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SEISMIC PERFORMANCE OF STRUCTURAL SYSTEMS EQUIPPED WITH BUCKLING-RESTRAINED BRACES

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ABSTRACT

Buckling-restrained braces (BRBs) are often employed for the seismic retrofit of existing buildings and the design of new structures, given their significant contribution in terms of stiffness and added damping. However, BRBs are characterized by a low lateral post-elastic stiffness, leading to excessive residual deformations that may compromise reparability. Moreover, accumulation of plastic deformations in the BRBs may compromise the capability of withstanding multiple earthquakes and aftershocks. The objective of this paper is to provide insight into the performance and residual capacity of dual systems made of BRB frames coupled with moment-resisting frames, through a simplified single-degree-of-freedom model. A non-dimensional formulation of the equation of motion is introduced, the statistic of the normalized peak, residual displacements and cumulated ductility of the system is evaluated for a set of ground motion records. Different values of the BRB target maximum ductility and coupled frame properties are considered.

SOMMARIO

I controventi ad instabilità impedita (BRB) sono spesso impiegati per l'adeguamento sismico di edifici esistenti e per la progettazione di nuove strutture, grazie al loro contributo significativo in termini di rigidezza e smorzamento aggiunto. Tuttavia, a causa della ridotta rigidezza in campo post-elastico, l'uso dei BRB potrebbe indurre eccessive deformazioni residue compromettendo la riparabilità. Inoltre eccessivi accumuli di deformazione plastica nei BRB potrebbero compromettere la capacità di sostenere terremoti ripetuti o aftershocks. L'obiettivo di questo lavoro è di fornire una visione d'insieme delle prestazioni e capacità residua di sistemi duali caratterizzati dall'accoppiamento di telai momento-resistenti e telai con BRBs. A tal fine si considera un modello ad un grado di libertà e una formulazione adimensionale dell'equazione del moto, e si valuta mediante un'analisi parametrica estesa la statistica degli spostamenti normalizzati, residui e della duttilità cumulata per un gruppo di terremoti, considerando diversi valori della domanda di duttilità dei BRBs e diverse proprietà dei telai accoppiati.

1 INTRODUCTION

Buckling-restrained braced frames (BRBFs) are a type of minimal damage structure where the horizontal forces are resisted and their energy dissipated by elastoplastic passive devices named buckling-restrained braces (BRBs) [1]. The use of BRBs is gaining popularity as lateral resisting system in seismic areas to be employed both for new constructions and rehabilitation of existing buildings. In BRBs, a sleeve provides buckling resistance to an unbonded core that resists axial stress. Hence, the core of the BRB can develop axial yielding in compression in addition to that in tension, ensuring an almost symmetric hysteretic behavior [1]. While the large and stable dissipation capacity of BRBs has been proven by many experimental studies [2], their low post-yield stiffness may result in inter-story drift concentration [1] and residual interstorey drifts in the range of 40 to 60% of the maximum drift [3] leading to high repair costs and disruption of the building use. This issue, which may impair the cost-effectiveness of BRBFs, could be avoided by using special steel moment-resisting frame (SMRF) in parallel with the BRBF to create a dual system configuration [4][5]. In [4] the seismic response of a 3-story and a 6-story BRBFs with and without a parallel SMRFs designed to resist the 25% of the design base shear is investigated, showing that the SMRF in parallel allows to reduce the residual drifts by about 50%, while providing similar performances in terms of peak inter-story drift demand. The efficiency of dual BRBF-SMRF systems is also demonstrated in [5] investigating a 7-story frame. BRBs are also employed to enhance the lateral strength, stiffness as well as the dissipation capacity of existing reinforced concrete buildings [6] forming a dual system. These studies evaluated the efficiency of dual BRBF-SMRF systems by considering only few case studies, without providing general indications on the influence on the seismic performance of values of important parameters such as the shear ratio, the stiffness ratio and target design ductility of the two systems.

In this paper, a comprehensive parametric investigation is carried out to shed light on this problem, and provide useful recommendations on the preliminary design. The problem is analyzed by assuming that both the BRBF and the SMRF can be described as single degree of freedom (SDOF) systems. While this approach is not suitable for describing the behavior of complex multi-level frames, it allows to derive a non-dimensional formulation of the problem and highlight the few characteristic parameters that control the seismic performance. The variation of these parameters permits to explore the performance of a wide ranges of configurations.

2 PROBLEM FORMULATION

The equation of motion governing the seismic response of a SDOF system representative of a dual system, as represented in Fig. 1(a), can be expressed as:

$$m\ddot{u}\left(t\right)+c_f\dot{u}\left(t\right)+f_f+f_b=\ddot{u}_g\left(t\right) \tag{1}$$

where m and c_f denote respectively the mass and the viscous damping constant of the system, f_f the resisting force of the frame, f_b the resisting force of the BRB, $\ddot{u}_g(t)$ the ground acceleration input. The frame is assumed to have an elastoplastic behavior, with initial stiffness k_f, yield displacement u_{fy} and ductility capacity μ_{fc} as reported in Fig. 1(b). A specific hysteretic constitutive model [1] is used for the BRB with initial stiffness k_b, yield displacement u_{by} and ductility capacity μ_{bc} as reported in Fig. 1(b).

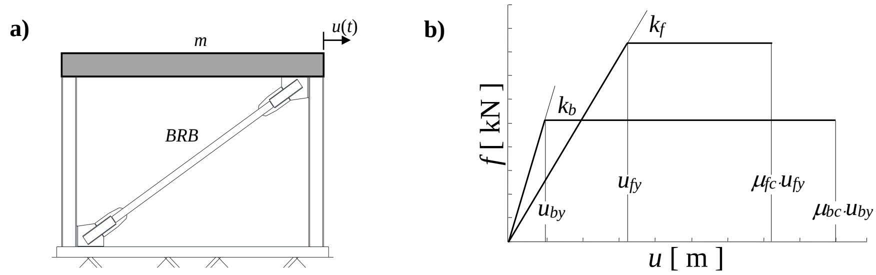

Fig. 1. (a) SDOF dual system with BRB, (b) Constitutive laws of the dual systems

Such a SDOF model can describe a wide range of structural configurations, e.g. the case of BRBFs combined with SMRFs to form a dual system [4][5] or retrofit applications involving BRBs inserted into existing reinforced concrete frames [6]. The seismic input uncertainty is treated by introducing a seismic intensity measure (*im*) [7]. The ground motion randomness for a fixed intensity level, *im*, usually denoted as record-to-record variability, can be described by selecting a set of ground motion realizations characterized by a different duration and frequency content and scaling these records to the common *im* value. The system response for a ground motion with an intensity *im* can be expressed as:

$$m\ddot{u}(t) + c_f\dot{u}(t) + f_f + f_b = im \cdot \ddot{\bar{u}}_g(t) \tag{2}$$

where $\ddot{\bar{u}}_g(t)$ denotes the ground motion records scaled such that $im = 1$ for that record. In this paper, the spectral acceleration, $S_a(\omega_0,\xi)$, at the fundamental circular frequency of the system, ω_0, for the damping factor ξ is employed as *im.*

2.1 Nondimensionalization of equation of motion

Based on Eqn.(2), the maximum relative displacement of the system, $u_{\max}$, can be expressed as:

$$u_{\max} = f\left(m, c_f, k_f, \mathrm{u}_{fy}, k_b, \mathrm{u}_{by}, im\right) \tag{3}$$

The 8 variables appearing in Eqn.(3) have dimensions: $[u_{\max}]$=L, $[m]$=M, $[c_f]$=MT^{-1}, $[k_f]$=ML^{-2}, $[u_{fy}]$,=L, $[k_b]$=ML^{-2}, $[u_{by}]$=L, $[im]$=LT^{-2} where the 3 physical dimensions are the time *T*, the mass *M*, and the length *L*. By applying the Buckingam Π-theorem [8], Eqn.(3) can be conveniently reformulated in terms of dimensionless parameters, denoted as Π-terms identifying the parameters that control the seismic response of the system and also reducing the number of variables. The problem involves 3 physical dimensions and 8 dimensional variables, thus, only 8 – 3 = 5 Π dimensionless parameters are needed. By selecting the systems mass *m*, the seismic intensity measure *im*, and the initial frame stiffness k_f as repeating variables, the Π-terms can be derived and after manipulation, the following alternative set of Π terms can be obtained:

$$\Pi_u = \frac{u_{\max}\omega_0^2}{im}\ ,\ \mu_f = \frac{u_{\max}}{u_{fy}}\ ,\ \mu_b = \frac{u_{\max}}{u_{by}}\ ,\ \xi = \frac{c_f}{2m\omega_0}\ ,\ \alpha = \frac{f_b}{f_f} \tag{4}$$

where $\omega_0^2 = (k_b + k_f)/m$ denotes the square of the circular frequency of the SDOF dual system. The parameters, μ_f and μ_b denote the ductility demand of the frame and the BRB respectively, while Π_u denotes the displacement demand normalized with respect to im/ω_0^2. It is noteworthy that by considering $S_a(\omega_0, \xi)$ as *im*, the nondimensional response Π_u, can be interpreted to as the displacement amplification factor being the ratio between $u_{\max}$ and the pseudo-spectral displacement $S_d(\omega_0, \xi) = S_a(\omega_0, \xi)/\omega_0^2$. The parameter α [6] is the ratio between the strength capacity of the bracing system and that of the frame. While the parameters μ_f, μ_b and Π_u depend on the response of the system through $u_{\max}$, α and ξ are independent from the response. Other response parameters of interest such as the normalized cumulative plasticity demand of the BRB $\mu_{b,cum}$, and the normalized residual displacement of the system μ_{res}, can be expressed as:

$$\mu_{b,cum} = \frac{u_{bp,cum}}{u_{by}} = f\left(\mu_f, \mu_b, \xi, \Pi_u, \alpha\right) \qquad \mu_{res} = \frac{u_{res}\,\omega_0^2}{im} = f\left(\mu_f, \mu_b, \xi, \Pi_u, \alpha\right) \tag{5}$$

It is noteworthy that the system response in terms of these parameters depends on the characteristics of the input via the circular frequency ω_0 [9].

3 PERFORMANCE ASSESSMENT METHODOLOGY

The objective of the proposed methodology is to evaluate how the coupled system behaves in correspondence of the design condition, i.e. when the design earthquake strikes the coupled system whose properties are defined by prefixed performance criteria. Account is made of the fact that the BRBs are designed to control the imposed seismic demand, whereby an optimal condition corresponds to the BRBs and the frame reaching simultaneously their target ductility capacity under severe earthquake intensities [6][10]. In this way the maximum exploitation of the system dissipation capacity is ensured and the design criterion imposes a constraint on the values that can be assumed by the problem nondimensional parameters.

By assuming a target ductility capacity μ_{bc} for the BRB, and a target ductility capacity μ_{fc} for the frame, the design condition is attained when $\mu_b = \mu_{bc}$ and at the same time $\mu_f = \mu_{fc}$ under the design earthquake input. In design practice, this condition is ensured by considering a deterministic performance measure [11], i.e. by considering the mean demand obtained for the different earthquake inputs describing the record-to-record variability effects. Given the system properties independent from the response ω_0, α, μ_{fc}, μ_{bc}, ξ, the design condition can be found by the following optimization problem: find the value Π_u^* of the normalized displacement demand such as $\overline{\mu}_f = \mu_{fc}$ and $\overline{\mu}_b = \mu_{bc}$, where the over score denotes the mean across the samples. The following procedure can be applied to ensure the attainment of the design condition under the set of records employed to describe the seismic input:

1. Select arbitrary values of $\overline{u}^*_{\max}$ and *m*, *e.g.* $\overline{u}^*_{\max}$ = 1m and *m* = 1ton, the corresponding nondimensional parameter values are:

$$c_f = 2m\omega_0\xi\,,\;\; u_{fy} = \overline{u}^*_{\max}/\overline{\mu}_f\,,\;\; u_{by} = \overline{u}^*_{\max}/\overline{\mu}_b\,,\;\; k_f = \frac{\omega_0^2 m}{1+\alpha u_{fy}/u_{by}}\,,\;\; k_b = \left(\alpha u_{fy}/u_{by}\right)k_f\,;$$

2. Scale the records to a common value of the intensity measure e.g. *im* = 1;
3. Perform nonlinear dynamic analyses for the different records;
4. Evaluate the mean system displacement response $\overline{u}_{\max}$, if $\overline{u}_{\max}$ is equal to the target value $\overline{u}^*_{\max}$, then $\Pi_u = \Pi_u^*$ where $\Pi_{\max}^* = \overline{u}^*_{\max}\,\omega_0^2 / im$, and go to step 5, otherwise multiply

im by the ratio $\overline{u}^*_{max} / \overline{u}_{max}$ and restart in step 2 (this procedure corresponds to a linear interpolation between the relation $\overline{u}_{max}$ and *im*);

5. Evaluate the statistics of μ_{res} and of μ_b.

Steps 1-4 ensure that the design condition of the frame and the BRBs attaining simultaneously their performance target under the design earthquake input is achieved.

4 PARAMETRIC STUDY

4.1 Assumptions and seismic input description

The performance of the systems corresponding to different values of ω_0, α, μ_{fc}, μ_{bc}, ξ is studied in this section considering the constraint posed by the attainment of the design condition, which corresponds to $\Pi_u = \Pi_u^*$. The parameter ω_0 is varied in a range corresponding to a vibration period $T_0 = 2\pi/\omega_0$ in the range between 0s and 4s. The strength ratio α assumes the values in the range between 0 and 100. The lower bound α =0 represents the case of the bare frame, whereas the upper bound represents the case of frame with pinned connections where the horizontal stiffness and resistance is provided only by the BRB. The parameter μ_{fc} assumes values in the range between 1 and 4. The case μ_{fc} = 1 corresponds to a design condition where the frame behaves in its elastic range under the design earthquake. The case μ_{fc} = 4 corresponds the a highly ductile behavior of the frame under the design earthquake. The parameter μ_{bc} assumes values in the range between 5 and 20. Values of 15-20 are typical of the ductility capacity of a BRB device. In some situations, such as the seismic retrofit of RC frames [6], the BRB device is arranged in series with an elastic brace exhibiting adequate over-strength. This leads to reduced values of the ductility capacity which may attain the lower bound of 5 for a very flexible elastic brace [12]. The value of 2% is assumed for the damping factor ξ.
A set of 28 ground motions is selected from the PEER strong motion database [13] on the basis of three fundamental parameters: site class, source distance, and magnitude. Ground motions associated with site class B, as defined in Eurocode 8 [14], a source-to-site distance, R, greater than 10km, and a moment magnitude, M_w, in the range between 6.0 and 7.5 are considered.

4.2 Parametric study results

Fig. 2 shows the median value of the normalized peak displacement demand Π_u^* versus the base shear ratio α, for different values of the target BRB ductility μ_{bc}. The different figures refer to different values of T_0 and of the target frame ductility μ_{fc}. All the curves attain the same value for α = 0 (SMRF only), and in particular for μ_{fc} =1 they attain a value of about 1. This result is expected, since for α = 0 the response is not dependent on the BRBs ductility capacity, and for μ_{fc} = 1 the system behaves (on average) elastically, so that the inelastic displacement coincides with the elastic one. On the other hand, for α = 0 and μ_{fc} =4, a simple bilinear oscillator is obtained and Π_u can be significantly different than 1. In particular, higher values of the normalized peak displacement Π_u^* are observed for low values of the period T_0. In the case of dual system (α > 0), for low periods and increasing values of α, the normalized peak displacement increases, whereas for high periods Π_u^* remains almost constant and slightly less than 1.
Fig. 3 shows the median value of the normalized residual displacement demand μ_{res} versus the base shear ratio α, for different values of the target BRB ductility μ_{bc}. The different figures refer to different values of T_0 and of the target frame ductility μ_{fc}. It can be observed that when the sys-

tem behaves linearly (α = 0, μ_{fc} =1), the residual displacements are zero. Obviously, adding in parallel to a linear system a nonlinear one (α > 0 in Fig. 3 (a, c, e)) results in an increase of residual displacements. This increase is higher for higher values of the target BRB ductility μ_{bc} and for lower vibration periods. On the other hand, if the frame exhibits a nonlinear behavior with a target ductility μ_{fc} = 4, then it is characterized by high residual drifts of the order of 50-60% of the peak ones, and adding in parallel the BRBs (α > 0 in Fig. 3 (b, d, f)) does not increase them. It is noteworthy that the values of μ_{res} for α = 0 are consistent with the ones observed in [15] on bilinear oscillators.

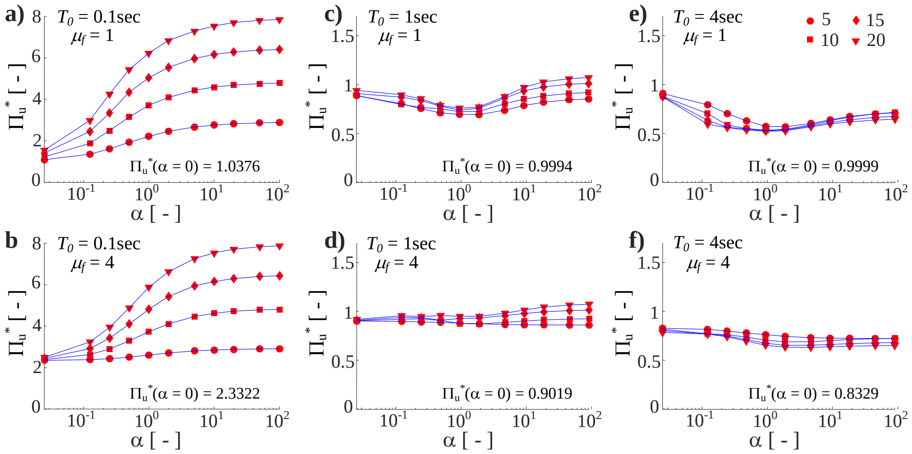

Fig. 2. Median value of the normalized peak displacement demand Π_u^* vs the base shear ratio α, for different values of T_0 (0.1, 1 and 4s), of μ_{fc} (1 and 4) and of μ_{bc} (5, 10, 15 and 20)

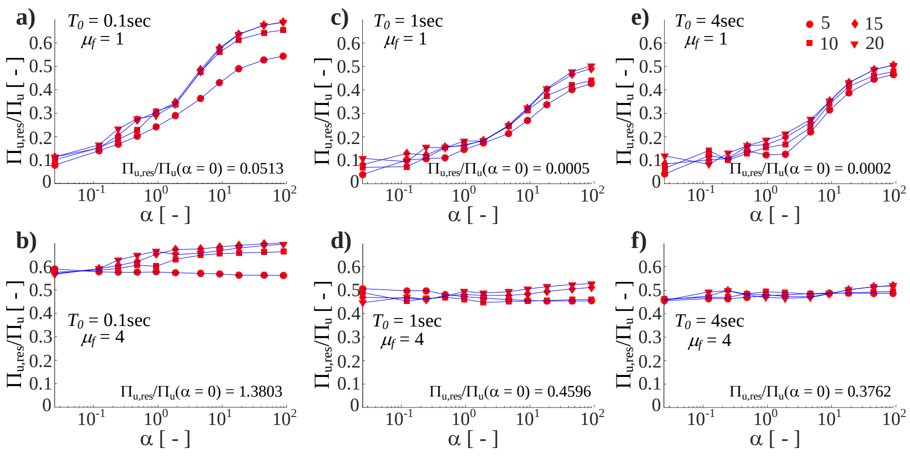

Fig. 3. Median value of the residual displacement μ_{res} vs the base shear ratio α, for different values of T_0 (0.1, 1 and 4s), of μ_{fc} (1 and 4) and of μ_{bc} (5, 10, 15 and 20)

Fig. 4 shows the median value of the cumulative plastic ductility demand in the BRBs $\mu_{b,cum}$ versus the base shear ratio α, for different values of the target BRB ductility μ_{bc}. The different figures refer to different values of T_0 and of the target frame ductility μ_{fc}. In general, the cumulative ductility demand reduces by increasing α because the system undergoes less cycles of vibrations. In other terms, by increasing α the system becomes more nonlinear and period elongation generally results in less cycles and less ductility accumulation under the same earthquake histories. In the case of pure BRBF (i.e. $\alpha = 100$), the cumulative ductility increases with the target ductility level. This increase is different for the different period considered. The obtained trends are quite different from those observed in [16], showing that the accumulated ductility ratios are nearly constant in BRBFs with $T_0 > 0.1$s. Moreover, there is an almost linear relation between $\mu_{b,cum}$ and μ_{bc}. Thus, the curves $\mu_{b,cum}/\mu_{bc}$ collapse into a single master-curve.

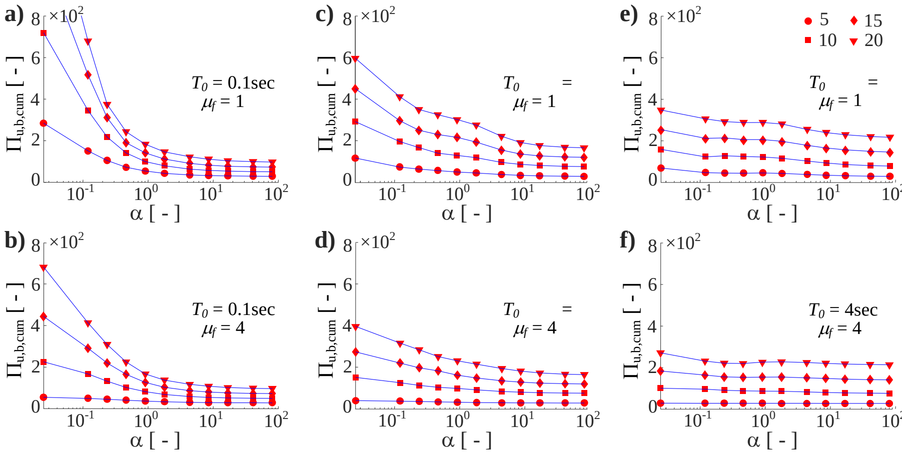

Fig. 4. Median value of cumulative plastic ductility demand in the BRB $\mu_{b,cum}$ vs the base shear ratio α, for different values of T_0 (0.1, 1 and 4s), of μ_{fc} (1 and 4) and of μ_{bc} (5, 10, 15 and 20)

5 CONCLUSIONS

This paper presented the results of study on the seismic performance of dual systems consisting of BRB frames coupled with moment-resisting frames, designed according to a criterion which allows to control the maximum ductility demand on the BRB frame and the coupled frame. A single-degree-of-freedom system assumption and a non-dimensional problem formulation allow to estimate the response of wide range of configurations while limiting the number of simulations. This permits to evaluate how the system properties, and in particular the values of the ratio α between the base shear of the BRB frame and the moment resisting frame, affect the median demand of normalized displacements, residual displacements, and cumulative BRB ductility. The study results provide information useful for the preliminary design of the coupled system, and for the performance assessment of existing frames coupled with BRBs.

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KEYWORDS

Buckling-restrained braces, moment-resisting frames, dual systems, cumulative ductility, residual displacement, seismic performance.