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THE SEISMIC RESPONSE EVALUATION OF A BRIDGE DECK, ISOLATED BY RUBBER BEARINGS

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Abstract: *Bridges and viaducts must ensure the road land connection between two points, even after some seismic actions. Avoiding or reducing potential total or partial destruction of these structures can be achieved by placing seismic systems between superstructure and bridges infrastructure. The natural aging of rubber as component of laminated rubbers anti-seismic bearings determined changes in horizontal and vertical stiffness. The paper presents a study based on actual data of the dynamic behavior of a seismic loaded bridge whose deck is isolated by visco-elastic laminated rubber bearings. In order to determine the bridge superstructure response depending on the insulation systems stiffness modification caused by natural aging of rubber four Vrancea (Romania) earthquakes records sets were used for loading the bridge superstructure. The conclusion of the study shows that a low classified earthquake ground motion can determine a more intense structural response compared to that induced by a normal classified earthquake ground motion in terms of using a poorly adjusted insulation system and the impact of core material aging effects*.

Key words: *bridge, earthquake, isolation bearing, rubber, aging, dynamical response*

1. INTRODUCTION

The viaducts and bridges anti-seismic design must be achieved in full compliance with the specificity of seismic area in which they will be built on so that the exposure to such action does not cause total or partial destruction of these objectives.

According to European standard EN 1998-2, 2005 The design of structures for earthquake resistance, Part two *Bridges*, a bridge or viaduct loaded by seismic actions must carry out after event the following requirements [1]:

- According to the first requirement, the bridge must not collapse (the ultimate limit state). The construction must ensure emergency traffic in safety conditions even in case of some dissipative elements damage.

- The second requirement also called the serviceability limit state involves damage minimizing to the bridge structure. It is accepted in accordance with this requirement the damage of secondary elements and those that dissipate seismic energy.

Based on the study of area's seismic peculiarities in which the bridge will be built on can be design or chosen the dynamic insulation systems whose basic function is to increase fundamental period of the structure so that the values for which seismic action produces large loadings (accelerations) to the system is avoided.

For some of the bridges and viaducts built the laminated rubber anti-seismic bearings were used for their insulation and dissipative properties, which is certainly an advantage, fig. 3a. A disadvantage of laminated rubber bearings used as anti-seismic systems for bridges consist in changing properties in time caused by the following possible issues:

- heavy traffic - the passing wheel over the rubber expansion most of the time produces shocks and vibration;
- earthquake ground motion;
- the atmospheric factors such as temperature and ozone.

The time variability of mechanical properties of laminated rubber bearings revealed scientifically a special interest considering the objectives for which these systems are used such as bridges and buildings. This aspect was investigated by numerous experimental and theoretical studies in this scientific field.

The paper's authors [2] have experimentally determined the rubber mechanical properties from anti-seismic bearings used to the Pelham Bridge of Lincoln City (England) which have been used for 40 years. The experimental testing revealed an increase about 10% of horizontally stiffness value.

In a similar research, a team of Japanese scientists [3] studied time variability of rubber mechanical properties of anti-seismic bearings used in buildings base isolation. After 10 respectively 22 years in use the experimental testing has proved the change of stiffness values on vertically and horizontally direction. According to this study the horizontally stiffness value has increased with 7% after 10 years and respectively with 11.7% after 22 years.

In addition to time, variability of rubber mechanical properties in the scientific literature were studied other factors such as the rubber materials changes used in manufacturing process or the ambient temperatures [4]. The paper [4] investigated the influence of rubber mechanical properties changes on lead rubber bearings response at different earthquake ground motion. The rubber mechanical properties changes were caused by ambient temperature, rubber materials variability in manufacturing process and rubber ageing.

The main objective of the paper was to study the anti-seismic isolated bridge superstructure (deck) response depending on the rubber ageing of High Damping Rubber Bearings (HDRB).

2. STRUCTURAL MODEL

The studied bridge is a theoretical structure located in an area characterized by moderate seismicity: Vrancea area of Romania. The bridge has a single deck whose resistance structure is consists of four beams "U" joined to each other at the top by a reinforced concrete plate. Each beam is supported at each end on two anti-seismic bearings; arrangement of bearings is illustrated in figures 1, 2. Has been considered that the anti-seismically system are the High Damping Rubber Bearings (HDRB) type with triorthogonal viscoelastic links [5], [6], [7] figure 3b, and 300x500x81 mm dimension, figure 3a.

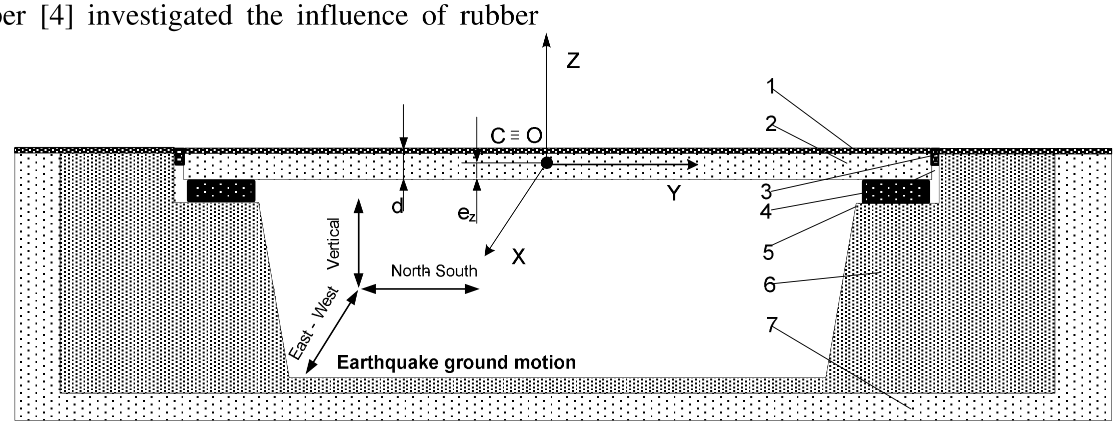


Fig. 1 The scheme of the analyzed bridge:
1 – The road surface; 2 - deck; 3 – sealing element; 4 – rubber support; 5 – rubber expansion joint; ; 6 - abutment; 7 - ground

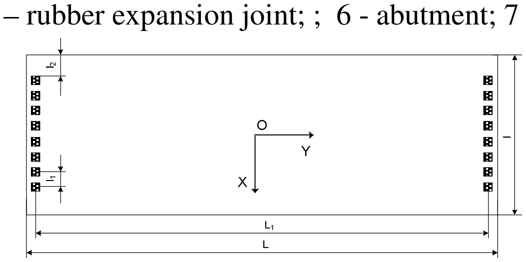


Fig. 2 Arrangement of bearings

The study of the dynamic behavior of a bridge with seismically isolated deck using HDRB isolation systems was made taking into account the following assumptions:
- the bridge has only one deck;
- the deck of the bridge (figure 2) was considered identical to a rigid solid dynamically isolated using a 16 HDRB isolation systems;
- the isolators were modeled as elements with triorthogonal viscoelastic links, [5], [6], [7];
- the ground motion is simultaneously transmitted at the deck only through the anti-seismic device;
- the stiffness and damping coefficients of the anti-seismic devices were considered as being linear and constant;
- the bridge is located in the seismic area of Vrancea.

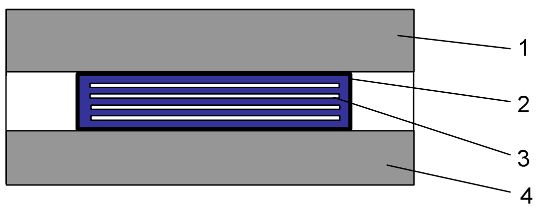


Fig. 3.a Seismic support made from laminated neoprene: 1 - deck; 2 - rubber; 3 - steel sheets; 4 - abutment

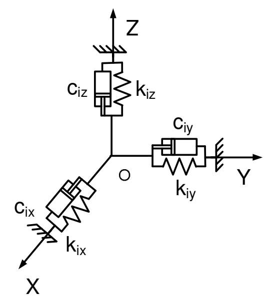


Fig. 3.b The physical model of the rubber bearing [5], [6], [7]

2.1 The mathematical model of the dynamic system

In order to elaborate the mathematical model the bridge deck was modeling as a rigid-solid with six degrees of freedom, seismically isolated by using a 16 HDRB isolation system. According to [5], [6], [7], the equations, which describe the bridge deck response, are written as follows:

$$\underline{I}\underline{\ddot{q}} + \underline{C}\underline{\dot{q}} + \underline{K}\underline{q} = \underline{f} \qquad (1)$$

where: $\underline{\underline{q}}$ - represents the vector of the generalized coordinates; $\underline{\dot{q}}$ - represents the vector of the generalized speeds; $\underline{\ddot{q}}$ - represents the vector of the generalized accelerations; f – represents the vector of the generalized forces; $\underline{I}$ - represents the inertia matrix; $\underline{C}$ - represents the dampening matrix; $\underline{K}$ - represents the rigidity matrix.

Given the geometrical symmetries of studied structure, the rigid movements are decoupled. In order to assess the bridge deck response for different earthquake ground motion, based on theoretical considerations of papers [5], [6], [7] and taking into account the proposed model structure (see Figures 1 ... 3) have been developed motion equations systems corresponding to these motion coupled modes:

- the mathematical model of subsystem with coupled motion (X, φ_y):

$$\begin{cases} m\ddot{X} + \dot{X}\sum_{1}^{16} c_{ix} + \dot{\varphi}_y \sum_{1}^{16} z_i c_{ix} + X\sum_{1}^{16} k_{ix} + \varphi_y \sum_{1}^{16} z_i k_{ix} = \sum_{i=1}^{16}\left(k_{ix}\delta_x + c_{ix}\dot{\delta}_x\right) \\ J_y\ddot{\varphi}_y + \dot{X}\sum_{1}^{16} z_i c_{ix} + \dot{\varphi}_y \sum_{1}^{16}(c_{iz}x_i^2 + c_{ix}z_i^2) + X\sum_{1}^{16} z_i k_{ix} + \varphi_y \sum_{1}^{16}(k_{iz}x_i^2 + k_{ix}z_i^2) = e_z \cdot \\ \qquad \sum_{i=1}^{16}\left(k_{ix}\delta_x + c_{ix}\dot{\delta}_x\right) \end{cases} \qquad (2)$$

- the mathematical model of subsystem with coupled motion (Y, φ_x):

$$\begin{cases} m\ddot{Y} + \dot{Y}\sum_{1}^{16} c_{iy} - \dot{\varphi}_x \sum_{1}^{16} c_{iy} z_i + Y \sum_{1}^{16} k_{iy} - \varphi_x \sum_{1}^{16} k_{iy} z_i = \sum_{i=1}^{16}\left(k_{iy}\delta_y + c_{iy}\dot{\delta}_y\right) \\ J_x\ddot{\varphi}_x - \dot{Y}\sum_{1}^{16} z_i\, c_{iy} + \dot{\varphi}_x \sum_{1}^{16}\left(c_{iy} z_i^2 + c_{iz} y_i^2\right) - Y\sum_{1}^{16} z_i k_{iy} + \varphi_x \sum_{1}^{16}\left(k_{iy} z_i^2 + k_{iz} y_i^2\right) = -e_z \cdot \end{cases} \quad (3)$$

where: m - the mass of the bridge deck; X - side slip movement; Y - forward-back movement; φ_y - rolling movement; φ_x - pitch movement; *i* - the number of HDRB isolation system, i=16; k_{ix} - horizontal stiffness of the isolation system *i* on OX direction; k_{iy} - horizontal stiffness for the isolation system *i* on OY direction; c_{ix} - damping coefficient *i* on OX direction; c_{iy} - damping coefficient *i* on OY direction; y_i, z_i - insulation systems coordinates in relation to the mass center C; J_x, J_y, J_z - principal moments of inertia; δ_y - displacement of the ground in the OY direction; $\dot{\delta}_y$ - velocity of the ground in the OY direction; δ_x - displacement of the ground in the OX direction; $\dot{\delta}_x$ - velocity of the ground in the OX direction; e_z - the distance between insulators and deck center of mass.

It was studied only horizontal movement of the bridge superstructure, as it considers that changes the mechanical properties of the isolation system in the vertical direction do not cause damage to the structural integrity of the deck.

2.2. Input earthquake ground motions

The manner of transmission of seismic excitation at deck's level is achieved as in figure 2 as follows:

- the abutments movement causes at the anti-seismic device level the elastic and damping forces occurrence: $\sum_{i=1}^{16}\left(k_y\delta_y + c_y\dot{\delta}_y\right)$;
- these forces cause the deck's movement: the translational movements on OY direction and rotation movements around OX axis.

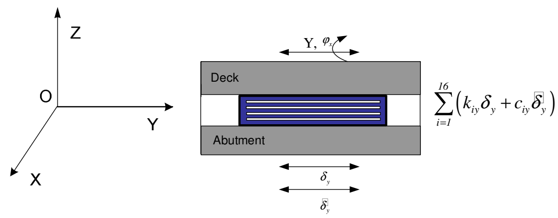


Fig. 4 The manner of transmission of seismic excitation at deck on OY direction

In the same way the earthquake ground motion are transmitted on the OX direction.

For the evaluation of the dependence between the kinematic parameters of vibration deck and the mechanical properties changes of HDRB isolation system caused by aging rubber, the bridge was loading by seismic signals recorded two earthquakes in the Vrancea (Romania) area [8]:

- Vrancea earthquake on August 30, 1986 (Mw=7.2)
  - recording point: Focsani City, Vrancea Hotel;
  - recording point: Vălenii de Munte City, Town Hall;
- Vrancea earthquake on May 30, 1990 (Mw=7.2)
  - recording point: Barlad City, Shelter ALA;
  - recording point: Ramnicu - Sărat City, Town Hall.

The seismic signals records and the data about them were taken from the web site of the National Institute for Research and Development in Constructions, Urban Planning and Sustainable Territorial Development "URBAN-INCERC" [8].

The classification of these earthquakes was done according to [9], [10] depending on the ratio between maximum acceleration recorded (in g) and top speed recorded, Table 1.

Table1

Classification of Vrancea earthquake by a_{max}/v_{max} ratio

Earthquake year code	Recording point	Direc tion	Bridge deck direction	a_{max} (m/s^2)	v_{max} (m/s)	Ratio $a_{max}(g)/v_{max}$	Earthquake class* [9], [10]
Vrancea 1986 FOC1	Focsani City, Vrancea Hotel	N07W	OY	1.988	0.267	0,75	low
		N97W	OX	2.878	0.201	1,45	high
Vrancea 1986 VLM1	Vălenii de Munte City, Town Hall	N84W	OY	1.869	0.227	0,83	normal
		N174W	OX	1.624	0.208	0,79	low
Vrancea 1990 BIR1	Barlad City, Shelter ALA	NS	OY	1.519	0.146	1,06	normal
		EW	OX	1.437	0.145	1,01	normal
Vrancea 1990 RMS1	Ramnicu - Sărat City, Town Hall	N102W	OY	1.252	0.284	0,44	low
		N168E	OX	1.604	0.289	0,56	low

*$a_{max}/v_{max}<0.8$ - low; $0.8<a_{max}/v_{max}<1.2$ - normal; $a_{max}/v_{max}>1.2$ - high [9], [10].

3. THE INFLUENCE OF HORIZONTAL AND VERTICAL STIFFNESS VARIABILITY OF THE ISOLATION BEARING ON DECK VIBRATION PARAMETERS RESPONSE

In the paper [3] the authors have been experimentally evaluated the rigidities according with both horizontal and vertical directions for laminated rubber-based insulators used within the seismically isolation of a building after 10 and 22 years respectively. In respect with the results within this paper, both rigidities have acquired changing of characteristics, such as briefly presented in table 2.

Table 2

The variability of rubber bearing stiffness in time [3]

Measured characteristic \ Moment in time	After 10 year in use	After 22 year in use
Vertical stiffness	increased about 16 to 19 %	increased about 13 to 15 %
Horizontal stiffness	increased about 7%	increased about 11,7%

The theoretical evaluation of the bridge deck response for earthquake ground motion was made for stiffness values of rubber bearing, presented in paper [3], corresponding to different level of rubber aging, table 3.

Table 3

The stiffness value of the rubber bearings [3]

Measured characteristic \ Simulation moment	Initial moment	After 10 year in use	After 22 year in use
Vertical stiffness	$k_{z0}=650\cdot10^6$ N/m	increased with 17% $k_{z10}=760.5\cdot10^6$ N/m	increased with 14 % $k_{z22}=741\cdot10^6$ N/m
Horizontal stiffness	$k_{y0}=3.15\cdot10^6$ N/m	increased with 7% $k_{z10}=3.37\cdot10^6$ N/m	increased with ~12 % $k_{z22}=3.52\cdot10^6$ N/m

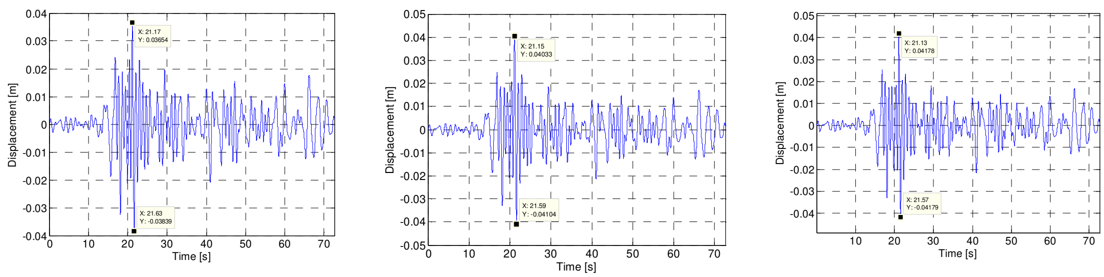
As this theoretically study to be as close as possible with reality, part of the numerical values of the parameters involved in the systems of equations (2), (3) were taken according with [7], where they have been presented for the existing bridge structure (the bridge on the Romanian A3 motorway): $m=992\cdot10^3$ kg, $k_{iz}=650\cdot10^6$ N/m, $k_{ix}=k_{iy}=3.15\cdot10^6$ N/m, $Jx=120.533\cdot10^6$ kgm^2, $Jx=15.133\cdot10^6$ kgm^2, $e_z=-1{,}45$ m, $z_i=-1{,}45$ m, d=2.5m, L=40m, $L_1=37.1$ m, $l_1=1.1$ m, $l_2=2.2$m.

Damping coefficients were determined according to mathematical relations presented in [12] for a frequency of 1.5 Hz and amortization rate of 10%: $c_{iz}=1.2\cdot10^6$ Ns/m, $c_{iy}=8.83\cdot10^4$ Ns/m. Considering the fact that the damping coefficient changes are negligible in relation to aging rubber aspect revealed in [4], [13], [14], these values were considered constant. This hypothesis highlights the exclusive influence of stiffness variation on the dynamic response of the superstructure.

4. RESULTS AND DISCUSSIONS

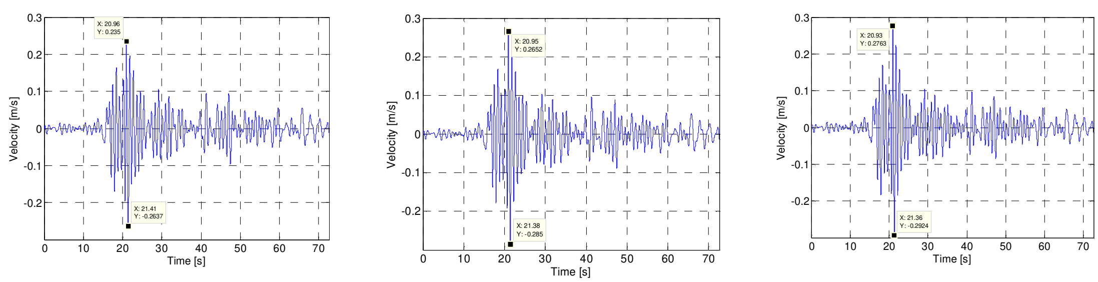
Solving the system of equations deferential (3) was made with MATLAB R14 [11], considering the bridge structure requested by through the four seismic signals (see Table 1), both on OX (EW) direction and on OY (NS) direction. In this section are presented the results for the following cases:

- earthquake ground motion 1986 Vrancea, recording station: Focsani City, Vrancea Hotel, direction NS - Figures 5,6,7 (displacement, velocity and acceleration respectively for superstructure response);



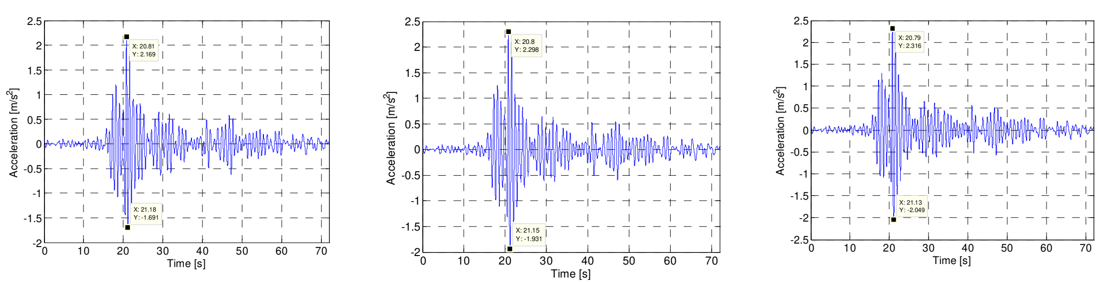
a. At initial time b. After 10 year c. After 22 year

Fig. 5 Displacement time-history of the deck



a. At initial time b. After 10 year c. After 22 year

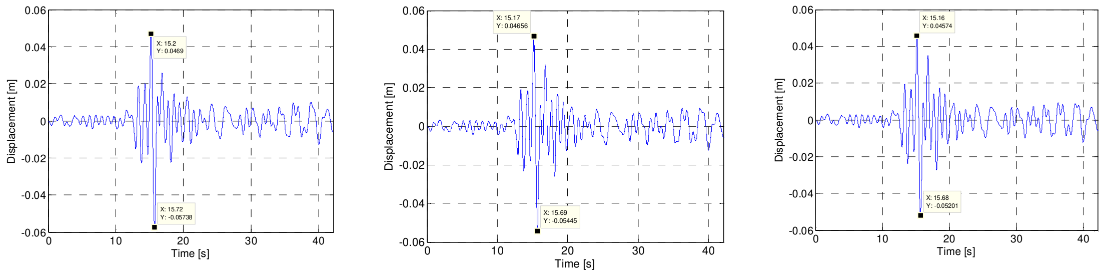
Fig. 6 Velocity time-history of the deck



a. At initial time b. After 10 year c. After 22 year

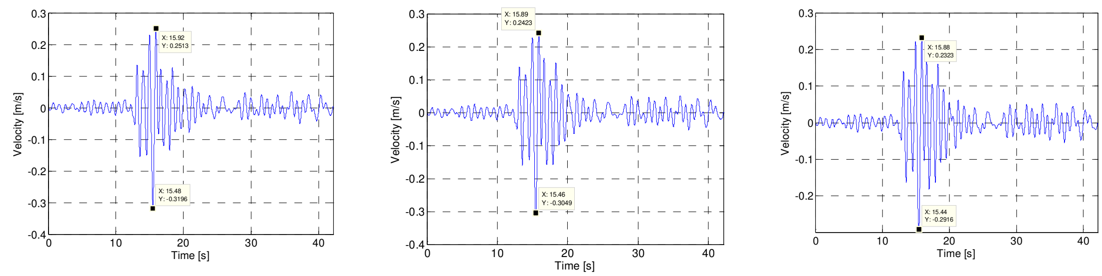
Fig. 7 Acceleration time-history of the deck

- earthquake ground motion 1986 Vrancea, recording station: Barlad City, Shelter ALA, direction N-S - (displacement, velocity and acceleration respectively for superstructure response) – Figures 8,9,10.



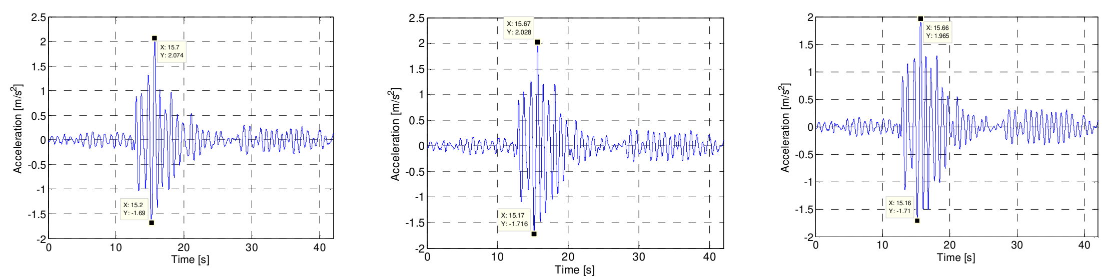
a. At initial time b. After 10 year c. After 22 year

Fig. 8 Displacement time-history of the deck



a. At initial time b. After 10 year c. After 22 year

Fig. 9 Velocity time-history of the deck



a. At initial time b. After 10 year c. After 22 year

Fig. 10 Acceleration time-history of the deck

The numerical variation of deck vibration parameters depending on the aging rubber for all seismic excitations considered NS on the direction (OY), was synthesized in Table 4.

Table 4

The numerical variation of deck vibration parameters

Event type		Recording point	Moment in time	Displacement variation (m)	Velocity variation (m/s)	Acceleration variation (m/s^2)
Earthquake	Vrancea 1986	Focşani	At initial time	-0.038÷0.036	-0.263÷0.235	-1.691÷2.169
			After 10 year	-0.041÷0.040	-0.285÷0.265	-1.931÷2.298
			After 22 year	-0.041÷0.041	-0.273÷0.292	-2.049÷2.316
		Valenii de Munte	At initial time	-0.057÷0.075	-0.448÷0.376	-2.76÷3.05
			After 10 year	-0.059÷0.078	-0.478÷0.409	-3.061÷3.298
			After 22 year	-0.060÷0.081	-0.499÷0.429	-3.275÷3.457
	Vrancea 1990	Bîrlad	At initial time	-0.057÷0.046	-0.319÷0.251	-1.69÷2.07
			After 10 year	-0.054÷0.046	-0.304÷0.242	-1.71÷2.02
			After 22 year	-0.052÷0.045	-0.291÷0.232	-1.712÷1.96
		Ramnicu Sarat	At initial time	-0.105÷0.093	-0.412÷0.200	-1.309÷1.535
			After 10 year	-0.104÷0.092	-0.405÷0.180	-1.295÷1.478
			After 22 year	-0.101÷0.092	-0.394÷0.188	-1.28÷1.426

The evolutions of the vibration parameters for bridge kinematical excitation with the two signals provided by the records of Vrancea earthquake in 1986, put into the evidence an amplification of maximum values of displacement, velocity and acceleration respectively, in the same time as changing of rigidity coefficients of laminated rubber based on insulators, table 5.

Table 5

The amplification of the deck bridge motion parameters

Event type	Recording point	Moment in time	The increase displacement (m)	The increase velocity (m/s)	The increase acceleration (m/s^2)
Vrancea 1986	Focşani	After 22 year	7.31%	9.9%	6.3%
	Valenii de Munte	After 22 year	7.4%	10.2%	11.5%

The excitation of the analyzed structure with signals provided by the records of Vrancea earthquake in 1990 reveals a quantitative diminishing of maximum values of displacement, velocity and acceleration respectively, for the deck bridge, as shown in table 6.

Table 6

The attenuation of the deck bridge motion parameters

Event type	Recording point	Moment in time	The displacement decrease (m)	The velocity decrease (m/s)	The acceleration increase (m/s^2)
Vrancea 1990	Bîrlad	After 22 year	9.6%	9.6%	5.6%
	Ramnicu Sarat	After 22 year	3.9%	4.5%	7.7%

The analysis of the previously presented results reveals that the same bridge structure, excited by different seismically signals, provides different dynamic responses. It is apparently a contradiction, and to elucidate this aspect was necessary a frequency domain analysis of the excitation signals comparative with natural frequencies of the deck bridge in respect with changing of rigidity on horizontal direction.

The natural frequency according with OY direction of the deck bridge insulated with 16 rubber-based devices, have a variable range, in respect with the rubber aging level, as follows: f_0=1.13 Hz – at initial time; f_{10}=1.17 Hz – after 10 years; f_{20}=1.20 Hz – after 22 years. These values have been evaluated with the following expression (4).

$$f = \frac{1}{2\pi}\sqrt{\sum_{i=1}^{16} k_{iy} / m} \qquad (4)$$

The spectral diagrams of the acceleration signals corresponding with the two-recorded Vrancea earthquakes (Figures 11,12), earlier paragraphs presented, supply following discussions and remarks:

- outstanding components of spectral diagram of Vrancea earthquake in 1986, recorded at Focsani, have a range of 1.15 – 4.17 Hz, which demonstrate the fact that the system has been also excited on main frequency. Thus, the resonance phenomenon provides the increasing of the maximum displacement of the deck bridge.

- similarly, it was observed that the Vrancea earthquake in 1990, recorded at Barlad, the outstanding frequencies within the acceleration spectrum have a range of 1.28 – 2.56 Hz, and does not contains the main frequency values of the deck bridge.

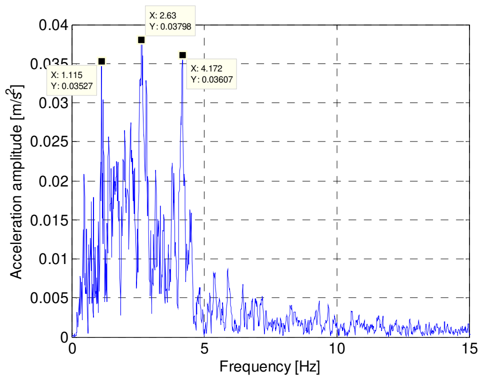


Fig. 11 Spectral representation of seismic acceleration signal, Vrancea 1986, Focsani

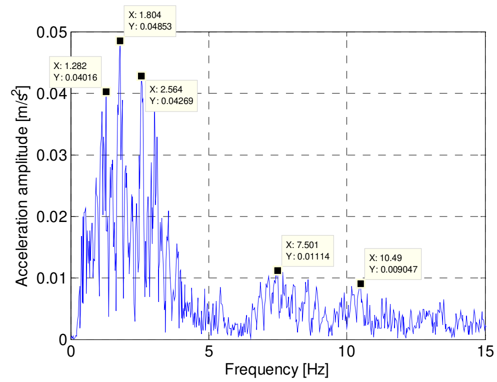


Fig. 12 Spectral representation of seismic acceleration signal, Vrancea 1990, Barlad

5. CONCLUSIONS

Changing of mechanical properties of tested rubber-based anti-seismically insulators due to the natural aging phenomena, provide different modifications of kinematical parameters of vibratory motion of a certain deck bridge, as a structural response of seismically excitations. Hereby, it was obtained amplifications or attenuations of peak values of these parameters, in respect with the same structural configuration of the analyzed system, which demonstrate the fact that this variable response depends on the outstanding frequencies within excitation signal comparatively with the main frequency of the structure.

The seismically actions that excite a bridge superstructure close by its natural frequency lead to resonance phenomenon, which involves the amplification of the kinematical parameters of the vibratory motion.

The concluding remarks of this work justify the hypothesis according with the avoiding of the uncertain dynamic effects within the certain structure requires a careful and elaborate analysis of the structural response for the entirely range of available seismically motions in respect with the geographical area localization of the respective structure.

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Evaluarea răspunsului seismic al tablierului unui pod, izolat prin dispozitive din cauciuc

Rezumat: Podurile si viaductele trebuie sa asigure legatura terestra rutiera intre doua puncte, chiar si in urma unor acţiuni seismice. Evitarea sau diminuarea posibilelor distrugeri, partiale sau totale, ale acestor structuri, se poate realiza prin amplasarea unor sisteme antiseismice intre suprastructura si infrastructura podurilor. Sistemele antiseismice pe baza de cauciuc vulcanizat, prezinta modificari ale rigidităților orizontale si verticale cauzate de imbatranirea naturală a cauciucului. Lucrarea de fata prezinta un studiu, bazat pe date reale, al comportarii dinamice a unui pod, supus actiunilor seismice, a carui tablier este izolat prin intermediul reazemelor vâscoelastice pe baza de cauciuc laminat. Au fost utilizate patru cutremure din zona Vrancea, Romania, fiind evaluat raspunsul suprastructurii podului, in functie de modificarea rigiditatii sistemelor de izolare cauzate de imbatranirea naturală a cauciucului. Concluzia acestui studiu arata faptul ca o miscare seismica de slabă intensitate poate induce un raspuns structural mult mai intens comparativ cu cel indus de un cutremul clasificat normal, in conditiile utilizarii unui sistem de izolare slab acordat si impactului efectelor imbatranirii materialului de baza.

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