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COMBINED PROTECTION OF BRIDGES EXPOSED TO EARTHQUAKE AND FLOOD DISASTERS WITH NEW RB-UPGRADED ISOLATION SYSTEM

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Abstract

Combined and extensive experimental and analytical study devoted to development of an integrated earthquake and flood protection (EFP) bridge system was performed. It represents an extension of the integral research project led by the fourth author, conducted in the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Ss. Cyril and Methodius University (Skopje), during three and a half years, 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)", involving five European countries and led by the fourth author. The presently introduced EFP bridge system represents a specific, extended segment of the integral research. The upgraded, seismically isolated (USI) system with integrated space flange (SF) energy dissipation (ED) devices has been developed as a mechanical passive concept to provide harmonized response of bridge structures to earthquakes. It was formulated as an adaptive system, which follows the adopted concept of global optimization of seismic energy balance, through utilization of newly designed dissipation devices as a supplementary damping level to bridge isolation. The new EFP-bridge system is based on obligatory incorporation of the following four integrated complementary systems: (1) Seismic isolation (SI) system, (2) Seismic energy dissipation (ED) system, (3) Combined earthquake and flood displacement limiting (EFDL) system composed of new and experimentally tested RB devices and (4) Uplift protection system (UP). With the extensive experimental quasi-static cyclic tests conducted by simulated, gradually increased displacement amplitudes, there were confirmed very stable hysteretic responses of the created prototype models of rubber buffer (RB) devices applicable for efficient protection of common and isolated bridges exposed to either strong earthquakes or flood disasters. Following the upgrading of the seismically isolated (USI) bridge system with energy dissipation devices, the adopted original rubber buffer (RB) devices represent an important additional line of defense against abrupt loadings due to earthquake and flood disasters.

Keywords: bridge, model testing, earthquake, flood, rubber buffer, safety

1. Introduction

In the past, extensive studies in the field of seismic isolation of bridges were mostly performed in worldwide recognized research centers in Japan, USA, Italy, and New Zealand. However, in recent years, contributions from many other countries have been increased and have resulted in proposal of many new ideas and concepts. Intolerable severe impacts to modern bridge systems have been observed during strong recent earthquakes [1, 2]. This has given rise to strong arguments about further needs for development and practical implementation of seismic isolation systems for seismic protection of bridges, [3, 4, 5, 6, 7]. However, in addition to problems arising due to strong earthquakes, continuous functioning of highway bridges and highway networks can be seriously disrupted by various other existing types of hazards. Studies involving flood disaster prevention and preparedness against mobility disruption by floods have regularly been conducted, [9]. These have also included two-dimensional flood inundation modelling, [10] and development of seismically resilient hinges for bridge piers [11]. In recent years, various technical standards have been newly developed or upgraded [12-13]. Following

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some specific observations published in prepared recent flood investigation reports [14], advanced concepts of protection of critical infrastructure systems located in a multi-hazard environment have been developed and proposed [15-19]. In this specific and wide research area, some fundamental studies have been realized. These have included determination of hydrodynamic forces on inundated bridge decks [20] and assessment of scour and other hydraulic actions on highway structures [21-22]. Recently, some integrated studies have been focused on development of practical measures assuring continuous functioning of entire road networks and providing assessment of road closure probabilities [23].
Presented in this paper is the developed new advanced earthquake and flood protection (EFP) bridge system, considering the results from the conducted combined and extensive experimental and analytical studies. Following the idea of upgrading of the developed, seismically resistant (USI) bridge system [5] involving seismic isolation and energy dissipation devices, the newly created specific rubber buffer (RB) devices have been added as an important additional line of defense against abrupt loadings due to earthquake and flood disasters. The resulting efficient bridge protection under possible bi-hazard effects was provided by means of the created new integrated earthquake and flood protection (EFP) system.

2. Concept of New EFP Bridge System

The presently introduced upgraded, seismically isolated (EFP) bridge system represents a newly created advanced technical concept developed as a specific segment of the integral research, Fig. 1. The previously developed upgraded seismically isolated (USI) system with integrated space flange (SF) energy dissipation (ED) devices, represented a passive mechanical technical concept providing safe harmonized response of bridge structures to earthquakes, [5]. It was formulated as an adaptive system, which follows the adopted concept of global optimization of seismic energy balance through utilization of newly designed, energy dissipation devices as a supplementary damping level to the bridge isolation.

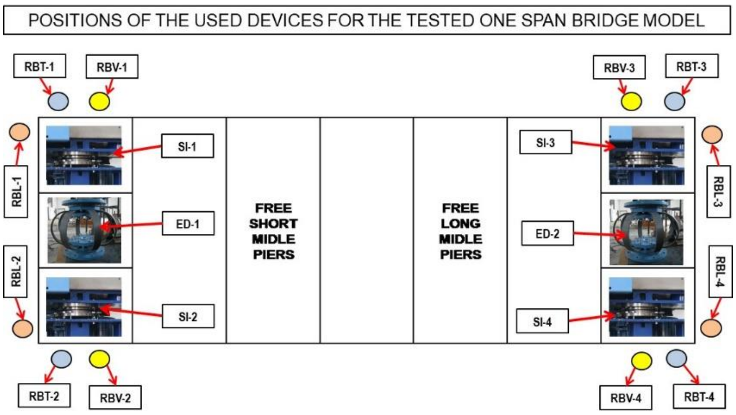

Fig. 1. Defined positions of the integrated devices in the tested EFP bridge model: Seismic isolation devices (SI), Energy dissipation devices (ED) and RB devices used in longitudinal, transversal and vertical direction.

The new EFP bridge system is based on obligatory incorporation of the following four integrated complementary systems: (1) Seismic isolation (SI) system, (2) Seismic energy dissipation (ED) system, (3) Combined earthquake and flood displacement limiting (EFDL) system composed of new and experimentally tested RB devices and (4) Uplift protection system (UP), Fig. 1. The developed SI and ED systems have been created and successfully implemented, [5]. However, with the conducted programmed quasi-static cyclic experimental tests under simulated, gradually increased displacement amplitudes, very stable hysteretic responses of the created new prototype models of rubber buffer (RB) devices have been confirmed. The created RB devices have been implemented very successfully in assembling a combined earthquake and flood displacement limiting (EFDL) system and an uplift protection system (UP). The created, integrally upgraded EFP bridge system represents a technically new applicable option for efficient protection of common and isolated bridges exposed to either strong earthquakes or severe flood disasters. Following the promoted further upgrading of the seismically isolated (USI) system with the adopted original rubber buffer (RB) devices in longitudinal-L, transversal-T and vertical-V-direction, an important additional line of defense against possible bi-hazard abrupt loadings involving severe earthquake and flood disasters is provided.

3 Prototypes of Used Devices in EFP Bridge Model

3.1 Prototypes of tested DSSSB isolation devices

The implemented isolation system used for the experimental EFP bridge model was assembled by use of the developed models of double spherical sliding seismic bearing (DSSSB) devices with two large-radii of spherical surfaces, Fig. 2). The DSSSB devices were originally designed, constructed and used in a previous investigation carried out by Ristic, J., et al., 2016, [7]. The targets that were set prior to the design and construction of the device were fulfilled: (1) very small horizontal reaction and friction forces (reaching maximum 4.3% of the vertical load), and (2) stable hysteretic behavior along the entire range of large displacements. It was confirmed that the hysteretic behavior of the implemented DSSSB devices could be successfully simulated with the experimentally defined representative bilinear analytical model.

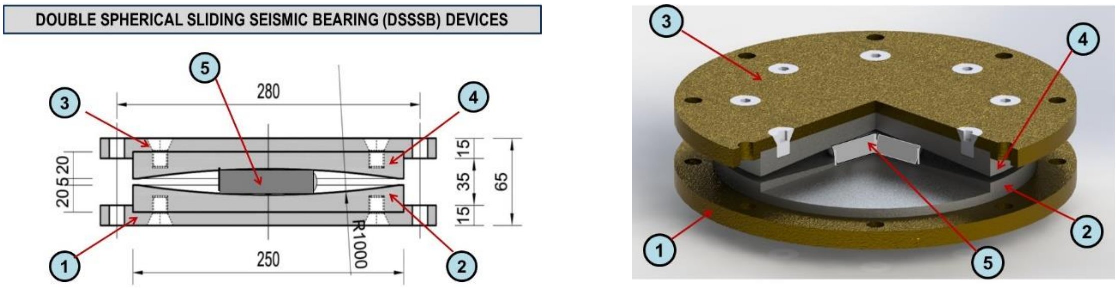

Figure 2. Basic elements of the constructed and used prototypes of DSSSB devices: (1) lower end metal plate; (2) lower spherical plate; (3) upper end metal plate; (4) upper spherical plate; (5) metallic slider;

Actually, the model was controlled by four parameters, DY=1.0 mm, FY=0.32 kN, DU=50.0 mm, FU=0.92 kN, defined experimentally under simulated vertical load and cyclic displacements with increasing amplitudes.

3.2 Prototypes of tested SF energy dissipation devices

The created seismic energy dissipation system installed in the tested EFP bridge prototype model was composed of the developed advanced steel space flange (SF) energy dissipation (ED) devices.

Table 1. Hysteretic behavior properties of SF-ED-M11 and SF-ED-M12 devices computed by using the formulated nonlinear FEM model and simulated cyclic displacements with increasing amplitudes

No.	**SF-ED Device M11: SF-ED-8C-L1R-T1**			**SF-ED Device M12: SF-ED-4C-L1R-T1**		
	Notation	FEM model	(%)	Notation	FEM model	(Δ%)
1	DY (mm)	5.0	100.0	DY (mm)	6.0	120.0
2	FY (kN)	21.0	100.0	FY (kN)	9.0	42.8
3	K0 (kN/mm)	4.0	100.0	K0 (kN/mm)	1.5	37.5
4	K1 (kN/mm)	0.18	100.0	K1 (kN/mm)	0.02	11.1
5	K1/K0	0.045	100.0	K1/K0	0.013	28.8

Up to date, SF-ED dissipation devices of the proposed type have been studied only by the first author and her collaborators involved in bridges, [7] and [25].

In this paper, the two basic types of SF-ED devices are presented in Table 1. The first SF device is composed of eight ED components, model M11, representing the SF-ED-8C-L1R-T1 device, Fig. 3. The second SF device consists of four ED components, model M12, representing the SF-ED-4C-L1R-T1 device, Fig. 4.

Fig. 3. Assembled SF-ED device type-1 (SF-ED-8C-L1R-T1): (1) lower base plate; (2) lower support plate; (3) upper base plate; (4) upper support plates; (5) SF-ED component

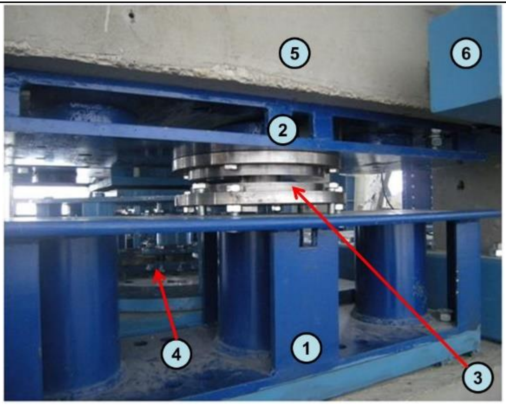

Fig. 4. Installed SF-ED device type-2 (SF-ED-4C-L1R-T1): (1) superstructure; (2) steel support of the DL-device; (3) steel support of the DSRSB device; (4) DSRSB device; (5) SF-ED component

Adopting the experimentally verified refined 3D nonlinear analytical model, the hysteretic responses of the assembled prototype devices exposed to cyclic loads were computed successfully. With the computed original results, it was confirmed that the adopted representative bilinear analytical model could be implemented to realistically model the full hysteretic behavior of the device. The defined parameters of the representative bilinear models are comparatively presented in Table 1.

3.3 Prototypes of tested displacement limiting RB devices

During strong earthquake vibrations, a limited number of very strong impulses may occur, followed by large displacement amplitudes, which are not controlled in a reliable engineering mode. Thus, the originally created advanced displacement limiting devices representing specific rubber buffer (RB) devices with provided wide geometrical and mechanical options, may be designed to reduce or eliminate earthquake damaging effects, Fig. 5.

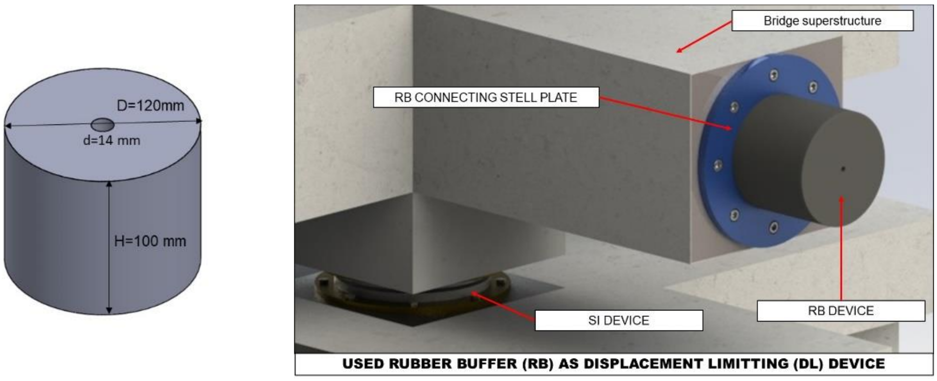

Figure 5. Geometry of the tested RB models used as displacement limiting devices.

However, if properly designed, the created RB devices can be also implemented to very efficiently protect large uncontrolled superstructure displacements in longitudinal (L), transversal (T) and vertical (V) direction, avoiding total collapse of bridge superstructure under generated, increasing or very strong damaging flood forces. If stiffness is properly designed, RB devices implemented in vertical (V) direction can be used to efficiently protect against uncontrolled vertical uplifting displacements and total collapse of the bridge superstructure under generated strong vertical flood uplift forces. Actually, the developed RB devices can be integrated to act as a specific interactive displacement limiting system, protecting efficiently against uncontrolled failure of the bridge superstructure under generated, uncontrolled combined horizontal and vertical forces during extreme earthquakes and floods.

Table 2. Testing program & tests of elements (specimens) of prototype models of RB devices

Test No.	RB Model	RB Element	Test type	D (mm)	H (mm)
1	M1	M1-RB-40SH-E1	*Original*	120	100
2		M1-RB-40SH-E1	*Repeated*	120	100
3		M1-RB-40SH-E2	*Original*	120	100
4		M1-RB-40SH-E2	*Repeated*	120	100
5	M2	M2-RB-50SH-E1	*Original*	120	100
6		M2-RB-50SH-E1	*Repeated*	120	100
7		M2-RB-50SH-E2	*Original*	120	100
8		M2-RB-50SH-E2	*Repeated*	120	100
9	M3	M3-RB-60SH-E1	*Original*	120	100
10		M3-RB-60SH-E1	*Repeated*	120	100
11		M3-RB-60SH-E2	*Original*	120	100
12		M3-RB-60SH-E2	*Repeated*	120	100
13	M4	M4-RB-70SH-E1	*Original*	120	100
14		M4-RB-70SH-E1	*Repeated*	120	100
15		M4-RB-70SH-E2	*Original*	120	100
16		M4-RB-70SH-E2	*Repeated*	120	100

An extensive testing program was conducted [24]. It included realization of specifically programed cyclic tests of the constructed prototype models of RB devices. Presented in this paper are the representative results obtained from the realized extensive experimental tests of rubber buffer prototype models. The key functioning targets of the displacement limiting RB devices are: (1) enabling physical limitation of maximum relative displacements of seismic isolation devices; (2) achieving the predefined physical limitation of the relative displacements by properly avoiding the so called “hard” structural impact; and, (3) providing efficient protection of seismic isolation (SI) and energy dissipation (ED) devices by assured limitation of relative displacements.

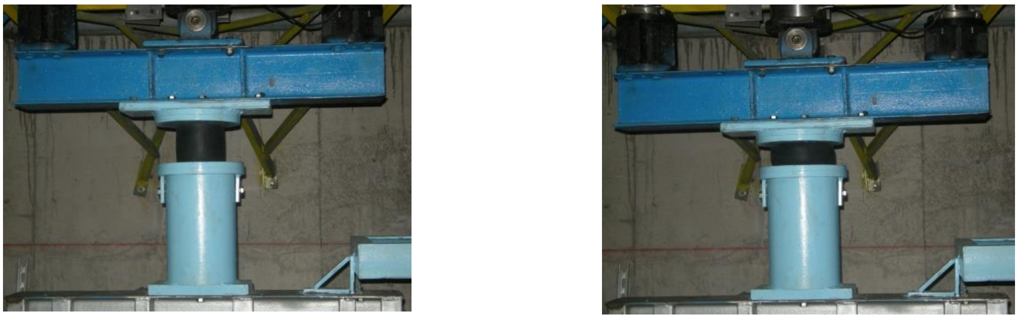

Figure 6. Experimental test set-up used for testing of the model prototypes of RB displacement control devices under simulated cyclic loads with increasing displacement amplitudes.

To achieve all the stated goals, prototype models of RB devices were designed and manufactured in the form of cylindrical rubber (pads) buffers cast by use of rubber characterized by four different values of hardness measured in shores, H40, H50, H60 and H70. To obtain comparative experimental results, two experimental test specimens of each type of RB devices, amounting to a total of eight specimens, were constructed.

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To investigate the effect of repeated loading, two tests (original and repeated) were performed on each test specimen. Therefore, the integral experimental program was extended to a total of completed 16 experimental quasi-static tests, Table 2. The presented experimental RB specimens were designed in the form of cylinders with a diameter of D=120 mm and height H=100 mm. In the middle of the cylinder, a central opening with a diameter d=14 mm was designed to be used for successful positioning of the experimental device prototype for its safe experimental testing, Fig. 6. Details of the produced original experimental models are shown in Table 2. More specifically, the table shows that, for each of the four RB models, two experimental elements (E1 & E2) were produced, meaning that the experimental program included testing of a total of eight different specimens. However, due to the need for getting an insight into the behavior of the innovative RB devices under repeated compressive loading effects, all 8 specimens were tested twice. The first (virgin) test was marked as original, while the second one was referred to as repeated, Table 2. Hence, the entire experimental program resulted in realization of a total of 16 cyclic experimental tests.

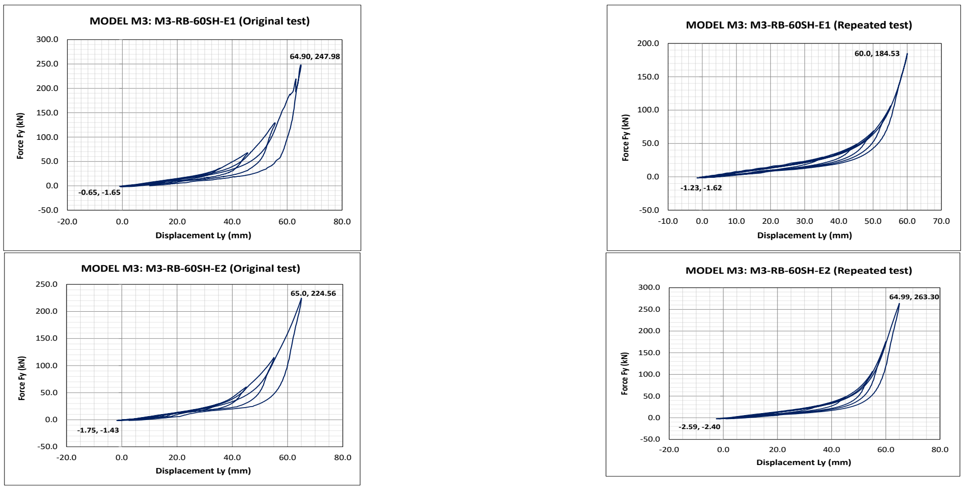

Figure 7. Recorded characteristic hysteretic response of model M3 during original and repeated tests of specimens M3-RB-60SH-E1 and M3-RB-60SH-E2 under simulated cyclic loads.

The role of the RB devices is to be effective only under generated compression forces during dynamic response of structures under strong earthquakes and floods. The experimental tests were realized by application of repeated compressive forces, which were increased in each successive cycle until reaching of the maximum “allowed” working level. Due to such defined specific experimental conditions, an adequate experimental frame was created, Figure 6. This frame enabled all the necessary conditions for the realization of the specified experimental tests. Testing was carried out by activation of an actuator in vertical direction in order to produce a compressive force upon the experimental element since it was fixed, on the upper side, to the constructed rigid steel frame. The experimental element (model) was completely made of rubber and, on the lower side, it was placed on a very rigid base that did not suffer any deformations, Figure 6. For “zero” point of deformation and “zero” point of force, there was selected a position indicating only a direct zero-contact between the actuator plate and the experimental rubber element, without transfer of any force (contact without force or zero contact). From that position, compressive forces were further simulated up to a certain initial level of deformation and then the deformation was returned to the zero point that represented a cycle. More concretely, a compression cycle was defined by loading up to a certain level of deformation and unloading down to zero deformation. The analogous cycles of loading and unloading were repeated a number of times, but in each successive cycle, the amplitude of deformation was increased. In that way, favorable conditions were created for identification of the real hysteretic behavior of all the tested experimental models up to the phase of deformations representing their optimal working level.

Fig. 6 (left) shows the experimental model with the defined zero level of deformations prior to the beginning of the realization of the experimental test, while Fig. 6 (right) shows the model with the realized considerable amount of total deformation (within the working deformation), being lower than the allowed working deformation, (D_{allowed}). In accordance with the provided conditions, it was clear that the realized experimental program provided original and highly valuable experimental results that enabled getting a realistic insight into the nonlinear-hysteretic behavior of the tested RB models and the respective elements. To demonstrate the evident suitability of the test results, Figure 7 shows four recorded hysteretic responses obtained from the conducted original and repeated tests of the specimens M3-RB-60SH-E1 and M3-RB-60SH-E2, under simulated cyclic loads.

4. Seismic Tests of EFP Bridge Model Under Simulated Earthquakes

Due to the size of the seismic shaking table (5.0 m x 5.0 m) and payload capacity, the originally designed EFP bridge prototype model had to be geometrically reduced in respect to the selected prototype. Adopted from these reasons was a geometrical scale factor of 1:9, which verified the referred constraints in this case, but with an 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 the 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 DSSSB isolation devices and SF energy dissipation devices were designed and produced to a reduced scale. The similitude law implies adopted relations for different parameters, all given in terms of the geometrical scale factor (*lr)*. Concrete material type C25/30 was used for construction of the RC segments of the bridge model, while for construction of the created SF devices, steel material type S355 was selected and applied.

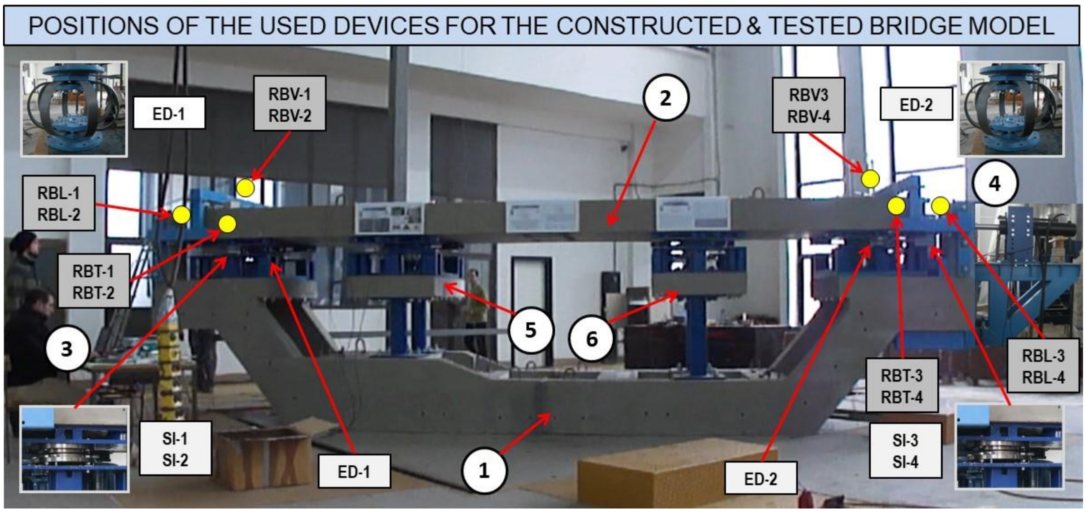

Fig. 8. Tested large-scale EFP bridge model composed of substructure (1), superstructure (2), left end support (3), right end support (4) and presently not-activated shorter (5) and longer (6) middle piers with indicated positions of the integrated devices: seismic isolation devices (SI), energy dissipation devices (ED) and rubber buffer (RB) devices used in longitudinal (RBL), transversal (RBT) and vertical (RBV) direction.

Regarding the proportions at the top level, the total length of the entire experimental bridge model was L=740.0 cm + 2 $*$ 20.0 cm + 2 $*$ 25.0 cm = 830.0 cm, Fig. 1 and Fig. 8. The RC deck was placed at a height distance of h_d = 40.0 cm from the highest RC substructure surfaces. This space (seismic gap) was used to install both the originally produced DSSSB devices and the new SF devices, Fig. 2 and Fig. 3.

Specially designed steel frame structures using steel profiles 100 mm x 120 mm were constructed and fixed to both ends of the tested EFP model. The shape of the frame structures was designed to provide favorable conditions for successful installation of the originally created and used rubber buffer devices in all three directions. The defined positions of the created and installed specific types of upgrading devices in the tested EFP bridge model are presented in Fig. 1 and Fig. 8.

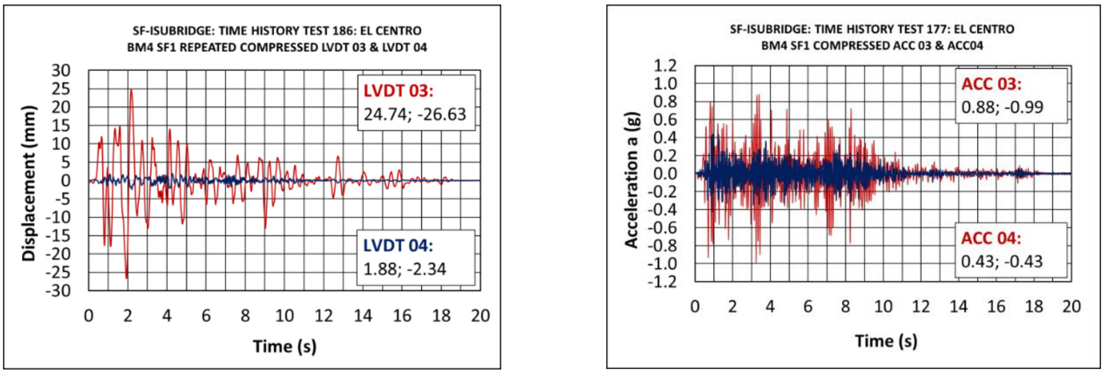

Figure 9. Relative superstructure displacement responses recorded by LVDT-03 & LVDT-04 (left) and acceleration responses recorded by ACC-03 & ACC-04 (right) during the EFP bridge model shaking table test conducted under simulated strong El-Centro earthquake.

Actually, in the tested EFP bridge model, there were integrated four constructed DSSSB seismic isolation devices (SI), then two originally created SF seismic energy dissipation devices (ED) and a respective number of displacement limiting devices, originally created, tested and used in the form of rubber buffer devices (RB). The positions of the rubber buffer devices were selected to be activated assuring limitation of displacements in longitudinal direction (RBL), transversal direction (RBT) and vertical direction (RBV), Fig. 1. After fabrication of all model segments and the specific SI, ED and RB devices and after preparing the other testing connections and instrumentation devices, the large-scale EFP bridge prototype model was assembled and tested in the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje.

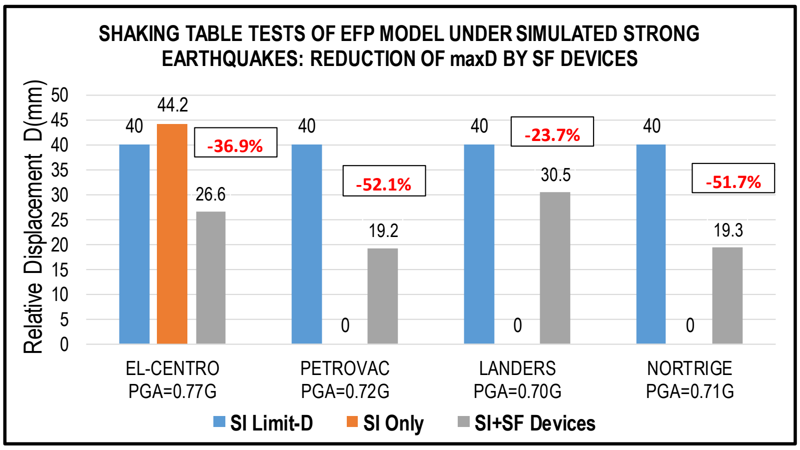

Figure 10. Advances of the EFP bridge system: Reduction of maximum relative displacements defined from the conducted seismic tests of the large-scale EFP model under simulated strong earthquakes.

With the adopted 20 active recording channels, approximately 5.000.000 numerical values were recorded in each single test. During the conducted four original and four repeated tests, a large experimental data volume containing about 40 million numerical values was obtained, integrally processed and analyzed.

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As an example, Fig. 9 presents the time history responses of displacements and accelerations recorded during the seismic test under simulated real strong El-Centro earthquake scaled to PGA=0.77g. The conducted seismic shaking table tests showed that the seismically isolated bridge by using DSSSB devices and upgraded complementary SF energy dissipation devices and RB displacement limiting devices represented a highly efficient and practical engineering option for protection of bridges exposed to strong earthquakes. Actually, the new EFP system exhibited safe and very favorable behavior under strong earthquake excitations. Based on processing of the recorded original numerical data obtained from the realized extensive shaking table seismic tests by simulating strong earthquakes, the main qualitative advances of the innovative EFP system are summarized in Fig. 10. Very stable, reliable and safe seismic response was observed in all test cases due to the provided significant reduction of maximum relative displacements amounting to 36.9%, 52.1%, 23.7% and 51.7%, respectively, in the case of the simulated El Centro, Petrovac, Landers and Northridge earthquakes. All recorded peak values were lower than the defined allowable design displacement of Da=40.0 mm for the seismic isolators. The importance of upgrading the isolated bridge with the new SF devices was experimentally validated and confirmed with the conducted initial quantification test of the model with the installed seismic isolation only. Under the simulated strong El-Centro earthquake, the tested isolated system, without installed SF devices, showed an unsafe response. Large excessive relative displacement amounting to maxD=44.2 mm was recorded, Fig. 10.

5. Loading of EFP Bridge Model Under Simulated Flood Loading

The extensive stability studies of bridge structures exposed to the effects of severe flood disasters that have been carried out so far have mainly been focused on protection of substructure elements. The effect of water pressure on bridge piers, possible undermining and failure of foundation of middle piers, damage to bridge abutments, washing off or damage to river beds and alike have been the subjects of these investigations. However, quite few investigations have been dedicated to development of a modern technology for bridge protection against damage or complete failure of superstructure elements under the effect of potential large forces generated by severe floods. This problem has not been investigated to a sufficient depth up to date and combined systems capable of protecting bridge superstructures against severe earthquakes and floods have not been developed.

Figure 11. Typical loading of bridges under flood disasters: Collapse of the Guyandotte river bridge under flood, March 4, 2015 (left) and common water level of Guyandotte river in West Virginia, USA (right).

The observed severe destructions of bridge superstructures resulted from inappropriate protection measures in many cases, Fig. 11. The presented investigations were directed toward development of a new system to enable successful bridge protection against strong earthquakes and severe flood disasters. The presently created combined EFP system possesses an advanced capability for successful protection of bridges exposed to strong earthquakes. This was confirmed with the conducted original seismic tests of the constructed large-scale EFP bridge prototype model.

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However, in the final research phase, detailed analytical study will be conducted to validate the capability of the same EFP system to successfully protect bridges subjected to expected severe flood loadings, including representative and critical load cases.

a) Safety analysis of the EFP system under symmetric transverse flood loading: To enable analysis of the bridge superstructure under symmetric transverse flood loading, the most important step to take is definition of the character and intensity of the flood loading. For design purposes, the symmetric transverse flood loading can be approximated by quasi-static loading. In that case, the distribution of the load would be uniform along the span length, while during the analysis, an increase of the load magnitude up to the defined limit would be enabled. However, according to their nature, loads generated during large floods are of dynamic character. In that case, the simulation of load forces requires definition of time functions of dynamic forces and expert analyses of structural response in time domain.

b) Safety analysis of the EFP system under non-symmetric transverse flood loading: Non-symmetric loading of the bridge superstructure could be more critical than symmetric loading in many cases. It is therefore very important to anticipate analysis of the stability of the bridge superstructure under generated large forces due to floods whose dominant effect is non-symmetric. As in the case of symmetric effects, in this case, one can also carry out quasi-static design analyses. However, more realistic and successful definition of the safety of the bridge superstructure can be achieved by expert analyses and simulation of dynamic effect of non-symmetric loads due to floods in transverse direction.

c) Safety analysis of the EFP system under combined transverse and uplift flood loading: The analyses of the stability of the bridge superstructure under combined transverse and uplift loading is very important since it can be the most critical option of loading. According to their nature, floods generate dynamic forces that can be spread in different directions. To confirm the real stability of the bridge structure, it is necessary to perform corresponding analyses under the effect of different combinations of potential loads due to severe flood disasters. Similarly, also in this case, loading can be treated as quasi-static for design purposes. However, during elaboration of final projects, it is necessary to define characteristic analysis combinations, considering all acting forces in the form of critical time functions, defined realistically by experts in hydrology and hydraulics. Realistic simulation of combined dynamic loads and detailed expert analyses in time domain may provide competent conclusions about the stability of the bridge superstructure under generated critical loads due to severe floods.

6. Conclusions

Based on the research results obtained from the conducted extensive experimental studies using the designed and constructed innovative EFP bridge model prototype, the following conclusions are drawn: (1) The novel DSSSB seismic isolation devices are very attractive and effective passive devices for seismic vibration isolation of bridges in arbitrary direction; (2) The new hysteretic multi-directional SF 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 used SF 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 created displacement limiting devices in the form of rubber buffers (RB) represent very effective obligatory devices acting as the last line of defense against excessive displacements of the bridge superstructure. Actually, the rubber buffers (RB) represent an efficient passive system, whose activation provides bridge safety during the most critical loads generated by very strong earthquakes or severe floods; (4) The obtained results from the conducted experimental tests confirmed that the new EFP system represented an original high performance seismic isolation option for bridges. The system was created based on optimized seismic energy balance and represents an advanced technical innovation capable of integrating the advantages of seismic isolation, seismic energy dissipation and effective displacement limitation. (5) The new results obtained from recent experimental tests have shown that the created innovative RB displacement limiting devices possess preferable characteristics and can be used as the

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last line of defense against extremely large lateral displacements; (6) Although only cyclic compressive loads were applied, occurrence of significant hysteresis and variable energy dissipation capacity was observed; (7) Although the tested RB specimens suffered very large total deformations and large distortions of their shape during the first experimental tests, they were able to regain their initial shape. Actually, the RB devices possess very specific, advanced and important shape-memory ability; (8) The difference in the restoring force is very large among rubbers of different hardness. This fact points out that selection of the rubber hardness is a very important step. Therefore, by adequate selection of rubbers of different hardness, it is possible to create different structural displacement limiting options in compliance with the specific requirements. (9) The created innovative EFP system represents a combined option for protection of bridge structures. The originally developed upgraded seismic isolation system was additionally upgraded with new advanced rubber buffer devices. The RB devices are optimally distributed in order to be activated in longitudinal, transversal and vertical direction. Actually, the created EFP system represents an advanced technical solution and can be regarded as efficient bi-hazard bridge protection technology and (10) During the next study phases, creative analytical study involving specific scenario modeling and refined simulations will be carried out, basically focused on validation of the EFP system response under simulated strong flood loadings and load combinations.

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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 (2018): 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] Ristic 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] Ristic 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] Arrighi C., Pregnolato M., Dawson R., Castelli F., (2019): Preparedness Against Mobility Disruption by Floods, Science of the Total Env., 654: 1010-1022, https://doi.org/10.1016/j.scitotenv.2018.11.191, 2019

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DOI: https://doi.org/10.5592/CO/2CroCEE.2023.70

[10] Bates P.D., Horritt M.S. and Fewtrell T.J., (2010): A Simple Inertial Formulation of the Shallow Water Equations for Efficient Two-dimensional Flood Inundation Modelling, J. Hydrol. 387(1–2): 33-45. doi: 10.1016/j.jhydrol.2010.03.027, 2010

[11] 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

[12] AASHTO: AASHTO LRFD, (2017): Bridge Design Specifications; 8th Edition, Washington, DC, 2017

[13] FEMA: HAZUS-MH MR1, (2003): Technical manual, Earthquake Model, Federal Emergency Management Agency, Washington, D.C., 2003

[14] EA: Carlisle Flood Investigation Report 2016. Environment Agency (EA), Cumbria County Council: https://www.cumbria.gov.uk/planning-environment/flooding/flood_investigation_reports_carlisle.asp, last access: 12 November 2020, 2016

[15] 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

[16] Argyroudis, S.A., Mitoulis, S.A., Winter, M.G., Kaynia A.M., (2019): Fragility of Transport Assets Exposed to Multiple Hazards: State-of-the-Art Review toward Infrastructural Resilience, Reliability Engineering & System Safety 191, 106567, 2019, 421 https://doi.org/10.1016/j.ress.2019.106567

[17] Carey T.J., Mason H.B., Barbosa A.R., Michael H.S., (2019): Multi-hazard Earthquake and Tsunami Effects on Soil–Foundation–Bridge Systems, J. Bridge Eng., 24(4), 04019004, doi: https://doi.org/10.1061/(ASCE)BE.1943-5592.0001353, 2019

[18] Gidaris, I., Padgett, J. E., Barbosa, A. R., Chen, S., Cox, D. T., (2017): Webb, B. and Cerato, A.: Multiple-hazard Fragility and Restoration Models of Highway Bridges for Regional Risk and Resilience Assessment in the United States: State-of-the-art review, J. Struct. Eng. 143 (3), 04016188, https://doi.org/10.1061/(ASCE)ST.1943-541X.0001672, 2017

[19] Gehl, P. and D'Ayala, D., (2018): System Loss Assessment of Bridge Networks Accounting for Multi-hazard Interactions. Structure and Infrastructure Engineering, 14(10), 1355-1371, 2018

[20] Kerenyi, K., Sofu, T. and Guo: J., (2009): Hydrodynamic Forces on Inundated Bridge Decks, Federal Highway Administration, FHWA-HRT-09-028, 2009

[21] Highways England (HE), (2012): Design Manual for Roads and Bridges BD 97/12 The Assessment of Scour and other Hydraulic Actions at Highway Structures: http://www.standardsforhighways.co.uk/ha/standards/dmrb/ vol3/section4/bd9712.pdf, last access: 12 May 2020, 2012

[22] Arneson, L.A., Zevenbergen, L.W., Lagasse P.F., Clopper, P.E., (2012): Evaluating Scour at Bridges, 5th Edition, Publication no. FHWA-HIF-12-003, Hydraulic Engineering Circular No. 18. U.S. Department of Transportation, Federal Highway Administration, 2012

[23] Ertugay K., Argyroudis S. and Düzgün H.Ş., (2016): Accessibility Modeling in Earthquake Case Considering Road Closure Probabilities: a Case Study of Health and Shelter Service Accessibility in Thessaloniki, Greece, Int. j. of disaster risk reduction, 17, 49–66, doi: 10.1016/j.ijdrr.2016.03.005, 2016

[24] Ristic J., Hajdari V., Misini L., Ristic D., (2022) Testing of Rubber Buffer Models Protecting Bridges Under Earthquakes and Floods, 16. Congress of Association of Structural Engineers of Serbia.

[25] Misini, M., Ristic, J., Ristic, D., Guri, Z., Pllana, N. (2019). Seismic upgrading of isolated bridges with SF-ED devices: Analytical study validated by shaking table testing, *GRAĐEVINAR, 71* (4), 255-272, doi: https://doi.org/10.14256/JCE.2274.2017