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MODELLING THE SEISMIC BEHAVIOUR OF BRIDGES WITH VISCOUS DAMPERS

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SUMMARY

The research work object of this presentation is related to the analysis of bridges, or viaducts, with the introduction of energy dissipating devices, namely viscous devices with a general behaviour model in the form $F(v) = Cv^{\alpha}$, where F is the force in the device, v is the velocity and C and α area characteristic constants of the device.

One of the problems in the use of such devices is that the analysis of the viaduct dynamic behaviour becomes more elaborated and difficult than the analysis of a viaduct with its seismic resistance based on the ductile capacity of the piers. For this last approach in viaduct design, a set of behaviour coefficients (q factors), that allows an approximate but simple linear dynamic analysis, is already available.

It is the purpose of this paper to describe simple rules to estimate parameters such as maximum displacements and forces induced in the devices and in the structures.

Most of the computer programs for dynamic analysis are not prepared to model this type of devices, whose behaviour is velocity dependent. This lead to use some equivalent models when it is necessary to perform a dynamic analysis of a structure with those devices. One of the most common equivalent models is the elasto-plastic with a maximum force on the device obtained from the velocity relation of the device. In this paper a study where the analysis with the true behaviour of the devices is compared with the results obtained with equivalent models is presented. The comparison is made in terms of displacements, velocities and accelerations on the bridge and forces on the devices. The dynamic analysis using devices with a force-velocity relation in the form $F(v) = Cv^{\alpha}$ were performed using a modified version of the program Drain-2D which includes a special developed new element.

Based on the results obtained with the multiple analysis on the dynamic behaviour of bridges with viscous devices, some conclusions and some rules for the estimation of the maximum displacements and forces are presented.

It is shown that simple rules may be used to assess the most important design parameters and the reliable estimates can be obtained.

INTRODUCTION

In seismic design of bridges and viaducts the use of paraseismic devices can be a simple and economical alternative to the traditional design where the structure behaviour under seismic action is fully dependent on the non-linear behaviour of "plastic hinges". From the already available paraseismic devices the hysteretic and viscous devices seem to play a major role, since they allow the designer to specify the location and the characteristics of the dissipative elements in the structure. Although these devices may be applied to any kind of structures their application is easier and more effective in bridges then in other type of structures. Finally it should be emphasised that structures designed with dissipative devices can be more economical than traditional ones (Marioni, 1994) (Marioni et al, 1997).

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One of the problems in the use of paraseismic devices is that the analysis of the dynamic behaviour of a viaduct with such devices, becomes more elaborated than the analysis of a viaduct with its seismic resistance based on the ductile capacity of the piers. For this last approach in viaduct design, a set of behaviour coefficients (q factors), that allows an approximate but simple linear dynamic analysis, is already available, as for structures with paraseismic devices a time non-linear analysis is usually necessary. Some codes, as the Eurocode 8 (CEN/TC250, 1994), are more severe in the type of analysis required for a bridge with dissipative devices than for a structure with it seismic behaviour based on the non-linearity of the piers.

In this paper, the evaluation of the seismic behaviour of bridges and viaducts with the inclusion of viscous dissipative devices is presented. In a viscous device the force depends mainly on the relative velocity between their extremities. Examples of viscous dissipative devices are the hydraulic devices with viscous fluids. The type of force-velocity relation presented by the devices depends mainly on the type of the fluid used.

Some of the most relevant results obtained in this study are presented, by means of an assessment of the maximum shear forces in the piers, maximum forces in the abutments, maximum deck displacements and also in terms of the maximum response values in the devices, including forces, displacements and velocities. All these results are presented as a function of the devices' characteristics. The obtained results justify the use of such devices in bridges and viaducts structures as it had already been the case in terms of similar applications to cable stayed bridges (Azevedo et al., 1997).

ANALYTICAL MODEL

In this study it is only considered the longitudinally behaviour of fully isolated bridges solutions with rigid decks. A viaduct deck is considered rigid if, under the earthquake action, the deformation of the deck in the longitudinally direction is negligible compared to the displacement of the piers tops.

According to the Eurocode 8 (CEN/TC250, 1994) definition, a bridge is considered fully isolated if the structure remains in the elastic range when subjected to a seismic action. In the following two different concepts of fully isolated viaducts were considered. The first one assumes that, in the longitudinal direction, the deck displacement is totally independent of the pier movement. In this case the longitudinal connections between the deck and the supports are achieved only through the dissipative devices located between the decks and the abutments. On the second solution, a very flexible connection between the deck and the piers is considered. The horizontal stiffness of this connection is assumed to be such that the horizontal movement of the deck with the piers, not considering the dissipative devices, presents a very low frequency considered in this study with a value of 0.5Hz.

The first solution can be realised with sliding devices at the piers top and the second model is representative of a solution with the deck supported on rubber bearings or with the deck rigidly connected to very flexible piers.

The study is mainly focused on the first isolation solution. The second concept is considered just to compare the results with the first one and to analyse the influence of a small increase in the longitudinally stiffness on the results obtained with a totally free deck. This second concept correspond to interesting practical solutions, since the designer can often take advantage from a small longitudinal stiffness, such as to improve the bridge behaviour under non-seismic actions.

To analyse the first solution the structures can be modelled with an element simulating the viscous device connecting a concentrated mass to the ground. The concentrate mass corresponds to the deck and part of the piers mass. In order to get generalised conclusions, a unitary value is considered to the mass in the model. The stiffness of the second solution is simulated by an elastic spring connecting also the mass to the ground, i.e. acting in parallel with the viscous device.

The computer program Drain2D/ICIST (Guerreiro & Bento, 1998), a modified version of Drain2D (Kannan & Powell, 1975) with the enhanced capability of simulating the behaviour of viscous devices by means of a new element, was used.

The referred new element was specially developed to allow the simulation of the intended viscous device behaviour, including a initial linear branch for small velocities values in which the general rule is not applicable. This linear branch simulates a essentially feature of viscous devices that should not developed significant forces for small velocities values resulting from, for example, the wind or braking actions.

For the viscous devices a general behaviour model in the form $F(v) = C\,v^{\alpha}$ was used, where F and v are the force and velocity, C and α are constants characteristic of the device. Three different values of the parameter α were considered: 0.25, 0.50 and 1.00. In figure 1 the configurations of the force-velocity relation curves are presented for different values of α. In the curves it also represented the linear branch, which, for the present study, was defined by the origin and the point corresponding to 10% of the maximum velocity and force corresponding to the defined seismic action and obtained without the consideration of the linear branch.

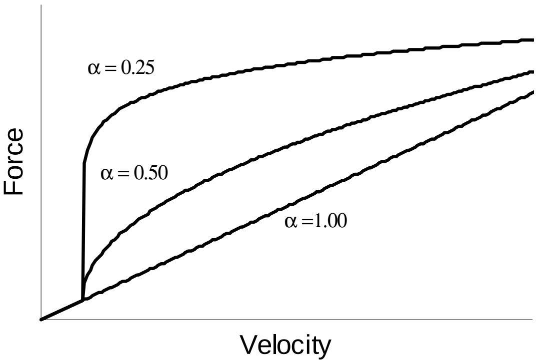

Figure 1 - Different types of the force-velocity relation for the viscous dampers.

When the value of α is lower than one, the curve has a strong force increase for low velocity values and small force increase for high velocities. In these cases there is a large amount of energy dissipated in each cycle.

For the complete definition of the devices it was necessary to specify the value of the constant C. To allow an analysis on the influence of the constant C on the structural response a wide range of values of this constant was tested. Values of the constant C between 0.10 and 10.0 were considered, since those values, together with the values considered to the parameter α, will cover forces corresponding to seismic coefficient varying from 1% to 50% of the weight.

It is important to refer that the values of C used in this study were calculated based on a model with a unit mass. This would allow the comparison between the obtained results and the behaviour of a model with different mass, but with the same ratio between the constant C and the respective mass. The units for C depend on the α value and must be in accordance with the velocity v and the force F, which, in the present study, were considered in m/s and kN respectively.

In this study a set of five artificial accelerograms was used. The series of accelerations were generated compatible with the response spectrum defined in Eurocode 8 – Part 2 (CEN/TC250, 1994), for a soil type B. A peak ground acceleration of 0.30g was considered. The total duration of the series is 30.0 seconds and the envelope function presented in the Annex E of the Eurocode 8 – Part 2 (CEN/TC250, 1994) was considered. As an example, one of the generated accelerograms is presented in Figure 2.

In Figure 3 the response spectrum defined in the Eurocode and the average response spectrum for the five acceleration series are represented. It is possible to observe the good agreement between the target and the average response spectrum.

All the tested models were analysed with the five acceleration series and the results referred in this work are the average of the maximum values obtained with each series.

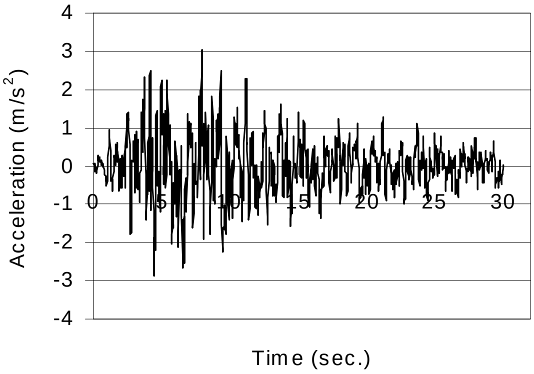

Figure 2 – Example of an artificial acceleration series.

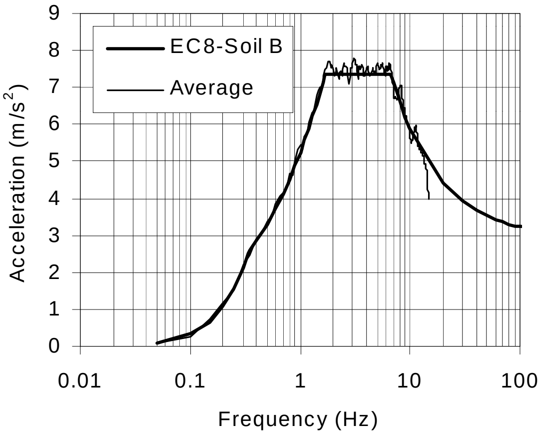

Figure 3 – Response Spectra EC8-Soil B (PGA=0.3g) versus average of generated series.

BRIDGE RESPONSE WITH VISCOUS DAMPERS

In this section the seismic behaviour of viaducts using dissipation devices of the viscous type is analysed.

The results for the solutions with the deck totally free over the piers and connected to the abutments only by the viscous devices are presented in Figure 4. The presented results are the maximum forces per unit mass in the devices and the maximum deck displacements. In Figure 5 the same results are presented but for the solution considering also a low stiffness elastic connection between the piers and the deck. The same models were analysed in a previous work (Guerreiro et al, 1998) with the difference that the viscous devices force velocity relationship was considered without the initial linear branch. The present and the previous (without the linear branch) sets of results are almost coincident and so it can be conclude that the initial linear branch does not affect the structure seismic response.

Figures 4 and 5 show that solutions involving a higher displacement control always lead to higher force levels in the devices. It is also possible to observe that the more efficient solutions, with better displacement control for the same force level, generally corresponds to low α values.

Comparing the results presented in Figures 4 and 5 a major conclusion can be pointed; for device solutions with low values of the constant C, the elastic stiffness of the structure has an important contribution on the displacement control. It is important to notice that the contribution of the elastic force is out of phase with the one transmitted by the devices, what means that, in a solution of this type there is always a force restraining the movement of the deck. The problem is that the forces transmitted to the structure must be controlled to limit the contribution of the piers to values lower than their elastic limit.

Figure 6 presents the forces in the structure corresponding to the device solutions considered in the study and whose results, in terms of devices response, were presented in Figure 5. The results presented in Figure 6 show that, for low C values, the forces transmitted to the structure are important and higher than the corresponding forces in the devices. According to these results the isolation solutions with low C values do not lead to an effective displacement control nor to lower forces in the piers.

For the analysis of the device response in terms of displacements a maximum value of 0.10m was considered as a limit. The results presented in Figures 4 and 5 show that, for viscous devices, only C values higher than one, which correspond to seismic coefficient about 6 to 8%, can conduct to maximum displacements below that limit.

For C values higher than 1 a significant reduction on the displacement is verified. For the device solutions in this range there is no influence of the elastic stiffness in the device forces. In the maximum displacements there is a light reduction when compared with the situation without spring.

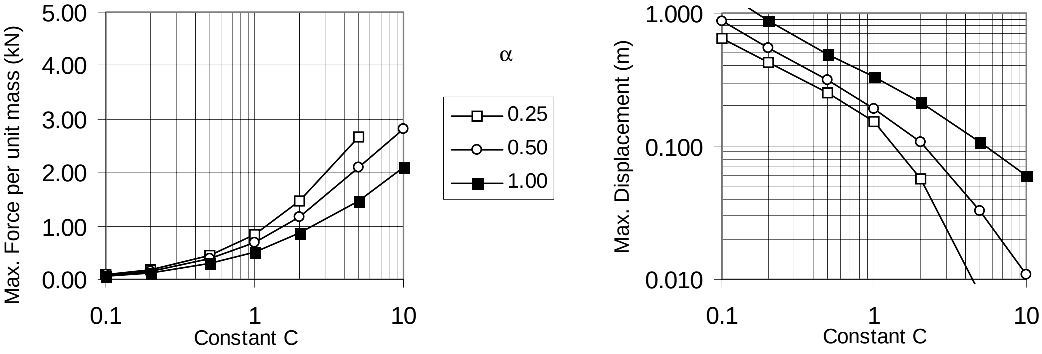

Figure 4 – Maximum forces and displacement in the viscous dampers – solution without elastic stiffness.

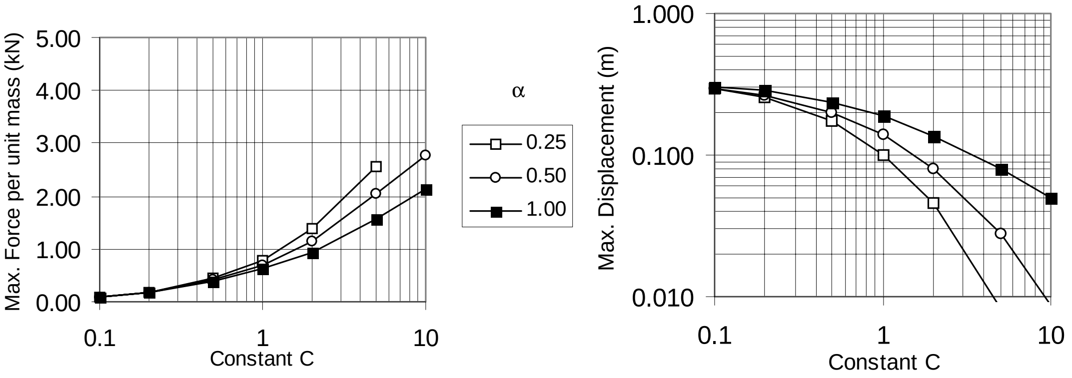

Figure 5 - Maximum forces and displacement in the viscous dampers – solution with elastic stiffness.

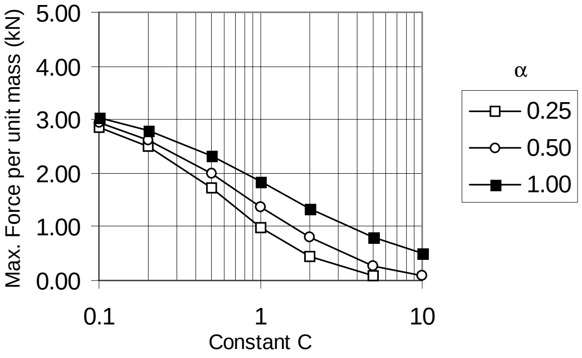

Figure 6 – Maximum forces in the structure for the solution with viscous dampers and elastic stiffness.

From these results it can be concluded that the best solutions corresponds to devices with C values higher than 1. The contribution of an elastic spring is irrelevant for the forces in the device and conducts to some negligible reduction in the displacements. From these results one can conclude that the consideration of the elastic stiffness of the structure is not important for the displacement control of the deck. However, the presence of the elastic force transmitted by the piers can be important to recover the initial position of the deck after an earthquake and to provide a minimum stiffness for deck slow movements. From this point of view, is important to know that it is possible to consider this kind of solution without the transmission of important forces to the structure if the right device solution is considered.

Figure 7 presents the maximum velocity in the devices for the two considered situations, with and without the structural stiffness. In both graphics presented in the figure, all the curves tend to a certain velocity when C values tends to zero. In the case of the solution without structural stiffness, the maximum velocity of the response is near 0.60 m/s which is the peak value of the soil velocity for the considered action, as it can be confirmed in the velocities response spectra presented in Figure 8. From these response spectra it can also be obtained the maximum velocity for an oscillator with 0.5Hz and 5% of damping, which are the characteristics of the equivalent linear oscillator considered in this study. The corresponding value is around 1.10m/s which is the maximum value of the response presented in the Figure 7 for the solution with structural stiffness. This shows that the maximum response velocity can be easily estimate through the corresponding response spectra. With this limit value for the velocity and knowing the characteristics of the device is possible to establish a maximum value for the force in the device.

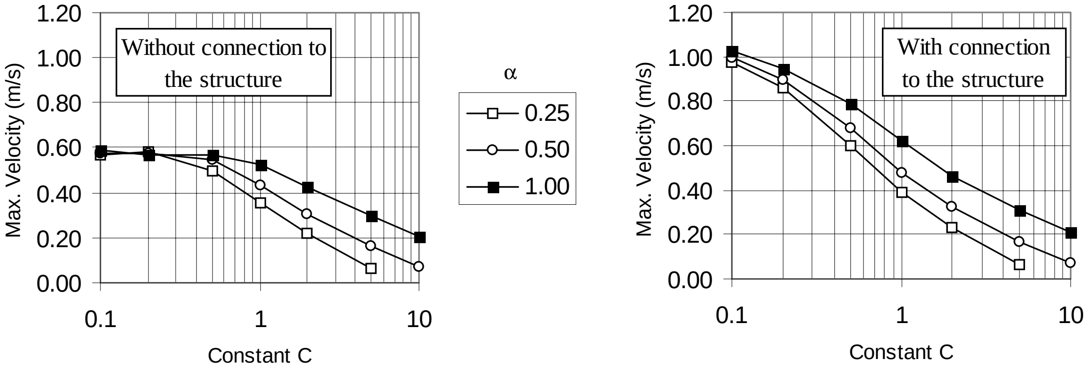

Figure 7 – Maximum velocities in the viscous dampers.

The velocity results presented in Figure 7 show that for values of C higher than one, the two sets of results become similar. It shows that for this range of C values one can get a good and conservative evaluation of the maximum velocity through the maximum value of the soil velocity instead of using alternative models such as an equivalent hysteretic oscillator. Anyway, if the chosen devices have a high value of C and low α values, the evaluation of the maximum velocity based on the maximum soil velocity can lead to significant errors (higher than 300%). However, for the cases where the difference in the velocity is higher the force-velocity relation is not linear (α<<1.0), and the corresponding error in the estimated value for the maximum force is considerably lower (less than 50%).

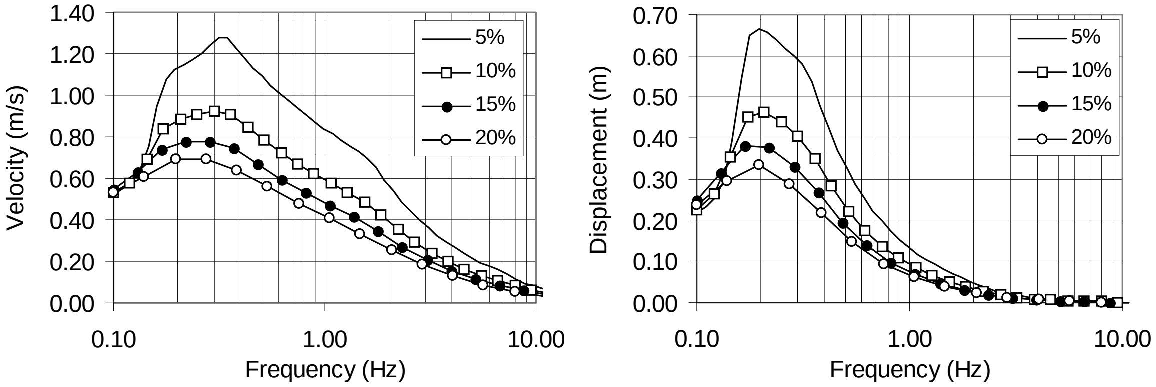

Figure 8 – Velocity and displacement spectra for the Eurocode 8 – Soil B seismic action (Pga 0 0.3g).

EQUIVALENT MODEL

Most of the computer programs for dynamic analysis are not prepared to model this type of devices, whose behaviour is velocity dependent. This lead to use some equivalent models when it is necessary to perform a dynamic analysis of a structure with those devices. One possible equivalent model is the elasto-plastic, which is usually associated with hysteretic devices.

The equivalent elasto plastic model can be defined as follows:

a) For the seismic action it is possible to obtain the relation between the maximum displacement and the viscous device characteristics (C and α). In the present study this relation is represented in figure 4. From this relation and from the characteristics of the specified device one can obtain the maximum displacement.

b) With the previous referred maximum displacement and through the displacement response spectrum, corresponding to the seismic action and to a certain value of the damping coefficient (5% for example), it is possible to obtain the frequency of a linear elastic single degree of freedom structure which has the same value of the maximum displacement. The displacement response spectrum is represented in figure 8. From the frequency, and since the mass is known, the initial stiffness of the hysteretic device can be evaluated.

c) The yielding force in the equivalent hysteretic device can be considered equal to the maximum force in the viscous device. This value is only dependent on the seismic action and on the viscous device characteristics (C and α), and can be easily obtained from the calculated maximum velocities (shown in figure 7 for the present study).

d) The post-yielding stiffness of the hysteretic device should be taken sufficiently lower to avoid significant force variations in the device resulting from small variations in the maximum displacements. On the other hand, the numerical problems associated with the analysis methods advise to consider a post-yielding stiffness different from zero. In the present study the post-yielding stiffness was taken as 2.5% of the initial stiffness.

The equivalent hysteretic device, defined according to the previous referred methodology, can be used even when some stiffness in the connection to the ground is considered.

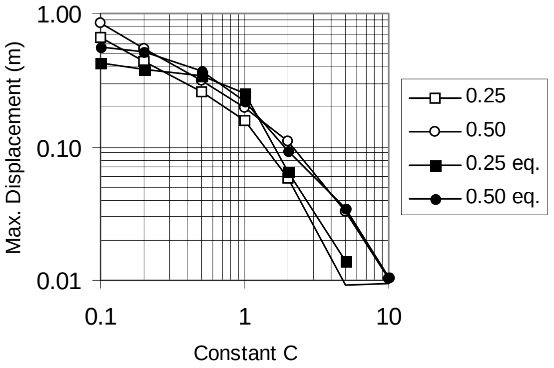

Figure 9 – Displacement comparison between viscous and equivalent hysteretic dampers (solution without stiffness).

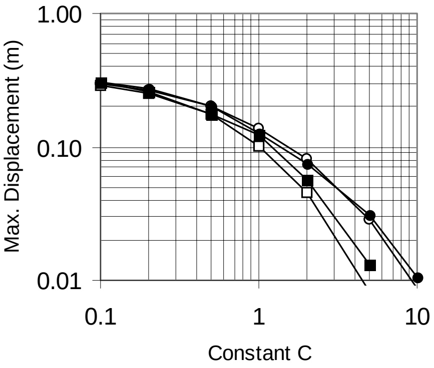

Figure 10 – Displacement comparison between viscous and equivalent hysteretic dampers (solution with stiffness).

In figure 9 it is presented the comparison of the displacements and velocities obtained from the model with a viscous device and the corresponding model with an equivalent hysteretic device. In figure 10 the same comparison is presented for the structure with some stiffness in he connection to the ground.

From the figures 9 and 10 it can be verified that the displacements results present a very good agreement, with errors never exceeding 10%.

The agreement in the velocity results is not so good, although the errors are always conservative. In terms of the maximum velocities the errors are between 20% and 50% for the structure without stiffness and between 2% and 30% when some stiffness is considered in the connection to the ground. It should be noted that those errors are note very important since the greatest differences occur for very low velocity values. On other hand the maximum velocity calculated with the equivalent hysteretic device are only useful in what concerns the confirmation of the adequacy of the viscous device characteristics initially specified.

CONCLUSIONS

The use of paraseismic dissipative devices is a relatively novel concept in seismic design. Although most of the existing applications have been in the field of bridge structures there is not a consistent methodology for their use and for the assessment of the corresponding benefits.

The results presented in this study confirm that the use of these dissipative devices is an efficient alternative concept to the ductility based design approach in viaduct structures. It is also shown that the dissipative approach leads to relatively easy to implement models at least in the design stages involving the analysis of alternative solutions and the pre-evaluation of the internal forces and displacements.

A main conclusion is that viscous devices are suitable for paraseismic applications and have proven to lead to effective solutions in terms of simultaneous forces and displacements control. Among the viscous devices, those having a force-velocity relationship ($F= C\ v^{\alpha}$) with lower α values are usually the most effective ones.

It is also shown that the evaluation of the viscous device response can be made in terms of the velocity or, as it is easier to do in practice, by means of an equivalent hysteretic model response.

An important conclusion is also that, if there is some available stiffness and resistance in the connection between the deck and the piers or abutments, it is possible to obtain optimised solutions without inducing significant forces in the structure. That stiffness as the advantage of guaranteeing recentering capability after an earthquake and can be use to improve the structure behaviour under other actions.

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