

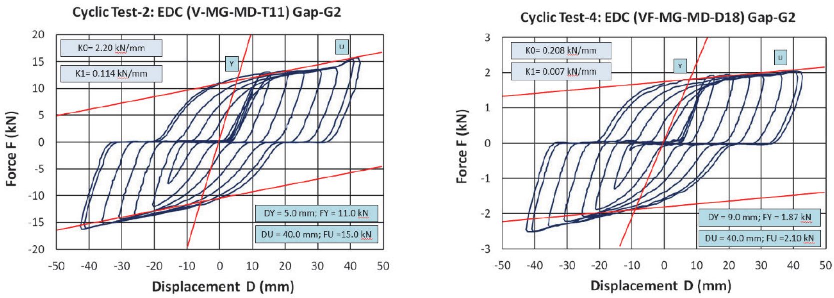


Figure 2. Experimentally defined hysteretic response under simulated cyclic loads of two typical components, V-MG-MD-T11 (left) and VF-MG-MD-D18 (right), tested with gap-G2

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. Based on performed detailed analysis of recorded extensive volume of original test results, hysteretic response and high energy dissipation properties have been defined for all types of V-MG, VF and CV component model prototypes, Fig. 2.

4 Refined modelling of CV-MG and VF devices and components

The important research part included refined modelling and hysteretic response simulation of innovative prototypes of V-MG, CV-MG and VF devices and components, Fig. 3 and Fig. 4. 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 vertical components, fixing base plate and upper plate used to simulate cyclic top displacements. Modeling and analysis of the hysteretic response and energy dissipation capacity of VF-ED devices and components has been done by the use of ABAQUS CAE software. With setting the real material characteristics, the element geometry, the contour conditions, the contact conditions, the imposed displacement conditions and other needed information, as well as, with providing refined discretization of the structure into fine finite element mesh, provided were corresponding conditions to compute results as exact as possible.

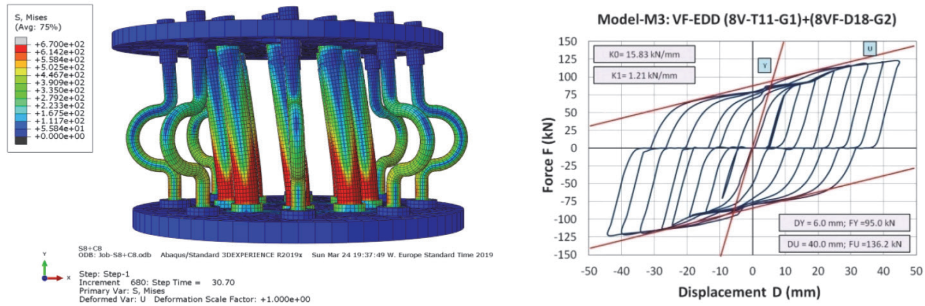


Figure 3. Typical stress distribution of VF-MG-ED device (left) and computed gap based hysteretic response of VF-MG-ED device prototype under cyclic loads (right), from used refined ABAQUS model

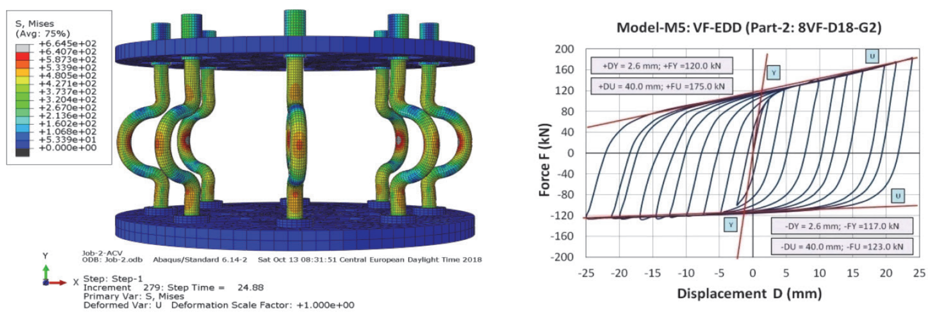


Figure 4. Micro-model of device part composed of 8VF-D18-ED components (left) and computed hysteretic response under simulated vertical (tension-compression) cyclic loads (right)

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 analyzed were the specific examples of partial devices assembled with different ED components, used as fixed or with different gaps G1 & G2. The resulting original and characteristic hysteretic responses of the system were successful in all cases.

5 Prototype testing of DSRSB seismic isolation devices

The seismic isolation (SI) system used within the USI-VF 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. 5), which were originally designed for the purposes of the planned various experimental investigation phases [5].

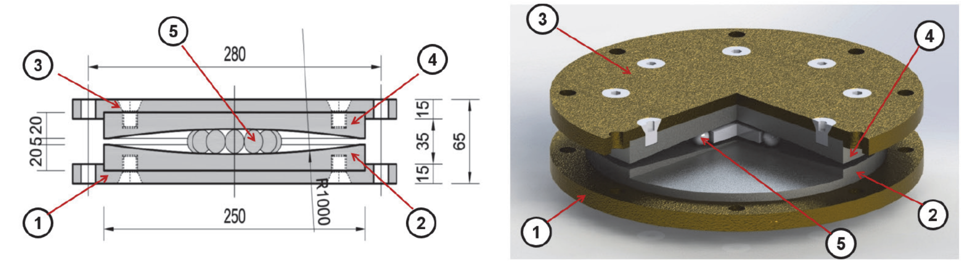
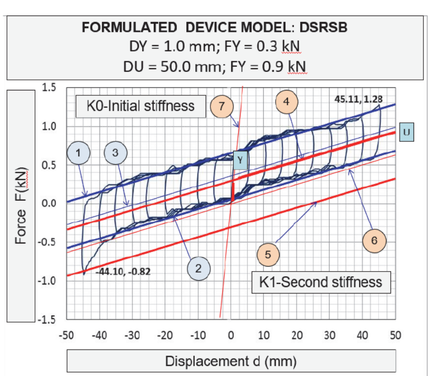


Figure 5. Prototype of designed, constructed and tested DSRSB devices: (1) Cross-section with geometrical properties and (2) Device view with characteristic cross-section (*Commonly re-used prototype*)

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. 5. 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 centers at 74 mm.

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. 6. 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. 6.

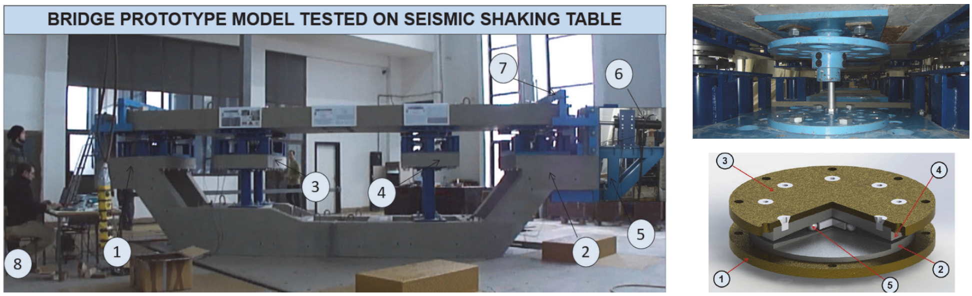


EXPERIMENTAL RECORDS:
1) upper envelope curve (EC)
2) lower EC
3) symmetric line
4) shifted upper EC
5) shifted lower EC
6) shifted symmetric line
7) recorded initial stiffness

Figure 6. Hysteretic response of tested DSRSB prototype [5]

6 Seismic shaking table tests of large-scale USI-VF bridge model

Due to the size of the seismic shaking table (5.0mx5.0m) and payload capacity, the originally designed USI-VF 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. 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 VF 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 VF-ED devices, Fig. 7 and Fig. 8. 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-VF 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, has been recorded, integrally processed and analyzed. In Fig. 9, as an example, presented are time history responses of displacements and accelerations recorded during seismic test under simulated real strong Petrovac earthquake scaled to PGA=0.73g. The conducted seismic shaking table tests have shown that upgrading of seismically isolated bridges with vertical VF energy dissipation devices represent an highly efficient and practically applicable system.



FFigure 7. 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

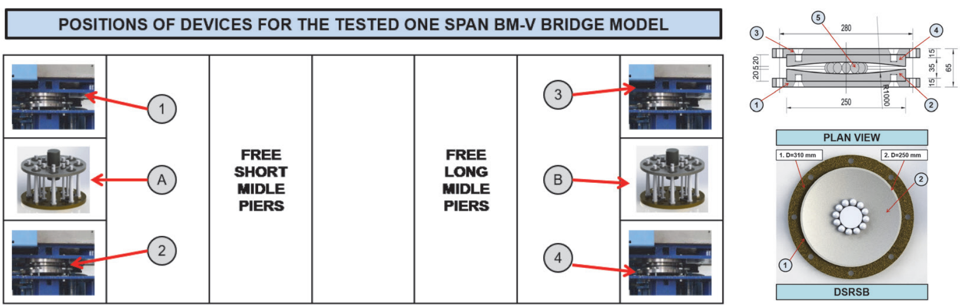


Figure 8. Defined positions of DSRSB devices (1 to 4, with details right) and V-MG-ED devices (A and B) of the tested one-span large-scale USI-V-MG (BM-V) bridge prototype model on seismic shaking table

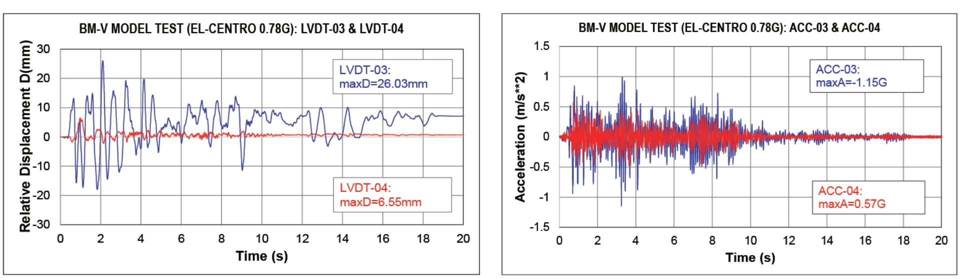


Figure 9. Relative superstructure displacement responses recorded by LVDT-03 & LVDT-04 (left) and acceleration responses recorded by ACC-03 & ACC-04 (right) during USI-VF (BM-VF) shaking table bridge model test conducted with simulated strong Petrovac earthquake

7 Conclusions

Considering the integral research results obtained from the conducted extensive experimental and theoretical studies using designed innovative USI-VF bridge model prototype, the following principal 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-fixed (VF) energy dissipation devices possess unique energy absorption features since they are capable of adapting their stable behavior to the arbitrary earthquake direction and to the actual level of seismic input energy. The new VF 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 defense 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-VF 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-VF 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 caried out, specifically directed to development of practical design rules of the developed new seismically safe USI-VF bridge system.

Acknowledgements

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References

[1] Yuan, W., Feng, R., & Dang, X. (2018): Typical Earthquake Damage and Seismic Isolation Technology for Bridges Subjected to Near-Fault Ground Motions. 2018 International Conference on Engineering Simulation and Intelligent Control (ESAIC). doi:10.1109/esaic.2018.00079.

[2] Kelly JM (1986): A Seismic Base Isolation: Review and Bibliography, Soil Dyn. and Earthquake Eng. 5(4): 202-216.

[3] Ristic D (1988): Nonlinear Behavior and Stress-Strain Based Modeling of Reinforced Concrete Structures under Earthquake Induced Bending and Varying Axial Loads, PhD Dissertation, School of Civil Engineering, Kyoto University, Kyoto, Japan.

[4] Ristic D, Ristic J (2012): New Integrated 2G3 Response Modification Method for Seismic Upgrading of New and Existing Bridges, In 15th World Conference on Earthquake Engineering, (WCEE), Lisbon, Portugal.

[5] Ristic J, Misini M, Ristic D, Guri Z, Pllana N (2017): Seismic Upgrading of Isolated Bridges with SF-ED Devices: Shaking Table Tests of Large-Scale Model, Građevinar, 70 (6): 463-485. doi: https://doi.org/10.14256/JCE.2147.

[6] Ristik J (2011): Comparative Seismic Analysis of RC Bridge Structure Applying Macedonian Seismic Design Regulations and Eurocodes. MSc Thesis, Theory of Structures Department, "Ss. Cyril & Methodius" Univ., Skopje, Macedonia.

[7] Ristik J (2016): Modern Technology for Seismic Protection of Bridge Structures Applying New System for Modification of Earthquake Response. PhD Thesis, Institute of Earthquake Engineering and Engineering Seismology (IZIIS), "Ss. Cyril and Methodius" University, Skopje, Macedonia.

[8] Ristic D, Dorka U, Lako A, Zenunovic D, Folic R (2013): Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies, NATO SfP Project 983828, Science for Peace and Security Programme, Final Report.

[9] Mitoulis et al. (2017) Seismic Performance of Novel Resilient Hinges for Columns and Application on Irregular Bridges. Journal of Bridge Engineering, 2017, 22(2), 04016114

[10] Argyroudis et al. (2020) Resilience assessment framework for critical infrastructure in a multi-hazard environment. Science of the Total Environment, 714, 136854. https://doi.org/10.1016/j.scitotenv.2020.136854