



## SEISMIC PROTECTION OF BRIDGES WITH APPLICATION OF NEW SYSTEM FOR SEISMIC RESPONSE MODIFICATION

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### ABSTRACT

Bridges are structures of high vital and strategic significance. Being essential part of every infrastructural system, highest level of reliability and durability is expected to be met during their whole exploitation period, especially in countries and regions with high seismicity, as is Republic of Macedonia and wider region of south east Europe. Seismic isolation and seismic energy dissipation devices are used all over the world with very different approaches and methodologies (see Kim et al. (2000), Iemura et al. (1998)), but all with one main goal – development of seismically safe structures, resistant to any earthquake impact. However, earthquakes having their stochastic and unpredictable nature, challenge the scientists in all world research centers to reexamine their work and strive for improvement (see Martelli et al. (2012)). Several earthquakes, which occurred in the last two decades, Kawashima & Matsuzaki (2012), including the very peculiar one in Bolu, Turkey, proved that even the most advanced technologies applied are put to test with uncertain outcome.

Our highest motivation and challenge is to conduct continuous development, improvement and upgrading of these advanced technologies for seismic isolation and seismic energy dissipation, contributing to the general safety and stability of bridge and other structures, hoping to be closer to the ultimate economically applicable solution with every taken step forward. Some of our most recent research result toward stated highly challenging goals are summarized and discussed in this paper.

### 1. INTRODUCTION

In this paper, presented and briefly discussed are selected research activities, (see also Ristic D. and Ristik J. (2012)), and selected original results obtained from the conducted three year international scientific project, supported by the NATO Science for Peace program, entitled *Seismic upgrading of bridges in South-East Europe by innovative technologies*, realized under directorship (PPD) of the third author of this paper. The project focuses on development, testing and improvement of various original technological options of innovative seismic energy dissipation components (EDC) and seismic energy dissipation devices (EDD), as well as on development and construction of large-scale innovative physical models of the selected typical bridge prototype structure for dynamic testing on seismic shaking table in IZIIS, Skopje. The main highlight of some of the herein presented innovative seismic dissipation devices is their advanced adaptive reaction with multi-level and multi-directional response to probable very strong earthquake impacts.

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The presented original research results in this paper represent some selected principal outcomes from the realized three main research phases as follows: (1) Experimental quasi-static testing of the developed innovative seismic energy dissipation devices (EDD) of horizontal H-type (Fig. 1.1) and EDD of complex C-type, (Fig. 1.2), as well as testing of the developed respective types of innovative energy dissipation components (EDC); (2) Experimental dynamic shaking table testing of the innovative bridge model (BM), (see Fig. 1.3), with built-in laminated-rubber seismic bearings (LRSB) shown in Fig 1.4 and double spherical rolling seismic bearings (DSRSB) shown in Fig. 1.5, as well as with different types of seismic energy dissipation devices (EDD), under simulated real earthquake records scaled to high intensities; and (3) Initial specific theoretical research devoted to development of advanced, powerful and generally applicable so-called three-dimensional stress-strain based micro-model for complex cyclic nonlinear behavior simulation of the tested innovative seismic energy dissipation components (EDC) of innovative H-type and C-type energy dissipation devices (EDD).



Figure 1.1 Innovative device for seismic energy dissipation of horizontal H-type



Figure 1.2 Innovative device for seismic energy dissipation of complex C-type



Figure 1.3 Innovative model of prototype bridge structure mounted on the seismic shaking table in the dynamic testing laboratory in IZIIS, Skopje

The above stated innovative study phases represent original and extensive experimental and analytical investigations, being the current doctoral thesis research of the first author, under mentorship of the second author, at IZIIS, University “Ss Cyril and Methodius”, Skopje.



Figure 1.4 Square laminated neoprene seismic bearing



Figure 1.5 Double spherical rolling seismic bearing

The main aim of this paper is our initial evaluation and discussion of the original results obtained comparatively from the two highly different approaches: (1) Reliable but very costly experimental testing approach and (2) Advanced analytical modeling approach, for the same energy dissipation components and energy dissipation devices.

## 2. QUASI-STATIC TESTING OF ENERGY DISSIPATION DEVICES

The quasi-static testing of energy dissipation devices presented in this paper included construction and testing of two specific types of energy dissipation devices (EDD) of H-Type and C-Type under simulated reversed cyclic loads.

The quasi-static tests were carried out using software and sensor-controlled actuator. The loading of the seismic energy dissipation components and devices was cyclic and gradual, applying small controlled portions of displacement increase in every step. Quasi-static tests were carried out for all types of devices and components of horizontal H-type and complex C-type, mounted directly on the innovative bridge model in combination with double spherical seismic rolling bearings. After those tests were completed, the full units of seismic energy dissipation devices were tested, also in combination with double spherical seismic rolling bearings.

On Figure 2.1 shown is selected representative original hysteretic curve horizontal force (kN) – displacement (mm) obtained from quasi-static testing of seismic energy dissipation component EDC-H, type 1.2. On Figure 2.2 shown is selected representative hysteretic curve horizontal force (kN) – displacement (mm) from quasi-static testing of seismic energy dissipation device EDD-H with two levels of built-in eight components of type 1.2 at level-1 and type 1.5 at level-2.

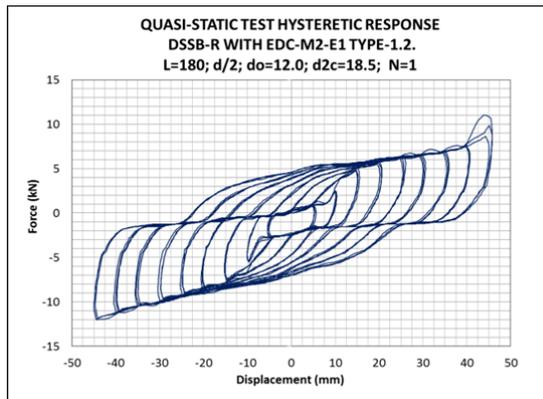


Figure 2.1 Obtained original hysteretic curve force (kN) – displacement (mm) from quasi-static testing of seismic energy dissipation component EDC-H

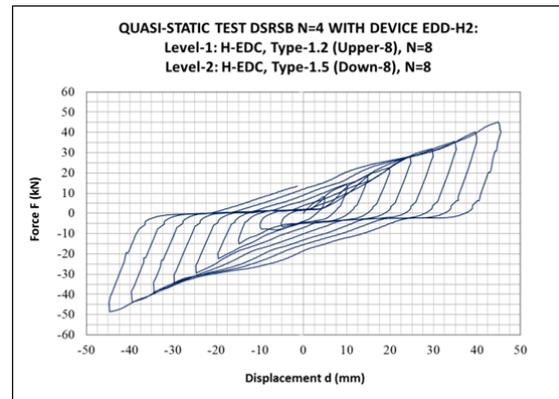


Figure 2.2 Obtained original hysteretic curve force (kN) – displacement (mm) from quasi-static testing of seismic energy dissipation device EDD-H

## 3. EXPERIMENTAL DYNAMIC TESTING ON SHAKING TABLE

The realized extensive experimental shaking table test program included creation, construction and testing of innovative large-scale bridge models on seismic shaking table with incorporated two innovative response modification model systems for ML-MD seismic protection of bridges.

The results from the completed experimental seismic shaking table tests are considered as basic realistic data for experimental validation of the actual response modification performances and generated efficiency of the created different options of the innovative bridge systems applicable for seismic upgrading of existing bridges and seismic protection of new important and large bridge structures located in seismic active regions.

The designed basic bridge model (BM) has been very successfully accommodated for specific and multi-purpose use providing very realistic results for full experimental validation of the proposed different response modification technologies for seismic protection of bridges.

The model was constructed in the scale 1/9, and consequently for conducting planed seismic shaking table tests, the considered input earthquake record was time-compressed by scaling factor 1/3.

The dynamic shaking table tests were carried out using selected records of the following earthquakes: (1) El Centro, (2) Landers, (3) Northridge and (4) Petrovac. The input records were scaled both in time and intensity according to the theory of similarity for physical models. On Figure 3.1 presented is selected representative time history acceleration response recorded at measuring channel ACC-01, from shaking table testing of Bridge Model-1 (BM1) with integrated seismic energy dissipation devices (EDD) of H-type, EDC type 1.2. The channel ACC-01 was used to record acceleration response at the top left side of the RC bridge deck, exactly in the direction of activation of the shaking table, i.e. under 45 degrees in respect to the bridge model. On Figure 3.2 presented is selected representative time history displacement response recorded at measuring channel LVDT-01, from shaking table testing of Bridge Model-1 (BM1) with integrated seismic energy dissipation devices (EDD) of H-type, EDC type 1.2. The channel LVDT-01 measured the displacement at the top left side of the RC deck, exactly in the direction of activation of the shaking table, i.e. under 45 degrees in respect to the bridge model. The shaking table input earthquake record Petrovac was scaled to maximal acceleration level of  $PGA=0.7g$ .

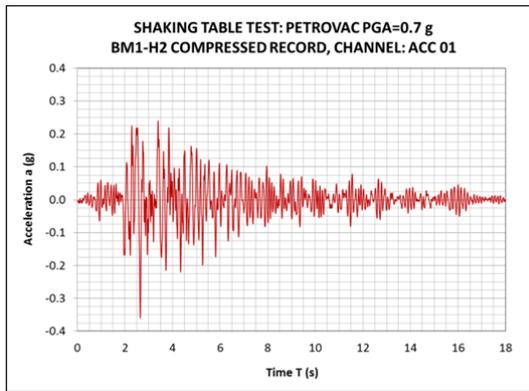


Figure 3.1 Recorded shaking table test acceleration response BM1-EDD-H2, EDC-T1.2; Petrovac 0.7g

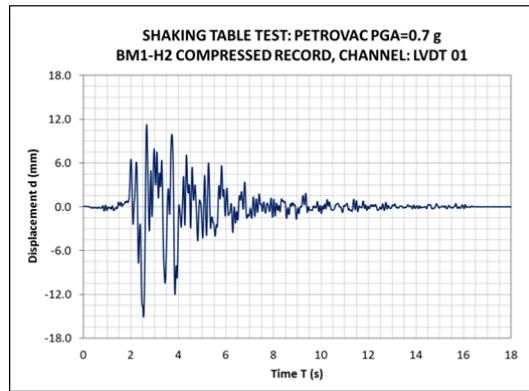


Figure 3.2 Recorded shaking table test displacement response BM1-EDD-H2, EDC-T1.2; Petrovac 0.7g

#### 4. QUASI-STATIC TESTING OF ENERGY DISSIPATION COMPONENTS

Additional quasi-static tests of the seismic energy dissipation components were carried out for each component separately, in order to exclude the contribution in the response from the double spherical seismic rolling bearings included in the previous tests of this type.

On Fig 4.1 and Fig 4.2 presented are 3D drawings of representative seismic energy dissipation components of horizontal-H device, type 1.1 and type 3.2, respectively. On Fig. 4.3 presented is 3D drawing of representative seismic energy dissipation component of complex-C device, type 2.1.

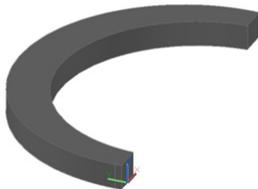


Fig 4.1 Seismic Energy Dissipation Component Horizontal Type 1.1

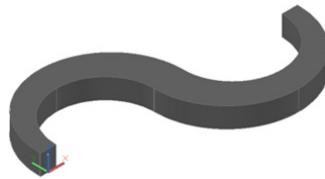


Fig 4.2 Seismic Energy Dissipation Component Horizontal Type 3.2

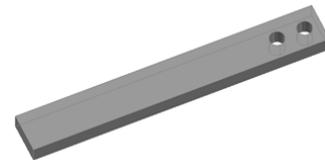


Fig 4.3 Seismic Energy Dissipation Component Complex Type 2.1

As preparation to the quasi-static tests, the seismic energy dissipation components of each horizontal-H type were mounted as pair in one plane, facing one towards another, (see Fig. 4.4). This kind of mounting was chosen as optimal in order to obtain equilibrium and to avoid buckling of the

tested components. The seismic energy dissipation components of complex-C type were tested separately as mounted test specimen, on prepared specific steel platform for test set-up, in the form of single cantilever element.



Fig 4.4 Mounted pair of seismic ED components of horizontal-H1 type for quasi-static testing

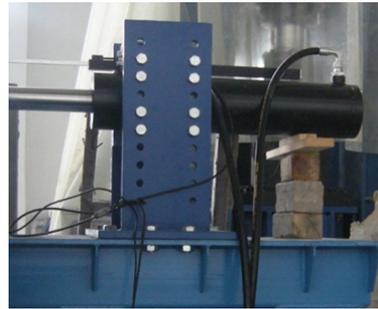


Fig 4.5 Software driven sensor-controlled actuator for quasi-static testing

As previously mentioned, the loading of the seismic energy dissipation components was cyclic and gradual, applying small controlled portions of displacement increase in every step controlled by software driven sensor-controlled actuator, Fig 4.5.

On Figure 4.6 presented is selected representative original hysteretic response horizontal force (kN) – displacement (mm) obtained from quasi-static testing of seismic energy dissipation component EDC-H1, type 1.1. The maximal intensity of the generated force is  $F_{max}=14.4$  kN for one component, for applied maximal displacement of  $d_{max}=41.9$  mm.

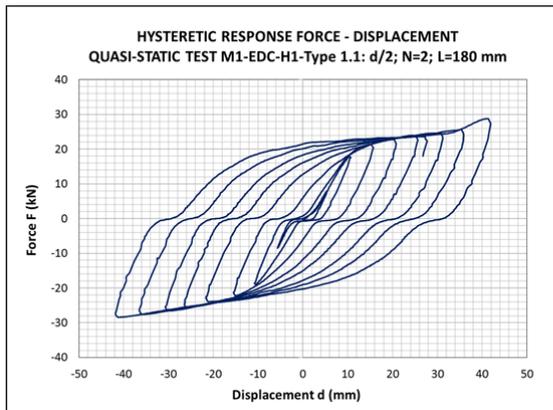


Fig 4.6 Obtained original hysteretic curve force (kN) – displacement (mm) from quasi-static testing of seismic energy dissipation component H1-Type 1.1

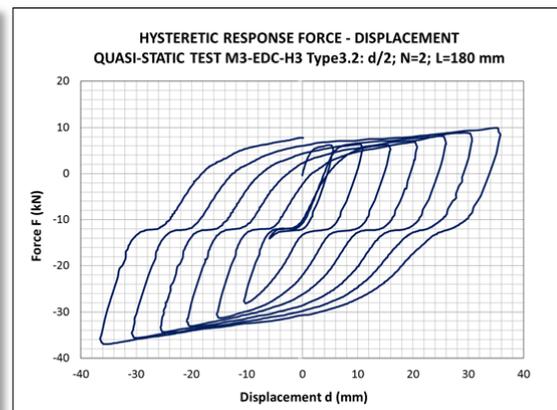


Fig 4.7 Obtained original hysteretic curve force (kN) – displacement (mm) from quasi-static testing of seismic energy dissipation component H3-Type 3.2

On Figure 4.7 presented is selected representative original hysteretic response horizontal force (kN) – displacement (mm) obtained from quasi-static testing of seismic energy dissipation component EDC-H3, type 3.2. The maximal intensity of the generated force is  $F_{max}=12.5$  kN for one component, for applied maximal displacement of  $d_{max}=36.5$  mm.

On Figure 4.8 presented is selected representative original hysteretic response horizontal force (kN) – displacement (mm) obtained from quasi-static testing of seismic energy dissipation component EDC-C, type 2.1. The maximal intensity of the generated force is  $F_{max}=5.7$  kN, for applied maximal displacement of  $d_{max}=41.6$  mm.

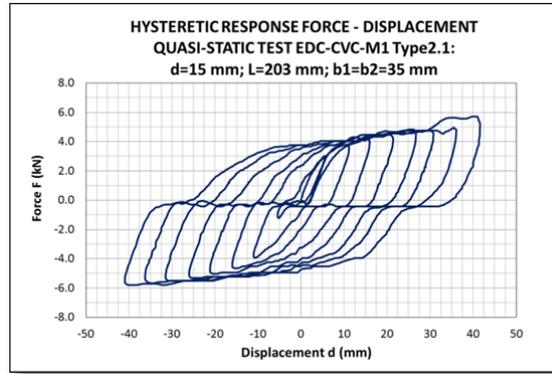


Fig 4.8 Obtained original hysteretic curve force (kN) – displacement (mm) from quasi-static testing of seismic energy dissipation component C-Type 2.1

## 5. ANALYTICAL TESTING OF ENERGY DISSIPATION COMPONENTS

The main objective of the micro-modeling of the new tested seismic energy dissipation components is to formulate advanced nonlinear analytical model capable to simulate real experimental results regarding the force – deformation relations, as well as the actual stress-strain distribution of each component, also providing verification of the quasi-static testing results.

In this paper presented is one selected representative result obtained for seismic energy dissipation component (EDC) of horizontal-H3 type 3.2. The analysis is carried out with the computer program FELISA/3M, developed by the second author of this paper. The seismic EDC with total length of  $l=180$  mm and constant thickness of  $t=15$  mm is radially divided to 20 equal finite elements, (see model in Fig. 5.1).

The seismic EDC is modelled using three dimensional solid finite elements with 20 nodal points and 27 Gauss integration points. The material characteristics for the steel are modelled to provide elastic-plastic behaviour, according to the von Mises principle. In the modelling of the EDC behaviour included are two types of stiffness hardening – strain hardening and kinematic hardening.

In order to get valid and reliable results from the micro-model analysis for comparison with the experimentally obtained ones, the loading input was considered identical as for the quasi-static test of the EDC and consists of application of the same predefined small portions of displacement increase – gradually step by step and following pre-defined cyclic type of displacement history.

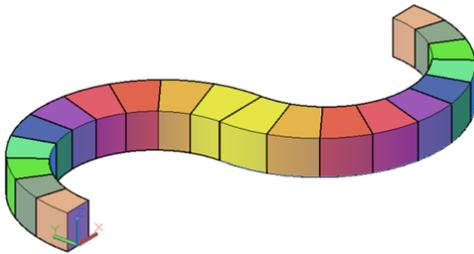


Figure 5.1 Seismic energy dissipation component H3-type 3.2 divided to 20 solid finite elements

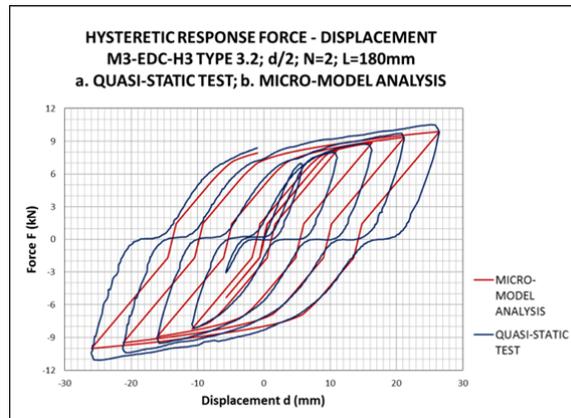


Figure 5.2 Hysteretic response for seismic energy dissipation component EDC-H3 type 3.2 from a. Quasi-static test and b. Micro-model analysis

At this point of the research there is very satisfactory progress and required similarity achieved between the numerically and experimentally obtained hysteretic response of the seismic energy dissipation component EDC-H3 type 3.2, as presented on Figure 5.2. The most important remarks to be made are the following: (1) The input cyclic displacement loading is simulated and applied with high precision level; (2) The generated peak force intensities in the seismic energy dissipation component are very close or matching for every loading cycle; (3) The levels of dissipated seismic energy are of the same order for the both hysteretic responses, obtained numerically and experimentally; (4) The inclinations of the envelope curve for the both hysteretic responses match with high accuracy; (5) From the comparatively obtained diagrams it can be observed that the main discrepancy between experimental and numerical results appears due to the gap which in reality exists on the pinned supporting end of the tested dissipation element. This initial gap tends to “flatten” the experimental diagram toward the abscise axis (resulting in almost zero stiffness) in all cycles when force value is near zero, which is not simulated by the numerical model.

In the next phases of the micro-model formulation and analyses further improvements are planned to be achieved, especially regarding the sophistication level of the mentioned boundary conditions modelling.

## 6. CONCLUSIONS

Considering research results obtained from the conducted extensive experimental and theoretical study presented above, using innovative bridge model prototype structure, the following general conclusions are derived:

- (1) The optimized seismic isolation devices are very effective for bridge seismic isolation and vibration control. However, for any particular bridge, seismic isolators should be designed based on advanced optimization process considering actual properties of energy dissipation devices. Applying the required expert knowledge, the designers will achieve successful selection of optimal seismic isolators;
- (2) The new multi-level multi-directional (ML-MD) H-Type and C-Type seismic energy dissipation devices possess unique energy absorption features since they are capable of adapting their behavior to the actual intensity of seismic input energy. Actually, the new H-Type and C-Type seismic energy dissipation devices provide the advanced features of earthquake response modification and control in all directions;
- (3) The displacement limiting devices are very effective for control of excessive displacement response of bridge superstructure. They actually represent very important safety devices providing final line of defense with reliably increased bridge seismic safety, particularly in the case of very strong earthquakes;
- (4) The proposed new H-Type and C-Type high performance seismic isolation and response modification system for bridges, optimally created based on balance of the seismic energy represent very efficient technical system with integrated innovative advantages of seismic isolation, seismic energy dissipation and efficient displacement control;
- (5) The new H-Type and C-Type response modification systems for seismic protection of bridges, based on multi-level seismic energy absorption and seismic energy balance show very high seismic control performances and can be practically used for full and uniform seismic protection of bridge structures in longitudinal and transversal direction under the effect of very strong future earthquakes.

## ACKNOWLEDGEMENT



At the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje, very extensive experimental and analytical research was realized in the frame of the approved innovative three year NATO Science For Peace and Security Project: *Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828)*, focused on fundamental research and development of innovative technology for seismic isolation and seismic protection of bridges (*New European large-scale scientific and research activity with participation of five countries: Macedonia: D. Ristic, PPD-Director, Germany, U. Dorka, NPD-Director, Albania, Bosnia & Herzegovina & Serbia.*

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