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Response of structures isolated with elastomeric bearings subjected to low-intensity earthquakes

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SUMMARY

When deformations of the rubber are small, its stiffness significantly increases. This increase of stiffness shortens the period of the structure and it may shift it into the resonant region in the earthquake acceleration spectrum. Therefore, the seismic isolation with elastomeric bearings may become ineffective. Due to the less effective base isolation the equipment installed in the structures can be particularly jeopardized. To identify when the standard elastomeric bearings become ineffective, a parametric study was performed. The yield force and yield displacement of bearings were varied. In this way the influence of the bearing nonlinearity and damping to the effectiveness of the base isolation was studied. The standard bilinear macro model of the elastomeric bearings could not be used in this parametric study, since it can not describe the response of the bearings in the small deformation range, realistically. Therefore, an enhanced macro model was studied and used in the analysis. Primarily, the floor acceleration spectra were analyzed since it was expected that the equipment, installed in the structures was jeopardized more than the structure itself. It was found that the standard elastomeric bearings were less effective when their response corresponding to the weaker earthquakes was more nonlinear. In these cases the applicability of the new smart semi-active elastomeric bearing, which can keep the stiffness independent of the load intensity was found feasible. This device is also briefly described.

Key words: *seismic isolation, numerical models, elastomeric bearings, floor spectra.*

1. INTRODUCTION

At the small amplitude response the stiffness of the rubber typically increases (due to the changes of the shear modulus *G*). It could be several times larger than stiffness corresponding to the high amplitude response. This increase of stiffness means shortening of the period of a structure, and consequently shifting of a structure towards the resonant region in the acceleration spectrum (see Figure 1). This means that relative accelerations of the storey masses (the ratio of accelerations of storey masses over the applied ground acceleration) can increase under the lower intensities of an earthquake, in some cases resulting in a considerable increase of accelerations of the installed equipment. The increase of the acceleration of the equipment could be in some cases so considerable, that their absolute values under the smaller intensities of an earthquake can be even larger of those corresponding to much stronger earthquakes (even 10 times stronger).

To identify when the high damping rubber bearings (HDRB) become less effective, a parametric study was performed. The main goal was to quantify the amplification in the response at weaker earthquakes (in absolute terms and relative to the response at strong earthquakes), due to the increase of rubber effective stiffness at smaller amplitudes, as well as to identify at what level of earthquake this effect becomes important. To obtain this information a non-linear floor acceleration spectra were studied. The selected results of the study are presented in Chapter 3.

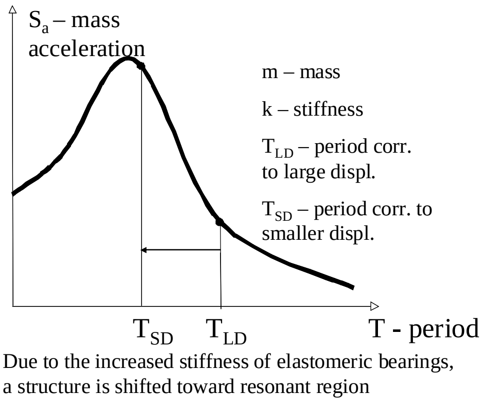


Fig. 1 Due to increased stiffness at weaker earthquakes, the structure is shifted toward the resonant region of the acceleration spectrum

The response of the HDRB subjected to weaker earthquakes could not be studied by the standard bilinear macro model, which is typically used for the analysis of isolated structures subjected to stronger (design) earthquakes. Therefore, a more realistic and enhanced Wen's macro model [1] was used in the parametric study. Comparison of the standard and enhanced models and related results are presented in Chapter 2.

If the installed equipment and the structure itself are jeopardized when they are subjected to weaker and more frequent earthquakes, it is feasible to use an isolator, which can keep the stiffness of the structure constant and independent of the load intensity. Such an isolator, has been developed in the frame of the 5th frame European project VAST-IMAGE. A consortium of industry (Maurer Söhne, Germany, the principal investigator; TARRC, Great Britain, BIKANI, Spain), university and institute research teams (CESI and ENEA, Italy; University of Ljubljana (ULJ), Slovenia; IFW, Germany) has collaborated within this project. The new device is briefly described in the Chapter 4.

2. ENGINEERING MODELS FOR STANDARD ELASTOMERIC BEARINGS

A standard macro model with bilinear force-displacement envelope (see dotted line in Figure 2) is typically used for modelling standard HDR bearings. This model is suitable for the analysis in the large strain range since the discrepancy with the actual behaviour in the small deformation range and unloading phase (see Figure 2a) has a small influence on the overall response. However, this discrepancy becomes important when the structure is subjected to weaker earthquakes when deformations of the HDRB are relatively small. In these cases the traditional bilinear model can not describe the actual response realistically. The stiffness in the initial loading phase, the "yielding force" as well as the amount of dissipated energy are typically overestimated if the traditional model is used (see Figure 2b).

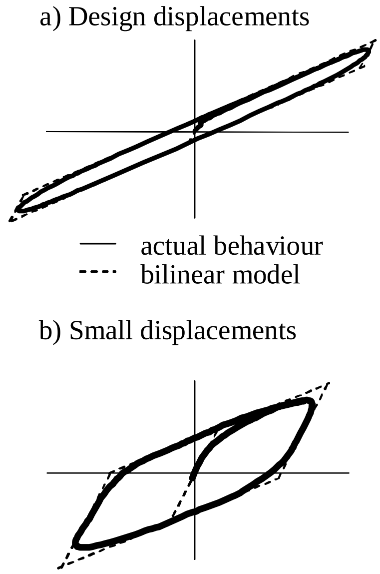


Fig. 2 HDRB: Actual response and response obtained using the traditional bilinear model

To estimate the response of an isolated structure, subjected to lower and moderate seismic load, more realistically, improved models were studied. Two available models, which can take into account the gradual change of stiffness in the initial loading as well as in the unloading phase, were compared. A model, developed by ENEL-HYDRO/ISMES [2] which was included into program ABAQUS [3] has been compared with the similar Wen's model incorporated into the program SAP2000 [4]. Both models yielded practically the same results. Therefore, the simpler Wen's model has been used in the further analyses.

The basic parameters of Wen's model are presented in Figure 3. They are: initial stiffness k, yielding force F_y, strain hardening *sh* and the exponent *exp* which defines the force-displacement relationship at the beginning of loading and unloading phase. The research team at the ULJ incorporated this model to an open source program system OpenSees [5], which becomes the reference program for nonlinear analysis of civil engineering structures. The same program system has been lately used for the analysis of the structures isolated with the new elastomeric bearings (see Chapter 5).

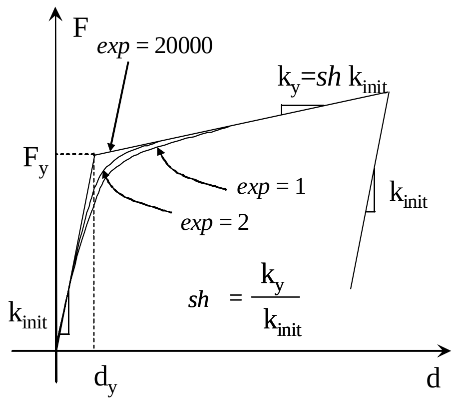


Fig. 3 Wen's model, used to model HDRB bearings

Hysteresis loops predicted by bilinear model of HDRB and those obtained with the improved model were compared for different levels of the earthquake load. Loops obtained in response to time-history inputs corresponding to *100%* and *20%* of the design earthquake are presented in Figures 4a and 4b, respectively. As it was expected, the larger differences were observed for the weaker earthquakes (Figure 4b). Similar conclusions have been obtained analysing other monitored quantities (e.g. the floor acceleration spectra at the top of the structure, which are described in the next section).

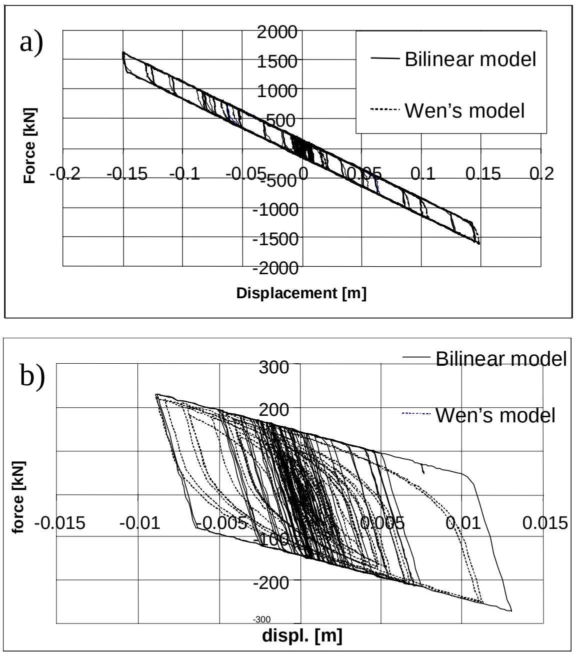


Fig. 4 Comparison of the response obtained by the Wen's and bilinear model: a) for design earthquake; b) for 20% of the design earthquake

3. PARAMETRIC STUDY

3.1 Structures and isolators analyzed, earthquake input

Different types of structures have been studied: a) idealized cantilever single-degree-of-freedom (SDOF) systems; b) idealized cantilever multi-degree-of-freedom (MDOF) systems; and c) a navy hospital constructed in Italy. In general the results obtained for different types of structures were not significantly different, therefore only the results for SDOF systems are presented and summarized in the paper.

Main properties of analysed SDOF structures are summarised in Figure 5. Different sets of standard HDRB isolators were used to isolate the structure. The "yield force" F_y and the corresponding displacement d_y were varied. In this way the initial stiffness was changing and the nonlinearity as well as the damping of the bearings was varied.

The properties of the basic type of isolator (type FD in Figure 5) were experimentally determined. To change its capabilities to dissipate the seismic energy, the corresponding force-displacements envelopes were modified in three ways:

- the force level, "yield force" F_y (see Figure 5) as well as the corresponding displacement d_y were increased for three times – this is the 3F3D type of isolator (see Figure 5);
- only the "yield force" F_y was increased three times (isolator 3FD);
- only "yield displacement" d_y was increased three times (F3D).

Five accelerograms were applied to all structures (corresponding spectra are presented in Figure 6). Those accelerograms were generated, based on the elastic acceleration spectra for the soil type B according to the standard Eurocode 8 [6], assuming the peak ground acceleration of a_g*=0.25g* for soil type A. According to EC8 standard the effective peak ground acceleration for soil type B is 1.2 times larger than for soil type A (a_g*=0.3g*).

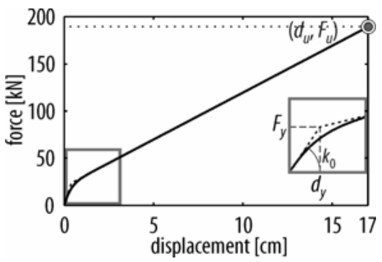
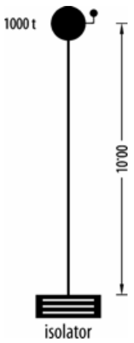
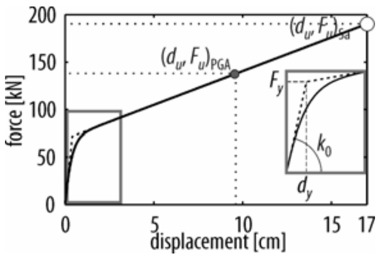
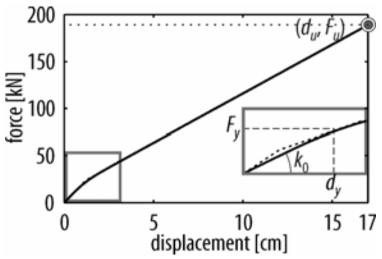
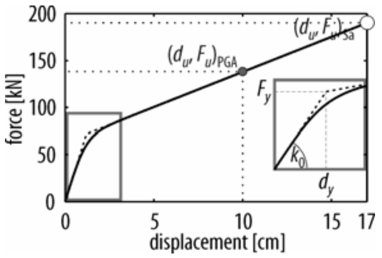
The peak ground acceleration was varied from *0.03g* to *0.30g* (soil type B) with a step of *0.03g*, for each accelerogram. As a result, 50 linear and 50 non-linear analyses have been performed for each analysed structure.

Additional studies were preformed for structures isolated with bearings 3FD and 3F3D, where the maximum intensity (PGA) was additionally increased to *0.48g*, and the accelerations were varied from *0.048g* to *0.48*g. These additional studies were carried out since the maximum displacement of these bearings did not reach the design level of *17 cm* when the structure was subjected to earthquake load of intensity *0.3g*. When the PGA was increased, mass acceleration at the top of the cantilever reached the same value as in the case of more linear types of bearings (FD and F3D) and lower peak ground acceleration of *0.3g*.

3.2 Response of the structures

The acceleration as well as the displacement responses obtained for low-level earthquakes did not exceed the values corresponding to the design earthquake in any of the analysed structures. Therefore it can be concluded that the structure itself is not jeopardized when subjected to weaker earthquakes. However, it was noted that the decrease of the acceleration and displacement responses was smaller than the corresponding decrease of the load intensity.

The secant, equivalent stiffness (see Figure 7a) is usually considered as the main design parameter of the HDRB. Its increase at low rubber shear strains can be substantial. However, it is important to realise that this increase is typically accompanied by an increase in (effective) damping (see the changes of damping for

	max PGA [g]	isolators	F – d envelope of isolators	ξ_{eff}	S_a [m/s²]	Properties of isolator
	0.30	FD		0.06	1.60	n = 9 k_o = 60 kN/cm F_y = 24 kN d_y = 0.4 cm F_u = 193 kN d_u = 17 cm
T_{ni} = 0.50 s T_i = 2.00 s 	0.30 (0.48)	3FD		0.30 0.23	0.97 1.60	n = 7 (9) * k_o = 180 kN/cm F_y = 72 kN d_y = 0.4 cm F_u = 137 (193) kN * d_u = 9.6 (17) cm *
	0.30	F3D		0.04	1.60	n = 9 k_o = 20 kN/cm F_y = 24 kN d_y = 1.2 cm F_u = 193 kN d_u = 17 cm
	0.30 (0.48)	3F3D		0.26 0.20	1.00 1.60	n = 7 (9) * k_o = 60 kN/cm F_y = 72 kN d_y = 1.2 cm F_u = 138 (193) kN * d_u = 10 (17) cm *

T_{ni} = fundamental period of non-isolated structure, T_i = fundamental period of isolated structure (at max deformation), ξ_{eff} = equivalent damping (at max deformation), n – number of isolators, k_o – initial stiffness of bearings, F_y – yield force, d_y – yield displacement, F_u – ultimate force demand, d_u – ultimate displacement demand
* values presented in brackets correspond to PGA of 0,48g

Fig. 5 Summary of the structures analyzed

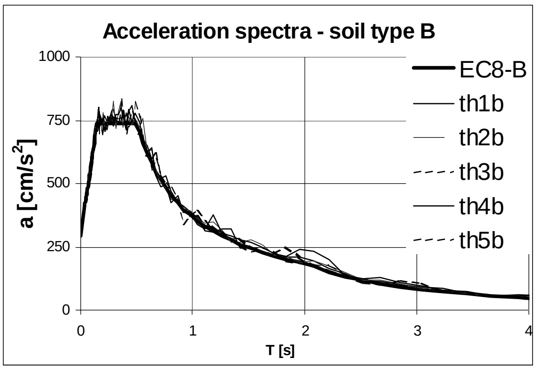


Fig. 6 Spectra corresponding to earthquake input

all analyzed types of bearings in Figure 7b). It is evident form Figure 7c that the effective damping (ratio of the grey and dotted area in Figure 7c) could be substantially larger at the small amplitude range than at the design displacement range. Consequently, the effect of changes in the equivalent stiffness at low displacements should never be analysed independently of changes in the damping. Ignoring the higher damping at smaller displacement amplitudes could create a false impression of the importance of the effect due to the change of stiffness. This observation was confirmed by the inelastic analysis as well as verified by the standard equivalent elastic procedure. At very small deformations of the bearing the equivalent damping decreases (shaded area in Figure 7b) while the stiffness continues to increase. So again it is necessary to consider the effect of changes in both the damping and the stiffness.

3.3 Response of the equipment – floor acceleration spectra

The response of the equipment was studied analyzing the floor acceleration spectra. These spectra represent the accelerations of the secondary mass (equipment) depending on its period (frequencies). The floor spectra are calculated in response to storey mass acceleration time-histories. The average floor spectra (for five different earthquake inputs) were analyzed.

The results of two sets of analyses are presented in the paper – one for the 3F3D type of isolator and the other for the F3D type. With these two cases the different degree of nonlinearity also results in a substantial difference between the equivalent damping. The results are presented in Figures 8 and 9. In each figure the plots give the floor spectra in terms of absolute accelerations of the equipment, corresponding to *2%* and *5%* damping of equipment.

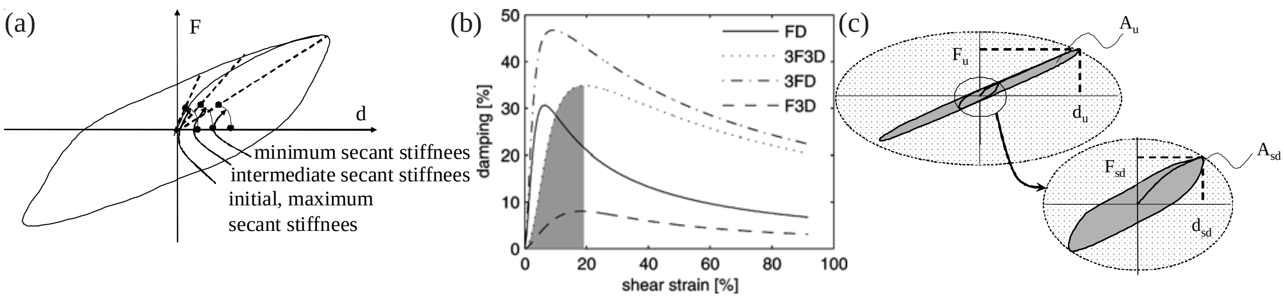


Fig. 7 HDRB: Changes of: a) equivalent stiffness; b) equivalent damping ξ_{ef}; and c) calculation of the equivalent damping ξ_{ef}

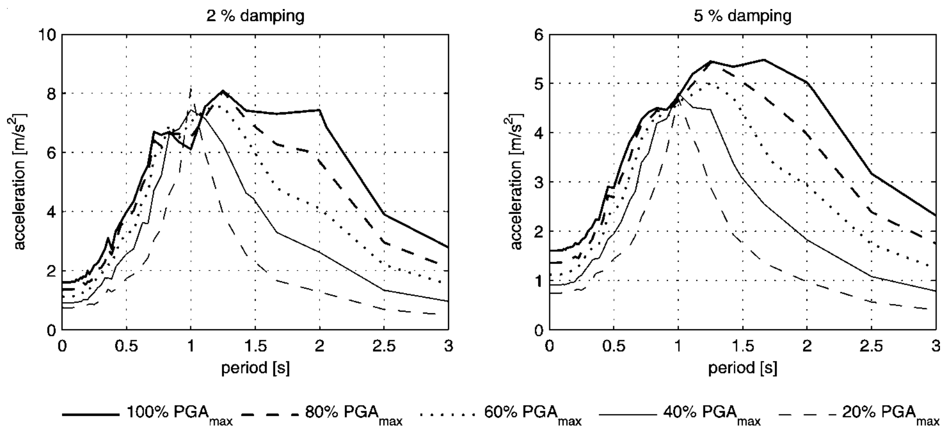


Fig. 8 Floor acceleration spectra in the structure isolated with 3F3D bearings

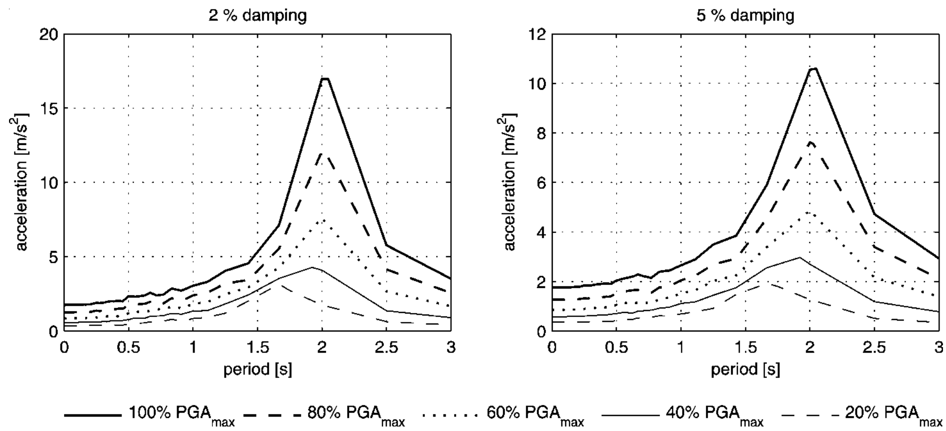


Fig. 9 Floor acceleration spectra in the structure isolated with F3D bearings

The average floor spectra indicate that there are cases when the acceleration of the equipment at weak earthquakes is similar or even greater than in the case of design earthquakes. This is documented for the equipment having relatively small damping and having natural period close to the period of the isolated structure at low intensity earthquakes. An example is the structure isolated with the 3F3D bearings. These bearings show a significant change of stiffness with displacements; the degree of nonlinearity is thus large as well as the damping (see Figure 5). The structure, which is isolated with this type of bearings, has a period of about *2 s* at the design displacements, while the period reduces to *1 s* for displacements produced by the lower seismic input (*20%* of the design earthquake). It is evident from Figure 8 that the safety and functionality of the equipment with periods close to *1 s* is potentially jeopardized when it is installed in a structure isolated with 3F3D bearings. The accelerations imposed on such equipment by an input only *20%* of design magnitude are seen to be of similar size to those corresponding to the design earthquake.

On the contrary, when the bearing exhibits a relatively small change in stiffness and the nonlinearity is relatively low (as in the case of F3D isolator) the equipment is not jeopardized at all. This is evident from Figure 9, where the floor acceleration spectra for structure, isolated with the F3D bearings are presented. These spectra differ markedly in character from those for the 3F3D isolators. In all cases accelerations produced by lower-intensity earthquakes remain substantially lower than those corresponding to design earthquake. Since the stiffness of the bearings does not change so significantly as in the case of 3F3D bearings, changes of the periods of the isolated structure are also smaller (*2 s* at the design earthquake and *1.6 s* at the *20%* of the design earthquake). Consequently the resonant region is more stable and it is not so significantly shifted like in the case of 3F3D bearings.

4. DESCRIPTION OF THE NEW MCE DEVICE

To protect primarily the installed equipment in the isolated structures subjected to weaker earthquakes, a new smart elastomeric isolator has been projected. A prototype of this device, which can reduce the stiffness at lower seismic intensity levels, has been designed by Maurer Söhne. The scheme of the new device is presented in Figure 10. It consists of the new material, magnetically controlled elastomer (MCE), which has been developed by IFW and TARRC. The new material consists of the rubber where the iron particles are vulcanized. These particles are added to be able to neutralize the increase of rubber stiffness in the small deformation range. The increase of the rubber stiffness is neutralized changing the magnetic flux density, produced by the permanent magnet, which is one of the main components of the new isolator.

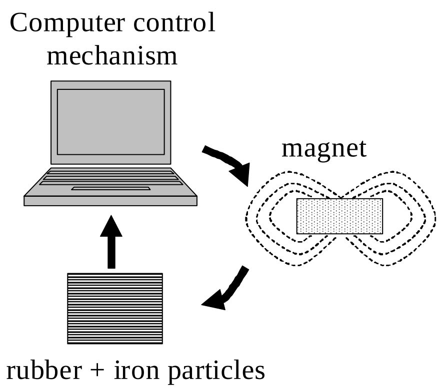


Fig. 10 Scheme of the new isolating MCE device

There are two states of the device: passive and active. In the passive state the magnetic filed of the permanent magnet is present and the large stiffness is ensured protecting the structure of excessive deformation produced by wind and other ambient vibrations. When the structure is subjected to lower level earthquakes the device passes to its active state, where the magnetic field is annulled and the stiffness is reduced reaching the value close to that corresponding to larger deformations. To switch between two states the device is provided by special control algorithm.

5. CONCLUSIONS

Standard HDRB with strong nonlinearity can lead to excitation of the equipment with a short period far below the structure's isolated period. The level of excitation due to earthquakes with an intensity of only *20%* of the design level can be comparable to that produced by the design earthquake. Thus the serviceability of sensitive equipment in isolated structures has to be considered for earthquakes well below the design level. In such cases the use of the new MCE device is feasible.

The excitation of the isolated structure itself due to the lower-intensity earthquakes has never exceeded that produced by design earthquakes. Although the ratios of the mass and peak ground accelerations are typically much higher when the structure is subjected to frequent earthquakes, the structure itself is not jeopardized.

The standard bilinear macro-model of HDRB becomes inefficient when the response of isolated structures subjected to lower-intensity earthquakes is analyzed. For such analyses the Wen's macro model is more appropriate. It can describe more realistically the response of the HDRB in the small deformation range.

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ODGOVOR KONSTRUKCIJA, IZOLIRANIH POMOĆU ELASTOMERNIH LEŽAJEVA, NA POTRESE NISKIH INTENZITETA

SAŽETAK

Krutost gume pri malim deformacijama može znatno narasti. Zbog toga se skraćuje period konstrukcije te se ona posljedično može pomaknuti ka rezonantnom području u potresnom spektru ubrzanja. Zato potresna izolacija s elastomernim ležajevima može postati neučinkovita. Pri tome je posebice ugrožena oprema, koja je instalirana u izoliranoj konstrukciji. Da bi se ustanovilo kada elastomerni ležajevi postaju neučinkoviti, urađena je parametarska studija, u kojoj su varirani sila tečenja i pomaci na granici tečenja ležaja. Na taj način je analiziran utjecaj nelinearnosti i prigušenja ležajeva na učinkovitost potresne izolacije. U ovoj studiji nije bilo moguće upotrijebiti standardni bilinearni makro model ležaja, budući da on ne može realno opisati njihov odgovor u području malih deformacija. Zato je analiziran i upotrijebljen poboljšan model. Prvenstveno su proučavani etažni spektri ubrzanja instalirane opreme, jer je oprema ugroženija od same konstrukcije. Ustanovljeno je da su standardni elastomerni ležajevi manje učinkoviti ukoliko je njihov odgovor pri slabijim potresima izrazito nelinearan. U takvim slučajevima se mogu upotrijebiti novi inteligentni semiaktivni elastomerni ležajevi kod kojih je krutost neovisna o intenzitetu opterećenja. Taj uređaj je također ukratko opisan.

Ključne riječi: *seizmička izolacija, numerički modeli, elastomerni ležajevi, etažni spektri.*