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Seismic response control of RC bridges with isolation and energy absorption elements

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ABSTRACT: A large number of multi-span girder bridges have experienced severe damages or total collapse during past strong earthquakes in many countries and different regions. The most typical damages are frequently manifested as partial or total collapse of the bridge superstructure due to very large or uncontrolled displacements of the main girders or integral bridge superstructures in the longitudinal direction. Such typical failure modes are most frequently produced due to bridge deck falling from the supports or collapse of the middle piers under rapid increase of response bending moments.

This study presents the results of conducted experimental and analytical studies devoted to investigation and development of appropriate not costly vibration control devices (VCD), composed of both isolation and energy absorption elements, whose instalation in the existing or newly designed bridges will basically provide effective contribution to significant improvement of the structural seismic stability, especially during strong earthquake ground motions.

1. INTRODUCTION

Considering the observed catastrophic effects of strong earthquakes to bridge structures in the past and necessity for qualitative improvement of its seismic stability, an attempt has been made in this study to introduce vibration control devices (VCD's) with capability for successful solution of bridge stability problems without significant cost increase. As displacement control device, rubber stopper elements have been presently considered and investigated in all necessary details.

In order to define the basic nonlinear behaviour characteristics of rubber stopper elements under high compressive loads and provide necessary informations for design of the bridge shaking table test model with built-in rubber elements, experimental quasi-static tests of selected different rubber specimens have been first carried out under simulated earthquake-like compressive loads. Actual effectiveness of rubber stopper elements have been further investigated in the second part of the experimental study through conducted numerous shaking table tests of bridge structure models with and without built-in rubber stopper elements under simulated both harmonic and real earthquake excitations. It was proved based on performed dynamic tests that the built-in soft or hard rubber stopper elements at both bridge ends play an important role in controlling the dynamic bridge response consequently resulting in significant displacement reduction in its longitudinal direction.

Based on results from the conducted and previous experimental tests, different nonlinear analytical models for three VCD types have been formulated for this study purposes as follows: simple nonhysteretic nonlinear model of a rubber stopper, nonlinear hysteretic model of a rubber stopper, nonlinear analytical model of energy absorption element, and analytical model for nonlinear response simulation of the installed neoprene bearings. Finally, intensive nonlinear studies of the prototype bridge structure were carried out with the developed computer program NORA (D. Ristic, 1988), applying in the analysis nonlinear behaviour properties of all the installed VCD's.

Based on performed extensive experimental and analytical studies of the dynamic response characteristics of continuous and discontinuous bridge structures with and without built-in VCD's, exposed to intensive earthquake effects, very informative comparative results were obtained which point out the achieved satisfactory controlling effects of the structural dynamic response with the well calibrated rubber stopper and energy absorption elements.

The conducted experimental and analytical studies clearly indicate that the built-in specific and adequately designed VCD's effectively increase the seismic stability of bridge structures, and/or directly contribute to decreasing of the displacement of the bridge superstructure in the longitudinal direction, and thus provide significant reduction of the moments in the middle piers. In this way, required conditions can be provided for more economical design and construction of seismic resistant reinforced-concrete bridge structures.

2. NONLINEAR QUASI-STATIC TESTS OF RUBBER STOPPER ELEMENTS

The present quasi-static experimental programme includes nonlinear tests of various rubber stopper elements (RS) representing the selected soft and hard rubber samples with different geometrical characteristics, in order to define its most essential nonlinear behaviour charactericties under repeated compressive loads. To experimentally investigate nonlinear behaviour of both types of rubber elements in all necessary details, nonlinear quasi-static tests were carried out on eight soft rubber elements type MG-50 with different details and on six hard rubber elements type 49-1-70 at the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology, Skopje.

Based on recorded experimental results for each of the tested rubber specimens, plotted were the resulting both axial load-deformation (P-δ) and corresponding stress-strain (σ-ε) nonlinear relations in separate figures. Representative examples of the recorded stress-strain relationships from experimental tests of soft and hard rubber elements are shown in Fig. 1.

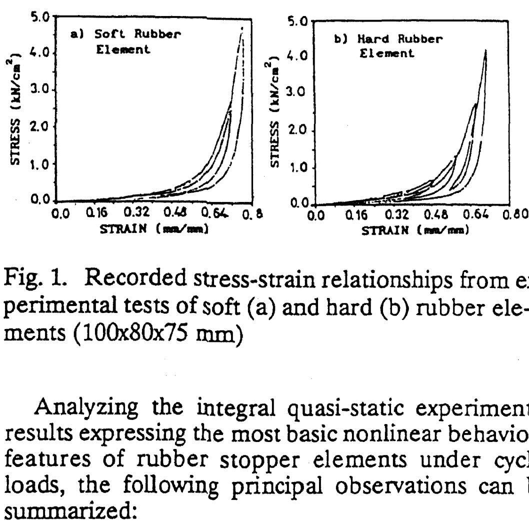

Fig. 1. Recorded stress-strain relationships from experimental tests of soft (a) and hard (b) rubber elements (100x80x75 mm)

Analyzing the integral quasi-static experimental results expressing the most basic nonlinear behaviour features of rubber stopper elements under cyclic loads, the following principal observations can be summarized:

a) For the initial lower stress levels ($\sigma = 2.0$ MPa), the tested both soft and hard rubber elements under cyclic compressive load showed quite clear linear behaviour within a large strain range ($\varepsilon = 0.40$-0.45);

b) Beyond this distinctive linear range, RS's behave strongly nonlinear, showing rapid increase of compressive stresses for the induced slight strain increase ($\sigma = 2.0$-50MPa, $\varepsilon = 0.55$-0.60).

c) This specific hardening capability of the rubber specimens to sustain high compressive stresses with a negligible increase of ultimate strains makes them appropriate elements for displacement control of real structures providing limitation of the dynamic displacements under strong earthquake ground motions.

d) Since the $\sigma - \varepsilon$ relationship for unloading in both ranges slightly deviates from that obtained under loading conditions, slightly pronounced hystereses were recorded. The hysteretic loops tend to become more pronounced with the increase of the compressive loads. However, the energy absorption capacity of rubber elements appear negligible and can be basically neglected in the process of their modeling and design.

e) Besides the described unloading pattern and slightly open hysteretic curves, rubber elements possess very good "recovering" characteristics since no significant plastic deformations have been observed after complete unloading even from the highest stress levels.

In order to investigate and confirm favorable effects of rubber stopper elements for structural displacement control under dynamic loads, specific shaking table tests of bridge structure model have been carried out. The selected results and test conditions are briefly described and discussed below.

3. DYNAMIC SHAKING TABLE TESTING OF BRIDGE STRUCTURE MODELS WITH AND WITHOUT RUBBER STOPPERS

The basic composition of the bridge structure model implemented for dynamic shaking table testing under simulated real earthquake effects without and with rubber stopper consisted of appropriately incorporated various components in order to realistically represent the most essential behaviour properties of actual bridge structures (Fig. 2).

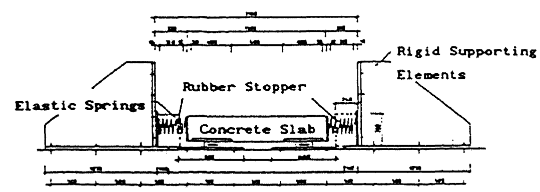

Fig.2. Designed shaking table test model providing tests with and without built-in rubber elements

Applying some model modifications as well as load variations, large number (about 90) dynamic tests were carried out in order to fully understand the dynamic response of the models in each separate case. In addition to different harmonic excitation, real earthquake records of El Centro (USA) and Ulcinj-Albatros (Montenegro) earthquakes were also used as input ground motions with different intensities. For comparative purposes, equivalent model tests without and with built-in RS's were conducted under the same test conditions.

Model test without rubber stopper and with installed smaller soft RS's tested under the same real earthquake motion were selected to be discussed in this paper as the two characteristic dynamic tests. For these tests, the obtained displacement time histories and plotted acceleration-displacement hysteretic relationships are presented in Fig. 3, left and right respectively. The comparison of the mentioned relationships show that the installed rubber stopper elements with appropriate geometrical and elastic characteristics may exert a significant influence upon displacement reduction and/or corresponding control of the dynamic response of the integral structural system under earthquake ground motions.

Summarizing the overall evidence gained via the performed dynamic shaking table tests of several bridge structure models with and without built-in rubber elements acting as rubber stoppers, the following principal conclusions may be drawn: (a) Dynamic tests of the bridge model without installed rubber stoppers basically showed much larger maximum bridge deck displacements in all comparative cases; (b) The installation of the rubber elements at both ends produce significant modification of the dynamic response of the model which is mainly manifested by effective restriction of the displacements in corelation with the effective rubber hardness; (c) Due to present hardening effect of the rubber stoppers, the time duration of the impact is extended which is an evident favorable performance; (d) The frequent impacts on rubber elements produce frequent change of the model dynamic characteristics contributing thus to avoid of possible resonant effects; (e) Finally, rubber stoppers showed in all cases very good recovering effects when used even for numerous dynamic tests.

4. MODELING AND VIBRATION CONTROL STUDY OF REAL BRIDGES UNDER STRONG EARTHQUAKE GROUND MOTIONS

Seismic vibration control of continuous and discontinious RC girder bridges with miltiple spans supported by neoprene bearings have been particulary studied within the framework of the present analytical investigations, since they are very frequently applied in many regions as the most common structural types. To discuss potential applicability of vibration control devices (VCD's) for bridge earthquake resistance improvement, in this paper presented are same analytical results obtained for analyzed discontinuous prototype bridge structure with flexibile central piers and three spans (L = 3 x 30.4 = 91.2 m). The bridge superstructure consists of discontinious slab because of the

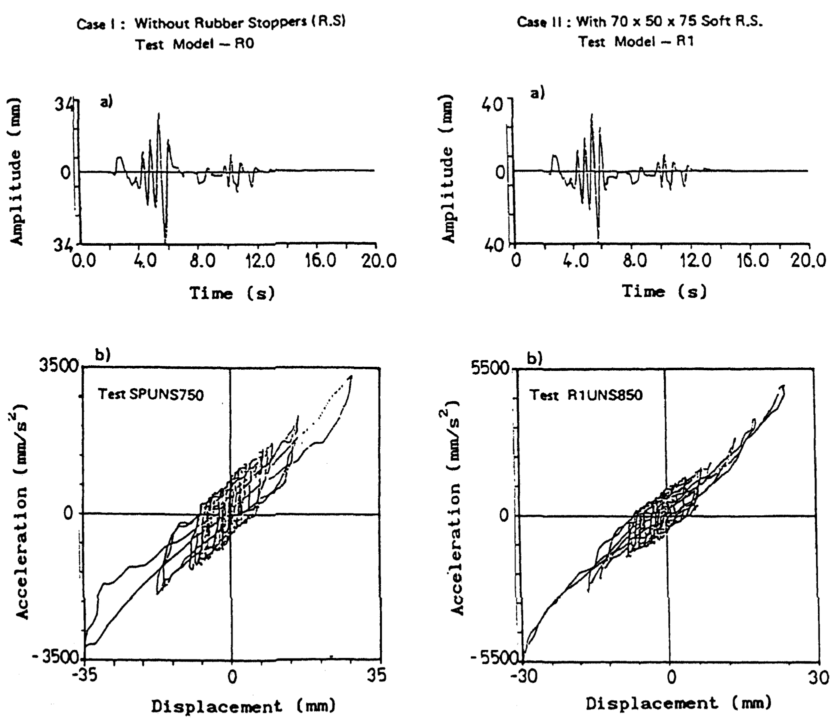

Fig.3. Comparative dynamic test results of model R0 without rubber stoppers (case I) and model R1 with smaller soft rubber stoppers (case II) for simulated Ulcinj-Albatros earthquake record

designed expansion joints and simple supported beams on neoprene bearings installed at the top of the box type central piers of different height.

For the purpose of a direct comparison of the dynamic response parameters of the structure with and without VCD's as specific elements under various ground motion intensities, beside the selected prototype another four defined prototype modification cases through incorporating different VCD's as specific elements were defined and analyzed.

4.1 Bridge model formulation without and with vibration control devices (VCD)

In order to improve the seismic safety of bridge prototype structure through control of its dynamic behaviour under strong earthquake effects, several additional elements have been adopted and modelled. The proposed and investigated elements as vibration control devices (VCD) in the present case basically include the following two different element types: (1) adequately designed rubber stopper elements modelled with RSMODEL, and (2) well-composed seismic energy absorption elements modelled by ABSEM model. Nonlinear analytical models, developed and proposed for realistic simulation of inelastic behaviour features of both types of considered vibration control devices are separately presented in Fig.4 and Fig.5, respectively. Capability and practical applicability of both proposed analytical

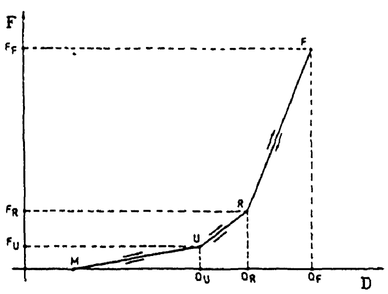

Fig.4. Proposed and implemented non-linear analytical model of a rubber stopper element

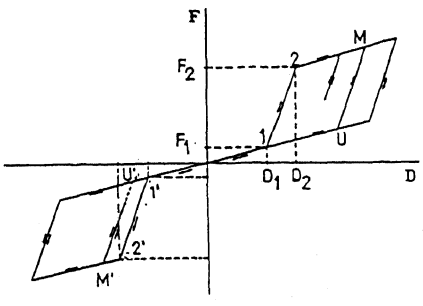

Fig.5. Proposed non-linear model of the implemented seismic energy absorption element

models have been initially confirmed based on available results from previously conducted experimental tests. However, to more realistically represent inelastic response of bridge neoprene bearings (due to possible bridge deck sliding), their modelling has been achieved through implementation of separately incorporated bilinear models, Fig.6.

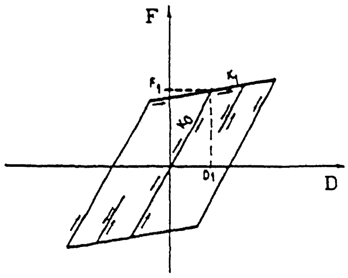

Fig.6. Proposed model for non-linear behaviour simulation of neoprene support element

Through modeling of the above described specific properties of rubber stopper elements, energy absorption elements and neoprene bearings along with stiffness and deformability characteristics of the remaining structural components, realistic discrete model of the integral structure has been formulated, Fig.7. For analysis of prototype structure as well as modified prototype with VCD specific elements, the same model topology has been applied providing easy comparison of the computed results.

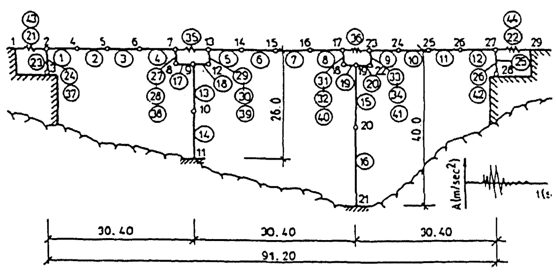

Fig.7. Formulated discrete mathematical model for prototype and modified bridge prototype

4.2 Computation of bridge inelastic earthquake response and principal observations related to its vibration control

Using the defined two mathematical models (Fig. 7) of the bridge with and without built-in VCD's as specific elements, computed were in both cases the structural inelastic seismic responses considering Montenegro (Ulcinj-Albatros) earthquake record, N-S component, with peak accelerations of Ap = 0.50 g.

The dynamic response of the bridge structure was analyzed considering the first 15 seconds characterized by pronounced acceleration amplitudes. The solution time step of $\Delta T = 0.005$ was adopted in both cases for the step-by-step numerical integration of the dynamic equilibrium equations. The a and b coefficients defining the Releigh damping matrix $C = \alpha[M] + \beta[K]$ were computed after analysis of structural dynamic characteristics ($T_1 = 0.612$ sec and $T_2 = 0.351$ sec) considering damping coefficient for the first and the second mode $\xi = 5\%$ of the critical damping.

Comparing the basic seismic response parameters (for the analyzed prototype and the modified prototype with the installed vibration control devices VCD), the following conclusions can be drawn in respect to the effectiveness of the built-in VCD's as specific: (a) Considering the fact that the superstructure is treated realistically as discontinuous structure (with two structural joints) supported through neoprene bearings, on respective bridge piers and since lateral rigidity of the neoprene bearings is limited, the induced moments in the middle piers are not excessive. However, comparing the lateral displacement response of the bridge superstructure in both cases, its very significant reduction can be observed in the case of incorporated vibration control devices, Fig.8; (b) Analyzing seismic response of the

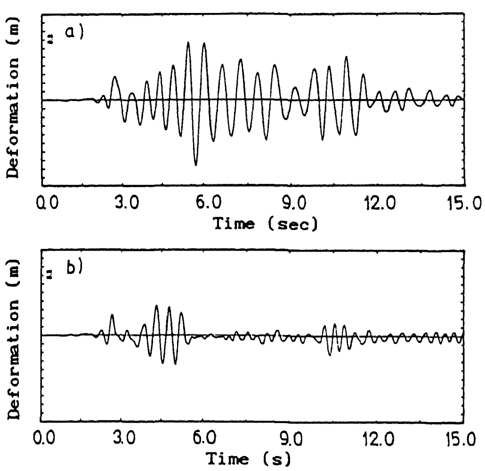

Fig.8. Displacement response history of bridge superstructure for analyzed case without (a) and with (b) installed vibration control devices

prototype structure (without built-in VCD) under the effect of the Ulcinj-Albatros earthquake (Ap = 0.50g), it may be concluded that the superstructure may be exposed to total failing due to the occurrence of larger lateral deformations in the neoprene bearings with present sliding of the bridge superstructure, Fig.9; (c) Regarding the achieved high seismic stability level of the bridge superstructure in the case of modified prototype (with built-in rubber stoppers at both ends

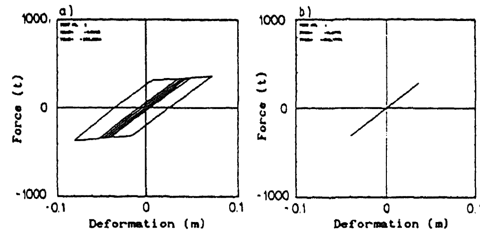

Fig.9. Neoprene hysteretic response for analyzed case without (a) and with (b) installed vibration control devices

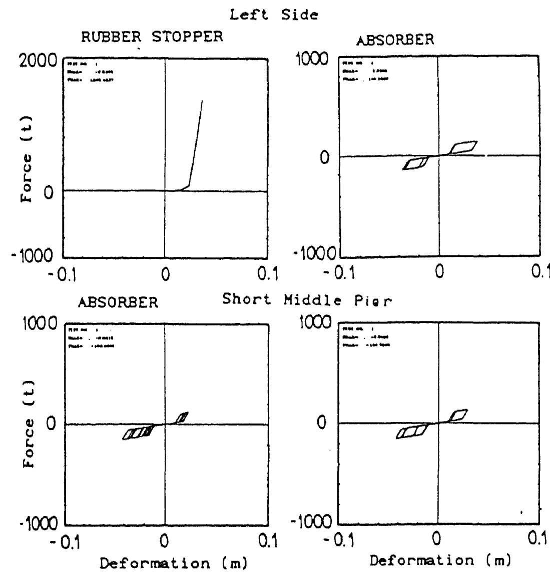

Fig.10. Typical inelastic response of the installed rubber stopper element (a) and energy absorption element (b)

and six absorbers over the supports) for a very high earthquake intensity (Ap = 0.5 g) it is clear that vibration control devices when appropriately designed may provide highly favourable structural seismic performances and coresponding increase of structural safety, Fig.10; (d) Finally, it was found from the present study that by the use of VCD's, improved structural seismic stability may be achieved for earthquakes of different frequency content as well as intensity levels.

5. CONCLUSIONS

The conducted integral experimental and analytical studies clearly showed that application of the vibration control devices may serve very favorable conditions for protection of engineering structures against expected strong and different earthquake ground motions. However, to achieve sucessful design of structural systems with built-in VCD's, detailed inelastic response analyses have to be carried out implementing adequate computer programs developed for such specific purposes as is for instance the developed computer programme NORA implemented for completion of the analytical studies presented and discussed in this paper. The selection of the locations, proportions, the rigidity and deformability characteristics of vibration control devices is a highly important engineering task since only optimum selected parameters may provide conditions for adequate and controlled dynamic behaviour of the structure under consideration. Finally, with the design of some typified elements with verified and most favorable characteristics, the practical design process can be very much simplified and reduced only to the selection of the type location and necessary number of certain typified elements with verified efficiency based on performed corresponding dynamic structural response analysis.

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