COMPARATIVE STUDY OF THE SEISMIC PERFORMANCE OF FRAMES USING DIFFERENT DISSIPATIVE BRACES

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SUMMARY

Different kinds of dissipative braces and their models are described. A numerical investigation is carried out considering the nonlinear seismic response of unbraced and damped braced frames. More precisely, a typical five-storey reinforced concrete (r.c.) frame, which is designed according to Eurocode 8, is considered. To protect the frame, the following dissipative braces are supposed inserted into the frame itself: cross-braces with hysteretic (friction or yielding) dampers, chevron braces with viscoelastic damper, diagonal brace with viscous damper. The effects produced by the dissipative braces on the response of the framed structure are evaluated assuming different properties of the frame members, braces and dissipative devices. Aspects concerning the behaviour and modelling of the dissipative braces are discussed.

INTRODUCTION

The insertion of dissipative braces proves to be effective in order to enhance the performance of a structure designed according to conventional aseismic design criteria. Simplified design procedures were proposed, which are based on the design spectrum concept with reference to a single-degree-of-freedom (SDOF) system representing the actual damped structure [Filiatrault and Cherry, 1990; Fu and Kasai, 1998]. However, many of these procedures are based on the assumption that the structure to be protected (e.g., a frame) behaves elastically. Only in few works the inelastic behaviour of that structure is taken into account (e.g., [Vulcano, 1994], in the case of cross braces with friction dampers; [Paolacci et al., 1998], considering viscoelastic dampers).

In this perspective it is considered very important to study the nonlinear seismic behaviour of single- or multi-degree-of-freedom systems which make use of different kinds of dissipative braces. Indeed, the comparison between different damped systems, considering aspects of their behaviour connected with both the structural model and the selection of suitable values for the characteristic parameters, is believed basic to develop practical analysis and design procedures.

In this paper the above aspects are discussed in the light of results for a SDOF system, which is representative of the actual damped structure, and for a five-storey r.c. frame in which are inserted different kinds of dissipative braces.

LAYOUT AND MODELLING OF DAMPED BRACING SYSTEMS

Actually a wide variety of energy dissipating devices is available for the passive control of vibrations (e.g., see [Soong and Dargush, 1997]). The dissipative bracing systems which were proposed differ for the particular arrangement of the braces (e.g., single diagonal brace, cross or chevron braces, etc.) and/or for the features of the dissipative device (in particular, by the way of dissipating energy: friction (FR), yielding (YL), viscosity (VS), viscoelasticity (VE)). Typical arrangements are schematically shown in Figure 1.

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More precisely, using the cross-bracing system shown in Figure 1a both FR and YL devices, based on the same mechanism, were adopted: the FR device consists of a mechanism with slotted slip joints containing friction brake lining pads, whereas the YL one consists of an inner steel frame whose shape is such that energy can be dissipated under uniform bending yielding. The systems shown in Figures 1b and 1c were adopted using dampers dissipating energy in different ways. Finally, the eccentrically braced system in Figure 1d, proposed and tested at the University of Berkeley, benefits from a double defence line, because it can resort to the dissipation capacity due to the yielding of the shear link in case the friction dampers should not slip. Apart from the system in Figure 1a, where the braces are assumed to be slender enough to buckle elastically (buckling load practically negligible), in all the other systems depicted in Figure 1 the braces are designed not to buckle.

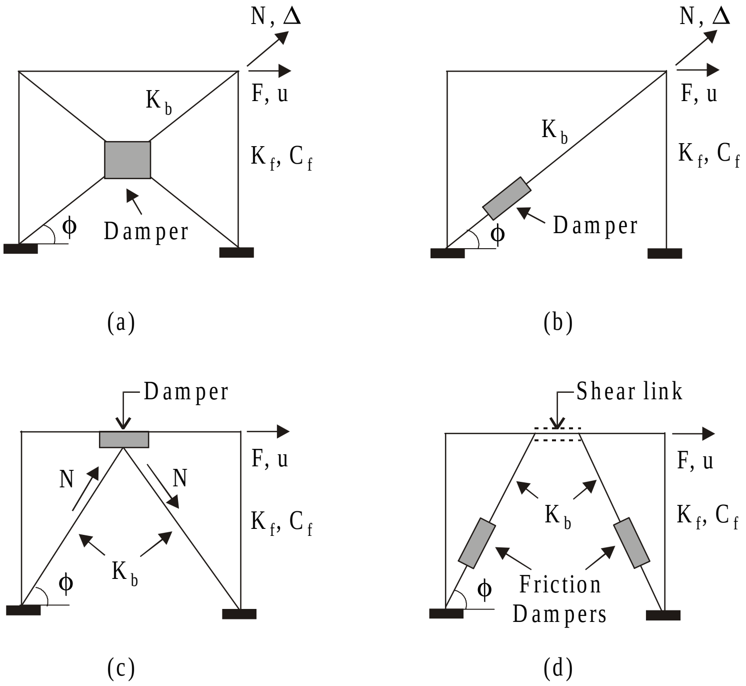


Figure 1: Damped bracing systems.

To simulate the behaviour of braced frames equipped with damping devices, suitable analytical models should be adopted to accurately describe the hysteretic behaviour of both the dissipative braces and the framed structure. In addition, the models should be relatively simple to carry out the analysis with a reasonable computational effort. In this paper aspects of the analytical modelling are discussed with reference to the dissipative braces, while the framed structure is simply idealized as to be elastic-perfectly plastic.

The behaviour of different kinds of dampers can be simulated by adopting the models and the idealized force-displacement (N_d-Δ_d) relations shown in Figure 2. More precisely, Figures 2a and 2b respectively refer to the friction and the metallic-yielding dampers, which can both be classified as hysteretic; while Figures 2c and 2d respectively refer to viscous and viscoelastic dampers, both considered as velocity-dependent. Other systems have characteristics that cannot be represented by one of the basic types shown in Figure 2: e.g. dampers made of shape memory alloys or frictional-spring assemblies with recentering capabilities. In what follows, only dampers whose idealized behaviour is depicted in Figure 2 are considered.

As shown in Figure 2a and 2b, hysteretic dampers are assumed as rate-independent with a stable hysteretic behaviour, which is idealized by a rigid-plastic law for a friction damper and by a bilinear law for a yielding damper. However, more refined models may be adopted. In particular, to simulate the hysteretic response of steel cross-braces equipped with the friction device (see Figure 1a), the authors [Vulcano and Mazza, 1999] adopted two different models: one simplified, elastic-perfectly plastic; the other one refined, to take into account that a previously buckled brace should recover before its shortening to work successively in tension. Also the behaviour of yielding dampers can be simulated using laws more sophisticated than that shown in Figure 2b.

Viscoelastic and pure viscous dampers, rate-dependent, generally exhibit mechanical properties which are functions of the (circular) frequency (ω), the temperature and the amplitude of motion. In this study only the dependence on the frequence is considered by tuning the relevant parameters to the fundamental frequency of the entire structural system. Both the above kinds of dampers are modelled as an elastic spring and a dashpot acting in parallel (Kelvin model, KM) or in series (Maxwell model, MM). Indeed, the pure VS damper model can be considered as a specialization of KM or MM assuming, respectively, $K_d^{(K)}=0$ or $K_d^{(K)}\rightarrow\infty$ (see Figs. 2c and 2d). Both the idealized force-displacement relations shown in Figures 2c and 2d refer to a sinusoidal motion of amplitude Δ_o and circular frequency ω. However, models and force-displacement relations more sophisticated than those reported above were proposed for both the VS and VE dampers: e.g., models based on the fractional derivative approach ([Tsai, 1993], [Kasai et al., 1993]) or Boltzmann's superposition principle ([Aprile et al., 1997], [Shen and Soong, 1995]).

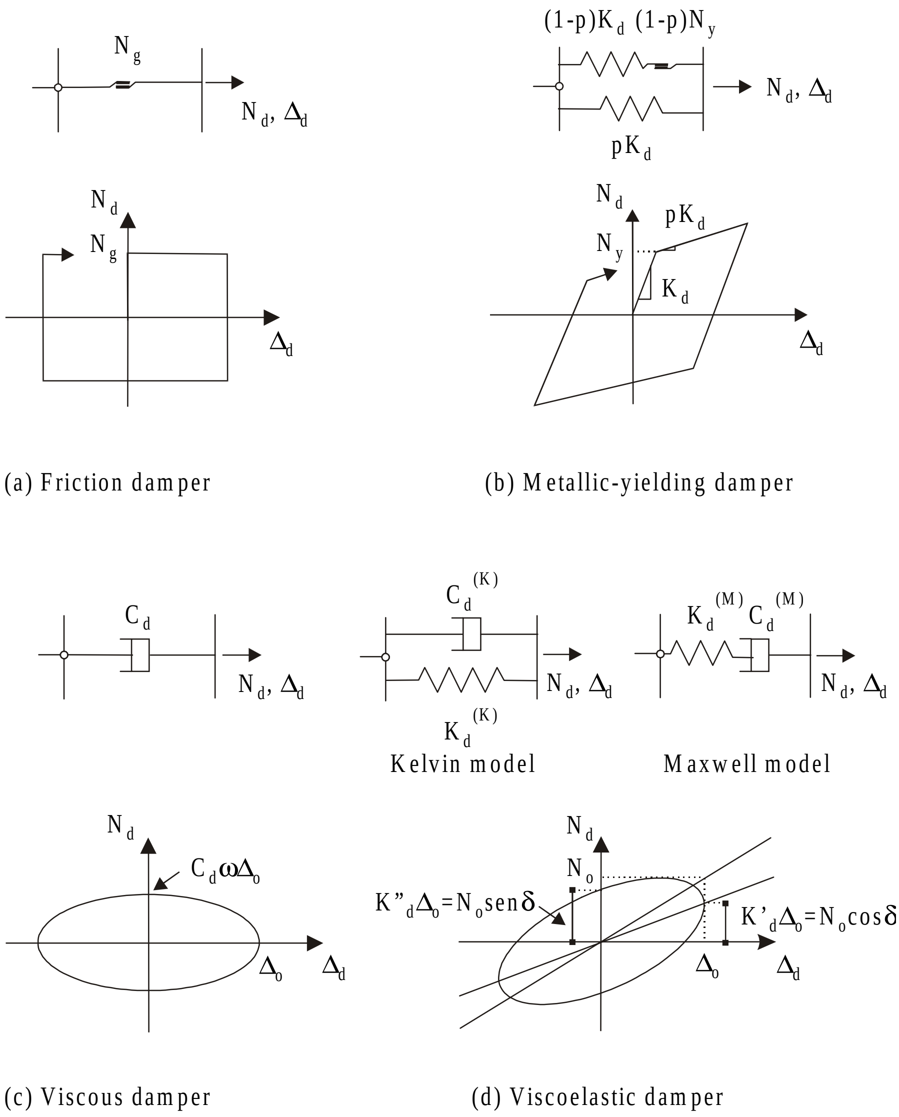


Figure 2: Modelling and idealized response of dampers.

Parameters and laws characterizing the idealized behaviour of the dampers considered in this study are synthetically reported below:

(a) Friction damper: N_g=slip-load force; N_{max}=tension-brace force at frame-yielding onset; $N^*=N_g/N_{max}$=slip-load ratio.

(b) Yielding damper: N_y=yielding force; $N^*=N_y/N_{max}$=yield-load ratio; K_d=initial damper stiffness; p=stiffness hardening ratio.

(c) Viscous damper: $N_d=C_d\,\dot{\Delta}_d$ (for linear fluid damper).

(d) Viscoelastic (solid) damper: C_d=effective damping coefficient; K'_d=G'A/h=storage (or effective) stiffness; K''_d=G"A/h=loss stiffness; $\tan\delta=K''_d/K'_d$=loss factor (=0.8÷1.4); G' and G"=shear-storage and shear-loss moduli; A=shear area of polymer layers; h=total thickness of polymer layers; $N_d=K'_d\Delta_d + C_d\,\dot{\Delta}_d$.

In a parametric study conducted in a companion paper [Vulcano and Mazza, 1999] the SDOF system shown in Figure 3 was considered. The system intends to simulate the response of a shear-type one-storey frame with dissipative braces arranged as shown in Figures 1a, 1b or 1c. For the sake of clarity, referring to the scheme in Figure 1b, the properties of the system are indicated in what follows: K_b is the horizontal elastic stiffness of the undamped brace; K_f, F_y, F_f and C_f represent, respectively, elastic stiffness, yielding force, elastic-plastic force and viscous-damping constant with reference to the unbraced frame; the strength level of the unbraced frame is characterized by the frame-strength ratio $\eta=F_y/Ma_{max}$, M being the mass of the system lumped at the top level and a_{max} the peak ground acceleration; F and u are, respectively, the inertial force and the relative displacement of the mass; F_b and F_d represent the horizontal components of the axial force for undamped brace and damper, respectively, while F_{db} is the analogous component of the axial force transmitted by the damped brace (e.g., $F_{db}=N\cos\phi$).

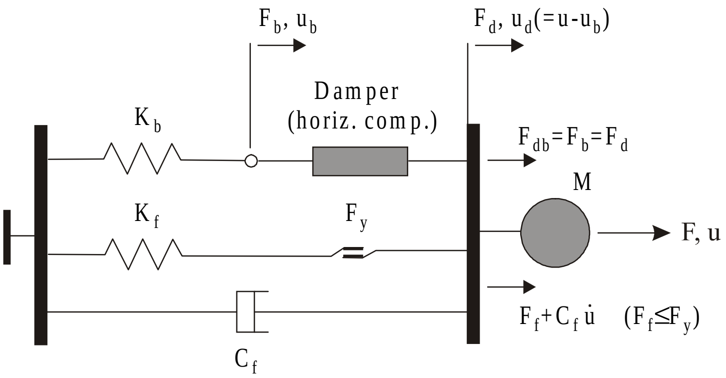


Figure 3: Modelling of a SDOF damped braced system.

For all the damped braces the elastic stiffness is characterized by the stiffness ratio $K^*=K_{db}/K_f$, where K_{db} is the horizontal elastic stiffness of the damped bracing system. In the case of a YL damper it can be assumed ($K_{db}=K_b$, in the case of a FR damper):

$$K_{db}=\frac{1}{1/K_b+1/K_d} \tag{1}$$

while in that of the VE damper, the storage and loss stiffnesses of the damped bracing system, as shown by [Fu and Kasai, 1998] assuming a sinusoidal motion, can be respectively expressed as:

$$K_{db}=\frac{(K_b+K'_d)K_bK'_d+K_bK''^2_d}{(K_b+K'_d)^2+K''^2_d} \quad ; \quad K''_{db}=\frac{K_b^2K''_d}{(K_b+K'_d)^2+K''^2_d} \tag{2a, b}$$

Equations (2) can be specialized for a VS bracing system by setting $K'_d=0$.

Moreover, in the cases of VE and VS damped braces of the SDOF system, the equivalent added damping ratio can be defined as:

$$\xi_{db}=K''_{db}/[2(K_f+K_{db})] \tag{3}$$

In the case of a frame with VE or VS damped braces an analogous damping ratio can be evaluated with reference to the j^{th} mode shape:

$$\xi_{db,j} = (\tan g\delta/2)\ [1- (\omega_{f,j} / \omega_{dbf,j})^2] \qquad (4)$$

where $\omega_{dbf,j}$ and $\omega_{f,j}$ represent the (circular) frequencies of the structure with or without damped braces, respectively.

NUMERICAL RESULTS

In the companion paper mentioned above, to study the effects produced by the insertion of different kinds of dissipative braces into a framed structure, a numerical investigation was carried out considering the nonlinear behaviour of the SDOF system in Figure 3 under strong ground motions. For this purpose different values of the parameters characterizing the behaviour of the dissipative braces were assumed; moreover, different models were adopted with reference to FR and VE bracing systems. In that study the results were shown in terms of displacement ductility demand for the framed structure, which can be considered representative of its damage. The results were obtained as an average of those corresponding to three artificial accelerograms whose average response spectrum matches the design spectrum adopted by [Eurocode 8, 1994] with reference to subsoil class B and peak ground acceleration a_{max}=0.35g.

The main conclusions drawn in the above study are summarized below:

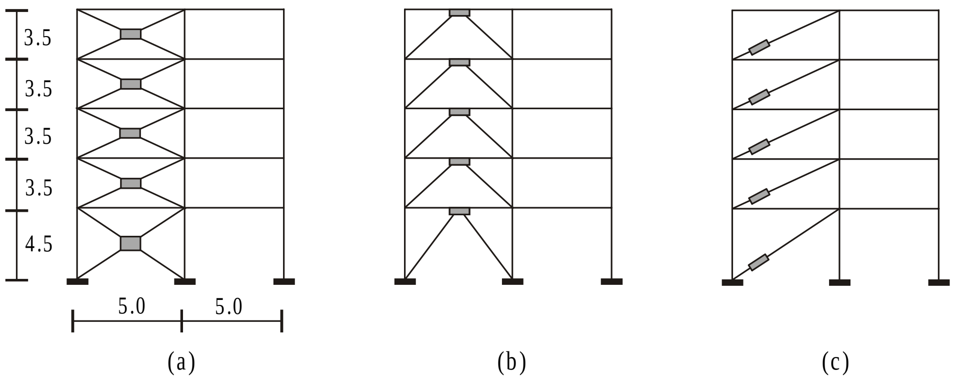
- When using braces with a hysteretic damper, a higher value of the stiffness hardening ratio can produce a better performance of the framed structure (even though this is not a general conclusion); in this case the beneficial effect is more evident for weaker framed structures, provided that a suitable value of the slip- or yield-load ratio N* is assumed in the range 0.5÷1, which is suggested for practical applications.
- In the case of FR damped systems, the selection of a suitable value of the slip-load ratio is more important in cases corresponding to unbraced frames with a relatively low period of vibration (T_f).
- The effectiveness of the VS damped bracing is more evident for systems corresponding to relatively stiff braces and/or weak framed structures.
- When using VE dampers the variation of the loss factor in the practical range (i.e. 0.8÷1.4) can be important for the effectiveness of the damped bracing system only in the case of a relatively weak frame; moreover, in the case of a relatively strong frame the performance of the framed structure is not appreciably enhanced, especially using a very stiff damper.
- The use of the refined model (instead of that simplified) for the FR damped bracing is recommended in the case of a rather weak framed structure.
- When modelling VE damped bracing, the difference between results obtained by the Kelvin and Maxwell models is more evident in the case of a relatively weak frame; moreover, the frame damage can be underestimated when, as in practice is often done, the brace deformability is neglected.

In this work the study is extended considering the test structures with different kinds of dampers shown in Figure 4. The framed part of the structures is a reinforced concrete (r.c.) frame which was designed according to [Eurocode 8, 1994] assuming different values of the behaviour factor q in the range 2.5÷6; details can be found in a previous work [Vulcano and Mazza, 1997], where the authors studied the effects produced by the insertion of cross-braces with friction dampers. The fundamental vibration period of the unbraced frame is T_f=0.645 sec and a corresponding viscous-damping factor of 5% is assumed.

All the considered dissipative braces were designed according to a "proportional stiffness criterion", which was also used in the work mentioned above, assuming the lateral storey stiffness of the braces proportional to that of the unbraced frame calculated with reference to the first mode shape of the unbraced frame itself. With this assumption the stiffness properties of the braces can be identified by a same value of the stiffness ratio (K*) at each storey and the fundamental vibration period of the (damped) braced frame can be calculated approximately as: $T_{dbf}=T_f/(1+K^*)^{1/2}$. An analogous distribution law was assumed for K''_{db}, when using VE and VS dampers;

further details regarding the properties of the VE or VS dissipative braces can be found in an other paper [Mazza and Vulcano, 1999].

Figure 4: Test structures with different dampers: (a) hysteretic; (b) viscoelastic; (c) viscous.



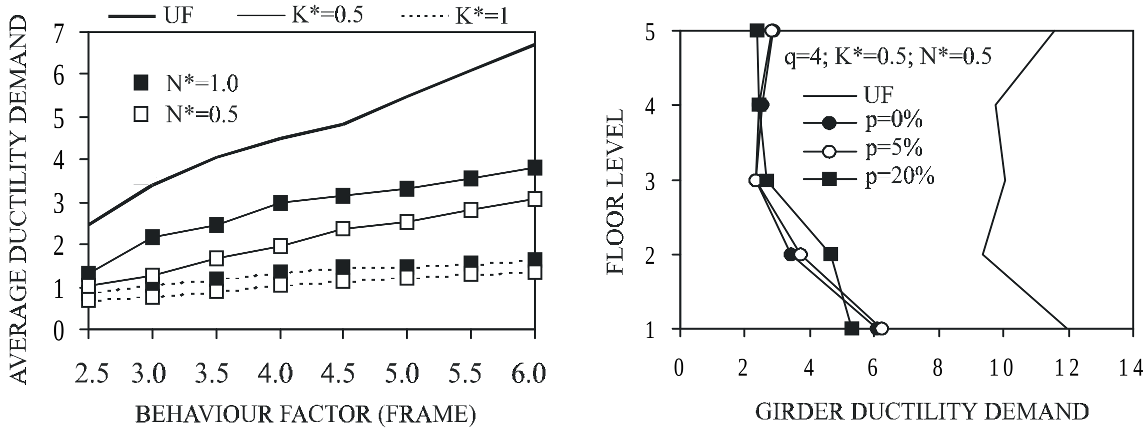
The nonlinear dynamic response of the test structures in Figure 4 is studied assuming an elastic-perfectly plastic behaviour for the unbraced frame, while for the dissipative braces the models illustrated above are used. A numerical procedure analogous to that adopted in previous papers [Vulcano, 1994; Vulcano and Mazza, 1997; Mazza and Vulcano, 1999] was implemented in a computer code. The following results have been obtained as the average of those for the three artificial motions used in the previous study with regard to the SDOF system.

In Figure 5a the average ductility demand for the frame is shown against the frame behaviour factor: the results obtained for the unbraced frame (UF) are compared with those for the FR damped frame in Figure 4a, assuming different values of the stiffness ratio (K*) and the slip-load ratio (N*). It is evident the greater effectiveness of the damped braces for increasing values of K*, even though the ductility reduction is quite marked assuming K*=0.5, which can be considered a rather low value. Moreover, a relatively high K* value (e.g., K*=2) leads to a negligible variation of the results when assuming N* varying in the range of practical interest (0.5÷1).

A comparison of results for the unbraced frame and braced frames with hysteretic dampers is shown in Figure 5b, where the girder ductility demand is reported. It should be noted that, even using a value of the stiffness hardening ratio (p) up to 20%, the average ductility demand remains comparable to that corresponding to lower p values, but the peak values (e.g., at the first and top floors) are lightly smaller than those for lower p values.

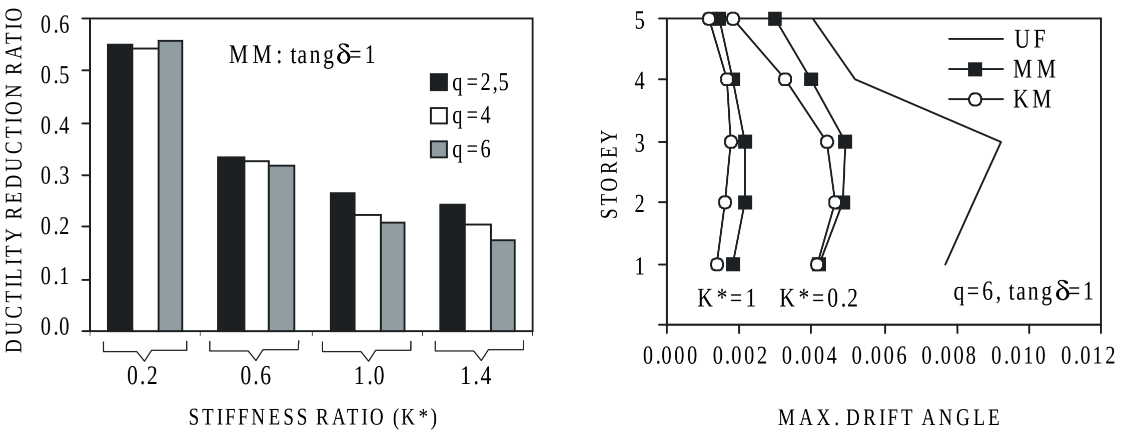
Results for structures with VE dampers are shown in Figure 6. More precisely, in Figure 6a the average ductility reduction ratio (=damped braced frame ductility/unbraced frame ductility) is reported against the stiffness ratio for different values of the frame behaviour factor (q). It is interesting to note that the above ratio depends substantially on the stiffness ratio K*, while the influence of the frame strength (i.e., q) can be practically neglected. These results have been obtained by using the Maxwell model to idealize the VE dampers, while the analogous ones by the Kelvin model were little more conservative. The same conclusion can be drawn with reference to the maximum drift angle shown in Figure 6b and to other parameters (maximum displacement, ductility of r.c. members) whose results are not reported herein. However, both the damper models prove the effectiveness of the VE damped braces, even assuming K*=0.2, i.e. a rather low value. As shown in a paper mentioned above [Mazza and Vulcano, 1999], the variation of the loss factor can have some influence for rather low K* values (e.g., K*<1), while its effect is practically negligible for rather high values (e.g., K*>1).

Lastly, in Figure 7 results for the unbraced frames are compared with those obtained for structures with VS (linear) dampers, assuming $K''_d/K_f=2$ and the values 1, 2 and 5 of the brace-stiffness ratio $K^*_b(=K_b/K_f)$: with these assumptions the corresponding values of the equivalent damping factor of the dissipative braces are about 11%, 25% and 51%, respectively. These results and other ones omitted for the sake of brevity, show that the effectiveness of the VS dampers increases for ever-increasing values of the brace stiffness.



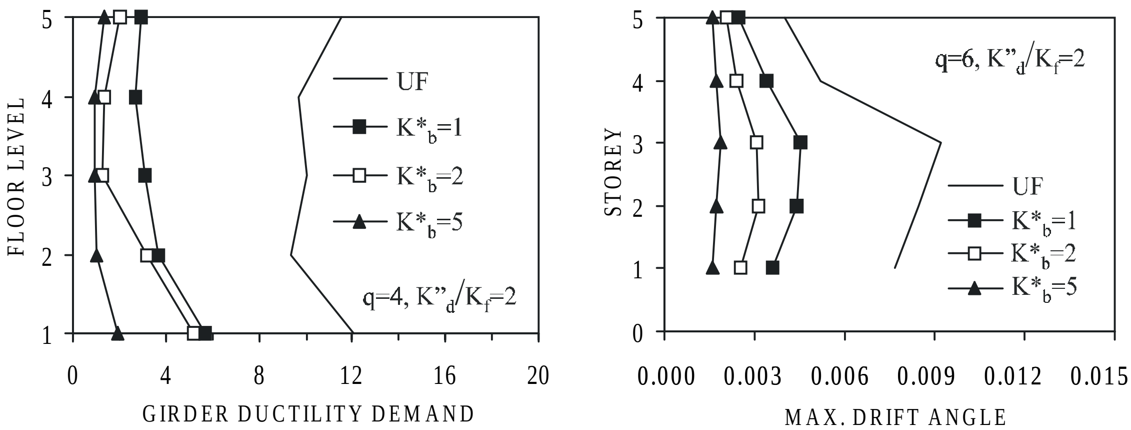
(a) (b)

Figure 5: Results for structures with hysteretic dampers in Figure 4a.



(a) (b)

Figure 6: Results for structures with viscoelastic dampers in Figure 4b, using Maxwell model (MM) and/or Kelvin model (KM).



(a) (b)

Figure 7: Results for structures with viscous dampers in Figure 4c.

CONCLUSIONS

The nonlinear seismic behaviour of r.c. frames with dissipative braces making use of different kinds of dampers has been studied. The following conclusions can be drawn from the results:

- The effectiveness of the damped braces using any kind of damper increases for increasing values of the stiffness brace; however this effect is quite marked even using relatively low values of this stiffness.

- Using FR (or YL) dampers, the average ductility demand for the frame can be reduced assuming stiffer braces, but the selection of a suitable value of the slip- (or yield-) load ratio can be important only in case that the stiffness ratio is relatively low (e.g., K*=0.5).

- Ever-increasing values of the stiffness hardening ratio for hysteretic dampers can lead to a reduction of peak values for the response parameters (e.g., the ductility demand for the frame members).

- Using VE and VS dampers, the ductility reduction ratio depends substantially on the bracing stiffness, while the influence due to different values of the frame strength is practically negligible.

- With regard to the modelling of the VE damper, in all the studied cases the Maxwell model was more conservative than the Kelvin model. Moreover, the variation of the loss factor can have some influence on the response for rather low values of the brace stiffness ratio (e.g., K*<1), while its effect is practically negligible for rather high values of this ratio (e.g., K*>1).

The present work was partially financed by M.U.R.S.T.
(Italian Ministry of the University and Scientific and Technological Research)

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