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EFFICIENT EARTHQUAKE PROTECTION OF RC BRIDGE STRUCTURES BY INSTALLATION OF OPTIMALLY DESIGNED ANTISEISMIC DEVICES

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ABSTRACT

Severe damage and total failure of modern RC bridge structures during recent strong earthquakes (Kobe. 1995, Japan) have clearly shown that the traditional, code-based practical design concept has to be systematically and critically revised and improved in order to introduce more reliable structural systems and achieve the required seismic safety level for this type of structures.

This paper presents the specific study results, demonstrating the achieved efficient earthquake protection of RC bridge structures by installation of optimally designed antiseismic devices. The main objective of the conducted study was investigation of practical advantages of the installed vibration control systems (VCD) in increasing the seismic stability of both, newly designed and retrofitted bridge structures in regions with the expected strong earthquake ground motions. The considered vibration control systems have comparatively been studied. The study resulted in a development of an optimized and efficient vibration control system very convenient for practical application providing successful earthquake protection of existing and newly designed highway bridges.

The most essential practical advantages, achieved by the installation of vibration-isolation and vibration-control systems is demonstrated through comparative seismic performances study of both, traditionally designed bridges and bridge structures with installed base-isolation and vibration control devices.

INTRODUCTION

The scientific-research field dealing with development of specific base isolation and vibration control systems applicable for reduction of seismic risk related to different engineering structures is a great challenge for investigators in the world today. Although certain ideas date from a longer period ago. organized scientific-research activities in this field have abruptly been intensified during the last decade so that the problems involved in this paper are dominantly encompassed by a specific and relatively new scientific discipline. Today, fundamental experimental and analytical investigations with an increasing practical application dominate in this field throughout the world.

Using their knowledge acquired from experiments realized within a longer period of time and analytical studies, the authors of this paper point to the practical advantages of installed vibration control systems in newly designed bridge structures as to increasing of seismic stability of revitalized existing bridges under intensive seismic effects.

DEFINITION OF NONLINEAR ANALYTICAL MODELS OF THE PROPOSED ELEMENTS FOR CONTROL OF DYNAMIC BEHAVIOUR

During the last few years, investigations have been performed at IZIIS for the purpose of providing sufficient seismic safety to bridge structures. Based on these investigations, proposed was incorporation of additional elements for isolation and absorption of seismic energy in structures that will enable control of their dynamic behaviour under strong earthquakes. The proposed vibration control system (VCS) consists of installed neoprene bearings for supporting of the superstructure, incorporated hysteretic energy absorbers at the same level and, where necessary, installed rubber stoppers at the ends of the bridge to control the extreme deformations of the structure in longitudinal direction under strong earthquakes. Using the nonlinear characteristics of the three basic elements and the models formulated for these elements, the research activities were further aimed at composing and optimizing of applicable variants of VCS systems for vibration control in real structures as well as investigation of their efficiency as to reduction of seismic risk even under the strongest earthquakes,

To investigate the safety of neoprene bearings as main structural elements of bridge structures, it is also necessary to model them adequately by a nonlinear analytical model.

Nonlinear Analytical Model of a Rubber Stopper "RSMODEL"

The main assumptions and conditions that have been taken into account when proposing the analytical model of a rubber stopper (RSMODEL) within the frameworks of these investigations can be summarized as follows:

a) The rubber element incorporated in the bridge structure and acting as a stopper is fixed only at one end (the abutment). In this way, it is exposed only to pressure under dynamic impact, whereas possible tension of the rubber element is avoided with the structural solution itself.

b) The rubber element could be fixed at the end abutment so that it touches the main girders under static conditions, or, as a second solution, a clearance could be left that will be computed according to the conditions of expansion of the superstructure due to local temperature variations.

Based on the above assumptions, the simplified analytical model of a rubber element acting as a stopper RSMODEL is defined by means of a polygonal line with four segments (Fig. 1) in order to provide adequate simulation of the real phases of behaviour of the elements which are defined by the experimental investigations performed at IZIIS.

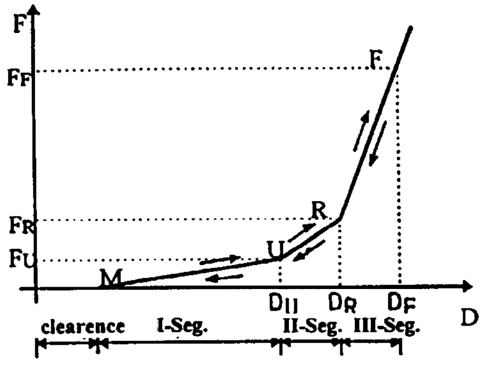

Fig.1. Model "RSMODEL

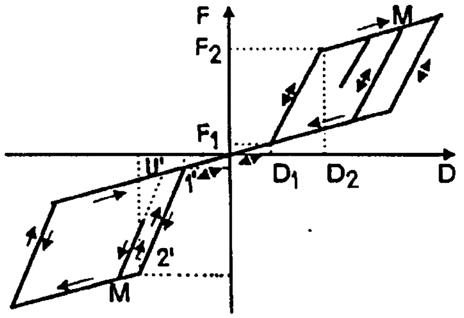

Fig.2. Model "ABSEM"

Analytical Model "ABSEM" of the Seismic Energy Absorption Element

Since the elements in the form of rubber stoppers are not always sufficient for controlling the dynamic behaviour of bridge structures, a necessity arises as to application of corresponding elements for seismic energy absorption also. The element for seismic energy absorption ABSEM is conceived as a system consisting of a steel element with an adequately designed initial rigidity combined with springs of a much lower rigidity that work in the initial phase until a contact is made between the structure and the steel element. This means that only the spring works under small displacements of the bridge superstructure, while the steel element which is practically the basic element of the energy absorption system is activated when these displacements are increased. The analytical model ABSEM (Fig.2) defined for simulation of the nonlinear behaviour of the seismic energy absorption element is successfully controlled by the parameters given in Tab.1.

Analytical Model "M1BILM" (for Neoprene Bearings)

To provide adequate dynamic stability of the bridge structure supported by neoprene bearings under strong earthquake excitation, it is necessary to provide normal functioning of all neoprene bearings within the prescribed limits for which it is necessary to control the displacements in tangential direction. For the purpose of adequate investigation of the dynamic behaviour of incorporated neoprene bearings in bridge structures, it is also necessary to define a nonlinear analytical model for them also. According to available data, it is shown that nonlinear behaviour of neoprene bearings can successfully be simulated by a bilinear analytical model. The bilinear model M1BILM (Fig.3) has therefore been applied for the neoprene bearings in the investigations presented in this paper. Its parameters have been taken from attests for standard neoprene bearings.

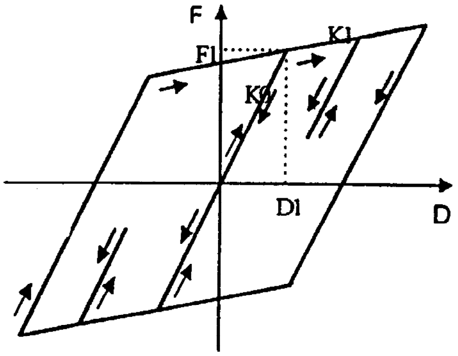

Fig.3. Model "M1BILM

The parameters defining the three analytical models presented in Table 1 are not always necessarily constants which enables successful modelling of rubber stoppers, absorbers and neoprene bearings with different stiffness and deformability characteristics.

Table 1 Nonlinear models		Input parameters for the defined nonlinear analytical models						
No.	Label							
1	RSMODEL	Dm	Du	Fu	Dr	Fr	Df	Ff
		0.005	0.015	125.0	0.025	830.0	0.042	20000
2	ABSEM	D1	F1	D2	F2			
		0.010	150.0	0.016	1150.			
3	M1BILM	K	Fy	K1				
		78700	3360.	0.100				

Discontinious Bridge System with Flexibile Central Piers (B1)

The direct comparison of the results obtained from the performed analytical studies of the dynamic behaviour of a discontinuous bridge system (Fig. 4) with two structural expansion joints and flexible central columns, with and without a VCS system enabled conceiving of the primary effects from the built-in elements under earthquake effects.

Structural Characteristics of the Selected Prototype. For analytical study of the dynamic behaviour of discontinuous bridge structures with flexible central columns, selected as a prototype was a real bridge structure with three spans (L=3x30.4=91.2 m) a superstructure constructed of prestressed plain beams, box-type central columns of different heights and plain beams supported by columns via neoprene bearings. The two central columns are constructed of reinforced-concrete. They have a box-type cross-section and are fixed at the foundation. At each span, the superstructure consists of four main girders-prestressed plain beams, connected with four transverse girders that along with the rigid bridge deck (d=18 cm) make a compact whole. On the superstructure, over the central columns, constructed are two expansion joints. To make a direct comparison of the parameters of the dynamic response of the structure without and with incorporated VCS elements under identical intensities of ground motion due to actual earthquakes, apart from the mathematical model of the prototype, defined is also a mathematical model for a modified prototype containing also elements for control of the dynamic behaviour. In all the analyzed cases, an identical discretization of the structure with the beam elements is made, i.e., the formulated mathematical models are different only in respect to the number and the type of the additional vibration control elements.

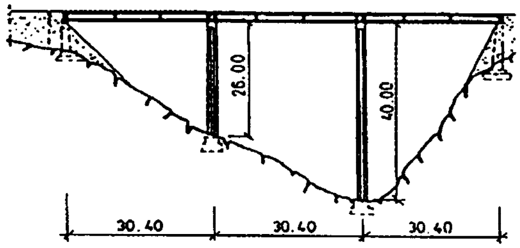

Fig.4.

Discontinious Bridge System with Stiff Central Piers (B2)

To finalize somehow the investigations into the dynamic behaviour of discontinious bridge structures with and without incorporated VCS elements, analyzed further are also bridge structures with stiff central piers.

Structural Characteristics of the Selected Prototype. For analytical investigation of the dynamic behaviour of discontinious bridge structures with short central piers, selected as a prototype is the same bridge structure as in the previous case (Fig. 4), with the only difference that the height of the central piers is lower amounting to h_1=8,0 m and h_2=16,0 m (Fig.5).

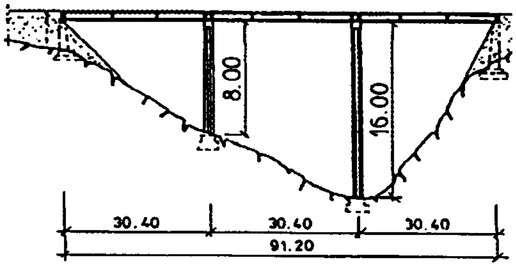

Fig.5.

Definition of Mathematical Models

To compute the dynamic response parameters of both bridge structures (B1and B2), defined are two identical mathematical models.

Mathematical model of a bridge-prototype without incorporated VCS- system (B1 and B2). The discrete mathematical model of the prototype without a VCS system consists of 36 incorporated finite elements (in model 1) and 29 nodal points (Fig. 6). The central columns of the prototype are modelled by two finite elements (13, 14 and 15, 16, respectively). The conditions of their support at the foundation are adopted as fixed. The superstructure of the prototype is discretized by 12 finite elements, the corresponding weights being concentrated at the corresponding 15 discrete nodal points. While defining the masses and the stiffness characteristics of the superstructure elements, adopted is the total width of the bridge deck. The resting of the prestressed girders on the end abutments and central columns has been simulated by neoprene bearings using the defined bilinear analytical model M1BILM.

Mathematical model of a modified prototype with incorporated VCS system (B1 and B2). The discrete mathematical model of the modified prototype with VCS elements consists of 44 finite elements and 29 nodal points with incorporated rubber stoppers and six absorbers. The rubber stoppers are incorporated at both ends whereas the six absorbers placed at the supports in this mathematical model are discretized by finite elements 43 ad 44 and finite elements 37, 38, 39, 40, 41 and 42, respectively.

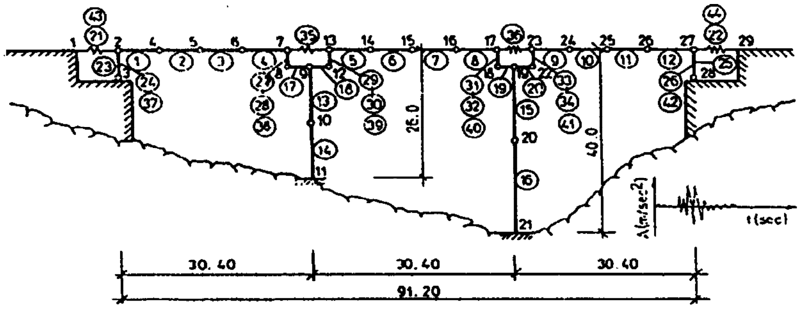

Fig.6.

For simulation of the nonlinear behaviour of the elements for vibration isolation and control constituting the VCS system, elaborated are subroutines which along with the main programme represent a programme package (SVIB) for investigation of the dynamic behaviour of bridge structures under earthquake effects.

Analysis of Dynamic Behaviour under Earthquake Effect

Using the defined mathematical model (Fig. 6) of the bridges, performed were two analyses of its dynamic response under the effect of the recorded Ulcinj-Albatros earthquake, N-S component and maximum peak accelerations of Ap=0.34 g and Ap=0.50 g. The Ulcinj-Albatros and El Centro earthquakes with maximum peak acceleration of Ap=0.5 g were taken as input excitations in the analysis of the modified mathematical model with two stoppers at the ends and six absorbers at the bearings.

Selected from the performed analyses of the nonlinear dynamic responses of the structure were only the most essential results, i.e., (1) displacement, velocity and acceleration response at points 7, 13 and 23 in x-direction; (2) moment and shear force response at point 11 (EL= 14), point of fixation of the shorter column; (3) moment and shear force response at point 21 (EL=16), point of fixation of the longer column; (4) dynamic response of the elements of the vibration control system (VCS) and the neoprene bearings.

Using the results (time histories) from all the performed dynamic analyses of the bridges (with flexible and stiff central piers) with and without incorporated VCS elements, selected were the characteristic maximal values (Table 2 and Table 3) that most directly point to the effects achieved by incorporation of the elements for control of the global dynamic response of the bridge structures.

COMPARISON AND DISCUSSION OF THE RESULTS FROM THE ANALYTICAL STUDIES

Comparing the main parameters of seismic response (for the main prototype and the modified system with VCS elements, Table 2 and Table 3), drawn are the following conclusions on the effectiveness of the incorporated system for control of vibrations in bridges with either flexible or stiff substructures and two structural expansion joints on the superstructure:

(1) Since the superstructure completely rests on neoprene bearings and due to the limited capacity of lateral rigidity of the neoprene bearings, the increase of moments in the central columns at the foundation level is not so critical (Table 2 and Table 3) because the neoprene bearings themselves contribute, through specific dynamic interaction, to the isolation of the transfer of vibration between the sub- and the super- structure as a result of the drastic discontinuity in rigidity.

(2) The main problem related to the analyzed bridges with incorporated neoprene bearings is the possible occurrence of large lateral displacements of the main girders that may result in their falling off the bearings which will be manifested by partial or total failure of the structure under strong earthquakes (Fig.7 and Fig.9).

Bridge with Flexibile Central Piers (B1)

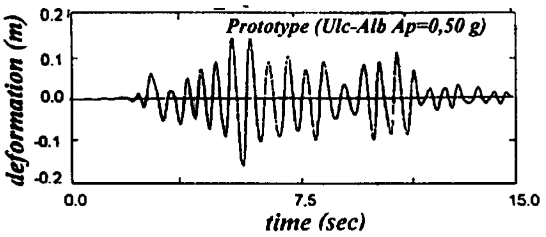

Fig.7. Displacement in X-X direction NP=13

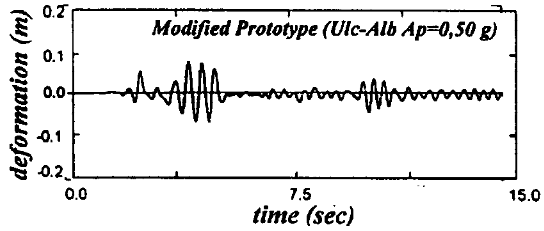

Fig.8. Displacement in X-X direction NP=13

Bridge with Stiff Central Piers (B2)

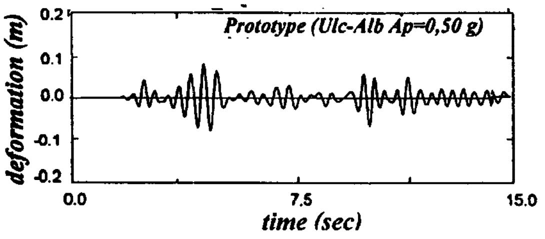

Fig.9. Displacement in X-X direction NP=13

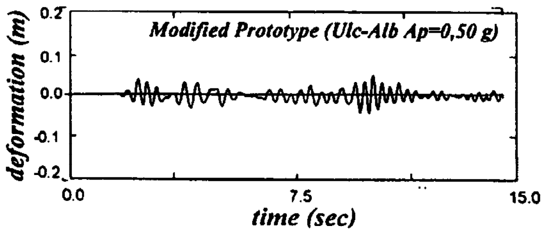

Fig.10. Displacement in X-X direction NP=13

(3) Analyzing the seismic resistance of the prototype (without VCS) under the effect of the Ulcinj-Albatros earthquake with Ap=0.34 g and Ap=0.50 g, it may be concluded that the stability of the superstructure is endangered due to the lateral deformations of the neoprene bearings that are larger than those allowed by the producer (D >d; d=4.2 cm), i.e., plastic deformations that take place in these bearings (Fig.11 and Fig.13).

Bridge with Flexibile Central Piers (B1)

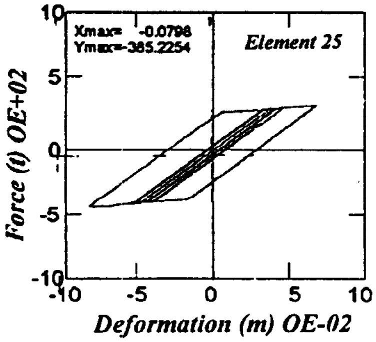

Fig.11. Neoprene of Prototype

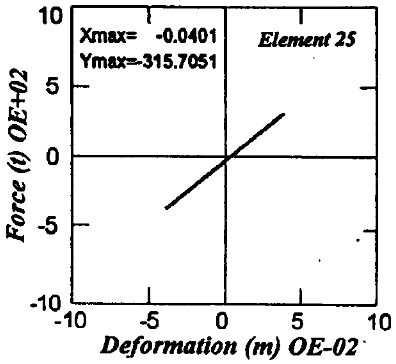

Fig.12. Neoprene of Modified Prototype

Bridge with Stiff Central Piers (B2)

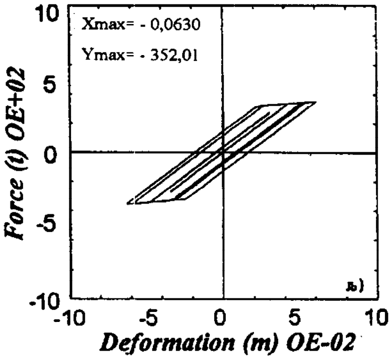

Fig.13. Neoprene of Prototype

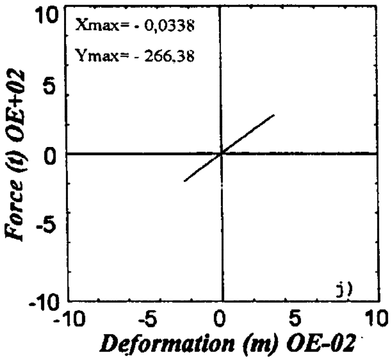

Fig.14. Neoprene of Modified Prototype

(4) As to the modified prototype, the elements of the VCS system are optimally brought into accordance based on the previously performed analyses. If the characteristics of the seismic response (Table 2 and Table 3) of such a proposed structural solution with incorporated VCS are analyzed, it may be concluded that the necessary level of seismic stability of the superstructure and the bridges in general (B1 and B2) is successfully provided for a very high earthquake intensity, Ap=0.50 g. It should be pointed out that seismic stability is successfully provided by incorporation of VCS systems also for earthquakes of different frequency content which is proved also by the performed analyses under the effect of two different earthquakes, Ulcinj-Albatros and El Centro.

(5) Analyzing all the relevant parameters of seismic response from the performed ample analytical investigations, it may be concluded that adequate protection of the structures by minimizing potential damage under expected strong earthquakes could be provided by incorporation of vibration control systems both in existing and newly designed bridge structures.

Table 2. Review of Characteristic Dynamic Response Parameters (Bridge with Flexibile Center Piers - B1)

No	Earthquake Excitation/Dynamic Response Parameters/Initial Dynamic Characteristics		Point	Prototype		Modified Prototype	
1	Type of Earthquake Record and Intensity (Ap)		-	Ulc-Alb (0,34 g)	Ulc-Alb (0,50 g)	Ulc-Alb (0,50 g)	El Centro (0,50 g)
2	Max. Displacement in X-Direction	D (m)	7	0,050	0,072	0,040	0,035
			13	0,110	0,156	0,070	0,076
			23	0,055	0,080	0,040	-
3	Max. Moments in the Piers	M (kN m)	11	21 000	30 000	20 000	19 000
			21	15 000	21 000	20 500	20 000
4	Max. Shear Force	Q (kN)	11	1 000	1 500	2 000	1 500
			21	1 000	1 400	1 600	1 500
5	Initial Dynamic Characteristics	T_1(s)	Mode - I	0,612	0,612	0,566	0,566
	Periods	T_2(s)	Mode -II	0,351	0,351	0,324	0,324

Table 3. Review of Characteristic Dynamic Response Parameters (Bridge with Stiff Central Piers - B2)

No	Earthquake Excitation/Dynamic Response Parameters/Initial Dynamic Characteristics		Point	Prototype		Modified Prototype	
1	Type of Earthquake Record and Intensity (Ap)		-	Ulc-Alb (0,34 g)	Ulc-Alb (0,50 g)	Ulc-Alb (0,50 g)	El Centro (0,50 g)
2	Max. Displacement in X-Direction	D (m)	7	-	0,030	0,020	0,020
			13	-	0,080	0,044	0,035
			23	-	0,060	-	-
3	Max. Moments in the Piers	M (kN m)	11	-	47 500	41 000	34 000
			21	-	47 500	30 000	21 000
4	Max. Shear Force	Q (kN)	11	-	6 300	5 600	4 750
			21	-	3 500	2 700	1 900
5	Initial Dynamic Characteristics	T_1(s)	Mode - I	-	0,418	0,392	0,392
	Periods	T_2(s)	Mode -II	-	0,311	0,288	0,288

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