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EXPERIMENTAL CORRELATIONS WITH CALCULUS PARAMETERS FOR A DYNAMIC SYSTEM EQUIPPED WITH ANTISEISMIC ELASTOMERIC DEVICES

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Rezumat

Lucrarea prezintă rezultatul încercărilor efectuate la cicluri cinematice cu deplasări instantanee armonice pentru elemente elastomerice cu rol de izolare dinamică în conformitate cu SR EN 1337-3 şi SR EN 15129. Valorile amortizării interne determinate pe standuri de încercare în condiţiile din documentele de referinţă trebuie corelate cu valorile sistemului de dispozitive antiseismice elastomerice ce echipează un sistem dinamic supus acţiunilor seismice exterioare.

În acest caz, pentru fiecare situaţie reală, proiectantul trebuie să realizeze corelaţia dintre cele două valori ale amortizării obţinute în laborator cu amortizarea specifică sistemului structural care este supus acţiunilor dinamice exterioare. Din lucrare rezultă echivalenţa necesară astfel încât, valorile experimentale să poată fi corectate în mod riguros şi să poată reprezenta parametrii reali ce trebuie luaţi în calcul.

Cuvinte cheie: elemente elastomerice, izolare dinamică, amortizare

Abstract

The paper presents the result of experimental tests done at kinematic cycles with instantaneous harmonic displacements, for elastomeric elements with dynamic isolation role, in accordance with SR EN 1337-3 and SR EN 15129. The values of the internal damping determined on testing stands under the conditions specified in the reference documents, must be correlated with the values of the antiseismic elastomeric device system which equips a dynamic system subjected to exterior seismic actions.

In this case, for each real situation, the design engineer must make the correlation between the two values of the damping obtained in laboratory with the damping specific to the structural system which is subjected to dynamic exterior actions. The necessary equivalence results from this paper so that the experimental values can be rigorously correlated and can represent the real parameters which must be taken into consideration.

Keywords: elastomeric elements, dynamic isolation, damping

1. INTRODUCTION

Antiseismic elastomeric devices are the fundamental elements in the composition, adjustment and performance capability of the base isolation systems during seismic actions.

Until the 90s the design and use of hyper elastic supports made of elastomers in various configurations were limited due to execution technologies. Presently, the updated industry is capable of efficiently making quality products at significantly large geometrical shapes and dimensions.

The evolution of the testing methods lead to both experimental system on the stand with displacements imposed by achievable laws, as well as precise measurements of the response function, including the hysteretic loop representation in real time.

In accordance with the European Standard EN 15129:2009, the conformity assessment and CE marking of the anti-seismic elastomeric isolators, used as components of the base isolation systems, are done.

Experimental research carried out on specialized testing facilities, under dynamic regime, is conducted. The testing should reproduce the loading conditions equivalent to the operation specific parameters mainly defined by the geometrical and mechanical characteristics determining the damping and stiffness parameters [1,2].

In order to determine the damping capacity, the elastomeric isolators are subjected to shearing by means of kinematic harmonic excitations defined under the form $x = A_0 \sin \omega_1 t$, where A_0 is the absolute displacement amplitude of the loaded plate edge, in respect to the fixed edge and ω_1 is the kinematic excitation pulsation [3]. In this case, considering of the hysteresis loop for the instantaneous viscoelastic force $Q = kx + c\dot{x}$ depending on the instantaneous deflection x, the loss factor of the internal energy η, representing the dissipation effect, as well as the equivalent critical damping fraction ζ_{eq} are determined.

The loading conditions showed that the isolator has no attached concentrated mass, meaning that $m \equiv 0$, and the excitation is kinematic exclusively with the harmonic displacement externally applied [4].

In this context, the damping expressed by the system parameter ζ_{eq}, defined by $\zeta_{eq} = \dfrac{\Delta W}{4\pi W_{el}^{\max}}$, differs as compared with the parameter ζ related to a linear viscoelastic system having the mass $m \neq 0$, expressed under the form of $\zeta = \frac{c}{2\sqrt{km}}$ [2].

Thus, the damping parameter ζ_{eq} could be determined by laboratory testing only. Thus, the actual structural analysis using the supporting and the base passive isolation system, having appropriate configuration, the values of parameter ζ_{eq} in correlation with the effective parameter ζ for the actual system, should be taken into account [5].

2. EXTERIOR HARMONIC ACTIONS APPLIED ON THE ELASTOMERIC ISOLATOR

This correlation between ζ_{eq} obtained under harmonic elastic deflection actions kinematic applied and ζ_d under dynamic actions could be performed, so that the energy dissipated under the kinematic regime ΔW_c would be equal to the energy dissipated under dynamic regime ΔW_d.

Figure 1 represents a physical system with a symmetric excitation system. The linear viscoelastic system characteristics are c and k, without an added mass.

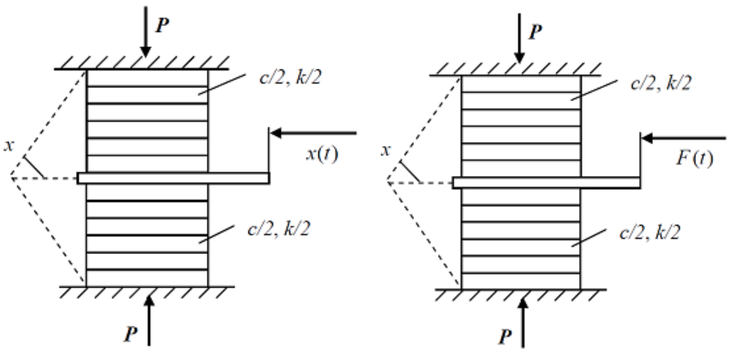

Figure 1. Physical Model with a Symmetric Excitation System (Kinematic and Dynamic)

2.1. Kinematic Excitation

Under the kinematic excitation, of the form $x(t) = A_0 \sin \omega_1 t$, the dynamic response related to the viscoelastic connection force $Q(t)$ is obtained as [6]:

$Q(t) = kx + c\dot{x} \equiv Q_0 \sin(\omega_1 t - \varphi_1)$ and further:

$$Q_0 = kA_0\sqrt{1+\eta_1^2} \quad (1)$$

$$tg\varphi_1 = \frac{c\omega_1}{k} = \eta_1 \tag{2}$$

The dissipated energy ΔW_c can be written as: $\Delta W_c = \pi c\omega_1 A_0^2$

If one introduces $c\omega_1 = k\eta_1$, the previous relation becomes:

$$\Delta W_c = \pi k\eta_1 A_0^2 \tag{3}$$

2.2. Dynamic Excitation

For the viaduct situated on the Transilvania Highway, made by the Bechtel Company and experimented on by ICECON SA, the simplified structural model is presented in figure 2. The viaduct is built from 20 beams of reinforced concrete, supported individually upon sets of identical bearings of elastomer. The 20 beams are grouped in four rows (Cx axis) by fives each (Cy axis), their joining performing constructional by means of a top plate manufactured of reinforced concrete as a bonding and leveling subfloor form.

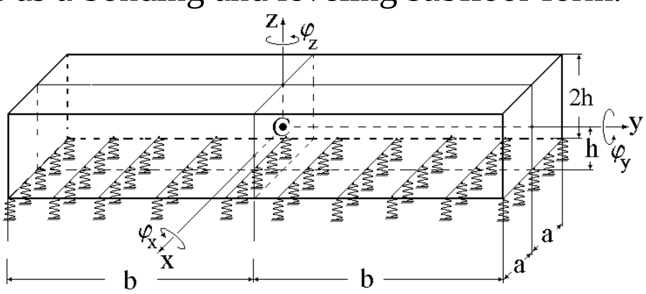

Figure 2. The simplified model of the viaduct with 20 beams of reinforced concrete

The inertial and geometric characteristics of the “Bechtel” viaduct are as follows:

a) dimensional quantities $2a = 13{,}2m$ and $2b = 200m$;

b) quantities of position in plane x_i, y_i, $i = \overline{1{,}80}$, with tabular values in height $z_i = h = 1{,}5m$;

c) inertial quantities of the viaduct:

- total mass $m = 4\ MKg$;
- mass moments of inertia:

$$J_{xy} = J_{yz} = J_{zx} = 0$$

$$J_x = J_z = 14\ GKgm^2$$

$$J_y = 64\ MKgm^2$$

- total weight: $Q = 40\ MN$

d) total number of bearings: $N = 80 \ buc$

The elastic characteristics of the identical bearings are established in five possible versions, only one being presented in this paper. In this situation, the proper pulsations (proper values) of the (elastic, inertial) decoupled vibrations will be established for each degree of freedom, thus: $X(p_x)$; $Y(p_y)$; $Z(p_z)$; $\varphi_x(p_{\varphi_x})$; $\varphi_y(p_{\varphi_y})$; $\varphi_z(p_{\varphi_z})$.

For each version of elastic supporting, the modification of the proper values and proper modes of the coupled vibrations on four subsystems (the decoupling being operational through the cases of geometric symmetry and elastic supporting) will be analyzed, thus: $X, \varphi_y(p_1, p_2)$; $Y, \varphi_x(p_3, p_4)$; $Z(p_5)$; $\varphi_z(p_6)$.

The introduced data in the Matlab numerical computing program are:

Dimensions: $2b = 200m$

$$2a = 13{,}2m$$

$$2h = 3m$$

Mass: $m = 4 \times 10^6 \, kg$

Computed inertial characteristics: $J_{xy} = J_{yz} = J_{zx} = 0$

$J_x = 13{,}336 \cdot 10^9 \, Kg \cdot m^2$; $J_y = 61{,}080 \cdot 10^6 \, Kg \cdot m^2$; $J_z = 13{,}391 \cdot 10^9 \, Kg \cdot m^2$

The elasticities depend on the chosen version, version 1 for the present paper: *Mageba bearing Type C, 300x400x80*: $k_{ix} \equiv k_x = k_{iy} \equiv k_y \quad [N/m]$ $k_{iz} \equiv k_z \quad [N/m] \quad i = \overline{1{,}80}$

For the Mageba bearing Type C, 300x400x80, presented in figure 3 one has the following initial data, while Tables 1 and 2 present the main obtained results:

$a' = 300mm$; $b' = 400mm$; $t = 80mm$; $T_e = 36mm$

$$T_e = 3 \cdot 12 = 36mm$$

$$t = T_e + 2 \cdot 14 + 4 \cdot 4 = 80mm$$

$$k_{1z} = k_z = 627 \cdot 10^6 \, N/m$$

$$k_{1x} = k_{1y} = 3 \cdot 10^6 \, N/m$$

$$\rho_k = \frac{k_{1z}}{k_{1x}} = 209$$

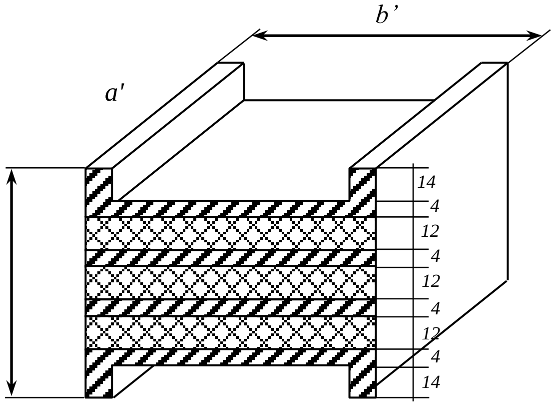

Figure 3. Mageba bearing Type C, 300x400x80

Table 1. Proper pulsations / frequencies of the uncoupled vibrations

Direction	X	Y	Z	φ_x	φ_y	φ_z
p [rad/s]	7,75	7,75	111,98	115,13	107,40	7,96
f [Hz]	1,23	1,23	17,82	18,32	17,09	1,27

Table 2. Proper pulsations and frequencies of the subsystems with decoupled motions

Subsystem	**Pulsation [rad/s]**	**Frequency [Hz]**	**Distribution coefficient [rad/m]**
(X,φ_y)	$p_1 = 7{,}74$	$f_1 = 1{,}23$	$\mu_1 = 128{,}163$
	$p_2 = 107{,}40$	$f_2 = 17{,}09$	$\mu_2 = 0{,}666$
(Y,φ_x)	$p_3 = 7{,}75$	$f_3 = 1{,}23$	$\mu_3 = -147{,}2705$
	$p_4 = 115{,}13$	$f_4 = 18{,}32$	$\mu_4 = -0{,}667$
(Z)	$p_5 = 111{,}98$	$f_5 = 17{,}82$	-
(φ_z)	$p_6 = 7{,}96$	$f_6 = 1{,}27$	-

Under the dynamic excitation of the form $F(t) = F_0 \sin \omega_2 t$, where F_0 represents the amplitude of the action, the displacement response $u = u(t)$ is obtained using the following instantaneous dynamic equilibrium equation:

$$c\dot{u} + ku = F_0 \sin \omega_2 t \tag{4}$$

Equation (4) underlines that one works with a I[st] order physical system, without mass, so its resonance is less. The solution $u(t) = A \sin(\omega_2 t - \varphi_2)$ should verify equation (4), leading to the following relation [5]:

$$A = \frac{F_0}{k} \frac{1}{\sqrt{1+\eta_2^2}}, tg\varphi_2 = \frac{c\omega_2}{k} = \eta_2 \tag{5}$$

Taking into consideration relation (5), the dissipated energy ΔW_d is given by the equation:

$$\Delta W_d = \pi k \eta_2 \frac{F_0^2}{k^2} \frac{1}{1+\eta_2^2} \tag{6}$$

and using the condition that $\Delta W_c = \Delta W_d$, results in

$$\eta_1 \eta_2^2 - \Psi^2 \eta_2 + \eta_1 = 0 \tag{7}$$

with $\Psi = \dfrac{F_0}{kA_0}$ being the dynamic multiplication factor.

From (7) one obtains η_2 under dynamic regime, depending on η_1 under kinematic regime, as follows:

$$\eta_2 = \frac{1}{2\eta_1}\left[\Psi^2 \pm \sqrt{\Psi^4 - 4\eta_1^2}\right] \tag{8}$$

a) the single solution of equation (8) is possible only under the following condition:

$$\Psi^4 - 4\eta_1^2 = 0 \quad (9)$$

and further

$$\Psi = \frac{F_0}{A_0 k} = \sqrt{2\eta_1} \quad (10)$$

In this case, the solution of equation (8) is under the form:

$$\eta_2 = \frac{\Psi^2}{2\eta_1} = \frac{2\eta_1}{2\eta_1} = 1 \tag{11}$$

Thus, the loss factor has a unitary value and $\zeta_2 = \frac{1}{2}\eta_2 = 0{,}5$. $\zeta_2^{\max} = 0{,}5$ represents the maximum value.

b) the actual and distinct solutions of equation (8) are possible only for $\Psi^4 - 4\eta_1^2 > 0$, or $\Psi > \sqrt{2\eta_1}$. In case of actual parametric values $0{,}2 \le \eta_1 \le 1{,}6$, the range for Ψ is obtained as $0{,}63 \le \Psi \le 1{,}78$.

As an example, an elastomeric isolator without additional mass, with $k = 1{,}5 \cdot 10^6\, N/m$, $\zeta_{eq} = 0{,}20, \eta_1 = 0{,}40$ is tested in laboratory under harmonic cycles having the linear amplitude $A_0 = 0{,}08$ m. Under harmonic dynamic regime, characterized by $F_0 = 120$ kN, the damping η_2 is obtained as follows:

$$\Psi = \frac{F_0}{kA_0} = \frac{10^5}{1{,}5 \cdot 10^6 \cdot 8 \cdot 10^{-2}} = 1 > \sqrt{2 \cdot 0{,}4} = 0{,}89$$

and from relation (8) it results in $\eta''_2 = 2{,}0$ leading to $\zeta'_2 = 0{,}25$ and $\zeta''_2 = 1{,}0$, respectively, both values being higher than $\zeta_{eq} = 0{,}20$.

3. HARMONIC SEISMIC ACTIONS ON THE ELASTOMERIC ISOLATOR

The dynamic model for the linear viscoelastic base isolation system, with *m*, *k* and *c* considered as system parameters, is represented in Fig. 4, for two distinct positions: under instantaneous translation motion and under the seismic action with the instantaneous acceleration $\ddot{u} = a_0 \sin \omega t$ [5].

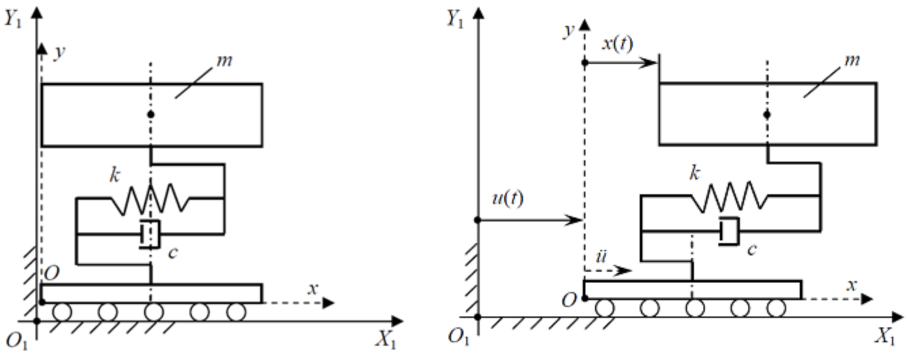

Figure 4. Dynamic Model of the Passive Isolation System

The equation of motion for the mass *m*, related to the fixed reference system $O_1X_1Y_1$ is of the form $m\ddot{x}_1 + c\dot{x} + kx = 0$ (12)

in which $x_1 = u + x$ represents the absolute displacement.

The relative displacement of the mass *m*, with respect to the moving reference system (having the acceleration $\ddot{u}$) Oxy is $x(t)$. Thus, one has:

$$m(\ddot{u} + \ddot{x}) + c\dot{x} + kx = 0$$

or $m\ddot{x} + c\dot{x} + kx = -m\ddot{u}$ (13)

If one introduces $\ddot{u} = a_0 \sin \omega t$, the previous relation becomes:

$$m\ddot{x} + c\dot{x} + kx = -ma_0 \sin \omega t \tag{14}$$

The final solution is:

$$x = A\sin(\omega t - \varphi) \tag{15}$$

in which A and φ are obtained from the condition that verifies equation (14). Thus, it results

$$A = \frac{a_0}{\omega_n^2} \frac{1}{\sqrt{(\Omega^2 - 1)^2 + 4\zeta^2\Omega^2}}; \; tg\varphi = \frac{2\zeta\Omega}{1 - \Omega^2} \text{ and } \Omega = \frac{\omega}{\omega_n}; \omega_n^2 = \frac{k}{m}. \tag{16}$$

The energy dissipated under seismic dynamic excitation regime, is [4,5]: $\Delta W_d = 2\pi\zeta \frac{m}{\omega_n^2} a_0^2 \frac{\Omega}{\left(\Omega^2-1\right)^2+4\zeta^2\Omega^2}$ and the condition $\Delta W_c = \Delta W_d$ leads to the following relation:

$$\zeta_{eq} = \frac{\alpha^2\zeta\Omega}{\left(\Omega^2-1\right)^2+4\zeta^2\Omega^2} \tag{17}$$

Further we have the second order equation in ζ, of the form $4\Omega^2\zeta_{eq}\zeta^2 + \left(\Omega^2-1\right)^2\zeta_{eq} = \alpha^2\Omega\zeta$ and having the solution:

$$\zeta = \frac{1}{8\Omega^2\zeta_{eq}}\left[\alpha^2\Omega \pm \sqrt{\alpha^4\Omega^2 - 16\Omega^2\left(\Omega^2-1\right)^2\zeta_{eq}^2}\right] \tag{18}$$

At resonance, for $\Omega = 1$, one obtains $\zeta_{rez} = \frac{1}{4}\frac{\alpha^2}{\zeta_{eq}}$ (19)

where $\alpha = \frac{a_0}{A_0\omega_n^2}$ is the acceleration multiplication factor.

As an example, an elastomeric isolator having $k = 1{,}5\cdot 10^6$ N/m, $\zeta_{eq} = 0{,}2$ is tested at $A_0 = 0{,}088$ m. For a structural system with $\omega_n = 2\pi$ subjected to a maximum acceleration $a_0 = 0{,}25g$, the result is:

$$\alpha = \frac{0{,}25\cdot 10}{0.088\cdot 4\pi^2} = 0{,}707$$

$$\zeta = \frac{1}{4}\frac{0{,}707^2}{0{,}2} = 0{,}62$$

meaning that ζ for the system is three times higher than ζ_{ech} determined in the laboratory.

4. CONCLUSIONS

The following conclusions can be synthesized based on the analysis intended to equalize the dissipated energy under different excitation regimes, kinematic and dynamic:

a) the testing method with kinematic excitation only, with harmonic displacement of the form $x(t) = A_0 \sin\omega_1 t$ allows the determination of the equivalent damping ζ_{eq}. This is specific to the isolation system under laboratory experimental configuration, only.

b) the damping evaluation under dynamic excitation for systems having actual dynamic behavior puts into evidence the necessity to determine the system parameter ζ as a function of the experimental parameter ζ_{eq};

c) ζ for the system under actual configuration depends both on the type of the dynamic excitation as well as the existence of the mass with inertial effect.

d) that a parametric correlation is required between the parametric values resulted from the product testing on stand and the necessary values which must be established as functional parameters in real experimental conditions of the antiseismic isolated building.

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