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DYNAMIC RESPONSE AND PERFORMANCE EVALUATION OF MULTISPAN HIGHWAY BRIDGES WITH DISPLACEMENT CONTROL

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SUMMARY

With implementation of neoprene pads or low elasticity high damping bearings, the flexibility of bridge structures is significantly increased resulting in reduction of pier shear forces and bending moments but significant increase of the superstructure displacements in longitudinal direction. To control the bridge deck displacements in longitudinal direction, rubber stoppers have been implemented at the bridge abutments. For demonstration of the established criteria, a multispan bridge structure composed of three deck elements supported by 10 piers and abutments resting on neoprene pads or low elasticity and high damping "Bridgestone" bearings has been analysed for local and distant earthquake time histories with PGA's of 20% for the Operating Level Earthquake and 60% for the Maximum Considered Earthquake. It was found that the effective performance of the bridge substructure as well as the superstructure could be assured by control of displacements and damage control of pier elements, satisfying the established criteria to maintain operation and control of damage without collapse of the bridge structure under the most severe earthquake excitations.

INTRODUCTION

Since the very beginning of development of earthquake engineering, it has been conceived that the earthquake potential of inflicting damage to structures is mainly due to the resonance between the fundamental periods of vibration of most of the structures and the frequency content of the seismic input. Despite this, many structures have been able to find ways to resist intensive excitations through avoiding the frequency domain in which the earthquake has the most destructive power, by prolongation of their natural period of vibration due to accumulated damage.

The concepts of isolation and dissipation are of interest particularly for bridges due to a series of potential advantages as to their specific structural characteristics. In most of the cases, bridges are strategic structures requiring a higher level of protection in order to be functional after a seismic event. Therefore, it is perhaps, good to concentrate the damage potential into several mechanic elements that can easily be checked and replaced, if necessary. In addition, a larger part of the mass of bridges is concentrated at the level of the deck, while the bearing elements of the superstructure are usually designed to remain elastic under an earthquake effect. It is a common practice, particularly in Europe, to design a continuous deck structure resting on bearings placed on the top of the piers. In this case, the bearings themselves can be designed as dissipaters by selecting their stiffness, yield strength and maximum displacement capacity in function of the required protection and the expected seismic intensity. This option is particularly suitable and common in case of improvement of existing structures from seismic aspect. Since bridges usually represent simple structures from the view point of expected structural response, corresponding correction of the distribution of stiffness in these structures is simpler than it is in the case of more complex structures. Therefore, the dissipating devices can be used for correction or regulation of the expected response by adding of flexibility to stiffer piers thereby avoiding possible unfavourable concentration of ductility demands.

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SELECTION OF A BRIDGE STRUCTURE FOR ANALYSIS

Selected for analytical investigation of dynamic behaviour of discontinuous bridge structures with flexible central piers has been a real reinforced-concrete structure on Skopje-Veles motorway, over the Vardar river, near the town of Veles. The bearing system of the superstructure is represented by main girders in the form of prestressed simple beams supported by piers through neoprene bearings. With the designed two expansion joints, the integral superstructure is, in fact, composed of three separate "units" of which the first and the last one run through three spans, while the central one extends over 5 spans, so that the total length of the bridge is L=363 m (Fig. 1)

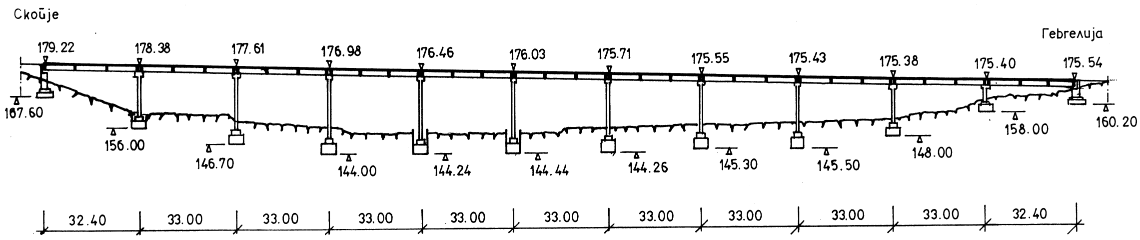


Fig.1. Longitudinal section of the bridge

The lower bearing structure consists of 10 central piers and two abutments. The central piers are designed as reinforced concrete ones, with solid cross-section of concrete class 30 and external proportions of 4,0 x 1,0 m, They rest on stepped foundation.

NONLINEAR MATHEMATICAL MODEL WITH SEISMIC BEARINGS

To conduct seismic analysis, a mathematical model of the selected bridge structure has been formulated. With the defined nonlinear mathematical model, the elements of the bridge structure have been more realistically modelled. In the model, all the structural elements have been modelled as nonlinear. The discrete nonlinear mathematical model with the indicated finite elements and nodal points is presented in Fig. 2.

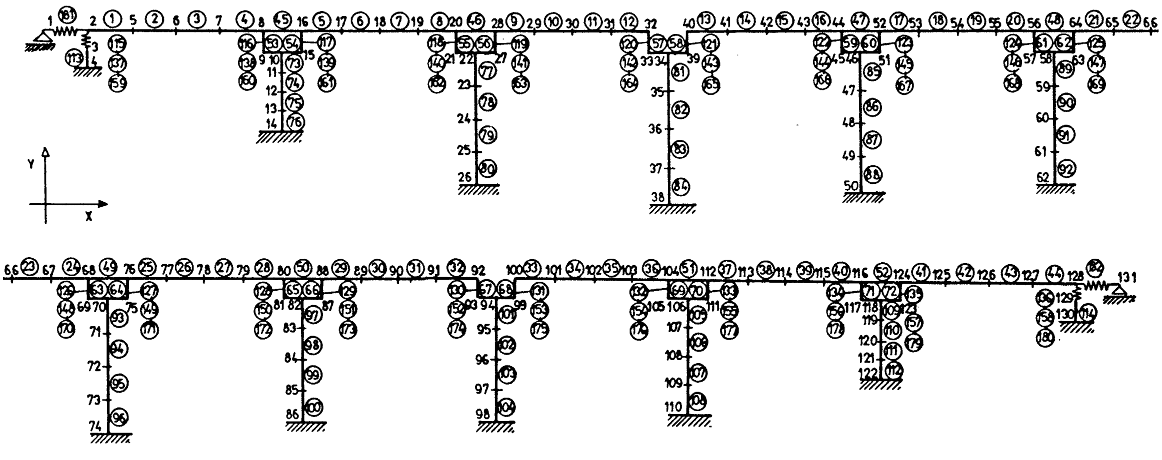


Fig.2. Nonlinear mathematical model composed of beam finite elements

The nonlinear elements of the piers, the main girders, the deck and the capitals of the piers have been modeled in such a way that the M-Φ diagrams have been considered as input parameters to define the behaviour of the elements in both elastic and plastic range of behaviour. The introducing of nonlinearity of these elements by means of the previously mentioned M-Φ curves is at the level of the so called "subelements". The seismic bearings have been modeled by nonlinear elements of the type of spring elements behaving in one or several directions. In this case, all the seismic elements have been modeled by three spring elements each, in axial, tangential and rotation direction.

CRITERIA FOR DEFINITION OF INTENSITY OF EARTHQUAKE EXCITATION

The seismic risk assessment for bridges shall depend on the required functionong and limited damage to the structural elements as well as on the corresponding intensitiees and frequency contents of earthquake effects during the serviceability period of such structures. To assure the required acceptable seismic risk, the performance of the structures is evaluated through analysis of their bearing and deformability capacity and qualitative assessment of their vulnerability and functioning. For that purpose, three basic criteria have been adopted, i.e., frequent, design and maximum earthquake with corresponding frequency of occurrence, and required controlled behaviour of the structure: completely functional, functional and with controlled damage under corresponding earthquake effects.

1. Frequent earthquake: An earthquake which occurs frequently during the serviceability of structures with probability of exceedence of 50% in 50 years (100 years return period). Under this earthquake, the bridge structure should remain in linear range maintaining complete functioning and should not suffer damages.

2. Design earthquake: An earthquake that may occur during the serviceability period of the structures with probability of exceedence of 10% in 50 years (return period of 500 years). Under this earthquake, the bridge structures should remain functional, with minor structural damages, dominantly in the supporting and other elements. The repair of such damages should not distrub the functioning of the structures.

3. Maximum earthquake: An earthquake with a probability of exceedence of 5% in 50 years (return period of 1000 years). The bridge structures of vital importance are with limited functioning because of the nonlinear behaviour of the structure and the suffered structural damage. The repair of damages is economically feasible and does not disturb the limited functioning.

BEARING CAPAICTY, MOMENT-CURVATURE M-Φ AND M-N DIAGRAMS FOR CHARACTERISTIC CENTRAL PIERS

The bearing capacity of the bridge structure has been investigated through the bearing capacity of selected characteristic piers and has been defined using the defined M-Φ diagrams for these piers. The M-Φ diagrams have been derived according to the specified criteria of behaviour of the structural elements of the bridge structures considering the corresponding cross-sections. A M-Φ relationship has been established for longitudinal direction (Fig. 3) for all the central piers because of their identical cross-section and reinforcement percentage. The variation of axial force in the central piers has been negligible and a mean value has been considered in defining the M-Φ relationship. Fig. 3 shows the M-N relationship for the central piers in longitudinal direction.

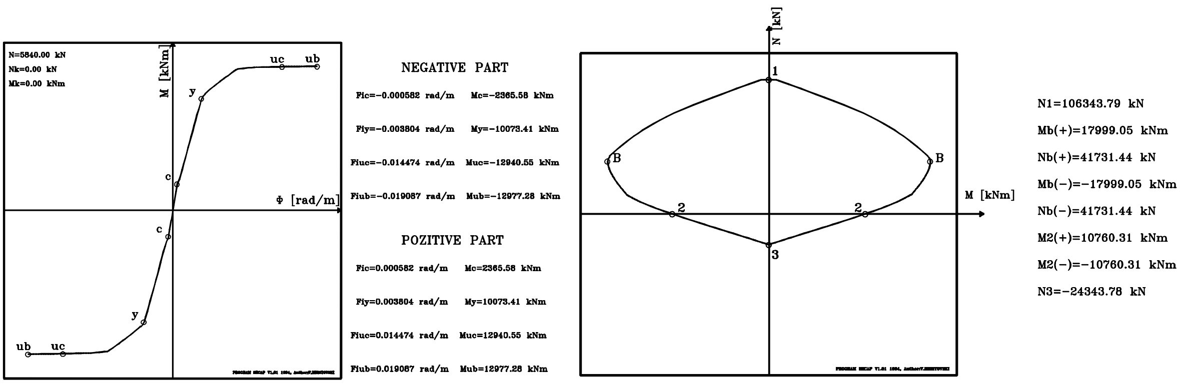


Fig.3. M-Φ and M-N diagrams for a cross-section at the foot of a central pier in longitudinal direction

The bearing capacity of the bridge structure has been investigated via the bearing capacity of the selected characteristic middle piers as follows: through the bearing capacity of pier S4-the highest pier of the structure supporting the first and the second deck, and through the bearing capacity of column S11, which is the shortest pier of the structure. The bearing capacity of the selected piers has been computed for longitudinal direction under the effect of El Centro earthquake with the defined maximum intensities of 0.2 g, 0.4 g and 0.6 g. Based on the performed control of bearing capacity of the middle piers under the effect of the defined intensities of the earthquake in the longitudinal direction of the structure (Table 1 and Table 2), it may be concluded that the yield point of reinforcement has not been achieved and that the seismic coefficient has reached a maximum value of 12.4%, which means that the piers possess sufficient bearing capacity in longitudinal direction, which accordingly holds for the bridge structure itself. Under maximum effect, there has been a decrease in the shear forces (15%) and bending moments in the piers (20%-35%) in the model with incorporated rubber stoppers in respect to those of the model without rubber stoppers.

Table 1. Bearing capacity of pier S4 with seismic bearings with and without rubber stoppers in longitudinal direction under the El Centro 1940 earthquake with maximum acceleration of 0.2, 0.4 and 0.6 g.

Earthquake excitation	Quantities at the foot of the pier			Bearing capacity		Seismic coefficient
El Centro 1940	Ng [kN]	Qs [kN]	Ms [kNm]	Ms/MY MY=10 073	Ms/MU MU=12 977	Qs / Ng
Bridgestone:						
0.2 g	5 815	195	1 709	0.170	0.132	0.034
0.4 g	5 815	328	3 060	0.304	0.236	0.056
0.6 g	5 815	478	4 416	0.438	0.340	0.082
Bridgestone and Rubber stopper:						
0.2 g	5 815	177	1 479	0.147	0.114	0.030
0.4 g	5 815	279	2 354	0.234	0.181	0.048
0.6 g	5 815	412	2 869	0.285	0.221	0.071

Table 2. Bearing capacity of column S11 with seismic bearings with and without rubber stoppers in longitu-dinal direction under El Centro 1940 earthquake, with maximum acceleration of 0.2, 0.4 and 0.6 g.

Earthquake excitation	Quantities at the foot of the pier			Bearing capacity		Seismic coefficient
El Centro 1940	Ng [kN]	Qs [kN]	Ms [kNm]	Ms/MY MY=10 073	Ms/MU MU=12 977	Qs / Ng
Bridgestone:						
0.2 g	4 880	230	2 764	0.274	0.213	0.047
0.4 g	4 880	412	4 621	0.459	0.356	0.084
0.6 g	4 880	606	6 837	0.679	0.527	0.124
Bridgestone and Rubber stopper:						
0.2 g	4 880	281	3 618	0.359	0.279	0.058
0.4 g	4 880	401	4 041	0.401	0.311	0.082
0.6 g	4 880	519	5 561	0.552	0.429	0.106

ANALYSIS OF PERFORMANCES OF BRIDGE STRUCTURES WITH ELASTOMERIC BEARINGS

Considering the fact that the design for obtaining the required strength and ductility itself cannot provide the required behaviour, it is necessary that the evaluation process becomes an important part of the design procedure. The term "evaluation" means evaluation of the performance of the structure under the effect of the defined earthquakes. This is a level of behaviour at which the requirements for deformability and the corresponding forces should be envisaged and compared to the capacities available. The most realistic process for verification is prediction of the deformations and the forces from the nonlinear analyses of time history using a series of representative defined earthquakes.

To present the process of quantitative assessment of behaviour, the selected bridge structure designed in compliance of valid regulations has been analyzed under the effect of El Centro 1940 earthquake, for three levels of ground acceleration (0.2, 0.4 and 0.6 g). Using the procedure for determination of the capacity of ultimate displacement of the pier as well as the defined ultimate displacements of the used seismic bearings type "Bridgestone", and having the displacements for the piers, the seismic bearings and the deck obtained from the dynamic analyses, we are able to compute and construct the ultimate profiles and the displacement response profiles for individual selected piers. Presented in Table 3 and Table 4 are the displacements and the response mechanisms as well as the dynamic displacement responses of the superstructure of pier S4 in longitudinal direction from the performed analyses of the nonlinear model with seismic bearings and the modified model with seismic bearings and incorporated rubber stoppers, respectively.

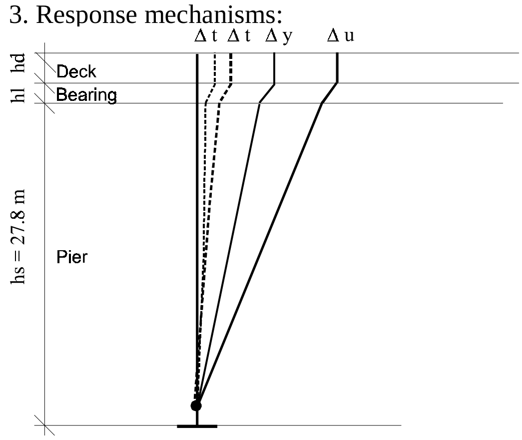
Table 3. Displacements and response mechanisms of pier S4 in longitudinal direction under frequent earthquake of 0.2 g and maximum earthquake of 0.6 g, El Centro earthquake, S00E component

El Centro 1940, S00E

1. Displacement at the pier and superstructure (cm)

Model	0.2 g Δs	Δl	Δt	0.6 g Δs	Δl	Δt
Bridgestone	8.1	6.9	12.2	23.9	16.1	30.7

3. Response mechanisms:



2. Displacement capacity

2.1. Pier: Δy = 113.5 cm Δu=194.4

2.2. Bridgestone: Δmax = 20.0 cm

3. Dynamic displacement response Δt (cm)

a. Model with Bridgestone bearings

maxΔ0.6 = 30.7 cm, t=4.2s

maxΔ0.2 = 12.2 cm, t=4.0 s

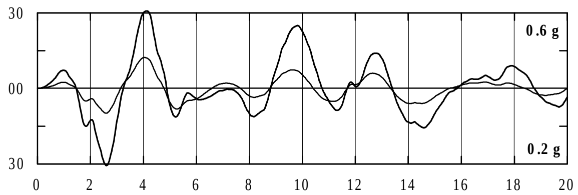
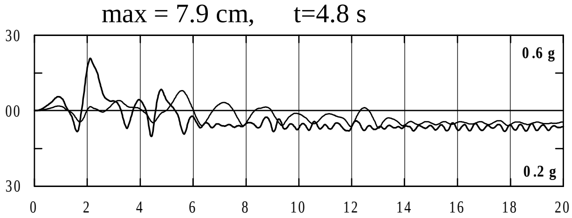


Table 4. Displacements and response mechanisms of pier S4 in longitudinal direction under the frequent earthquake of 0.2 g and maximum earthquake of 0.6 g, El Centro earthquake, S00E component.

<table>
<tr><td colspan="7">El Centro 1940, S00E</td><td rowspan="4">2. Displacement capacity
2.1. Pier Δy = 113.5 cm Δu =
2.2. Bridgestone: Δmax = 20.0 cm</td></tr>
<tr><td colspan="7">1. Displacement at the pier and superstructure (cm)</td></tr>
<tr><td rowspan="2">Model</td><td colspan="3">0.2 g</td><td colspan="3">0.6 g</td></tr>
<tr><td>Δs</td><td>Δl</td><td>Δt</td><td>Δs</td><td>Δl</td><td>Δt</td></tr>
<tr><td>Bridgestone and Rubber Stoppers</td><td>7.6</td><td>8.1*</td><td>7.9</td><td>11.8</td><td>21.8</td><td>13.9</td><td rowspan="2">3. Dynamic displacement response Δt (cm)
a. Model with Bridgestone bearings and rubber stoppers
max=13.9cm t=2.1 s
max = 7.9 cm, t=4.8 s

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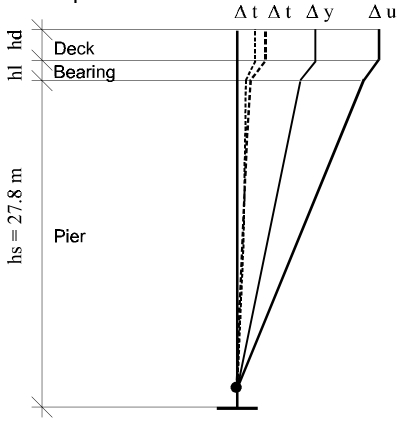
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SEISMIC RISK ASSESSMENT BASED ON PERFORMED ANALYSES OF PERFORMANCES OF BRIDGE STRUCTURES

Based on a large number of analyses on performances of bridge structures with seismic bearing of the "Bridgestone" type, we have been able to assess the seismic risk. To provide the structure with sufficient ductility and strength, it is necessary that the deformations obtained for the defined levels of earthquake be slighter than the deformations related to acceptable damages and functioning of the structure.

For an earthquake defined as a frequent one, the following assessment of the performance of the bridge structure can be made: the structure is in the linear range of behaviour. It has suffered no damage, i.e., the bridge structure is completely functioning in longitudinal direction and has no damages.

For the earthquake defined as a design one for which negligible damage is allowable, the following assessment of the performance of the bridge structure can be made: the structure is still in the linear range of behaviour, without any damage. Under this earthquake, the bridge structure is operational, without damages in longiduinal direction.

For the earthquake defined as the maximum one, for which nonlinear behaviour of the structural elements and damage to the structural elements is allowable but the structure should be still functional (slowed down function), the following assessment of the performance of the bridge structure could be made: the superstructure has suffered large longiduinal displacements, but the relative lateral displacements of the bearings are still not exhausted so that the stability of the structure is not endangered. For this earthquake level, it can be stated that the bridge structure suiffers damage in longitudinal direction but they are negligible and do not endanger the stability of the bridge structure as a whole, which means that the structure remains functional.

In the case when the bridge structure with seismic bearings has incorporated rubber stoppers, the effects are decreased as are also the displacements of the superstructure and at the top of the central columns and the structure does not suffer any significant damage.

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