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THE EFFECT OF USING DIFFERENT DEVICE NUMERICAL MODELS ON THE GLOBAL NONLINEAR BEHAVIOUR OF BASE ISOLATED STRUCTURES

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ABSTRACT

In this paper a sensitivity analysis on the effect of B.I. device modeling on the nonlinear behavior of base isolated multistory frames is carried out. For this purpose, the equivalent linear viscous model and two bilinear hysteretic models are considered. The comparison among superstructure response parameters obtained from dynamic nonlinear analyses, shows a substantial agreement among the models, and allows for considering the linear viscous model as the most convenient one, especially in the case of parametric analysis.

KEYWORDS

Base isolation device models, High damping rubber bearings, Equivalent viscous damping, Multistory base isolated frames.

PREFACE

The energy dissipation mechanisms of the devices used within Base Isolation Systems differ substantially depending on the specific typology of the device. Even within a single typology like the one referred to in this paper, i.e. High Damping Rubber Bearings (HDRB), it is not definite if the dissipation is completely either of viscous or of hysteretic nature, and therefore if it is dependent upon strain rate or maximum displacement.

Several papers have been published with reference to this problem by providing the experimental response and evidencing the difficulties arising in numerical simulation (Stanton and Roeder, 1991; Harris and Stevenson, 1989). Among these, here it is simply reminded that Kelly (1991) suggests to adopt an intermediate form between hysteretic and viscous models, in which the dissipated energy depends on the displacement to approximately the 1.5th power. In (Ahmadi et Al., 1994) instead, two different nonlinear models, respectively of the hysteretic and Kelvin type, are proposed for underlining the effects of nonlinearities on the response of rubber isolators to earthquake ground motions. Always with reference to single isolators in (De Luca et Al., 1994a) the experimental response of rubber devices, subjected to different ground motions, is compared to numerical simulations performed through a linear Kelvin model and different nonlinear hysteretic models. The comparison is carried out for different earthquakes, scaled up to different intensities in order to evidence the accuracy of the numerical models in simulating the response to smaller than the design earthquake.

No definite answer on the best numerical model to be used for reproducing the nonlinear response of HDRB can be found in the literature, since the actual behaviour is strongly dependent upon compounding of rubber. Furthermore a question might arise on the adequacy of adopting the previous models when a complete analysis of MDOF systems has to be performed. In this case, in fact the question is: how numerical modelling of the device can interact with nonlinear behaviour in the superstructure?

The analysis which is proposed in this paper is of the comparative type, since the nonlinear response of MDOF systems, in which the superstructure is driven into high inelastic deformation field, is computed by adopting different numerical models (linear and nonlinear) of the isolation system. The response is compared in terms of displacements, shear forces and plastic rotations.

In the first part of the paper some experimental results are also briefly synthesised in order to underline that stiffness and damping properties do not depend solely on maximum deformation and strain rate, but also on other factors, thus demonstrating the unfeasibility of arranging an uniquely defined numerical model. It seems therefore more reasonable to investigate on the implications of adopting some of the most commonly used device models, which means to estimate the scatters among the values of structural response parameters obtained by adopting different, quite simplified models for the B.I. devices.

THE EXPERIMENTAL BEHAVIOUR OF B.I. DEVICES

A typical cyclic behaviour obtained from a static shear test on high damping bearings is shown in figure 1. Similar cycles can be obtained through sinusoidal tests. Within the large experimental program, still in progress in Italy, to which this single test pertains, it has been demonstrated that the most significant properties of the device, i.e. horizontal stiffness and damping capacity, not only depend upon strain rate and maximum deformation, but also on other parameters, such as vertical pressure, scaling factor, shape factor and aspect ratio.

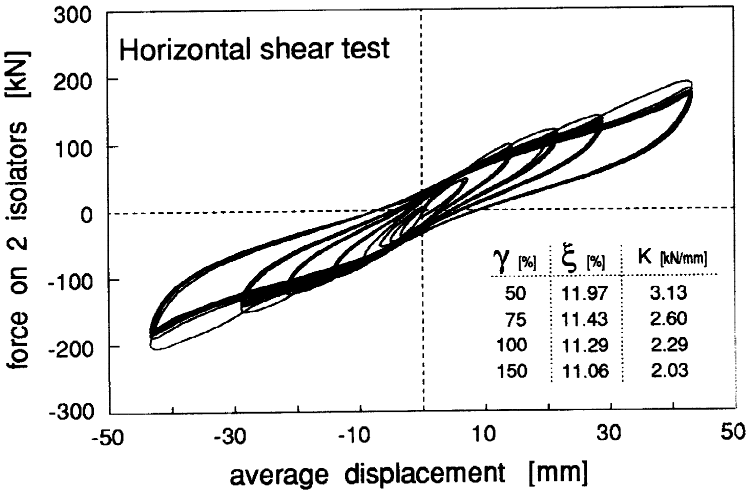


Figure 1 Experimental cyclic response of HDRB.

As an example, in the figures 2 (a) and (b) are reported the values of the equivalent damping ratio, computed, on the basis of experimental test loops, through the well known relationship:

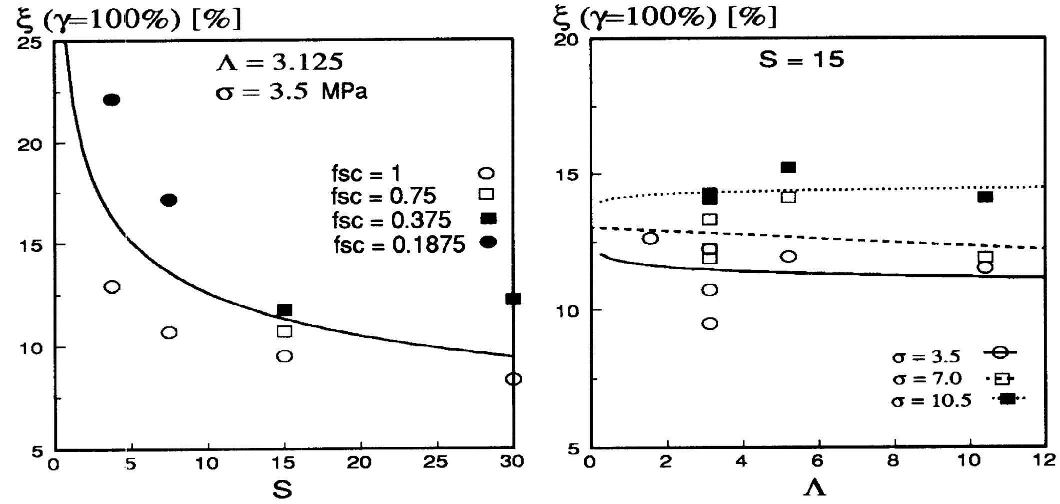
$$\xi_{eq} = W_d / 4\pi \ W_s \tag{1}$$

where W_d is the dissipated energy while W_s is the elastic stored energy. Both the values of W_d and of W_s are in this case estimate on the base of experimatal loops at a shear strain equal to 100%.
In particular the figure 2 (a) describes the variation of ξ_{eq} with the shape factor S, which for a circular bearing, like the ones which these data refer to, is defined by:

$$S = \Phi / 4t \tag{2}$$

where Φ is the diameter and t is the single rubber layer thickness. In order to highlight the effect of shape factor S on the equivalent damping of the device, the data depicted in figure 2 (a) are relative to devices characterised by different values of S, but by the same aspect ratio Λ, which is a measure of the sensitivity of the device to buckling and is defined as the ratio of diameter to total rubber thickness of the device. The trend of the results shows a strong dependence of equivalent damping on the shape factor S.

In figure 2 (b) the variation of ξ_{eq} with the aspect ratio Λ is reported for devices characterised by the same value of the shape factor, equal to 15, and subjected to different values of average vertical pressure. From this figure it can be derived that bearings with the same shape factor substantially are not very sensitive to the value of Λ, at least at shear strains equal to 100%. In addition it can be observed that the applied vertical load has a significant effect on equivalent damping. All these results confirm that it is too simplified the assumption of rubber device properties depending solely upon strain rate and maximum deformation.



Figures 2 (a) and (b) Experimental variation of equivalent damping ratio with shape factor S (a) and aspect ratio Λ (b).

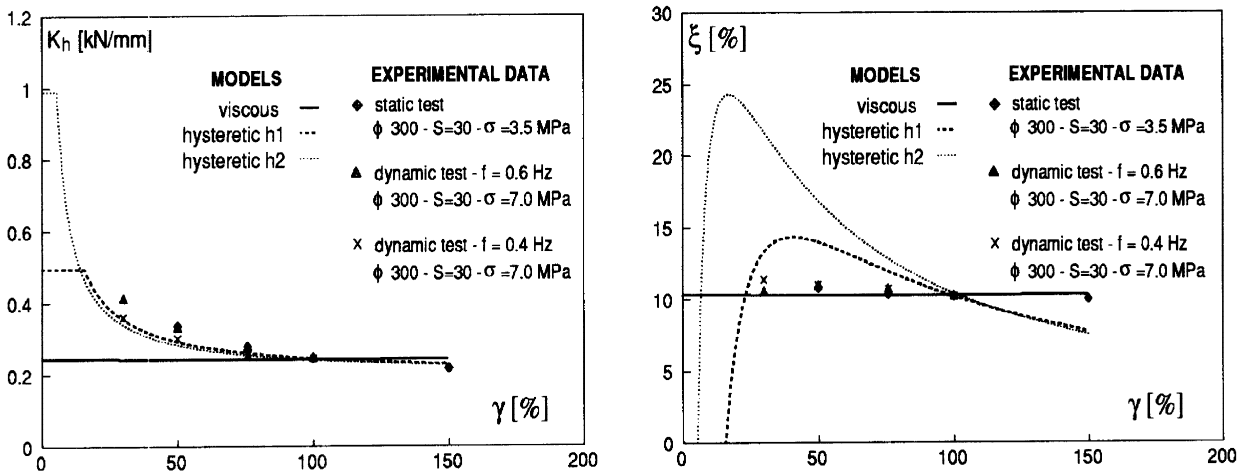
NUMERICAL MODELS FOR B.I. DEVICES

The previous considerations highlight the complexity of the behaviour of high damping elastomeric bearings and the consequent difficulties of simulating in a refined manner such behaviour through SDOF numerical models. Furthermore, while for SDOF systems more refined models, though probably in any case inadequate, could be suggested, in the case of MDOF systems , in which the well known equation of motion:

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_g \qquad (3)$$

represents a large system of nonlinear equations, the only two reasonable models for the B.I. devices are the nonlinear hysteretic and the linear viscous ones, in which a measure of the equivalent viscous damping is usually derived from equation (1). As it has been shown in (De Luca et Al., 1994a) with reference to a SDOF system, despite the higher computational effort there is no evidence for preferring the hysteretic models in the numerical simulation of the HDRB experimental behaviour.

In this paper the comparison of the response of MDOF systems, representative of multistory base isolated frames, obtained with different numerical assumptions made for the isolation devices, is carried out. The comparison among the results of numerical analyses is specifically aimed to evaluate the sensitivity of the structural response to the adoption of different numerical models for the B.I. system. In particular for the B.I. devices the linear viscous model and two different hysteretic bilinear models are adopted. The values of effective (secant) stiffness and equivalent damping ratio provided by these three models are respectively reported in figures 3 (a) and (b) as a function of the horizontal strain in the device.



Figures 3 (a) and (b) Comparison among experimental data and computed values of device model parameters.

In the figure some experimental data, appropriately nondimensionalised to fit the design values assumed in the models, are also provided in order to better clarify the accuracy of each model. Concerning the experimental data, it can be observed that in the actual B.I. devices, while the equivalent damping ratio can be considered practically constant on a wide range of deformations, the secant stiffness shows a strong variation. It is immediate to derive that the linear viscous model provides a better correspondence in terms of equivalent damping, while the hysteretic ones provide better results in terms of effective stiffness, especially at small values of deformation, being on the contrary less accurate in the simulation of the actual damping. Such a poor correspondence in terms of damping, obtained also in the case of more refined models, is the major drawback consequent to the adoption of hysteretic models for B.I. devices.

This fact can be somehow explained by figure 4, from which it is possible to understand the procedure for calibrating a bilinear hysteretic model (De Luca et Al.,1995). Having defined the isolation period T_I (in this case equal to 3 *sec*) and therefore the design displacement D obtained from the code displacement spectrum (UBC,1991), and fixed the value of the design deformation γ, then the values of the parameters of the equivalent linear viscous model, i.e. the secant stiffness and the equivalent damping ratio (in this case fixed equal to 10%), are univocally defined. On the contrary for the bilinear model, in addition to values of the secant stiffness and of the equivalent damping at the design deformation, one more parameter has to be fixed for completely defining the model. In fact, as shown in figure 4, the bilinear model is defined through the specification of two points (P_y, P_D), respectively representative of yielding and design conditions. Most commonly, in the definition of the model reference is made to the parameters shown in fig.4, i.e. K_1, K_2, K_{sec} and ξ_{eq}.

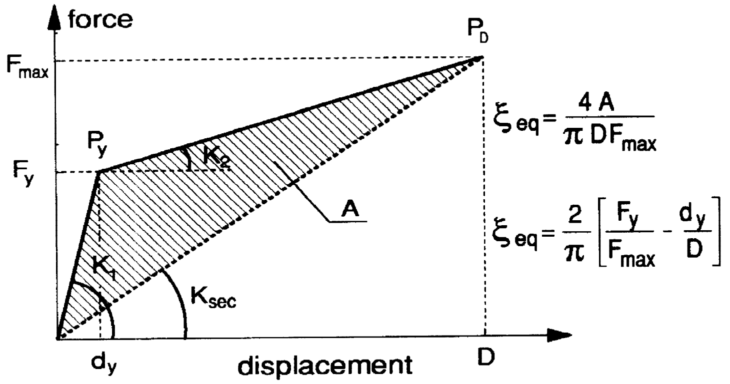


Figure 4 Parameters of the hysteretic bilinear model.

In this paper the additional parameter of the bilinear models has been set to the ratio of the initial to the secant (at the design deformation) stiffness K_1/K_{sec}. In particular two different values of this ratio (2 and 4), fitted on the basis of experimental results available in the inherent literature (Kelly, 1991) have been considered, leading to two different bilinear hysteretic models, in the following respectively appointed as **h1** and **h2**. The corresponding force displacement laws for the h1 and h2 models, both specified for two different soil type conditions, i.e. the S1 and S3 soil type defined by the UBC 91 provisions, are reported in figure 5.

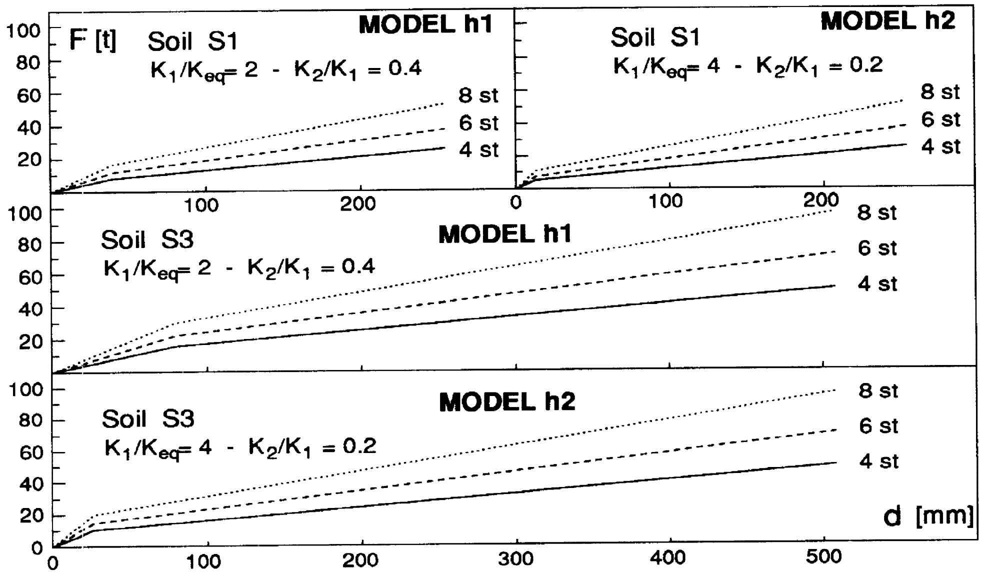
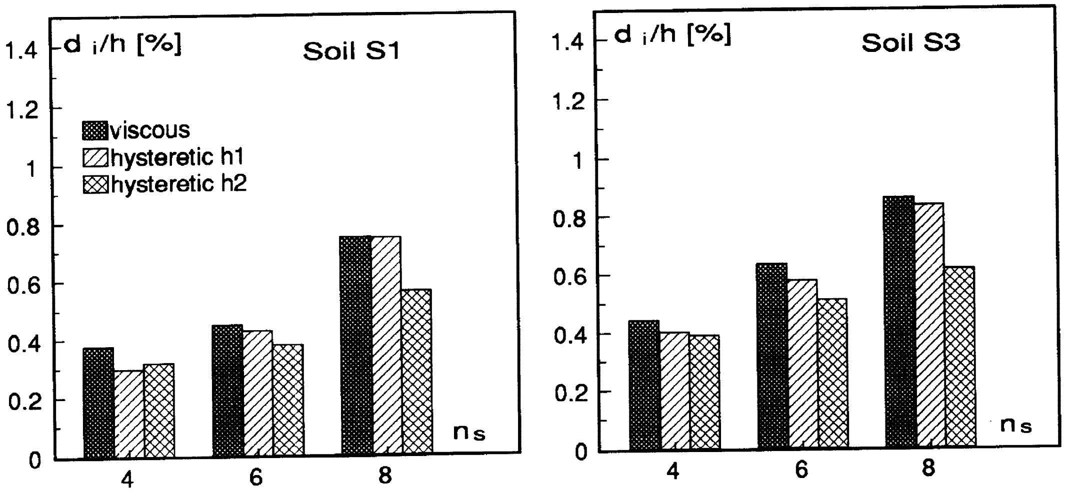


Figure 5 Device hysteretic models adopted in the numerical analyses of 4, 6 and 8 story frames.

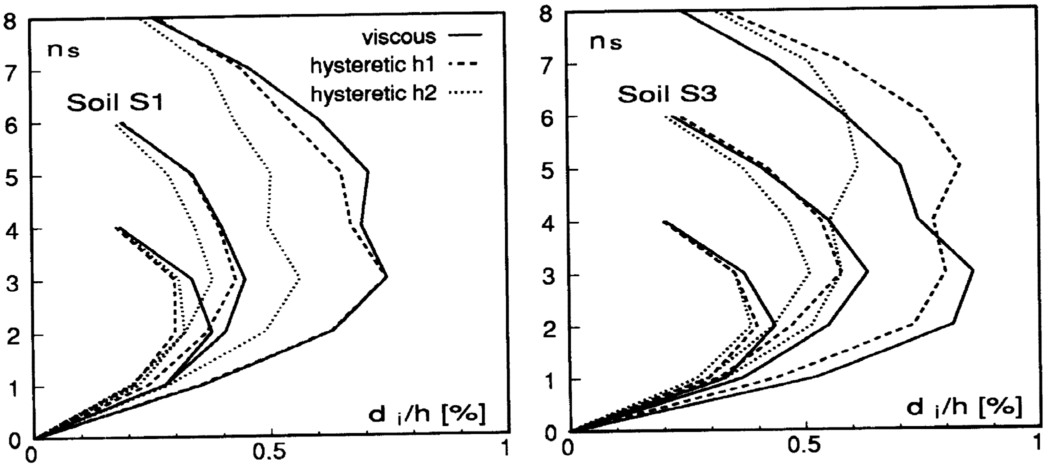
NUMERICAL RESULTS

The sensitivity analysis has been carried out on base isolated steel frames, with number of story equal to 4, 6 and 8, each of them designed in accordance to UBC 91 provisions, both for S1 and for S3 soil type conditions. The geometrical configuration and the sections of the structural elements are described in a previous paper (De Luca et Al.,1994b). Nonlinear dynamic structural analyses have been carried out with UBC spectrum compatible acceleration time histories through the DRAIN-2DX (Prakash et Al, 1993) computer code. The nonlinear model of the beam-columns elements in the upper part is elasto-plastic, with 1% hardening, and accounts for both P-Δ effects and bending-axial interaction.



Figures 6 (a) and (b) Comparison among the maximum interstory drift ratio obtained through different device models.

In the figures 6 (a) and 6 (b) are reported the results of the analyses performed on the 4, 6 and 8 story frames, in terms of ratio of maximum interstory drift to interstory height d_i/h. The figure 6 (a) is relative to frames designed according to S1 soil type and subjected to S1 spectrum compatible acceleration time history, while the figure 6 (b) refers to S3 soil type. From these figures it can be underlined that small scatters do exist between the maximum interstory drift obtained by means of the linear and the bilinear h1 models for all the analysed frames. In general major differences can be observed between results obtained by means of the two hysteretic h1 and h2 models. In fact, as previously emphasised, the two hysteretic models, even if they present the same secant stiffness and equivalent damping at the design displacement, have a different yielding point and therefore exhibit a different global behaviour.

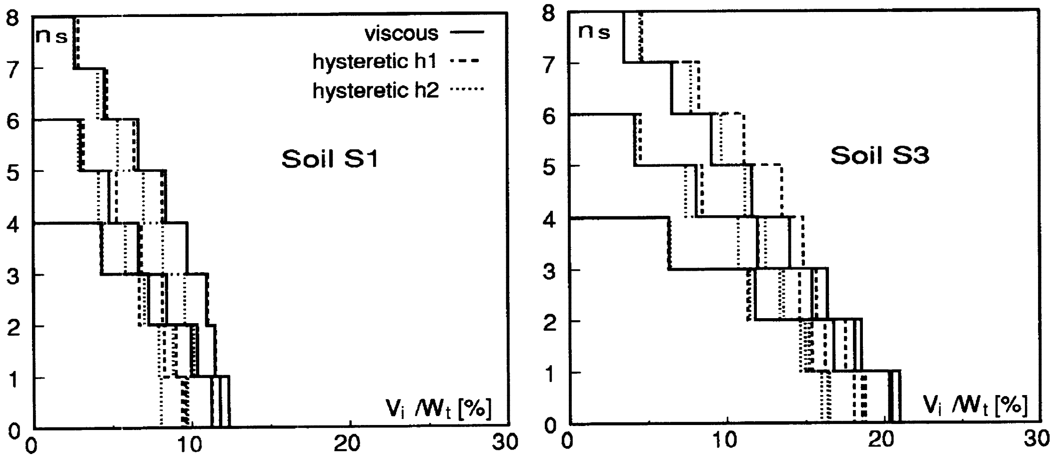


Figures 7 (a) and (b) Distribution of maximum interstory drift for the 4, 6 and 8 story frames.

In the figures 7 (a) and 7 (b) the maximum interstory drift values obtained from the numerical analyses at each single story, always expressed in terms of ratio to the story height, have been plotted for the 4, 6 and 8 story frames. The figures 7 (a) and 7 (b) respectively refer to S1 and S3 soil type conditions. In both the figures a comparison among the results obtained by using the three different models for the B.I. system is provided. The comparison substantially confirms the equivalence in terms of peak structural response between results obtained by means of the viscous and the hysteretic h1 models, while major scatters can be observed considering the results obtained by means of the hysteretic h2 model. It can also be underlined that for all but the S3 soil-8 story frame, the three models show a similar shape of the interstory drift envelope, even if the h2 model shows a more uniform peak response at the various story, probably as an effect of the higher damping.

In the figures 8 (a) and 8 (b), for the different multistory frames, the value of the summation of the maximum column shear forces at each story, obtained through the use of the linear, h1 and h2 models for the B.I. system, is represented in terms of ratio to the global seismic weight of the frame. This representation of the results, even if cannot strictly be considered as the envelope of the story shear, provides a measure of the seismic forces transmitted by the isolation system to the upper structure. Like in the previous figures, the figure 8 (a) makes reference to S1 soil type conditions while the figure 8 (b) refers to S3 soil type conditions. The same considerations previously drawn concerning the sensitivity of the structural response to the use of the three models of B.I. devices can be repeated here: very close distributions of the shear force at the different stories are obtained by means of the viscous and h1 hysteretic model, with some lightly greater scatters arising in the case of S3 soil-8 story frame. Lower shear forces are transmitted to the superstructure by using the h2 hysteretic model.

In conclusion the analyses carried out with artificial records demonstrate that the peak response of base isolated structures is practically independent of the model adopted for the devices. In particular different nonlinear hysteretic and linear viscous models provide similar results in terms of maximum superstructure displacements and shear forces. It has also been found that even the accelerations transmitted to the superstructure do not substantially vary. These last results are not reported in the paper for brevity.



Figures 8 (a) and (b) Distribution of summation of maximum column shears for the 4, 6 and 8 story frames.

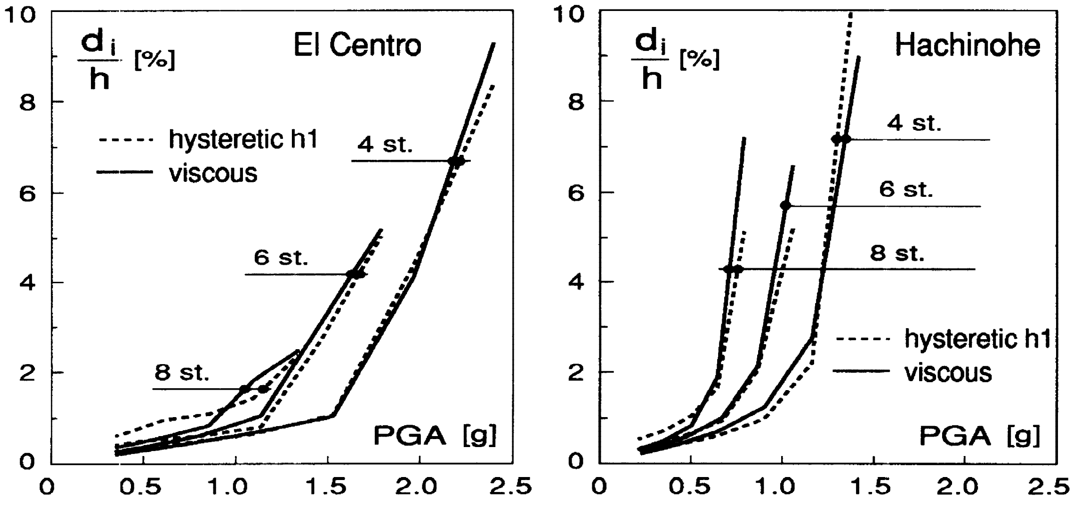
EXTENSION OF THE SENSITIVITY ANALYSIS

The previous results have been obtained by applying to the base isolated structures two artificial acceleration time histories, respectively compatible to the S1 and S3 soil type UBC design spectra, in order to compare the structural response obtained by means of the diffrent models at a device deformation state close to the design one. When historical acceleration records are adopted as seismic input for the numerical analyses, larger scatters among the results coming from different B.I. device modeling are likely to arise, mainly due to the different response of the viscous and hysteretic models to seismic inputs which drive B.I. system to deformation coinditions different from the expected ones, i.e. the design deformation. Therefore the sensitivity analysis has been further extended to a wider range, by applying to the base isolated structures two natural acceleration records (El Centro and Hachinohe), both as recorded and scaled at increasing value of PGA. In particular the acceleration time histories have been scaled up to values of PGA (equal to about 2.5 g for the El Centro record and 1.5 g for the Hachinohe record) such to drive the upper structural elements well beyond the plastic threshold, and therefore the frames in a highly nonlinear range of behaviour.

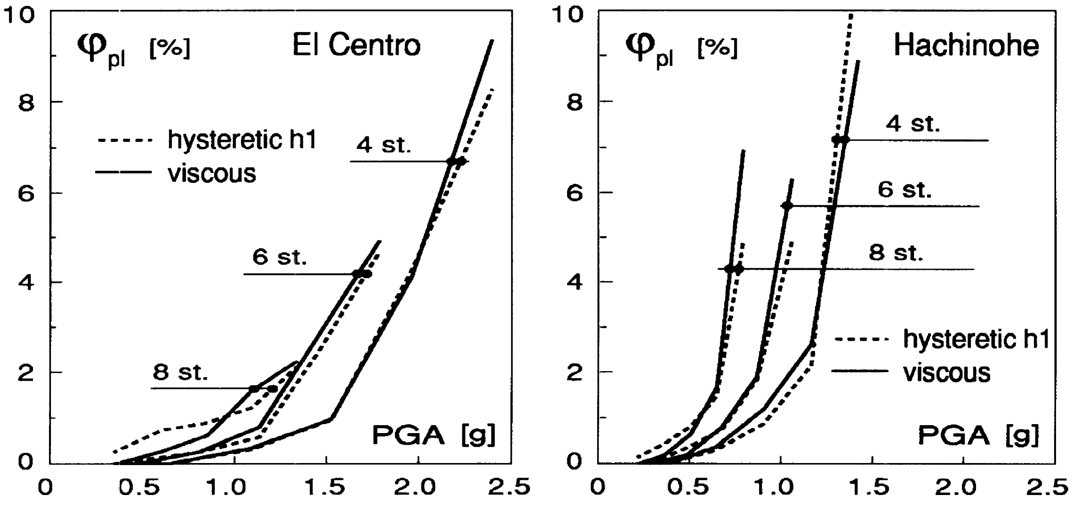
In the figures 9 and 10 are reported the results of the sensitivity analysis at increasing PGA values, respectively in terms of maximum interstory drift and maximum plastic rotation. Each of the figures appointed as (a) refers to the results obtained under the El Centro acceleration record, while the figures appointed as (b) are relative to the numerical results derived under the Hachinohe record.

The curves plotted in the figures 9 (a) and 9 (b), relative to the viscous and the hysteretic h1 model, indicate very similar values of the response parameters obtained with the two different models. The global trend is therefore characterised by practically the same threshold-type behaviour (sharp increase of the structural response already found in other papers like Vestroni et Al. (1991) ,De Luca et Al. (1994b), Occhiuzzi et Al. (1994)), independently on the B.I. device model. This result can somehow allow for the use of the viscous model in numerical analyses developed in the context of the research aimed to the definition of design level for base isolated structures.

The above observations can be repeated with reference to the results represented in figure 10 (a) and 10 (b), where the maximum plastic rotations experienced by the plastic hinge at the end of the structural members are depicted as a function of the peak ground acceleration of the seismic input. The comparison of the curves relative to the viscous and hysteretic models highlight almost an identical trend and therefore strengthens the confidence in the use of the linear viscous model even if the upper structure exhibits a highly nonlinear behaviour. This statement appears very significant, especially with reference to examined response parameter, i.e. plastic rotation, which even in fixed base structure is not a very stable response parameter.



Figures 9 (a) and (b) Comparison among maximum interstory drift at increasing PGA of the seismic input



Figures 10 (a) and (b) Comparison among maximum plastic rotation at increasing PGA of the seismic input

CONCLUSIONS

In this paper after having briefly shown that the modeling of the nonlinear response of HDRBs is a difficult task, since both stiffness and equivalent damping not only depend upon strain rate and amplitude deformation, a comparison of the nonlinear response of MDOF systems, in which the superstructure is driven in a highly nonlinear range, has been carried out. The comparison has demonstrated that the adoption of nonlinear hysteretic or linear viscous models for the devices leads to similar results in terms of superstructure peak response, described by means of interstory drifts, plastic rotations or shear forces. Despite of the higher computational effort and the increased difficulties in defining and characterising the model, the hysteretic models do not lead to better results.

It seems therefore that the linear viscous model is even more adequate than the nonlinear hysteretic ones, due to its capacity of better simulating damping properties. This statement is more stringent in the case parametric nonlinear analysis should be carried out, or in general when enough experimental results providing the device behaviour at different conditions are not available.

Since the analyses carried out in this paper also concern the case of historical records differently scaled, it can be stated that these conclusions hold also in the case in which the model is calibrated at a given value of deformation, but the seismic input subjects the device to different amplitudes than the design assumed ones.

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