doi.org/10.62683/SINARG2025.036

Research paper

A METHOD FOR SEISMIC PROTECTION OF BRIDGES USING NEW UPGRADED NVF-ISOLATION SYSTEM: SHAKING TABLE TESTS OF BRIDGE MODEL

Jelena Ristic[1], Danilo Ristic[2]

Abstract

Presented in this paper is a new method representing efficient innovative system for seismic protection of bridges, created with upgrading of isolated bridge with developed specific uniform NVF devices. Capability of the new NVF seismic protection system for bridges was fully demonstrated with the conducted extensive seismic shaking table tests of large-scale bridge prototype model. The constructed bridge prototype model was assembled based on optimal upgrading of its basic isolation system, comprised of specific double spherical rolling seismic bearing (DSRSB) devices, with the originally created efficient uniform vertical fixed (NVF) complementary upgrading devices. The specific research segment devoted to development of the present NVF upgraded bridge system was originally created and realized by the authors as a part of an innovative research project. The presented research segment was realized at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Ss. Cyril and Methodius University in Skopje, North Macedonia, within the innovative NATO Science for Peace and Security Project "Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828)", involving five European countries. The composed upgraded isolated rolling system with uniform NVF energy dissipation (ED) devices represent suitable integrated passive mechanical bridge system providing harmonized response of integral bridge structure subjected to strong earthquakes. The adopted system is based on global optimization of seismic energy balance, achieved through utilization of newly designed dissipation devices as a supplementary damping to the bridge isolation. The new NVF seismic protection system is based on incorporation of the following three integrated complementary systems: (1) Double spherical rolling seismic isolation (DSRSB) system, (2) Created NVF energy dissipation (ED) system and (3) Displacement limiting (DL) system. The created NVF bridge system represents a qualitatively new construction strategy providing upgraded structural seismic safety and efficient modification of the seismic response in bridges located in seismically active regions.

Key words: *bridge, seismic safety, seismic response, seismic isolation, energy dissipation*

[1] Coordinator & Lead Researcher, PhD, RESIN Laboratory of Industrial Sciences and Technology, Republic of N. Macedonia, jelena.ristic@resinlab.mk, https://orcid.org/0009-0002-3283-917X

[2] Prof. PhD, Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Ss. Cyril and Methodius University in Skopje, Republic of N. Macedonia, danilo.ristic@gmail.com, ORCID: https://orcid.org/0009-0007-7293-4514

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, 4, 5, 6, 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 NVF system that can provide qualitative seismic upgrading of isolated bridges by using of innovative NVF energy dissipation devices [8]. The tested uniform upgrading system for seismic protection of bridges, NVF 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 uniform new vertical fixed (NVF) energy dissipation devices.

2. CONCEPT OF NVF BRIDGE SYSTEM

The NVF bridge system was created as a novel adaptable technical option incorporating three specific complementary and obligatory systems:

Seismic isolation system: The implemented seismic isolation (SI) system was selected to respectively assure safe vertical load carrying capacity resulting from the super-structure weight and low cumulative stiffness in horizontal direction effective for seismic isolation.

Energy dissipation system: The new vertical fixed energy dissipation devices (NVF devices) represent a novel technical structural option created with advanced hysteretic response performances and implemented for assembling of the bridge energy dissipation system. The NVF devices had to be designed with respect to the performances of the seismic isolators, successfully creating conditions for their optimal interactive response.

Displacement limiting system: The displacement limiting (DL) system was created using the developed specific DL devices capable of reducing or eliminating a critical earthquake impact effect. The DL system actually represents the last line of defense.

2.1. Concept of multi-directional NVF energy dissipation devices

Structural system: The created new vertical fixed energy dissipation devices (NVF devices) consist of eight main structural parts, Figure 1a).

- Bottom fixing plate (for bottom fixation of eight vertical NVF components);
- Fixing segment of NVF component;
- Vertical fixed multi-directional NVF component;
- Curved segment of NVF component;
- Upper fixing and activating plate (for upper fixation of NVF components);
- Welding-based component fixation;
- Stiff upper segment fixed to the super-structure;
- Locations for possible installation of additional eight NVF components (left).

Geometrical characteristics of the created and used NVF energy dissipation components are presented in Figure 1b). (right).

CONSTRUCTED AND TESTED VF-MD ENERGY DISSIPATION DEVICE: a) ASSEMBLED VF-MD DEVICE; b) VF-MD COMPONENT

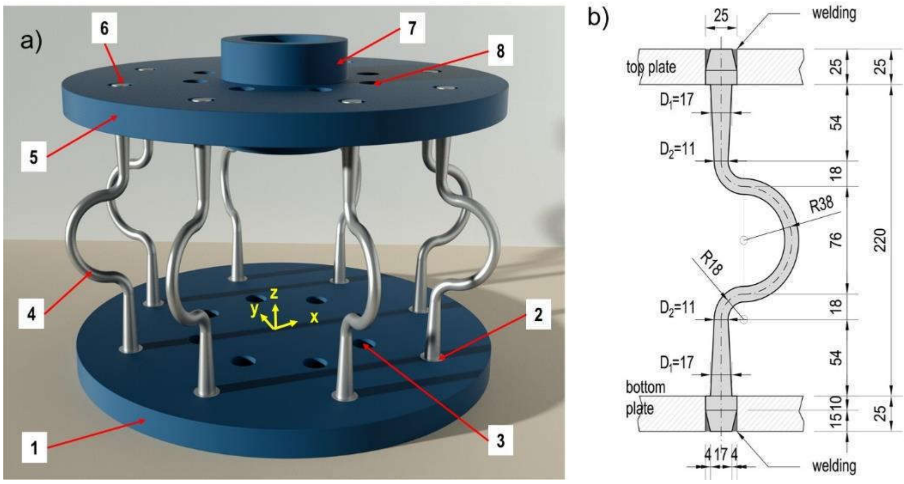


Figure 1. Originally designed and constructed prototype model of NVF device consisting of: 1. Bottom fixing plate; 2. Fixing segment of NVF component; 3. Vertical fixed multi-directional NVF component; 4. Curved segment of NVF component; 5. Upper fixing and activating plate; 6. Welding-based component fixation; 7. Stiff upper segment fixed to the super-structure; 8. Locations for possible installation of additional eight vertical fixed NVF components (left) and geometrical characteristics of created NVF energy dissipation component (right).

3. EXPERIMENTAL TESTING OF NVF BRIDGE SYSTEM

Shaking table testing program and set-up of bridge model: To obtain a reliable and relevant evidence on the seismic performances of the created NVF bridge system, an integral study comprising specifically targeted and extensive experimental research was adopted:

a) Bridge model testing program: The integral shaking table testing program included realization of different types of shaking table tests on a large-scale bridge model, including: (1) Sine-sweep tests on the bridge model with mounted isolation only. The programmed sine-sweep tests were conducted to confirm the actual recorded initial value of the fundamental vibration period and damping of the base isolated, not upgraded, bridge model; (2) Seismic test on the basic bridge model having isolation only. This seismic test was considered as referent, providing evidence on the seismic response of the bridge system without NVF upgrading devices; (3) Seismic tests on the NVF bridge model under simulated near-field earthquakes. The tests were performed to investigate the response of the upgraded bridge under simulated strong near-field earthquakes with different frequency content; (4) Seismic tests on the NVF bridge model under simulated semi-resonant earthquakes. Actually, these series of tests were carried out to investigate the response of the upgraded bridge under simulated semi-resonant or far-field earthquakes with different frequency content.

b) Set-up of bridge model: To provide simulation of the seismic response in longitudinal and transversal direction, the bridge model was spaced diagonally on the IZIIS seismic shaking table, Figure 2. It was composed of a stiff RC model sub-structure (SUB-S), model super-structure (SUP-S) in the form of an RC slab, left (abutment) support (LS), right (abutment) support (RS), shorter middle piers (SMP), longer middle piers (LMP), two DSRSB devices at the left support (1,2), two DSRSB devices at the right support (3,4), location for the NVF device at the left support (A), location for the NVF device at the right support (B), a steel frame for installation of two DL devices above the left support and a steel frame for installation of two DL devices above the right support.

The typical full-scale prototype bridge was selected with configuration suitable for the proposed seismic upgrading. The three-span bridge superstructure had a total length of 58.5m (15.75+27.0+15.75), while the piers had different heights (9.50 and 11.70m). Formed between the RC bridge deck and the sub-structure supports was a seismic gap suitable to accommodate seismic isolation and energy dissipation devices. The constructed bridge model was geometrically reduced in respect to the prototype bridge based on an adopted geometric scale factor of 1:9 in order to match the dimensions and the load capacity of the shaking-table, Ristic, J., [7]. Considering the addressed modeling factors, the combined true replica-artificial mass simulation model was adopted as the most adequate. The total length and width of the model sub-structure amounted to 8.30m and 1.50m, respectively.

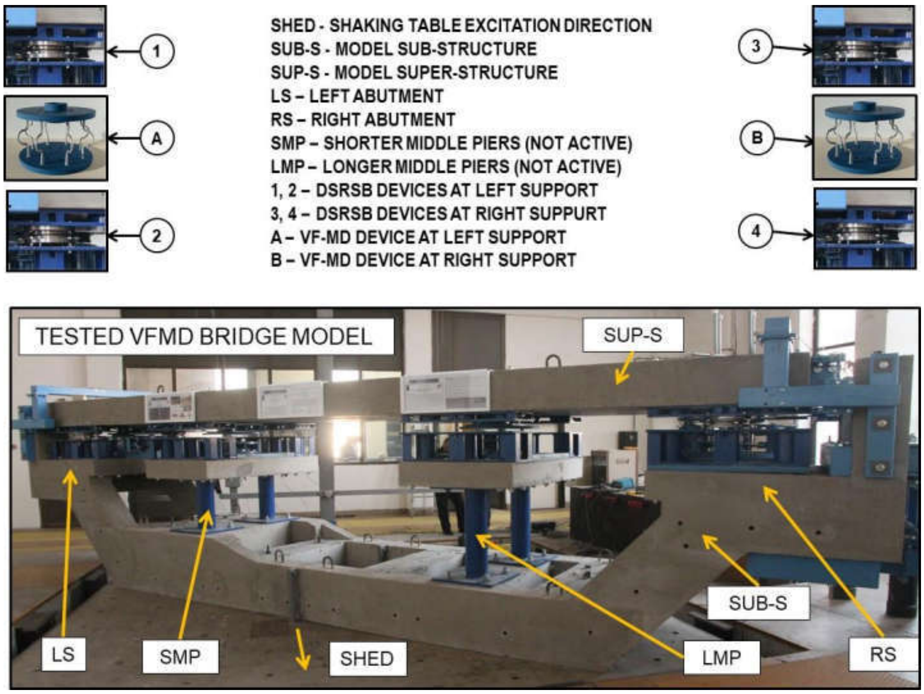
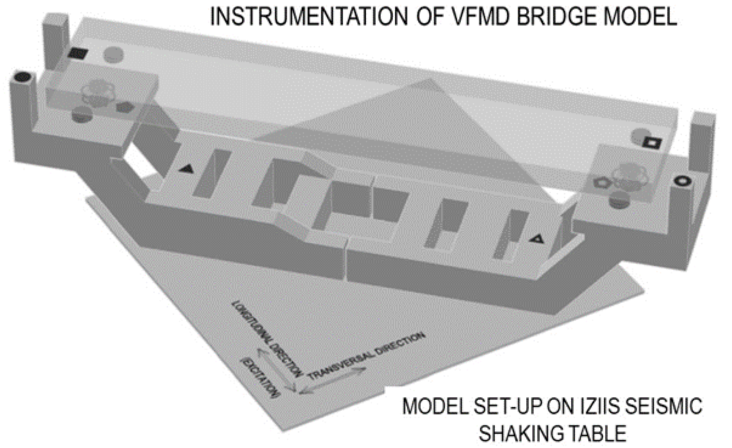


Figure 2. Constructed NVF bridge prototype model tested on the IZIIS seismic shaking table

The thickness of the model superstructure deck was conveniently increased to compensate for the additional superstructure load and to enable realistic simulation of the generated large inertia forces. In the presented tests, the mid-piers were not used and the tested model was transformed into a one-span structure. The existing steel components were manufactured of S355 steel class, while C25/30 concrete type was used for the construction of the concrete components.

c) Instrumentation of bridge model: The successfully used extensive instrumentation system of the model, Figure 3, was presented in details before by Ristic, J., [7]. It consisted of the adopted identical instrumentation devices, including: (1) Four LVDT transducers (four linear variable differential transformers) for recording response time histories of relative displacements between the sub- and super- structure; (2) Four LP transducers (linear potentiometers) for recording absolute response displacements, assured by fixation of one of their ends to the referent points located beyond the shaking table and (3) Twelve acceleration sensors (ACC) to record the acceleration time history responses of the selected six characteristic model points in longitudinal and transverse direction, respectively.



CH 01	NP1	⬟	L	LVDT-01
CH 02	NP1	⬟	T	LVDT-02
CH 03	NP2	⬠	L	LVDT-03
CH 04	NP2	⬠	T	LVDT-04
CH 05	NP3	▲	L	LP-01
CH 06	NP4	△	L	LP-02
CH 07	NP7	■	L	LP-03
CH 08	NP8	□	L	LP-04
CH 09	NP3	■	L	ACC-01
CH 10	NP3	■	T	ACC-02
CH 11	NP4	□	L	ACC-03
CH 12	NP4	□	T	ACC-04
CH 13	NP5	●	L	ACC-05
CH 14	NP5	●	T	ACC-06
CH 15	NP6	○	L	ACC-07
CH 16	NP6	○	T	ACC-08
CH 17	NP7	▲	L	ACC-09
CH 18	NP7	▲	T	ACC-10
CH 19	NP8	△	L	ACC-11
CH 20	NP8	△	T	ACC-12

Figure 3. Instrumentation of the tested NVF bridge model: Acquisition channels and respective recording sensors

d) Sine-sweep testing of bridge model with isolation only: Seven repeated sine-sweep dynamic tests were initially conducted under low intensity sine-sweep dynamic inputs (0.02g to 0.05g) simulated by the shaking table. Generating different sine-sweep input signals with a wide range of frequencies (1 to 35Hz), a large volume of data was obtained. Using the recorded data, for the tested bridge model with mounted isolation only, the value of the fundamental period amounting to T_o=0.522s and damping amounting between 3.0 and 3.5%, were successfully defined.

e) Seismic testing of bridge model with isolation only: The basic, initial seismic test on the bridge model with installed isolation device only was conducted to directly assess the contribution of the created NVF energy dissipation devices implemented in the next study phase. In that respect, the initial test was realized under the simulated El Centro earthquake scaled to PGA = 0.81 g. From the conducted seismic test, a large unacceptable maximum relative displacement amounting to 42.34 mm was recorded. It was larger than the defined allowable displacement of 40.0 mm. However, in the case of the tested upgraded NVF bridge system presented in the next section, the maximum relative displacements were reduced to fully controlled values.

3.1. Testing of NVF bridge model under near-field earthquakes

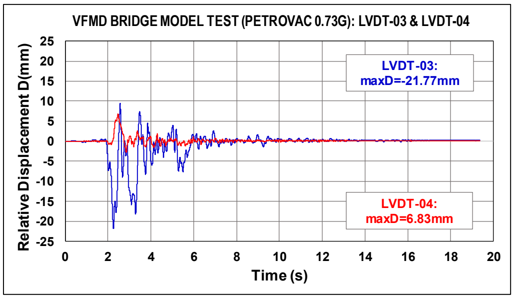
The actual seismic response of the created NVF bridge system under earthquake excitations was controlled by the interactive effects of the nonlinear responses of the integrated seismic isolation and energy dissipation devices. To fully demonstrate the actual behaviour of the installed specific devices and the resulting global seismic response of the integral NVF bridge system, experimental seismic tests were conducted. The performed shaking table seismic tests provided a full evidence regarding the seismic performances of the NVF bridge system at the global level. The detailed insight into the response characteristics of the seismic isolation and the NVF energy dissipation devices was also obtained from the conducted experimental study. The basic testing details and related observations from the original shaking table seismic tests are briefly summarized.

a) Simulated seismic input: Seismic testing of the NVF bridge model was performed under selected four different near-field earthquake records, characterized by representative frequency contents [7]. Following the relations from the similitude law, the original earthquake records were time compressed for a time factor of t_f = 1/3, calculated with the respective formula $t_f = 1 / (lr)^{0.5}$, where lr=9 and representing the originally considered geometrical scale of the bridge model. To obtain representative experimental results, high earthquake intensities were simulated by scaling of the respective records to high levels of peak ground accelerations amounting to PGA=0.75g for the El Centro (1940) earthquake record, PGA=0.73g for the Petrovac (Montenegro, 1979) earthquake record, PGA=0.77g for the Landers earthquake record and PGA=0.93g for the Northridge earthquake record. The ground-shaking records used in this study belong to the permanent seismic data base of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Ss. Cyril and Methodius University in Skopje. The existing seismic database for testing was created in the specific MTS shaking table operational format. Selection of ground shaking parameters should be carefully made considering the specific research objectives and the existing technical testing conditions.

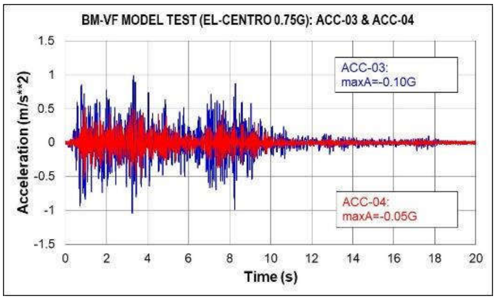
Table 1. Peak relative sub-super structure displacements recorded by LVDT sensors during the original shaking-table tests on the NVF bridge model under simulated strong (compressed) near-source earthquakes

B1. SEISMIC TESTS SIMULATING COMPRESSED EL-CENTRO & PETROVAC EARTHQUAKE						
No.	O-T1: C-El-Centro, PGA=0.75G			O-T2: C-Petrovac, PGA=0.73G		
	Channel	MaxD (-) (mm)	MaxD (+) (mm)	Channel	MaxD (-) (mm)	MaxD (+) (mm)
1	LVDT-01	-32.40	29.34	LVDT-01	-14.54	18.23
2	LVDT-02	-5.27	3.79	LVDT-02	-2.44	5.54
3	LVDT-03	-26.04	17.96	LVDT-03	-21.77	9.43
4	LVDT-04	-6.72	3.01	LVDT-04	-2.76	6.83
B2. SEISMIC TESTS SIMULATING COMPRESSED LANDERS & NORTHRIDGE EARTHQUAKE						
No.	O-T1: C-Landers, PGA=0.77G			O-T2: C-Nortrige, PGA=0.93G		
	Channel	MaxD (-) (mm)	MaxD (+) (mm)	Channel	MaxD (-) (mm)	MaxD (+) (mm)
1	LVDT-01	-12.90	13.15	LVDT-01	-33.21	29.56
2	LVDT-02	-3.73	3.86	LVDT-02	-3.21	10.79
3	LVDT-03	-11.80	18.78	LVDT-03	-31.24	29.72
4	LVDT-04	-3.64	2.57	LVDT-04	-6.55	7.35

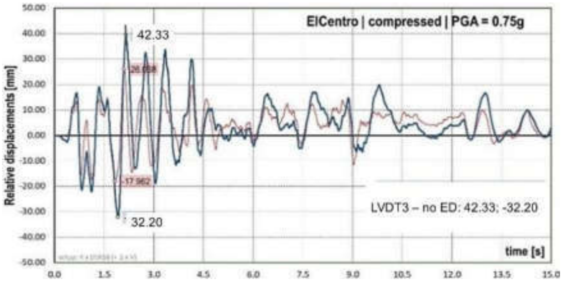
b) Data acquisition system: Due to the complexity of the conducted seismic tests, extensive experimental data files were recorded from each acquisition channel. Specifically, having an extensive set of 20 instrumented channels and some extra channels of sensors for controlling of the shaking table, along with the used highly refined data sampling rate, from each seismic test, about 5 million numerical values were recorded. The integral testing process, involving sixteen shaking table tests, was very successfully completed. All sensors provided correct and complete experimental records. Following the systematic data processing (existence of about 80 million numerical data), representative results showing the system response were selected, processed and presented.



(a)



(b)



(c)

Figure 4. Recorded time-history responses of the NVF bridge model tested under simulated compressed strong Petrovac earthquake: (a) relative displacements and (b) acceleration responses of the superstructure recorded by ACC-03 & ACC-04. Recorded relative displacements of the NVF bridge with seismic isolators only (blue) under simulated compressed El-Centro earthquake (c).

c) Recorded relative displacements: The peak relative displacements, including positive and negative pulses, recorded during the seismic tests on the NVF bridge model under simulated four strong near-field earthquakes, are presented in Table 1. To graphically illustrate the recorded seismic responses of the tested NVF bridge model, Figure 4 shows the time history responses of relative displacements and accelerations of the characteristic measuring point 1, obtained during the test conducted under the simulated Petrovac earthquake. For the selected characteristic measuring point 1, Figure 4 (a) and Figure 4 (b), respectively show the recorded relative superstructure displacements and accelerations, in longitudinal (L) and transverse (T) direction, comparatively. Based on the results obtained from the experimental study, the following observations were summarized: The displacements recorded in L direction, representing the direction of the earthquake excitation, are dominant; (2) The displacements in T direction, normal to the earthquake excitation, are small and insignificant; (3) The maximum peak relative displacement amounting to Dmax = -32.40 mm was smaller than the allowable displacement of the seismic isolators amounting to Da = 40.0 mm, and (4) The new NVF bridge system is capable of advancing the seismic performances and providing a stable seismic response. With the recorded in all cases, the reduced relative displacements, Table 1, the advantages of the adopted NVF energy dissipation devices are clearly demonstrated.

d) Recorded accelerations: From the presented acceleration time-histories in L and T direction of the superstructure recording point 1, Figure 4 (right), it is evident that the recorded maximum accelerations are, in this case, significantly smaller than the input acceleration. The peak accelerations can be larger than the input acceleration in some cases, but they are not significantly amplified. Such response characteristics directly reflect the achieved advanced effects of the tested NVF bridge system.

e) Recorded absolute displacements: Considering the time-histories of absolute displacements recorded in L direction by the installed LP sensors on the sub- and super-structure segments of the tested NVF bridge model, a correct control of the seismic shaking table and successful accomplishment of the data recording process was confirmed in all realized testing cases.

3.2. Testing of NVF bridge model under far-field earthquakes

a) Testing objectives: The advanced seismic performances of the NVF bridge system subjected to strong near-field earthquakes are integrally demonstrated in section 3.1, based on the results obtained from the realized related seismic tests. Critical spectral amplitudes of the simulated earthquakes were avoided by the introduced DSRSB isolation system.

Table 2. Peak relative sub-super structure displacements recorded by LVDT sensors during the original shaking-table tests on the NVF bridge model conducted under simulated real (not compressed) earthquakes

B1. SEISMIC TESTS SIMULATING REAL EL-CENTRO & PETROVAC EARTHQUAKE						
No.	O-T1: R-El-Centro, PGA=0.52G			O-T2: R-Petrovac, PGA=0.29G		
	Channel	MaxD (-) (mm)	MaxD (+) (mm)	Channel	MaxD (-) (mm)	MaxD (+) (mm)
3	LVDT-03	-29.86	19.80	LVDT-03	-35.60	32.83
4	LVDT-04	-3.70	2.354	LVDT-04	-10.07	7.44
B2. SEISMIC TESTS SIMULATING REAL LANDERS & NORTRIGE EARTHQUAKE						
No.	O-T1: R-Landers, PGA=0.27G			O-T2: R-Nortrige, PGA=0.25G		
	Channel	MaxD (-) (mm)	MaxD (+) (mm)	Channel	MaxD (-) (mm)	MaxD (+) (mm)
3	LVDT-03	-24.51	26.06	LVDT-03	-38.59	34.76
4	LVDT-04	-11.31	8.89	LVDT-04	-5.55	1.03

Incorporating the novel NVF energy dissipation devices, the damping of the created NVF system was significantly increased. However, having an enlarged vibration period of the first mode, the system became more sensitive to long period (far-field) earthquakes.

To fill this clearly evident investigation gap, the seismic response of the NVF bridge system exposed to long period earthquakes was also experimentally studied. Specifically, well targeted series of seismic tests with simulated far-field earthquakes were conducted.

b) Testing conditions: Analyzing the computed response spectra for the compressed and uncompressed earthquake records, a suitable and quite relevant testing scenario was defined. The used compressed earthquake records were relevant to simulate near-field earthquakes since they were derived following the test model similitude law. However, regarding the uncompressed real earthquake records, it was observed that the dominant part of their response spectra was distributed near the fundamental period of the assembled NVF bridge system. Having in mind the significance of this observed property, the recorded uncompressed earthquake records were considered to represent a suitable and evidently relevant earthquake input option for realization of the planned extensive seismic testing of the NVF bridge system under simulated far-field earthquakes.

c) Testing results: From the realized integral seismic testing program, voluminous numerical data was obtained. However, as early as during the first seismic test, a highly intensified seismic response was observed. Therefore, the further seismic testing concept was accordingly modified. Specifically, the actual PGA value of any earthquake record was carefully adjusted to fully satisfy the dynamic shaking table payload and to properly assure the model safety in each conducted individual seismic test.

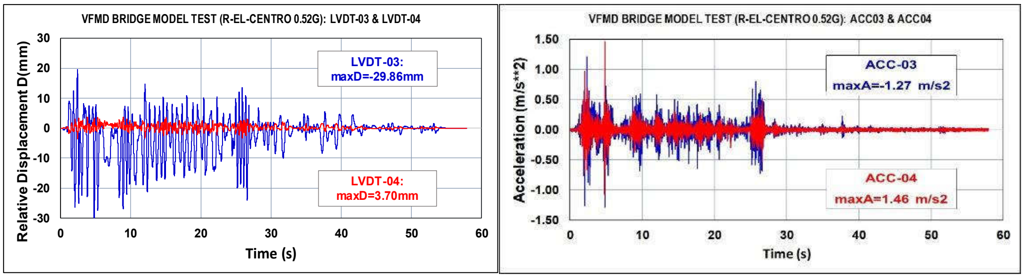


Figure 5. Superstructure relative displacements (left) and acceleration responses (right) recorded respectively by LVDT and ACC sensors during seismic test of NVF bridge model simulating real strong El-Centro earthquake

Table 2 shows the recorded peak relative sub- super- structure displacements during the original shaking table tests on the NVF bridge prototype model conducted by simulation of real (not compressed) long-period earthquake records. It was evident that the obtained maximum relative displacements were remarkably larger, even though the long-period earthquakes were simulated with lower PGA values. Respectively, the used earthquake records were accordingly scaled, El-Centro to PGA=0.52G, Petrovac to PGA=0.29G, Landers to PGA=0.27G and Northridge to PGA=0.25G. Fig. 5 respectively shows the time history response of the superstructure relative displacements recorded by LVDT-3 and LVDT-4 (left) and the time histories of acceleration responses recorded by ACC-03 & ACC-04 (right), during the NVF model test performed by simulation of the real strong El-Centro earthquake. With the presented tests realized by simulation of far-field earthquakes, the safety of the NVF system was also confirmed, because the PGA values became much lower due to their very significant attenuation with distance.

4. SUMMARY OF RESEARCH RESULTS

The capability of the NVF bridge system to protect bridge structures subjected to very strong near-field earthquakes is graphically demonstrated in Fig. 6. Having the installed novel NVF devices, the system provided suitable modification of the seismic response. In all test cases, the maximum recorded relative superstructure displacement was significantly reduced.

Suppressing the maximum relative displacements in all test cases below the allowable displacement of the isolation devices amounting to 40.0 mm, a stable, safe and reliable seismic response was confirmed. On the contrary, an unsafe seismic response was shown in the comparative test of the bridge system having isolation only, since the maximum relative displacement became larger than the allowable displacement of the seismic isolation devices.

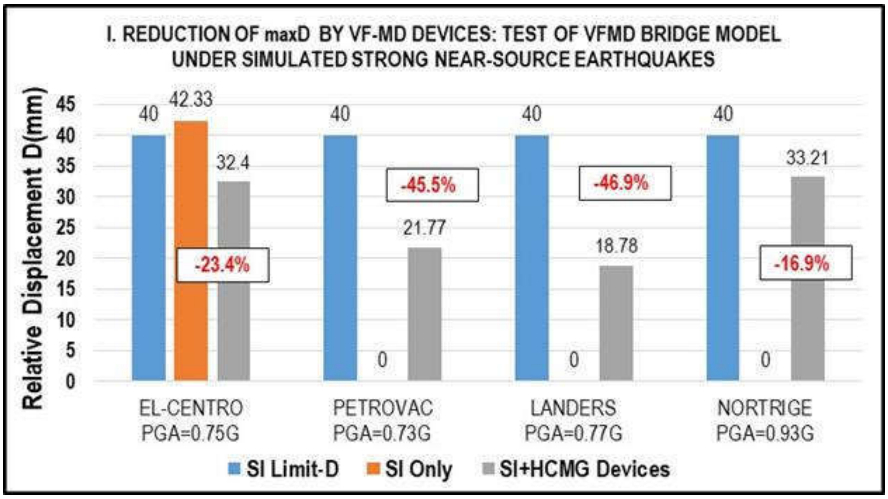


Figure 6. Confirmed reduction in maximum relative displacement by the installed NVF devices: Shaking-table tests of the NVF bridge model under simulated strong near-source earthquakes

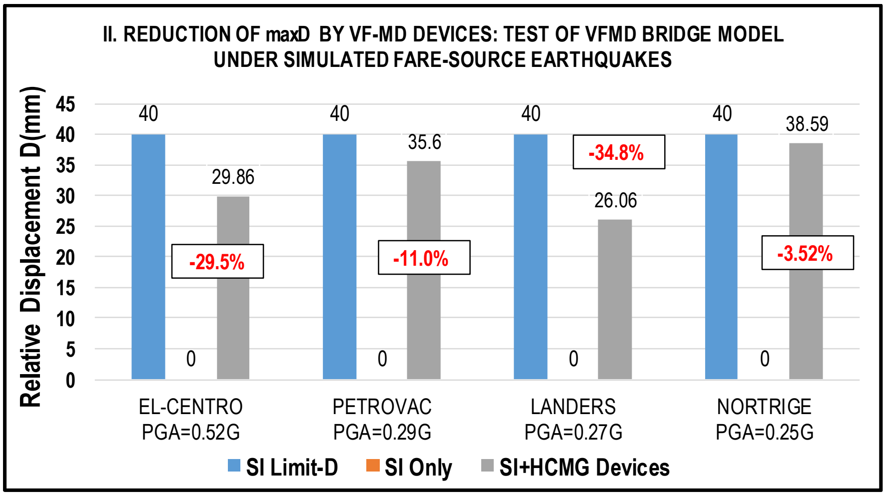


Figure 7. Confirmed reduction in maximum relative displacement by the installed NVF devices: Shaking-table tests of NVF bridge model under simulated far-source earthquakes

Similarly, the capability of the NVF bridge system to optimally protect bridge structures subjected to far-field (longer period) earthquakes is shown in Fig. 7. From the experimental test results, it is evident that the recorded maximum relative displacements are below the allowable displacement in all cases. The suitability of the NVF bridge system for seismic protection of bridges under far-field earthquakes is evident, specifically regarding the recorded rapid attenuation of the maximum ground accelerations.

5. CONCLUSIONS

Considering the derived and processed voluminous original experimental results, involving about 160 million numerical data recorded during the performed extensive shaking table seismic tests on the large–scale NVF bridge model, along with the observed unique supplementary results, the following conclusions were summarized:

1) It was experimentally confirmed that the created NVF energy dissipation device, involving a technically new option for increasing damping through uniform adaptable nonlinear response, provided advanced capability for energy dissipation and effective upgrading of isolated bridges exposed to near and far field earthquakes.
2) The required validity of the initial dynamic properties of the tested and modeled NVF bridge system was confirmed with the obtained very good correlation between the fundamental period defined experimentally with sine-sweep dynamic tests and the value calculated with the formulated analytical model.
3) The possible unsafe seismic response of the assembled bridge model with DSRSB isolation only was demonstrated with the conducted comparative seismic proof test. An unstable seismic response of the bridge with isolation only was obtained because the recorded maximum relative superstructure displacements were larger than the allowable displacement of the implemented seismic isolation devices.
4) For the seismic input characterizing strong near-field earthquakes, the NVF bridge system showed an advanced seismic protection capability. The stable and harmonized seismic response was confirmed with the conducted respective seismic shaking table tests. In all test cases, the maximum relative superstructure displacements remained significantly below the allowable displacement due to the efficient upgrading effects induced with the NVF energy dissipation devices.
5) Analogously, in the case of an earthquake input characterizing long-period or far-field earthquakes, the NVF bridge system again showed a satisfactory system seismic protection. Specifically, in all conducted seismic tests under simulated relatively high seismic intensity, the recorded maximum relative superstructure displacements remained below the allowable displacement. The upgrading effect of the NVF energy dissipation devices was experimentally confirmed.
6) The capability of the formulated new phenomenological nonlinear analytical model to realistically simulate the complex seismic response of the NVF bridge system under simulated near- and far-field earthquakes can be confirmed based on results obtained from the extensive experimental study. Specifically, in the future analytical studies, the required high correlation level can be established regarding the seismic responses predicted analytically and those recorded during the conducted the present original and representative seismic tests.
7) The experimentally validated NVF bridge system, involving adaptive NVF device for seismic response modification, can be successfully implemented in real practice for advanced seismic protection of bridges potentially exposed to strong near- and critical far-field earthquakes.

ACKNOWLEDGMENTS

The research was realized in the Institute of Earthquake Engineering and Engineering Seismology, "Ss Cyril & Methodius" University in Skopje, in the frames of the innovative NATO Science for Peace and Security Project: Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828), with participation of five countries: North Macedonia: Danilo Ristic, Leader & PPD-Director, Germany: Uwe Dorka, NPD-Director, Albania: Arian Lako, Bosnia & Herzegovina: Damir Zenunovic & Serbia: Radomir Folic. The extended support to the realization of the project is highly appreciated.

REFERENCES

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

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

[3] Ristic Danilo: **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, 1988.

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

[5] Ristic Jelena, Misini Misini, Ristic Danilo, Guri Zijadin, Pllana Nebi: **Seismic Upgrading of Isolated Bridges with SF-ED Devices: Shaking Table Tests of Large-Scale Model.** *Građevinar,* 2017*, 70* (6): 463-485.

[6] Ristic Jelena: **Comparative Seismic Analysis of RC Bridge Structure Applying Macedonian Seismic Design Regulations and Eurocodes. MSc Thesis, Department for Theory of Structures.** "Ss. Cyril and Methodius" University, Skopje, Macedonia, 2011.

[7] Ristic Jelena: **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, 2016.

[8] Ristic Danilo, Dorka Uwe, Lako Arijan, Zenunovic Damir, Folic Radomir: **Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies.** NATO SfP Project 983828, *Science for Peace and Security Programme*, Final Report, 2013.