EFFICIENT BRIDGE SEISMIC ISOLATION SYSTEM WITH INNOVATIVE MULTI-LEVEL SEISMIC ENERGY BALANCE

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ABSTRACT :

Development of advanced technology applicable for efficient prevention of heavy earthquake damage and total collapse of existing and new bridges in future earthquakes was challenging motivation of the second author to start with realization of long-term pilot-innovative project entitled: "High Performance Seismic Isolation of Bridges". The developed new technology for qualitatively improved seismic protection of bridge structures is based on application of the patented "GOSEB3" system for construction of seismically safe structures. Qualitative step of GOSEB3 (generation-3) innovative seismically-resistant bridge system, is created with full multi-level global optimization of seismic energy balance. The innovative project was officially nominated by the Government of the Republic of Macedonia to represent new and advanced national achievements in the field of INVENTIONS AND SCIENCE. The research activities have been continued in the frame of 3-year bilateral scientific project Macedonia-Serbia (2005-2007). The new "GOSEB3" high performance seismic isolation system for bridges, actually represent very important technical innovation capable of integrating the advantages of seismic isolation, seismic energy dissipation and effective displacement control. Furthermore, the new seismic isolation system for bridges based on multi-level seismic energy absorption and optimized seismic energy balance shows very high seismic control performances and can be used for full seismic protection of new and seismic revitalization of existing bridges in longitudinal and in transversal direction under the effect of very strong earthquakes. The present research activities are continued to provide conditions for wide practical application of the invented GOSEB3 seismic isolation system..

KEYWORDS: Bridges, seismic isolation, nonlinear response, energy dissipation, vibration control, seismic vulnerability

1. URGENT NEED FOR ADOPTION OF ADVANCED TECHNOLOGY

Observed severe damages and total collapses of bridge structures in recent earthquakes (U.S.A., Japan, China, etc.), Fig. 1 to Fig. 6, has pointed out the urgent need for adoption of an advanced technology for qualitative seismic safety improvement of classical bridge systems. Considering this widely recognized need, the development of an advanced bridge system was considered as the main objective of our initial three-year project carried out in the frame of the joint Macedonian-U.S. scientific and technological cooperation, realized through the U.S. Technical Agency: Department of Transportation (DOT). Prof. D. Ristic (the second author of the paper) acted as the principal investigator from Republic of Macedonia, Institute of Earthquake Engineering and Engineering Seismology (IZIIS), University "Ss Cyril and Methodius", Skopje. The principal investigator on the USA part was Prof. M. D. Trifunac, Representing School of Engineering, Department of Civil Engineering, University of Southern California, Los Angeles. The realized joint cooperative project was initially directed towards a comprehensive study of the existing innovative bridge seismic isolation systems, applicable for efficient earthquake protection of multi-span bridges under the strongest future earthquakes. In the next project phase, our emphasis was put on development of anti-seismic bridge bearings (ABB) of high efficiency and simple application capability.

Fig. 1: Loma Prieta, U.S.A., 1989: M=7.1, Cypress Bridge Failure

Fig. 2: Tangshan, China, 1976: Super-Structure Collapse

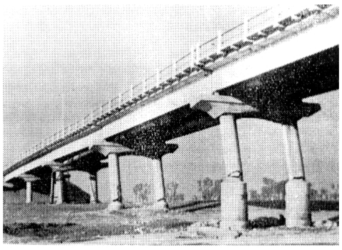

Fig. 3: Tangshan, China, 1976: Sub-Structure Collapse

Following the systematic study of the existing systems, the next step in our research was concentrated on innovative developments. Particular attempt was made to create an innovative and efficient bridge-seismic isolation concept. The efficiency of the anti-seismic bridge bearings (ABB) for earthquake protection of multi-span bridges was intensively studied including: (a) Bridge systems with flexible piers, (b) Bridges with stiff (short) piers, and (c) Bridges comprising both flexible and stiff middle piers. Finally, significant work was devoted to development of analytical models and analytical procedures capable of realistic earthquake response prediction of bridges with and without installed anti-seismic devices.

Fig. 4: Kobe, Japan, M=7.2, 1995: Collapse of Hanshin Line

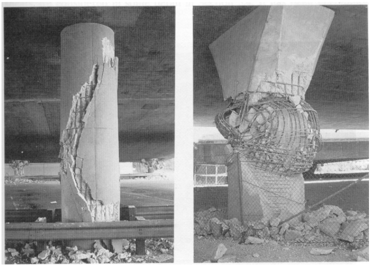

Fig. 5. Nortrige, U.S.A., 1994, M=6.7: Pier's Shear Failure

Fig. 6: Kobe, Japan, M=7.2, 1995: (Nishinomiya Harbur Bridge)

2. RECENT RESEARCH UNDER NEW SCIENTIFIC PROJECT

Direct and indirect losses observed during recent strong earthquakes have been very extensive. For example in the city of Kobe (1995), Japan, the total losses were estimated at more than 100 billion dollars. It happened within only 20–30 seconds. More than 5500 people lost their lives and even more were injured. It is clear that a new generation of seismically safe structures should be introduced. Creating a possibility for future prevention of such heavy earthquake catastrophes to bridge structures was the main and challenging motivation of the second author to initiate realization of a new innovation (pilot) project entitled "High Performance Seismic Isolation of Bridges". The new project should actually contribute to the realization of the intended "creative vision for construction of seismically safe bridges in the twenty-first century". The research activities are being continued in IZIIS, in the frame of the recently started new 3-year bilateral Macedonia-Serbia and Montenegro (2005-2007) scientific project and will be more concentrated on qualitative improvement of the system performances and creation of conditions for successful practical application of the innovative GOSEB3 System.

3. ADVANCED CONCEPT OF GOSEB3 BRIDGE SEISMIC ISOLATION SYSTEM

A new technology for qualitatively improved seismic protection of bridge structures is introduced with the patented "GOSEB3" system for construction of seismically safe bridge structures.
The new "GOSEB3" innovation represents a high performance seismic isolation system for bridges based on an

optimized seismic energy balance. This has been achieved by the integration of: (1) the advantages of seismic isolation by an adopted optimized "seismic isolator", (2) the advantages of the seismic energy dissipation by the adopted new multi-level seismic energy dissipation device or "seismic energy absorber", and (3) the advantages of the effective displacement control by the incorporated optimized "rubber stopper" at appropriate locations. This integral innovative concept is characterized by the achieved very high vibration control performances.

4. EFFICIENT SEISMIC PROTECTION OF BRIDGES WITH GOSEB3 SEISMIC ISOLATION SYSTEM

To perform initial system verification, very extensive analytical seismic response analysis was performed considering the selected appropriate bridge prototype with an optimized GOSEB3 seismic isolation system.

4.1. Characteristics of the Selected Prototype

For analytical study of the dynamic behavior characteristics of the GOSEB3 system, a representative bridge prototype structure with three spans and total length L=3x48.00m=144.00m, Fig. 7, was selected. The super-structure is designed as a continuous system composed of four prestressed main beams connected with a strong RC slab D=18.0 cm. The sub-structure consists of two end supports (abutments) and two central piers with different heights. The piers are fixed to the stiff RC footings and are considered to have a solid RC cross-section (a/b=4.0 x 1.0 m). The four super-structure main girders are supported by seismic isolators installed on the top of four sub-structure supports (abutments and piers). At all the four bridge supports, innovative two-level "seismic energy absorbers", K10 and K15, active in longitudinal and transverse direction, or in general case active in all directions, are installed. Finally, "rubber stoppers" are incorporated at both super-structure ends, as an additional displacement control device.

4.2. Formulated Total-Nonlinear Mathematical Model for Longitudinal Direction

Extensive seismic response study was performed applying the formulated appropriate total nonlinear mathematical model of the selected bridge prototype structure.

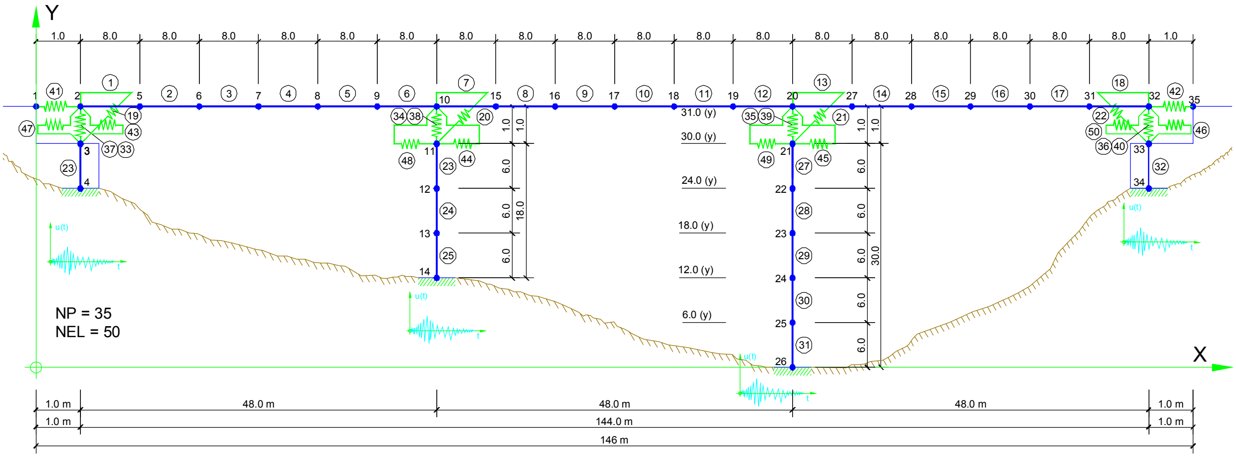

Fig. 7. Formulated Total-Nonlinear Mathematical Model for Longitudinal Direction-x of the Bridge Prototype Designed With Installed GOSEB3 Seismic Isolation System

The discrete mathematical model consists of 46 finite elements and 34 nodal points, Fig. 7. All the RC elements of the bridge sub-structure and super-structure were modeled as nonlinear based on the incorporated non-linear M-Φ relations. The simulation of nonlinearity of these elements was qualitatively improved by application of M-Φ curves at the level of the so called "sub-elements". The incorporated different seismic isolation devices were modeled by the formulated advanced nonlinear spring elements with introduced realistic simulation of their very specific non-linear behavior features. For simulation of the nonlinear behavior of the seismic isolators, energy absorbers and rubber stoppers, there were elaborated new specific computer subroutines providing advanced analysis of dynamic behavior of bridge structures under earthquake effects.

4.3. Non-Linear Seismic Response of GOSEB3 Bridge in Longitudinal Direction

In the initial phase, the bridge non-linear seismic response was analyzed in longitudinal direction by consideration of two different earthquake records: El-Centro record, and Ulcinj-Albatros record. The PGA of both records was considered very high. In the case of the first two analysis, the earthquake records were scaled to a very high intensity level (PGA=0.5g). In the case of the second two analysis, the earthquake records were considered to be at an extremely high intensity level (PGA=0.7g).

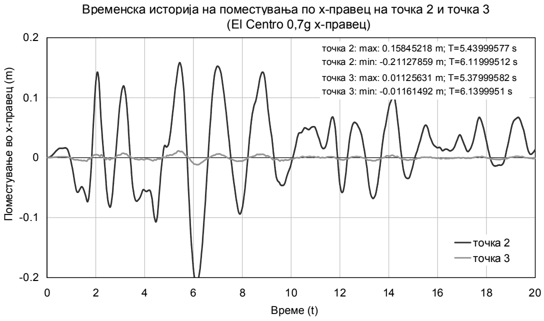

Fig. 8: El-Centro, 0.7g: Comparative Plot of Displacement Time-History, Direction-x, NP=2 and NP=3.

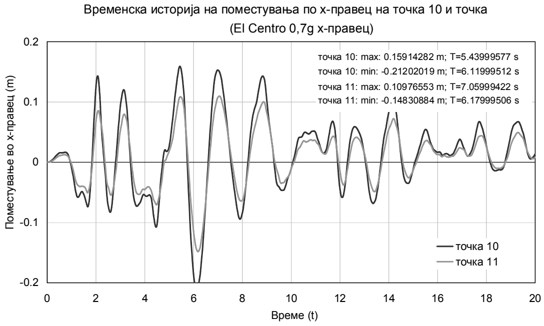

Fig. 9: El-Centro, 0.7g: Comparative Plot of Displacement Time-History, Direction-x, NP=10 and NP=11.

In this paper are only presented selected typical results demonstrating the seismic performances of the system. First, the different and separate displacement response of the bridge sub-structure and super-structure was observed. This observation is shown in Fig. 8, Fig. 9, Fig. 10 and Fig. 11.

Fig. 8 shows the response in the case of the El-Centro earthquake with PGA=0.7g, and demonstrates a comparative plot of displacement time-history in x-direction for NP=2 and NP=3 (left support). Fig. 9 shows the response under the El-Centro earthquake with PGA=0.7g, demonstrating a comparative plot of displacement time-history in x-direction for NP=10 and NP=11 (above the shorter pier).

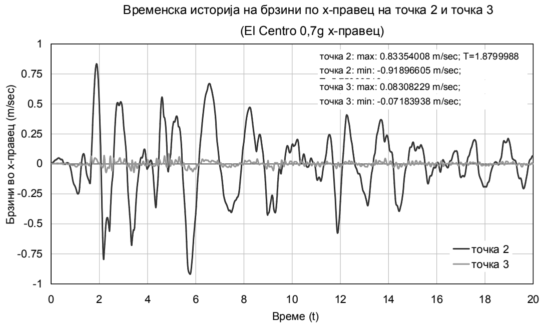

Fig. 10: El-Centro, 0.7g: Comparative Plot of Velocity Time-History, x-direction, NP=2 and NP=3.

Fig. 11: El-Centro, 0.7g: Comparative Plot of Velocity Time-History, x-direction, NP=10 and NP=11.

Fig. 10 shows the response under the El-Centro earthquake with PGA=0.7g, and demonstrates a comparative plot of velocity time-history in x-direction for NP=2 and NP=3 (left support). Fig. 11 shows the response under the El-Centro earthquake with PGA=0.7g, demonstrating a comparative plot of velocity time-history in x-direction for NP=10 and NP=11 (above the shorter pier).

Fig. 12 shows the response under the El-Centro earthquake with PGA=0.7g, and demonstrates the full-response of the seismic isolator above the left support, x-direction: EL=37. Fig. 13 shows the response under the El-Centro earthquake with PGA=0.7g, demonstrating the full-response of the seismic isolator above the shorter pier, x-direction, EL=38.

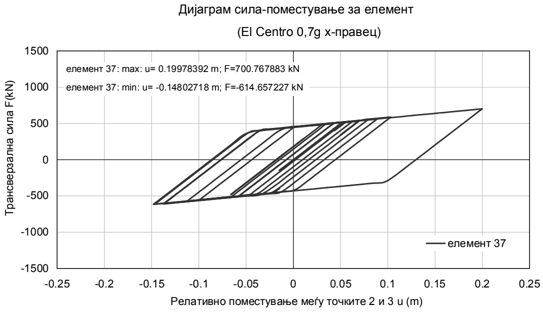

Fig. 12: El-Centro, 0.7g: Full-Response of Seismic Isolator Above Left Support, Direction-x: EL=37.

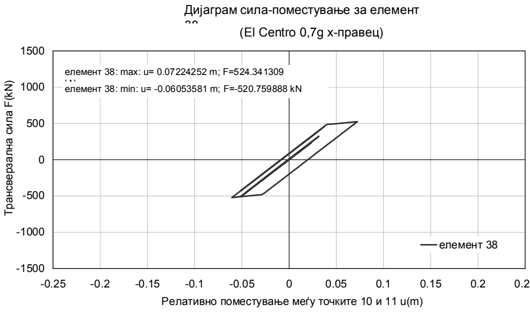

Fig. 13: El-Centro, 0.7g: Full-Response of Seismic Isolator Above Shorter Pier, Direction-x, EL=38.

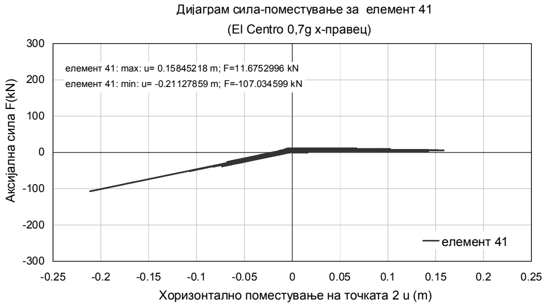

Fig. 14: El-Centro, 0.7g: Full-Response of Rubber Stopper, Left-Side, x-direction: EL=41.

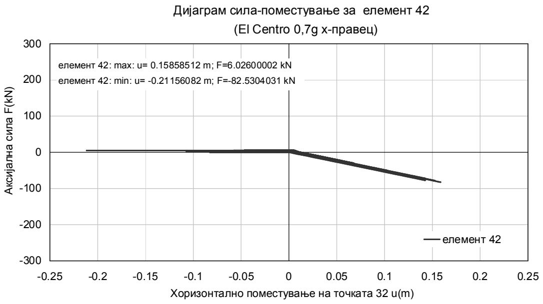

Fig. 15: Full-Response of Rubber Stopper, Right-Side, x-direction, EL=42.

Fig. 14 shows the response under the El-Centro earthquake with PGA=0.7g, and demonstrates the full-response of the rubber stopper above the left support, x-direction: EL=41. Fig. 15 shows the response under the El-Centro earthquake with PGA=0.7g, demonstrating the full-response of the seismic rubber stopper above the right support, x-direction: EL=42.

Fig. 16 shows the response under the El-Centro earthquake with PGA=0.7g, and demonstrates the full-response of the hysteretic G2 absorber-K10 above the left support, x-direction: EL=43. Fig. 17 shows the response under the El-Centro earthquake with PGA=0.7g, demonstrating the full-response of the hysteretic G2 absorber-K15 above the left support (parallel with K10), x-direction: EL=47

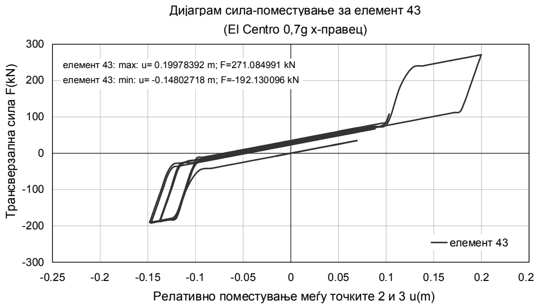

Fig. 16: El-Centro, 0.7g: Full-Response of the Hysteretic G2 Absorber-K10 Above the Left Support, x-direction: EL=43.

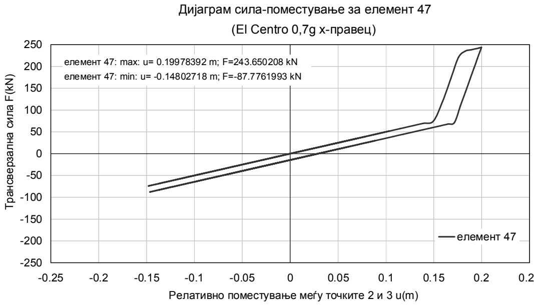

Fig. 17: El-Centro, 0.7g: Full-Response of the Hysteretic G2 Absorber-K15 Above the Left Support, x-direction: EL=47.

Fig. 18 shows the response under the El-Centro earthquake with PGA=0.7g, and demonstrates the base moment-curvature hysteretic response of the left pier, x-direction: NP=14. Fig. 19 shows the response under the

El-Centro earthquake with PGA=0.7g, and demonstrates the base moment-curvature hysteretic response of the right pier, x-direction: NP=26.

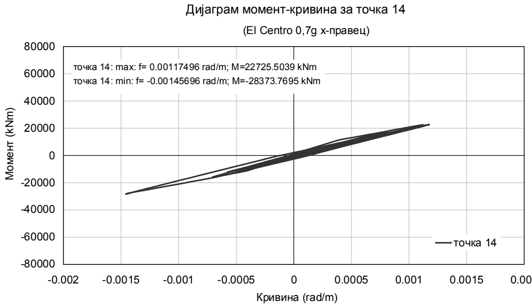

Fig. 18: El-Centro, 0.7g: Base Moment-Curvature Hysteretic Response of the Left Pier, x-direction: NP=14.

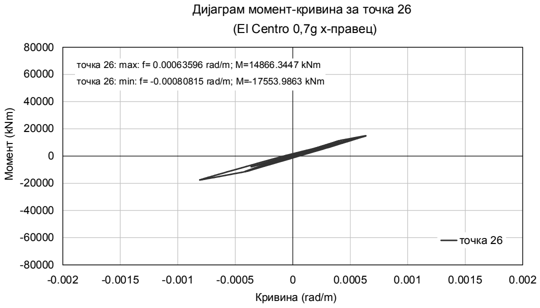

Fig. 19: El-Centro, 0.7g: Base Moment-Curvature Hysteretic Response of the Right Pier, x-direction: NP=26.

4.4. Non-Linear Seismic Response of GOSEB3 Bridge in Transversal Direction

Analysis of the non-linear bridge seismic response in transversal direction was performed considering the same two earthquake records: the El-Centro record, and the Ulcinj-Albatros record. The PGA of both records was also considered very high. In the case of the first two analysis, the earthquake records were scaled to a high intensity level (PGA=0.5g). In the case of the second two analysis, the earthquake records were considered to be at an extremely high intensity level (PGA=0.7g).

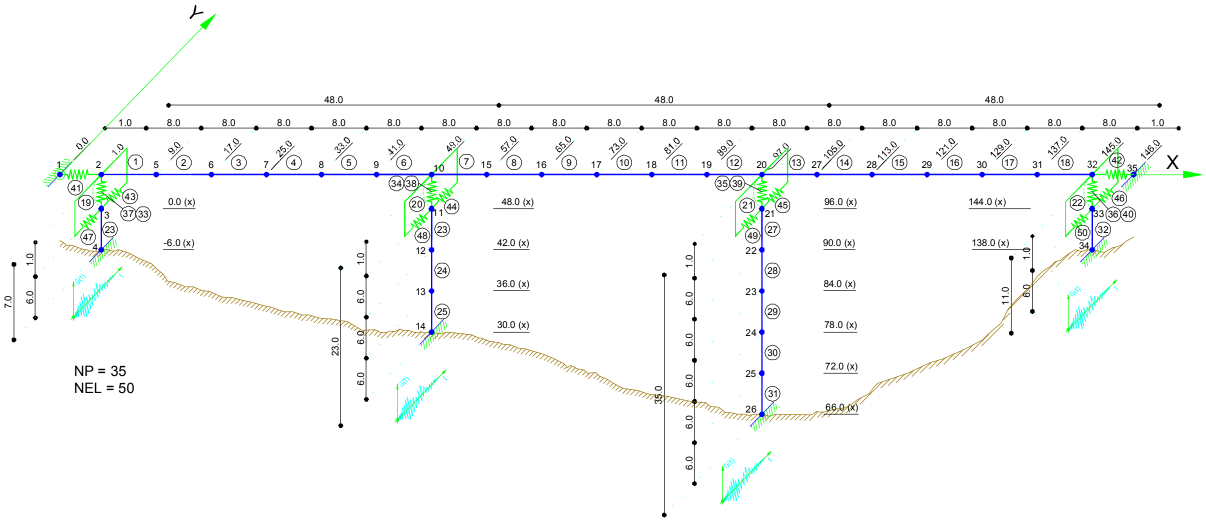

Fig. 20. Formulated Total-Nonlinear Mathematical Model for Transversal y-direction of the Bridge Prototype Designed With the Installed GOSEB3 Seismic Isolation System

Analogously, to study the seismic response of the bridge prototype structure in transversal direction, a corresponding nonlinear mathematical model, Fig. 20, was formulated. The formulated discrete mathematical model consists of 46 finite elements and 34 nodal points. All the RC elements of the bridge sub-structure and super-structure were modeled as nonlinear by incorporating M-Φ relations at the level of the so called "sub-elements". Analogously, the incorporated seismic isolation devices were modeled by special nonlinear spring elements with introduced realistic simulation of the specific non-linear behavior features of the respective seismic isolation device.

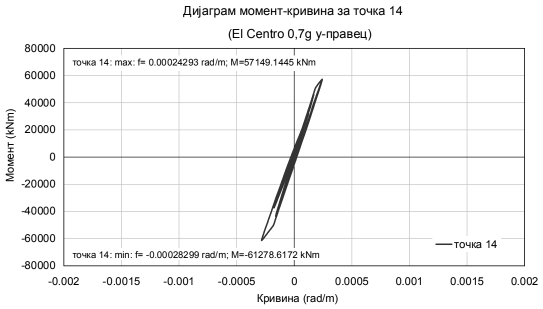

Fig. 21: El-Centro, 0.7g: Base Moment-Curvature Hysteretic Response of the Left Pier, y-direction: NP=14.

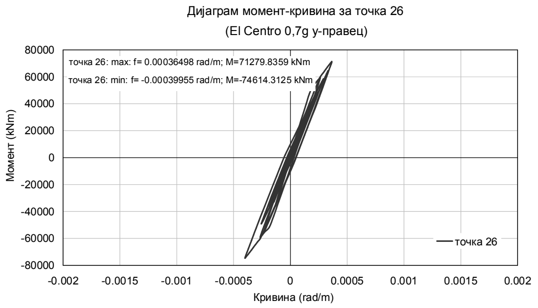

Fig. 22: El-Centro, 0.7g: Base Moment-Curvature Hysteretic Response of the Right Pier, y-direction: NP=26.

To demonstrate the high seismic safety of the bridge in transversal direction, only two representative figures are presented. Fig. 21 shows the response under the El-Centro earthquake with PGA=0.7g, and demonstrates the base moment-curvature hysteretic response of the left bridge pier, y-direction: NP=14. Fig. 22 shows the response under the El-Centro earthquake with PGA=0.7g, and demonstrates the base moment-curvature hysteretic response of the right pier, y-direction: NP=26. Both relations are nearly linear.

In the longitudinal direction, both the corresponding relations showed also nearly linear behavior of the bridge piers. This "perfect" response achievements for very high seismic intensities clearly demonstrated that the "High Performance Seismic Isolation of the Bridge" was successfully achieved with the new GOSEB3 seismic isolation system.

5. CONCLUSIONS

Based on the research results obtained from the conducted extensive theoretical study applying the selected representative bridge prototype structure, the following conclusions are derived:

1. The optimized seismic isolators are very effective for bridge seismic vibration control. However, for any particular bridge, seismic isolators should be selected based on an advanced optimization process. Seismic isolators are today available on the market with different proportions and physical characteristics. Applying the required expert knowledge, the designers are able to achieve successful selection of seismic isolators.
2. The new multi-level "GOSEB3" hysteretic seismic energy absorber possesses unique energy absorption features since it is capable of adapting its behavior to the actual intensity of the input seismic energy. Actually, the "GOSEB3" hysteretic energy absorber provides the most innovative and advanced features of multi-level earthquake response in all directions.
3. The optimized rubber stoppers are very effective for excessive displacement control of the bridge super-structure. It is clear that the "GOSEB3" rubber stoppers represent highly efficient system devices providing additional contribution to the improvement of the bridge seismic safety, particularly in the case of very strong earthquakes.
4. The new "GOSEB3" high performance seismic isolation system for bridges, created based on an optimized seismic energy balance actually represents a very effective technical innovation capable of integrating the advantages of seismic isolation, seismic energy dissipation and effective displacement control.
5. Finally, the new "GOSEB3" seismic isolation system for bridges based on multi-level seismic energy absorption and optimized seismic energy balance shows very high seismic control performances and can be used for full seismic protection of bridges in longitudinal and transversal direction under the effect of very strong earthquakes.

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