DISPLACEMENT-BASED DESIGN OF DISSIPATIVE BRACES AT A GIVEN PERFORMANCE LEVEL OF A FRAMED BUILDING

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ABSTRACT:

The insertion of dissipative braces proves to be very effective in order to enhance the performance of a framed building under seismic loads. For a widespread application of this technique, practical design procedures are needed. In this paper a design procedure aiming to proportion damped braces in order to attain, for a specific level of seismic intensity, a designated performance level of the structure is proposed. Exactly, a proportional stiffness criterion, which assumes the elastic lateral storey-stiffness due to the braces proportional to that of the unbraced frame, is combined with the Direct Displacement-Based Design, in which the design starts from a target deformation. To check the reliability of the design procedure, a six-storey reinforced concrete (r.c.) plane frame, representative of a medium-rise symmetric framed building, is considered as a test structure, which primarily designed in a medium-risk seismic region, has to be retrofitted as in a high-risk seismic region by insertion of braces equipped with either hysteretic dampers or viscoelastic ones. Nonlinear dynamic analyses are carried out, under real and artificially generated ground motions, by a step-by-step procedure. Frame members and hysteretic dampers are idealized by bilinear models, while the viscoelastic dampers are idealized by a six-element generalized model describing the variation of the mechanical properties depending on the frequency, at a given temperature.

KEYWORDS: Framed building, damped braces, performance based design, displacement based design, nonlinear seismic analysis

1. INTRODUCTION

Damped bracing systems prove to be very effective for controlling the seismic response of framed buildings (e.g., Christopoulos and Filiatrault, 2007). They differ for arrangement of the braces (e.g., single diagonal, cross or chevron braces) and/or features of the damping devices: i.e., displacement-dependent (e.g.: friction damper, FR; metallic-yielding damper, YL) or velocity-dependent (e.g.: viscoelastic damper, VE; viscous damper, VS). FR and YL dampers present a mechanism of energy dissipation which depends on the storey drift and becomes active when preset stress levels are reached or overcome. VE and VS devices dissipate energy due to viscoelasticity or viscosity of elastomers or fluids, whose properties generally depend on the load frequency and temperature.
For a widespread application of the dissipative braces, practical design procedures are needed. According to the philosophy of the *Performance-Based Earthquake Design* (Bertero, 2002), a performance design objective is obtained coupling a performance level (e.g., fully operational, operational, life safe or near collapse) with a specific level of ground motion (e.g., frequent, occasional, rare or very rare, corresponding, respectively, to a return period of 43, 72, 475 or 970 years). Specifically, two alternative approaches can be followed: (a) the Force-Based Design (FBD) approach combined with required deformation target verification (e.g., see Ponzo *et al.*, 2007, or Kim *et al.*, 2003, referring to YL or VS dampers, respectively); (b) the Direct Displacement-Based Design (DDBD) approach, in which the design starts from a target deformation (e.g., see: Vulcano and Mazza, 2007, and Mazza and Vulcano, 2008a,b, in case of YL dampers; Kim and Choi, 2006, in case of VE dampers).
In this paper a design procedure, aiming to proportion steel braces equipped with YL or VE dampers in order to attain, for a specific level of seismic intensity, a designated performance level of a framed structure, is presented. To check effectiveness and reliability of this design procedure, a six-storey r.c. plane frame, representative of a medium-rise symmetric framed building, is considered as primary structure. After proportioning damped bracing systems with different properties for enhancing the performance of the primary frame, the nonlinear dynamic responses of unbraced and damped braced frames are compared under real and artificial motions.

2. DIRECT DISPLACEMENT-BASED DESIGN PROCEDURE

A proportional stiffness criterion, previously proposed for FR and YL dampers (Vulcano, 1994) and then generalized for VE and VS dampers (Vulcano and Mazza, 2002), which assumes, at each storey, the same value of the stiffness ratio K^*_{DB}(=K_{DB}/K_F, being K_{DB} the lateral stiffness of the damped braces and K_F that of the unbraced frame), is combined with the DDBD method, mentioned above.
In the case of YL dampers, K_{DB} can be expressed as for an in-series model depending on the brace stiffness, K_B, and the elastic stiffness of the damper, K_D. Moreover, the distribution law of the yield-load (N_y) is assumed similar to that of the elastic force induced in the braces by the lateral seismic loads (e.g., those corresponding to the first-mode shape). The selection of the N_y value at a generic storey can be restricted to the range ($0.5N_{max}$, N_{max}), where: the lower bound aims to avoid yielding of dampers under service gravity loads and moderate seismic (or wind) loads; the upper bound should avoid any yielding of frame members before yielding of dampers, as well as the occurrence of undesirable phenomena in the frame columns (e.g., buckling, brittle failure of r.c. columns, etc.). Due to the above assumptions, the yield-load is such to have at each storey the same value of the ratio $N^*=N_y/N_{max}$.
In the case of VE damped braces, the distribution law of the loss stiffness, K''_{DB}, is assumed similar to that of the storage stiffness, K_{DB}; loss and storage stiffnesses depend on the stiffness of a brace, K_B, and the properties of the supported VE damper (i.e., storage stiffness, K'_D=G'A/h, and loss stiffness, K''_D=G"A/h, being: G'=shear storage modulus; G"=shear loss modulus; A=shear area; h=total thickness of the polymer layers).
Note that a FR damper can be considered as a YL damper with a rigid-plastic law (i.e., a damper with stiffness hardening ratio r_D=0); while, a linear VS damper as a VE damper having loss stiffness K'_D=0.
The main steps of the proposed design procedure are summarized below with reference to diagonal braces with either YL dampers or VE ones. Further detail in the case of YL dampers can be found in the papers by Vulcano and Mazza, 2007, and Mazza and Vulcano, 2008a.

2.1. Hysteretic dissipative braces

Step 1: Pushover analysis of the given frame and Equivalent Single Degree of Freedom (ESDOF) system
Nonlinear static (pushover) analysis of the primary frame is carried out to obtain base shear-top displacement curves: i.e., ($V^{(F)}$-d) for the frame and (V^*-d^*) for the ESDOF system (Fajfar, 1999). Once both these curves are idealized by a bilinear law and the displacement at a selected performance level of the frame (d_p) is fixed, ductility μ_F(=$d_p/d_y^{(F)}$; $d_y^{(F)}$=yield displacement), stiffness hardening ratio r_F and equivalent stiffness $K_e^{(F)}$(=$V_p^{(F)}/d_p$; $V_p^{(F)}$=base shear at the performance displacement) can be evaluated for the frame. Then, the equivalent viscous damping due to hysteresis $\xi_F^{(h)}$ can be calculated as

$$\xi_F^{(h)}(\%) = \kappa\left\{63.7\frac{(\mu_F-1)(1-r_F)}{\mu_F[1+r_F(\mu_F-1)]}\right\} \tag{2.1.1}$$

where the parameter κ, which accounts for the mechanical degradation, depends on the structural type (e.g., according to ATC 40, 1996, κ can be assumed equal to 1/3 in case of poor structural behaviour).

Step 2: Equivalent viscous damping due to hysteresis of the damped braces (ξ_{DB})
Once the constitutive law of the equivalent damped brace is idealized as bilinear, the corresponding viscous damping, $\xi_{DB}=\xi_{DB}(\mu_{DB}, r_{DB})$, can be evaluated by an expression analogous to Eq. 2.1.1 (but without κ). The ductility of the equivalent damping brace, μ_{DB}, can be assumed according to the design criteria specified above for selecting N_y (then: $\mu_F \le \mu_{DB} \le 2\mu_F$), while the corresponding stiffness ratio, r_{DB}, can be expressed as

$$r_{DB} = \frac{1/K_B + 1/K_D}{1/K_B + 1/(r_D K_D)} = \frac{r_D\left(1+K_D^*\right)}{1+r_D K_D^*} \quad ; \quad K_D^* = \frac{K_D}{K_B} \tag{2.1.2a,b}$$

where r_D is the stiffness hardening ratio of the damper and the ratio K^*_D(=K_D/K_B) can be reasonably assumed rather less than 1. Moreover, μ_{DB} can be expressed as (μ_D=damper ductility)

$$\mu_{DB} = 1+(\mu_D-1)\left(1+r_D K_D^*\right)/\left(1+K_D^*\right) \tag{2.1.3}$$

Step 3: Effective period of the frame with damped braces (DBF)
Assuming a suitable value of the elastic viscous damping for the framed structure (e.g., as commonly done,

$\xi_F^{(e)}$=5%), the equivalent viscous damping of the damped braced frame (DBF) is:

$$\xi_e(\%) = 5 + \xi_F^{(h)} + \xi_{DB} \tag{2.1.4}$$

where $\xi_F^{(h)}$ and ξ_{DB} have been calculated in steps 1 and 2, respectively. Then, the effective period (T_e) of DBF can be evaluated as the period corresponding to the performance displacement d_p, by means of the displacement spectrum (S_D-T) for the viscous damping ξ_e.

Step 4: Effective stiffness of the equivalent damped brace
Once the mass of ESDOF system, m_e, is calculated (see Fajfar, 1999), the effective stiffness of DBF can be obtained as

$$K_e = 4\pi^2 m_e / T_e^2 \tag{2.1.5}$$

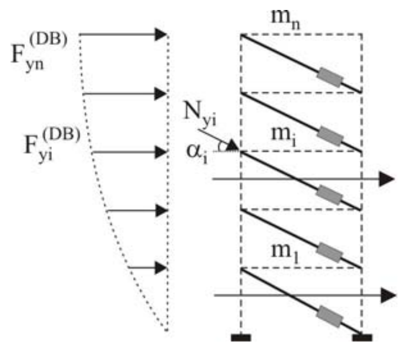
Then, the effective stiffness required to the damped braces is easily evaluated as

$$K_e^{(DB)} = K_e - K_e^{(F)} \tag{2.1.6}$$

Step 5: Strength properties of the damped brace
The base shear-displacement curve representing the response of the damped braces of the actual structure ($V^{(DB)}$-d) is idealized as bilinear. Specifically, the base-shear contributions due to the damped braces of the actual structure at the performance and yielding points ($V_p^{(DB)}$ and $V_y^{(DB)}$, respectively) are:

$$V_p^{(DB)} = K_e^{(DB)} d_p \quad ; \quad V_y^{(DB)} = V_p^{(DB)} / \left[1 + r_{DB}(\mu_{DB} - 1)\right] \tag{2.1.7a,b}$$

Step 6: Design of the hysteretic damped braces of the actual structure
According to the proportional stiffness criterion, it can be reasonably assumed that a mode shape (e.g., the first-mode shape: $\{\phi_1, \ldots, \phi_n\}^T$) of the primary frame remains practically the same even after the insertion of damped braces. This design criterion is preferable in the case of a retrofitting, because the stress distribution remains practically unchanged. Thus, the properties of the damped braces can be defined as indicated in Fig. 1, being m_i the mass at the generic storey i^{th} and $d_y^{(DB)}$ the yielding displacement of the damped bracing system.



$$V_{yi}^{(DB)} = \sum_{j=i}^{n} F_{yj}^{(DB)} \qquad V_y^{(DB)} = \sum_{i=1}^{n} F_{yi}^{(DB)}$$

$$\begin{cases} F_{yi}^{(DB)} = \dfrac{m_i \phi_i}{\sum_{j=1}^{n} m_j \phi_j} V_y^{(DB)} \\ N_{yi} = \dfrac{V_{yi}^{(DB)}}{\cos\alpha_i} \\ K_i^{(DB)} = \dfrac{V_{yi}^{(DB)}}{(\phi_i - \phi_{i-1}) d_y^{(DB)}} \dfrac{1}{\cos^2\alpha_i} \end{cases}$$

Figure 1 Quantities for design of diagonal braces with YL dampers

2.2. Viscoelastic dissipative braces

Step 1: Pushover analysis of the given frame and Equivalent Single Degree of Freedom (ESDOF) system
Similarly to the step 1 discussed above for hysteretic dissipative braces.

Step 2: Equivalent viscous damping due to VE damped braces (ξ_{DB})
Once the constitutive law of the equivalent damped brace is idealized as elliptical, under a sinusoidal motion, the corresponding viscous damping ξ_{DB}(=0.5K"$_{DB}$/K_{DB}), can be evaluated by the expressions of K"$_{DB}$ and K_{DB} proposed by Fu and Kasai, 1998. After some transformations, it comes out

$$\xi_{DB} = 0.5\eta_D \Big/ \left[1 + K_D^* + K_D^*\eta_D^2 + \frac{1}{K_D^* K_B^*}\left(1 + 2K_D^* + K_D^{*2} + K_D^{*2}\eta_D^2\right)\right] \tag{2.2.1}$$

where: the loss factor η_D(=G"/G'=0.8÷1.5) is obtained, at a given temperature, as function of the fundamental (circular) frequency of the entire damped structure, $\omega_{1,DBF}$, which can be calculated (primarily) assuming a trial value of K^*_{DB} (then, at each storey of the actual frame it is assumed: $K_{DB}=K^*_{DB}K_F$); $K^*_D(=K'_D/K_B)$ is the stiffness ratio of a VE damper, for which a suitable value (e.g., rather less than 1) can be assigned (note that if the K_B value is high enough, $K^*_D \cong K^*_{DB}$ assumes practically the same value at each storey); $K^*_B(=K_B/K_F)$ can be expressed as

$$K^*_B = K'_D / \left(K^*_D K_F\right) \tag{2.2.2}$$

Specifically, K'_D can be obtained, after some transformations starting from the expression of K_{DB} proposed by Fu and Kasai, 1998:

$$K'_D = K_{DB} \frac{\left(1+K^*_D\right)^2 + \eta_D^2 K_D^{*2}}{1+K^*_D+\eta_D K^*_D} \tag{2.2.3}$$

Step 3: Effective period of the frame with damped braces (DBF)
Similarly to the step 3 discussed above for hysteretic dissipative braces.

Step 4: Effective storage stiffness of the equivalent damped brace
The effective stiffness of DBF, K_e, and the effective stiffness required to the damped braces, $K_e^{(DB)}$, are calculated as in the step 4 for hysteretic dissipative braces (see Eqs. 2.1.5 and 2.1.6, respectively).
Finally, the stiffness ratio of the equivalent damped brace can be obtained as

$$K^*_{DB} = K_e^{(DB)} / K_e^{(F)} \tag{2.2.4}$$

and compared with the trial value assumed in the step 2. Then, steps 2÷4 are solved iteratively until the difference between the K^*_{DB} values obtained in two consecutive loops is less than a prefixed tolerance.

Step 5: Storage stiffness and loss stiffness of the VE damper of the actual structure
As said above, the distribution of K_{DB} is assumed according to the proportional stiffness criterion. Then, for a VE damper, the storage stiffness K'_D is calculated by Eq. 2.2.3 and the loss stiffness K''_D as

$$K''_D = \eta_D K'_D \tag{2.2.5}$$

3. TEST STRUCTURES

A typical six-storey residential building with a r.c. framed structure, whose symmetric plan is shown in Fig. 2a, is considered as a reference for this study. For the sake of simplicity, the central plane frame lying along the horizontal direction of the ground motion is assumed as test (primary) structure, considering the tributary mass resulting from the overall building and the gravity loads corresponding to the tributary area marked in Fig. 2a. Geometric dimensions and size of the sections of the primary frame are shown in Fig. 2b. The gravity loads on the girders are represented by a dead load of 21 kN/m at the top floor and 25 kN/m at the other floors, and a live load of 10 kN/m at all the floors. A masonry-infill, distributed in elevation along the perimeter (Fig. 2a), is taken into account considering a vertical load of 40 kN at each exterior joint of the test structure in Fig. 2b. A cylindrical compressive strength of 25 N/mm^2 for concrete and a yield strength of 375 N/mm^2 for steel are assumed.

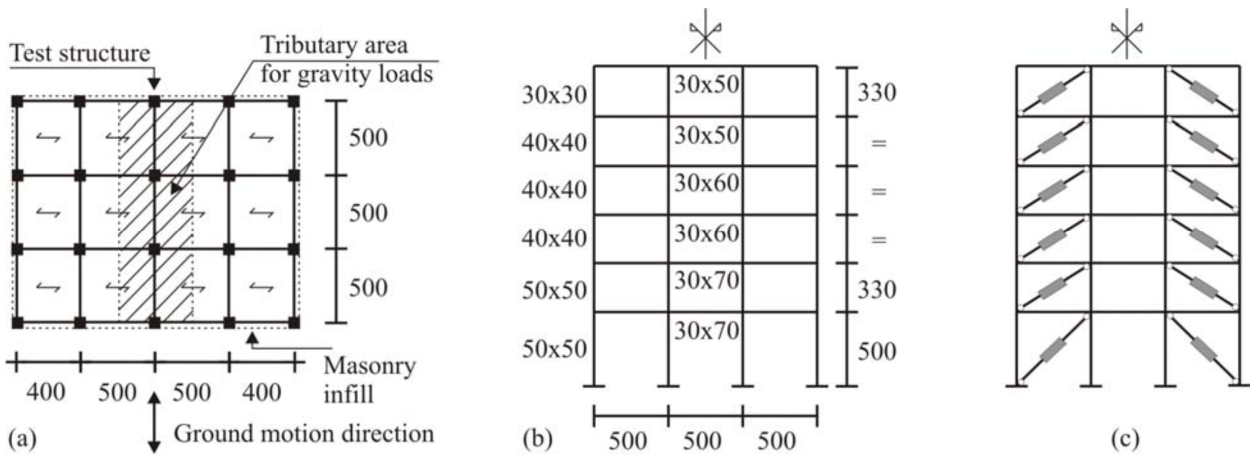


Figure 2 R.c. framed building and test structures (dimensions in cm):
(a) plan; (b) elevation of the unbraced frame; (c) elevation of a damped braced frame

The first three vibration periods of the unbraced frame (Fig. 2b) are: T_1=0.988 s; T_2=0.383 s; T_3=0.245 s. The test frame is designed according to the Italian seismic code (by Italian Ministry of Public Works) in force in 1996, for a medium-risk seismic region and a medium soil class. The design is carried out to comply with the ultimate limit states. Detailing for local ductility is also imposed to satisfy minimum conditions for the longitudinal bars of the r.c. frame members. Further detail can be found in a previous work by the authors (Mazza and Vulcano, 2008b). The nonlinear static analysis of the test framed structure is carried out by a step-by-step procedure (Mazza and Vulcano, 2008a), assuming an elastic-perfectly plastic (e.p.p.) behaviour. In Fig. 3 the capacity curves obtained for the test structure and ESDOF system are reported, considering the base shear (V) normalized respect to the total seismic weight of the structure (W). The nonlinear analysis is stopped once the ultimate value of the curvature ductility demand, evaluated according to the provisions of Eurocode 8 (2004), is attained at some critical section of the frame: exactly, this occurred at the top of an external end section of the first-floor girder. Moreover, yield (V_y^*-d_y^*) and ultimate (V_y^*-d_u^*) points of the idealized e.p.p. base shear-displacement curve for ESDOF system are indicated in Fig. 3. The ultimate ductility, $\mu_{F,u}$=4.86, is so obtained for the test frame.

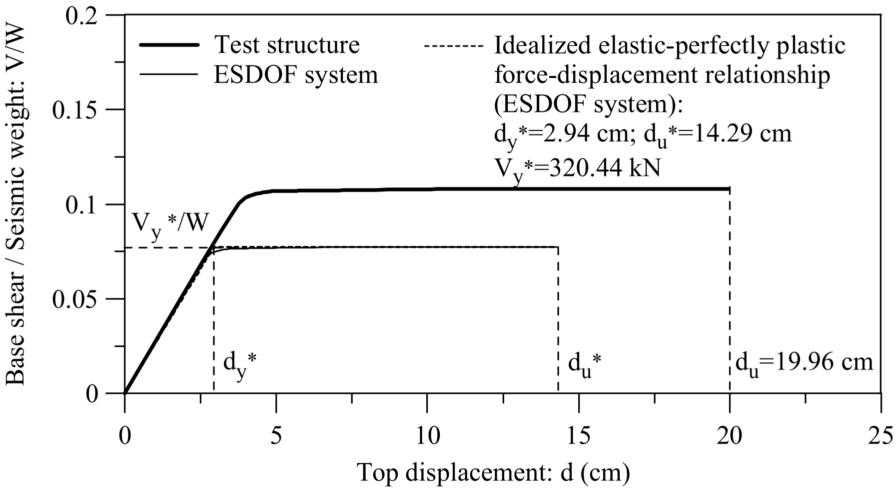


Figure 3 Capacity curves for the test structure in Fig. 2b and ESDOF system

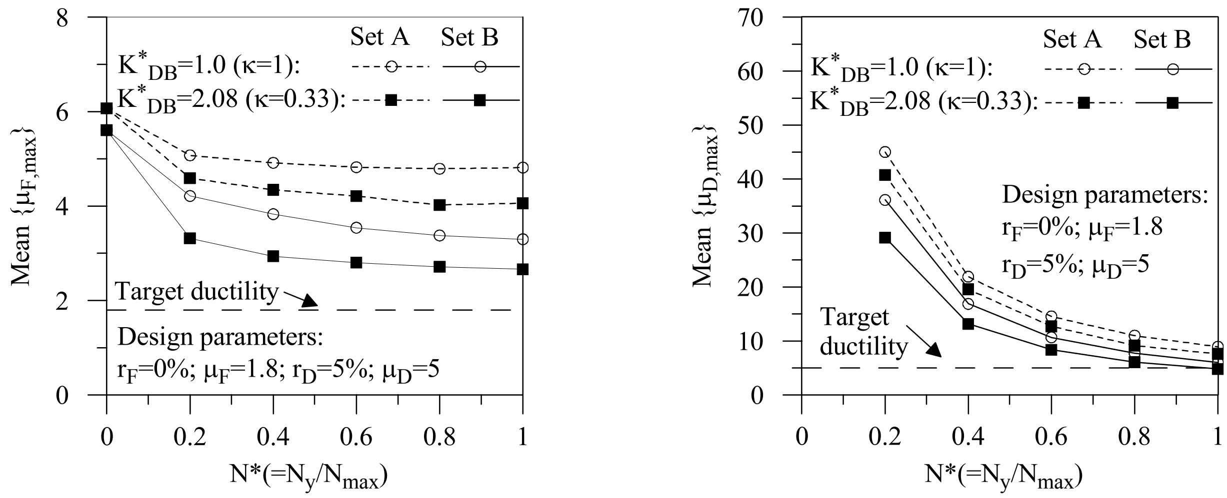
For the purpose of retrofitting the test structure from a medium-risk region up to a high-risk seismic region, diagonal steel braces equipped with either YL dampers or VE ones are inserted, at each storey, in the lateral bays (Fig. 2c). The design of the damped braces is carried out according to the procedure described in Section 2, considering seismic loads according to Eurocode 8 (2003), i.e. assuming: soil class C, subsoil parameter S=1.25; high-risk seismic region, PGA=peak ground acceleration=0.35g. Specifically, distribution laws are reported in Table 3.1 for properties of YL damped braces (i.e.: yield-load, N_y, assuming N^*=1; storey stiffness, $K_{DB}\cong K_D$, assuming a brace rigid enough) and VE damped braces (i.e.: storage stiffness, $K_{DB}\cong K'_D$, and loss stiffness, $K''_{DB}\cong K''_D$, assuming a K_B value high enough), considering the same value of the frame ductility (e.g., μ_F=1.80). The distribution laws for YL damped braces correspond to two values of the reduction factor κ (i.e., 1 and 0.33).

Table 3.1 Properties of damped braces with YL dampers (κ=1 or 0.33) or VE dampers (κ=0.33), assuming μ_F=1.80

With YL dampers ξ_{DB}=40.3%			κ=1; $\xi_F^{(h)}$=28.3% K^*_D=0.2; K^*_{DB}=1.0		κ=0.33; $\xi_F^{(h)}$=9.4% K^*_D=0.2; K^*_{DB}=2.08		With VE dampers ξ_{DB}=23.2%	κ=0.33; $\xi_F^{(h)}$=9.4% K^*_D=0.2; K^*_{DB}=1.59	
Storey	μ_D	r_D (%)	N_y (kN) for N*=1	$K_{DB}\cong K_D$ (kN/m)	N_y (kN) for N*=1	$K_{DB}\cong K_D$ (kN/m)	Storey	$K_{DB}\cong K'_D$ (kN/m)	$K''_{DB}\cong K''_D$ (kN/m)
6	5	5	13.3	15496	27.7	32426	6	24631	26762
5	5	5	28.5	34845	59.4	72913	5	55836	60666
4	5	5	42.3	39902	88.1	83495	4	64008	69545
3	5	5	53.0	44192	110.4	92472	3	71006	77148
2	5	5	60.4	73009	125.6	152769	2	117438	127597
1	5	5	77.2	40591	160.6	84935	1	65360	71014

3. NUMERICAL RESULTS

A computer code was prepared according to the procedure described in the paper by Mazza and Vulcano, 2008a. Specifically, the behaviour of a YL damper is idealized by a bilinear law, while that of a VE damper is idealized by a six-element generalized model (Mazza and Vulcano, 2002). A numerical investigation is carried out to evaluate the effects produced by the insertion of damped braces under real and artificial motions. More precisely, seven recorded ground motions (set A), available in the on-line *European Strong Motion database* (European Commission for Community Research) were selected taking into account the assumptions made, with regard to seismic intensity and soil class, in the design of damped braces for retrofitting the primary frame. Moreover, three artificial motions (set B), everyone with a duration of 12 seconds, were generated by using the computer code SIMQKE (Gasparini and Vanmarcke, 1976), with a value of PGA close to that of the corresponding target EC8 spectrum (i.e., PGA=1.25×0.35g=0.44g). The results discussed below have been obtained as an average of those corresponding to either the motions of set A or those of set B.
Firstly, to evaluate the effects due to the assumption of different values of the reduction factor κ of $\xi_F^{(h)}$, in Fig. 4 curves representing the mean ductility demand for r.c. frame members (Fig. 4a) – calculated as mean of the maximum curvature ductility of all the frame members ($\mu_{F,max}$) - and for YL dampers (Fig. 4b) - calculated as the mean of the maximum values ($\mu_{D,max}$) at each storey - are plotted against the yield-load ratio N^* (note that N^*=0 corresponds to the unbraced frame). The design (target) values of ductility (i.e., μ_F=1.80 and μ_D=5, respectively indicated by a dashed line in Fig. 4a and Fig. 4b) lead to the following values of the stiffness ratio of the YL damped braces, K^*_{DB}: 1.0 for κ=1 and 2.08 for κ=0.33. As can be noted, for a N^* value, the mean ductility demand for κ=0.33 is less than that for κ=1, under either real ground motions (set A) or artificial ones (set B). Moreover, the control of the frame damage (Fig. 4a) is more evident under ground motions of set B rather than under those of set A. This behaviour is because spectral accelerations of some real motions are higher than those of the artificial motions, whose response spectra are very close to EC8 spectrum (see Mazza and Vulcano, 2008b). Finally, the reduction of the ductility demand for the frame members is evident, provided that a suitable value of N^* is assumed in the range 0.5÷1. The curves show an evident decrease in a range of relatively low values of N^* and a rather stable trend for higher values of N^*. However, the selection of N^* should be restricted to a rather narrow range close to the optimum value (e.g., in this case: $N^*_{opt.}$=1), because the variation of $\mu_{D,max}$ for YL dampers (Fig. 4b), in the range of N^* indicated above (i.e., N^*=0.5÷1), is rather evident.

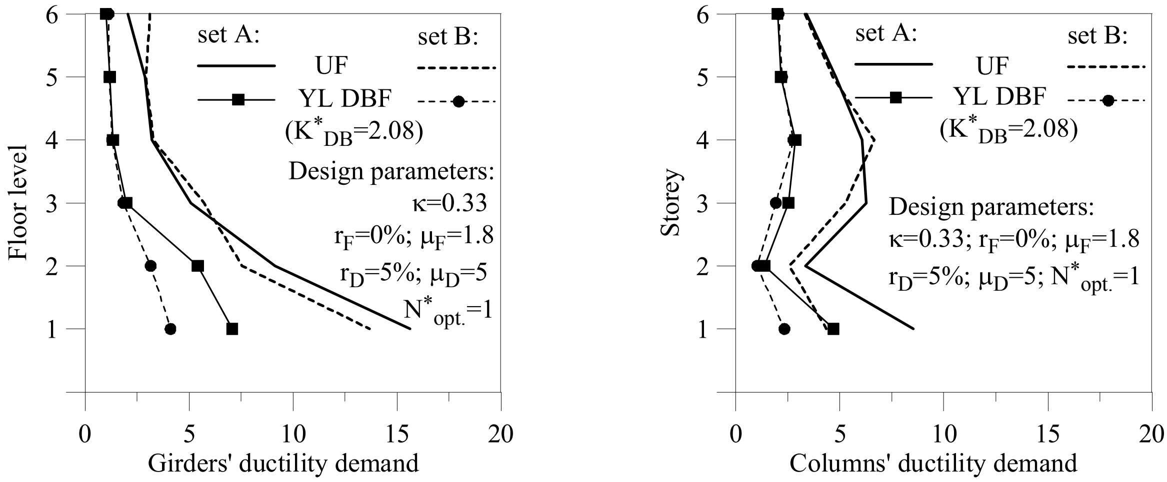


(a) r.c. frame members (b) YL dampers

Figure 4 Mean ductility demand assuming different values of N^* and κ

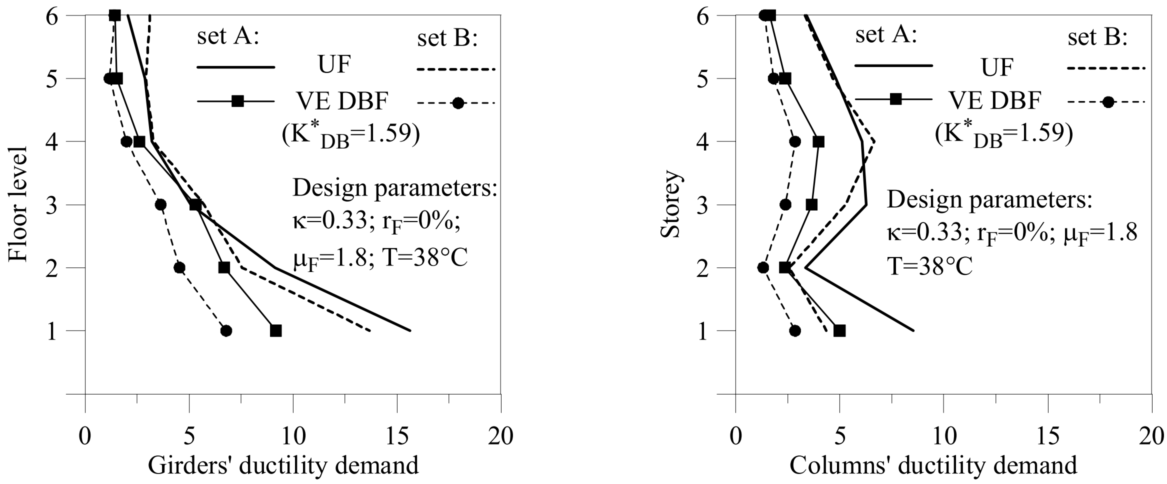
It is worth to mention that, as observed in the paper by Mazza and Vulcano, 2008b, a significant reduction of the difference between numerical and target values of the mean ductility demand is obtained under motions of set B, assuming κ=0.33: specifically, for N^*=1.0, the mean ductility demand, calculated with reference to either $\mu_{F,4val}$ (assuming for each frame member the mean of the four curvature ductility demands obtained considering, at each end section, the two loading directions) or $\mu_{D,max}$ (see Fig. 4b), underestimates the corresponding design value only of about 3.6% (against 16.9% for κ=1) or 3.3% (against 20.8% for κ=1), respectively. Further results, omitted for brevity, showed that the distribution law of dampers' ductility demand is almost uniform along the height and rather close to the design value (i.e., μ_D=5) under motions of set B, unlike what happens under motions of set A which induce a large variability, with higher values towards the lower storeys.

To check the effectiveness of the YL and VE dissipative braces for controlling the local damage undergone by the r.c. frame members, in Figs. 5 and 6 the ductility demands attained by girders (Figs. 5a÷6a) and columns (Figs. 5b÷6b) under motions of set A and set B are shown along the frame height, in the cases of unbraced frame (UF) and damped braced frames (YL DBF or VE DBF). More precisely, the curves in the case of YL damped braces (Figs. 5a,b) correspond to the optimum value of N^* (i.e., $N^*_{opt.}$=1), while those in the case of VE damped braces (Figs. 6a,b) have been obtained assuming the mechanical properties of a VE material for an ambient temperature T=38°C (Mazza and Vulcano, 2002). As can be observed, in all the examined cases the reduction of the ductility demand due to insertion of damped braces, in comparison with the case of the unbraced frame, is even more than 100%, but with higher peak values of ductility demand under motions of set A. Moreover, it is interesting to note that the ductility demand for frame members is comparable using either YL damped braces or VE ones, even though the value of the stiffness ratio required to YL damped braces (i.e., K^*_{DB}=2.08) is greater than that assumed for VE damped braces (i.e., K^*_{DB}=1.59).



(a) (b)

Figure 5 Ductility demand for r.c. members of unbraced (UF) and YL damped braced frames (YL DBF), under real (set A) and artificial (set B) ground motions



(a) (b)

Figure 6 Ductility demand for r.c. members of unbraced (UF) and VE damped braced frames (VE DBF), under real (set A) and artificial (set B) ground motions

5. CONCLUSIONS

The nonlinear seismic response of a r.c. framed structure with YL or VE damped braces, designed according to the proposed DDBD procedure, was studied under real and artificial ground motions. The results show that this procedure is effective and can be easily used for practical applications. The procedure is reliable under artificial motions, provided that a suitable value is used for the reduction factor κ (e.g., κ=0.33). However, to make the procedure conservative under real motions, which present scattered spectral values, further studies are needed to calibrate a suitable correction factor. The ductility demand for r.c. frame members is comparable when using YL or VE dampers; however, to get the same value of the frame ductility demand (e.g., μ_F=1.80), the stiffness ratio required to YL damped braces (e.g., K^*_{DB}=2.08) is greater than that of VE damped braces (e.g., K^*_{DB}=1.59).

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REFERENCES

Applied Technology Council (1996). Seismic Evaluation and Retrofit of Concrete Buildings, vol. 1, *Report no. ATC 40* , Redwood City, CA.

Bertero, V.V. (2002). Innovative Approaches to Earthquake Engineering. *Edited by G. Oliveto, University of Catania, WIT Press* 1-84.

Christopoulos, C. and Filiatrault, A. (2007). Principles of passive supplemental damping and seismic isolation. *Edited by IUSS Press, Istituto Universitario di Studi Superiori di Pavia*, Italy.

Eurocode 8 (2003). Design of structures for earthquake resistance - part 1: general rules, seismic actions and rules for buildings. *C.E.N., European Committee for Standardization.*

Eurocode 8 (2004). Design of structures for earthquake resistance - part 3: assessment and retrofitting of buildings, *C.E.N., European Committee for Standardization*, Draft no. 7.

European Commission for Community Research. *European Strong Motion Database* (on-line), *http://www.isesd.cv.ic.ac.uk/ESD*.

Fajfar, P. (1999). Capacity spectrum method based on inelastic spectra. *Earthquake Engineering and Structural Dynamics*, 28, 979-993.

Fu , Y., and Kasai, K. (1998). Comparative study of frames using viscoelastic and viscous dampers. *Journal of Structural Engineering, ASCE*, Vol. 124, No. 5, 513-522.

Gasparini, D. and Vanmarcke, E. (1976). Simulated Earthquake Motions Compatible with Prescribed Response Spectra. *Massachusetts Institute of Technology, Department of Civil Engineering*, U.S.A..

Italian Ministry of Public Works (1996), *Norme tecniche per le costruzioni in zone sismiche.*

Kim, J. and Choi, H. (2006). Displacement-Based Design of Supplemental Dampers for Seismic Retrofit of a Framed Structure. *Journal of Structural Engineering*, 132:6, 873-883.

Kim, J.K., Choi, H.H. and Min, K.W. (2003). Performance-based design of added viscous dampers using capacity spectrum method. *Journal of Earthquake Engineering*, 7:1, 1-24.

Mazza, F. and Vulcano, A. (2008a, b). Displacement-based seismic design procedure for framed buildings with dissipative braces. (a) Part I: Theoretical formulation; (b) Part II: Numerical results. *2008 Seismic Engineering International Conference commemorating the 1908 Messina and Reggio Calabria Earthquake (MERCEA08),* Reggio Calabria, Italy. American Institute of Physics Conference Proceedings, U.S.A, Vol. 1020 (part two).

Ponzo, F.C., Dolce, M., Di Cesare, A., Vigoriti, G. and Arleo, G. (2007). A design procedure for energy dissipating displacement-dependent bracing system for r/c buildings”, *Procs. of the 10th World Conference on Seismic Isolation, Energy Dissipation and Active Vibrations Control of Structures*, Istanbul (Turkey).

Vulcano, A. (1994). Design of damped steel bracing systems for seismic control of framed structures. *Procs. of the 10th European Conference on Earthquake Engineering,* Vienna, 4, 1567-1572.

Vulcano, A. and Mazza, F. (2002). A simplified procedure for the aseismic design of framed building with dissipative braces. *Procs. of the 12th European Conference on Earthquake Engineering,* London, paper n. 735.

Vulcano, A. and Mazza, F. (2007). Performance Based Design of Braces Equipped with Dampers for the Seismic Protection of Framed Buildings. *Procs. of the 4th Int. Conference on the “Conceptual Approach to Structural Design”*, Venice (Italy). CI-Premier Pte Ltd, Singapore.