SEISMIC PERFORMANCE OF STEEL DUAL SYSTEMS WITH BRBs AND MOMENT-RESISTING FRAMES

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ABSTRACT

Buckling-restrained braces (BRBs) are energy dissipation devices which have proven to be very effective in improving the performance of existing and new building frames. However, their post-elastic stiffness may lead to excessive residual deformations in the systems to be protected, and this may cause irreparable damage and jeopardize the capability of withstanding multiple shocks. Previous studies demonstrated that buckling-restrained braced frames (BRBFs) can be used in conjunction with special moment-resisting frames to form a dual system, able to minimize the residual drifts and optimize the performances of the BRBFs. The objective of this present paper is to provide recommendations regarding the proportioning in terms of forces, stiffness and ductility of the two systems. For this purpose, an extensive parametric analysis under the single degree of freedom approximation for the dual system is carried out to shed light on the parameters that control the seismic performance and residual capacity of frames equipped with BRBs. A non-dimensional formulation of the problem allows investigating wide ranges of configurations, including the case of BRBFs and the case of BRBFs forming a dual system with moment-resisting frames. The results of this study provide useful information for the preliminary sizing and the optimal choice of the design parameters of structural systems equipped with BRBs.

Keywords: Buckling-Restrained Braces; Dual Systems; Cumulative Ductility; Residual Displacement; Seismic Performance

1. INTRODUCTION

Buckling-restrained braces (BRBs) are elastoplastic passive energy dissipation devices (*e.g.* Soong and Spencer 2002, Christopoulos and Filiatrault 2006) employed in buckling-restrained braced frames (BRBFs) to resist the horizontal seismic-induced forces and dissipate the seismic energy. The use of these devices is gaining popularity for both new constructions and rehabilitation of existing buildings. In BRBs, a sleeve provides buckling resistance to an unbonded core that resists axial stress. As buckling is prevented, the core of the BRB can develop axial yielding in compression in addition to that in tension, ensuring an almost symmetric hysteretic behaviour.

While the large and stable dissipation capacity of BRBs is corroborated by many experimental studies (*e.g.* Black *et al.* 2002, Merritt el al. 2003), their low post-yield stiffness may result in inter-story drift concentration, (Zona *et al.* 2012), and large residual inter-storey drifts. The latter problem is associated with high repair costs and disruption of the building use or occupation (Erochko *et al.* 2010). Sabelli *et al.* (2003) studied the seismic performance of buckling-restrained braced frames (BRBFs) reporting residual drifts on average in the range of 40 to 60% of the maximum drift. Usually, residual drifts lower than 0.5% are deemed acceptable for building frames since they would allow building reparability, *e.g.* doors, windows and elevators would still be functional (Iwata *et al.* 2006, McCormick *et al.* 2008). However, BRBFs designed according to the codes may exhibit residual drifts higher than this limit even under the design basis earthquake. In addition, the performance under

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aftershocks may also be jeopardized by excessive residual drifts due to the main shock.

This issue, which may impair the cost-effectiveness of BRBFs, could be avoided by using a special steel moment-resisting frame (MRF) in parallel with the BRBF to create a dual system configuration (Kiggins and Uang 2006, Ariyaratana and Fahnestock 2011, Baiguera *et al.* 2016). The ASCE/SEI 7-10 (2010) considers the situation of a dual system that combines a stiff primary seismic force-resisting system (*e.g.* BRBFs) with a special MRFs, as schematically represented in Figure 1. According to ASCE/SEI 7-10 (2010), the MRF in dual systems should be capable of resisting at least 25% of the prescribed seismic force. Kiggins and Uang 2006 investigated the seismic response of a 3-storey and a 6-storey BRBFs with and without a parallel MRFs designed to resist the 25% of the design base shear, showing that the MRF 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-MRF systems is also demonstrated in Ariyaratana and Fahnestock (2011) while using as case study a 7-storey frame. BRBs are also employed to enhance the lateral strength, stiffness as well as the dissipation capacity of existing reinforced concrete (RC) buildings (Freddi *et al.* 2013, Di Sarno and Manfredi 2010). RC frames and BRBFs also form a dual system, with the former often contributing to more the 25% of the total base shear.
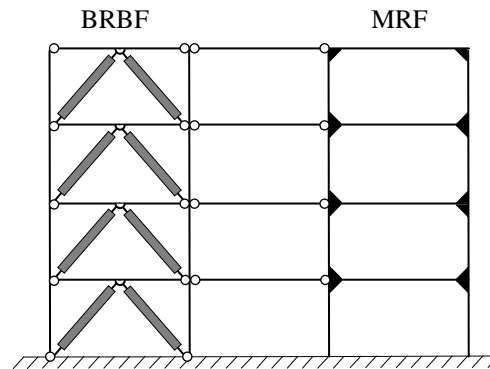

Figure 1. Schematic dual system combining a buckling-restrained braced frame (BRBF) and a special moment resisting frame (MRF)

The works above evaluated the efficiency of BRBFs used to form dual systems by considering only few case studies, without providing general indications regarding the influence of the shear ratio, stiffness ratio and target design ductility of the two systems on the seismic performance and their optimal values. In this work, an extensive parametric investigation is carried out to shed light on this behavioural aspect, and provide useful recommendations for preliminary design. The problem is analysed by assuming that both the BRBF and the MRF can be described as single degree of freedom (SDOF) systems. This representation, demonstrated suitable for low-rise frames under some regularity conditions (*e.g.* Kim and Seo 2004, Choi and Kim 2006, Ragni *et al.* 2011, Maley *et al.* 2010), allows to derive a non-dimensional formulation of the problem and highlight the few characteristic parameters that control the seismic performance. By changing the values of these parameters, it is possible to explore the performance of wide ranges of configurations under a set of ground motion records representative of the uncertainty of the seismic input.

Engineering demand parameters (EDPs) of interest include the peak normalized response, the normalized residual displacements, and the cumulative ductility demand in the BRBs. These EDPs are evaluated in correspondence of the design condition, where the BRBF and MRF attain simultaneously their target ductility capacity. It is noteworthy that some response parameters such as the residual displacements may exhibit larger dispersion due to record-to-record variability effects compared to others (Ruiz Garcia and Miranda 2006). Thus, the reported parametric study results include not only the median (estimated by the geometric mean GM), but also the lognormal standard deviation β of the EDPs of interest. In order to provide recommendations useful for the optimal design of the coupled system, different design choices are investigated, corresponding to various combinations of the ductility demand of the BRBF and MRF, within the respective capacity limit.

2. PROBLEM FORMULATION

2.1 Equation of motion

The equation of motion governing the seismic response of a SDOF system representative of a dual system, as represented in Figure 2(a) can be expressed as:

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

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 BRBF, $\ddot{u}_g(t)$ the ground acceleration input.
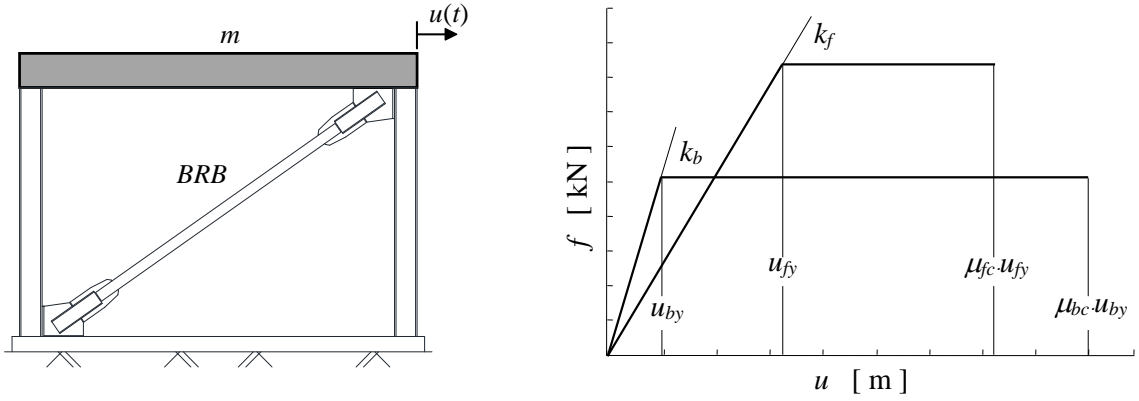

Figure 2. a) SDOF dual system with BRB, b) Constitutive law of the dual systems.

The frame is assumed to have elastoplastic behaviour, with initial stiffness k_f, yield displacement u_{fy} and ductility capacity μ_{fc} as reported in Figure 2(b). The BRBF system has a constitutive law described by the model of Zona and Dall'Asta (2012). This model is characterized by a number of parameters describing the hardening and the hysteretic behaviour. In order to keep the problem as simple as possible, most of them are assumed as fixed and the BRBF hysteretic behaviour is controlled only by the initial stiffness k_b, the yield displacement u_{by} and ductility capacity μ_{bc}. These parameters are the ones which exhibit significant variation from device to device and they are the design parameters explicitly reported in catalogues. The two models working in parallel, whose constitutive behaviour is illustrated in Figure 2(b), are representative of the dual SDOF system.

Such a model can describe a wide range of structural configurations, *e.g.* the case of BRBFs combined with MRFs to form a dual system (Kiggins and Uang 2006, Ariyaratana and Fahnestock 2011, Baiguera *et al.* 2016) or retrofit applications involving BRBs inserted into existing RC frames (Freddi *et al.* 2013, Di Sarno and Manfredi 2010).

The seismic input is characterized by significant uncertainty affecting not only its intensity, but also the duration and frequency content. As usual in Performance Based Earthquake Engineering, the uncertainty of the seismic input is treated by introducing a seismic intensity measure (IM) (Shome *et al.* 1998, Freddi *et al.* 2017) whose statistical description is the object of the hazard analysis. 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:

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

where $\bar{\bar{u}}_g(t)$ denotes the ground motion records scaled such that $im = 1$ for that record.

The choice of an appropriate IM for the problem should be driven by criteria of efficiency, sufficiency,

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and hazard computability (Shome *et al.* 1998, Freddi *et al.* 2017, Tubaldi *et al.* 2015, Galasso *et al.* 2015). In this paper, the spectral acceleration $S_a(\omega_0, \xi)$, at the fundamental circular frequency of the system, ω_0, and for the damping factor ξ is employed as IM.

2.2 Non-dimensional formulation

Based on Equation 2, the maximum relative displacement of the system, u_{max}, under the fixed ground motion with history $\ddot{u}_g(t)$, can be expressed as:

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

The 8 variables appearing in Equation 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 (Barenblatt 1987), Equation 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, which are given below a physical interpretation:

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

where $\omega_0^2 = (k_b + k_f)/m$ denotes the square of the circular frequency of the SDOF dual system.
The parameter δ denotes the displacement demand u_{max} normalized with respect to the displacement value im/ω_0^2. By considering $S_a(\omega_0, \xi)$ as *IM*, it 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 parameters μ_f and μ_b denote the ductility demand respectively of the MRF and the BRBF. The parameter α, representing the ratio between the strength capacity of the bracing system and that of the frame, was already employed in Freddi *et al.* (2013) for evaluating the retrofit effectiveness of BRBFs inserted within a reinforced concrete frame. The strength ratio considered in SEI/ASCE 7-10 (2010) to define a dual system is equal to:

$$\frac{V_f}{V_b + V_f} = \frac{1}{\alpha + 1} \tag{5}$$

Thus, α should be lower than $\alpha_d = 3$ for the system to be considered as dual.
It is important to observe that while the parameters μ_f, μ_b and δ of Equation 4 depend on the response of the system through u_{max}, the parameters α and ξ are independent from the response.
Other EDPs of interest for the performance assessment can be derived from the non-dimensional solution. In particular, the following EDPs are considered:

$$\mu_{b,cum} = \frac{u_{bp,cum}}{u_{by}} \ , \ \delta_{res,el} = \frac{u_{res}\omega_0^2}{im} \ , \ \delta_{res} = \frac{u_{res}}{u_{max}} \ , \ \alpha_{abs} = \frac{a_{max}}{im} \tag{6}$$

where $\mu_{b,cum}$ denotes the normalized cumulative plasticity (*i.e.*, ductility) demand of the BRBF, $\delta_{res,el}$ the ratio between the residual displacement and the peak spectral displacement of the system, δ_{res} the

ratio between the residual and the peak inelastic displacement of the system, and α_{abs} the absolute acceleration a_{max} normalized by the seismic intensity im.

The system response in terms of these EDPs depends on the characteristics of the input via the circular frequency ω_0. In fact, seismic inputs with the same intensity im but with different characteristics propagate differently and have different effects on systems with different natural frequencies ω_0. This has been demonstrated in Tubaldi et $al.$ (2015) by considering SDOF systems with nonlinear viscous dampers but the same reasoning holds for the problem considered in this study. Alternatively, the ratio ω_0/ω_g between the bare system frequency and a frequency synthetically representing the ground motion frequency content could be considered (Dimitrakopoulos et $al.$ 2009, Karavasilis et $al.$ 2011 and Málaga-Chuquitaype 2015).

3. PERFORMANCE ASSESSMENT METHODOLOGY

The objective of the proposed study is to evaluate how the coupled system behaves in correspondence of the design condition, defined by the target ductility levels of the BRBF and the MRF (Freddi et $al.$ 2013, Zona et $al.$ 2012), respectively μ_{bt} and μ_{ft}, corresponding to the design earthquake input. More specifically, assuming a target ductility level $\mu_{bt} \leq \mu_{bc}$ for the BRBF and a target ductility level $\mu_{ft} \leq \mu_{fc}$ for the frame, the design condition corresponds to $\mu_b = \mu_{bt}$ and $\mu_f = \mu_{ft}$ under the assumed seismic input. For example, the BRBF may be designed to attain a ductility demand $\mu_{bt} = 10$, while the MRF may be designed to remain elastic with $\mu_{ft} = 1$. In design practice, this condition is ensured by considering a deterministic performance (Dall'Asta et $al.$ 2016), $i.e.$, by considering the mean ductility demand obtained for the different earthquake inputs describing the record-to-record variability effects.

The above design criterion imposes a constraint on the values that can be assumed by the non-dimensional problem parameters, which makes the methodology different from those followed in other researches on similar systems employing non-dimensionalization and considering free parameters variations (Tubaldi et $al.$ 2015, Karavasilis et $al.$ 2011, Málaga-Chuquitaype 2015). Given the system properties independent from the response ω_0, α, μ_{ft}, μ_{bt}, ξ, the design condition can be found by the following optimization problem: find the value δ^* 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, and thus $\overline{\mu}$ denotes the mean ductility demand. 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. Assign arbitrary values to the target mean displacement demand $\overline{u}_{max}^*$ and to m, $e.g.$ $\overline{u}_{max}^* = 1$ m and $m = 1$ton. The corresponding non-dimensional parameter values are: $c_f = 2m\omega_0\xi$, $u_{fy} = \overline{u}_{max}^* / \overline{\mu}_f$, $u_{by} = \overline{u}_{max}^* / \overline{\mu}_b$, $k_f = \omega_0^2 m / \left(1 + \alpha u_{fy}/u_{by}\right)$, $k_b = \left(\alpha u_{fy}/u_{by}\right)k_f$;
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 $\delta = \delta^*$, where $\delta^* = \overline{u}_{max}^* \omega_0^2 / im$, and go to step 5. Otherwise multiply im by the ratio $\overline{u}_{max}^* / \overline{u}_{max}$ and restart step 2. This procedure corresponds to a linear interpolation between the relation $\overline{u}_{max}$ and im. If this procedure does not converge, resort can be made to any optimization algorithm;
5. Evaluate the statistics of δ_{res}, $\delta_{res,el}$, α_{abs}, and $\mu_{b,cum}$.

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

4. PARAMETRIC STUDY

4.1 System properties

The performance of the systems corresponding to different values of ω_0, α, μ_{ft}, μ_{bt}, ξ is studied in this section considering the constraint posed by the attainment of the design condition, which corresponds to $\delta = \delta^*$. The parameter ω_0 is varied in a range corresponding to a vibration period $T_0 = 2\pi/\omega_0$ in the range between 0 and 4 sec. The strength ratio α assumes the values in the range between 0 and 100. The lower bound $\alpha = 0$ 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 BRBF. The parameter μ_{ft} assumes values in the range between 1 and 4. The case $\mu_{ft} = 1$ corresponds to a design condition where the frame behaves in its elastic range under the design earthquake. The case $\mu_{ft} = 4$ corresponds to a highly ductile behaviour of the frame under the design earthquake. The parameter μ_{bt} assumes values in the range between 5 and 20. Values of 15-20 are typical ones for the ductility capacity of a BRB device. In some situations, such as the seismic retrofit of RC frames (Freddi *et al.* 2013), 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 (Ragni *et al.* 2011). The value of 2% is assumed for the damping factor ξ in this study.

4.2 Seismic input description

A set of 28 ground motions is considered in the parametric study to describe the record-to-record variability (Tubaldi *et al.* 2015). The records have been selected from the PEER strong motion database (FEMA P695) 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, 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. The record number is deemed sufficient to obtain accurate response estimates, given the efficiency of the intensity measure employed (Shome *et al.* 1998).

4.3 Parametric study results

Figure 3 shows the GM of the normalized peak displacement demand δ vs the base shear ratio α, for different values of the target BRBF ductility μ_{bt}. The different figures refer to different values of T_0 and of the target frame ductility μ_{ft}. All the curves attain the same value for $\alpha = 0$ (MRF only), and in particular for $\mu_{ft} = 1$ they attain a value of about 1. This result is expected, since for $\alpha = 0$ the response is not dependent on the BRBF's ductility capacity, and for $\mu_{ft} = 1$ the system behaves (on average) elastically, so that the inelastic displacement coincides with the elastic one. On the other hand, for $\alpha = 0$ and $\mu_{ft} = 4$, a simple bilinear oscillator is obtained and δ can be significantly different than 1. In particular, higher values of the normalized peak displacement δ are observed for low values of the period T_0. In the case of dual system ($\alpha > 0$), for low periods and increasing values of α, the normalized peak displacement increases, whereas for high periods δ remains almost constant and slightly less than 1.

Figure 4 illustrates the variation of the normalized displacement response dispersion. The lowest dispersion values are observed for $\alpha = 0$. For low periods, the dispersion increases for increasing values of α, of μ_{bt}, and of μ_{ft}, and can attain very high values of the order of 1 in the case of pure BRBF. For the other, higher periods considered, it is practically constant and equal to about 0.5. These trends also reflect the reduction of efficiency of the *IM* considered in this study, yielding an almost null dispersion only in the case of $\alpha = 0$ and $\mu_{ft} = 1$, *i.e.*, of the elastic bare frame. It is noteworthy that the dispersion is not exactly 0 even for this case, because only the mean ductility demand is equal to 1, and thus for some records the system behaves inelastically.
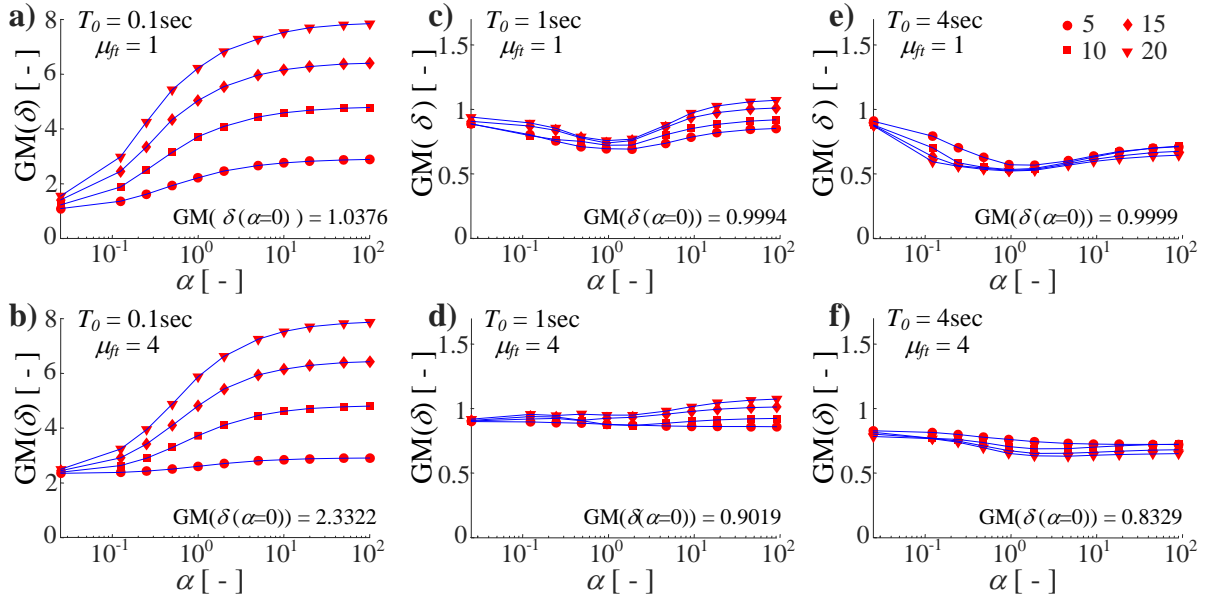
Figure 3. Geometric mean of the normalized peak displacement demand δ vs the base shear ratio α, for different values of T_0 (0.1, 1 and 4 sec), of μ_{ft} (1 and 4) and of μ_{bt} (5, 10, 15 and 20)
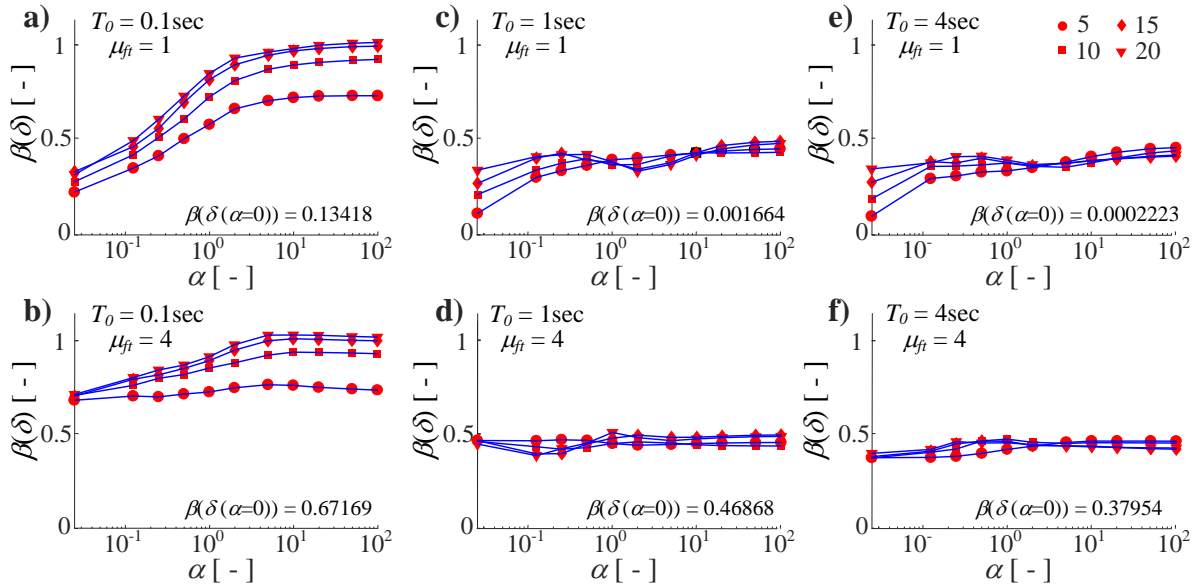

Figure 4. Dispersion of the normalized peak displacement demand δ vs the base shear ratio α, for different values of T_0 (0.1, 1 and 4 sec), of μ_{ft} (1 and 4) and of μ_{bt} (5, 10, 15 and 20)

Figure 5 shows the GM of the normalized residual displacement demand δ_{res} vs the base shear ratio α, for different values of the target BRBF ductility μ_{bt}. The different figures refer to different values of T_0 and of the target frame ductility μ_{ft}. In general, the period T_0 does not influence significantly this response parameter. Moreover, when the system behaves linearly ($\alpha = 0$, $\mu_{ft} = 1$), the residual displacements are zero. Obviously, adding in parallel to a linear system a nonlinear one ($\alpha > 0$ in Figure 5 (a, c, e)) results in an increase of residual displacements. This increase is higher for higher values of the target BRBF ductility μ_{bt}. Thus, high values of α must be avoided to limit residual displacements. The limit $\alpha_d = 3$ posed by SEI/ASCE 7-10 (2010) on the maximum values of α in dual systems provides a good control of the residual displacements, ensuring values of δ_{res} lower than 0.25. On the other hand, if the frame exhibits a nonlinear behaviour with a target ductility $\mu_{ft} = 4$, then it is characterized by high residual drifts of the order of 40% of the peak ones, and adding in parallel the

BRBs ($\alpha > 0$ in Figure 5 (b, d, f)) does not increase them significantly. It is noteworthy that the values of δ_{res} for $\alpha = 0$ and $\mu_{ft} = 4$ are similar to the ones observed in Liossatou and Fardis (2015) for an elasto-plastic system with a strength reduction factor of 4 under a different set of records than the one considered in this study.
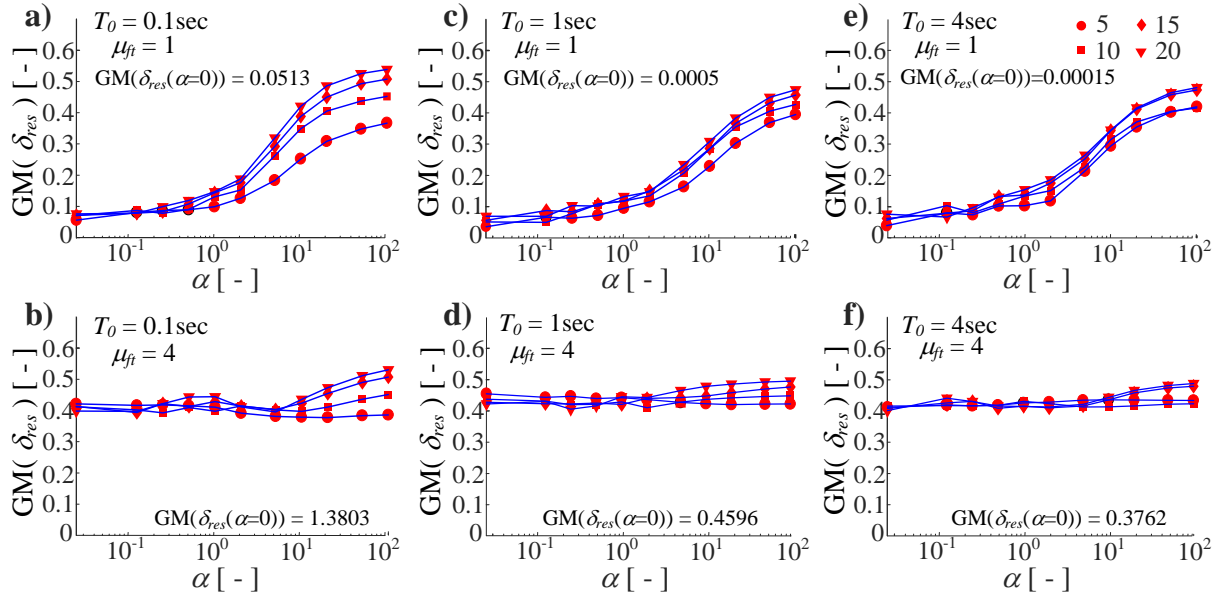

Figure 5. Geometric mean of the normalized residual displacement demand δ_{res} vs the base shear ratio α, for different values of T_0 (0.1, 1 and 4 sec), of μ_{ft} (1 and 4) and of μ_{bt} (5, 10, 15 and 20)

Figure 6 shows the values of the dispersion of δ_{res}. These values are very high, particularly for low values of the frame ductility capacity and low values of α. However, it should be noted that the dispersion is similar to the coefficient of variation (c.o.v.) only for low values of β. In fact, the values assumed by the c.o.v. for δ_{res} are never higher than 1.5.
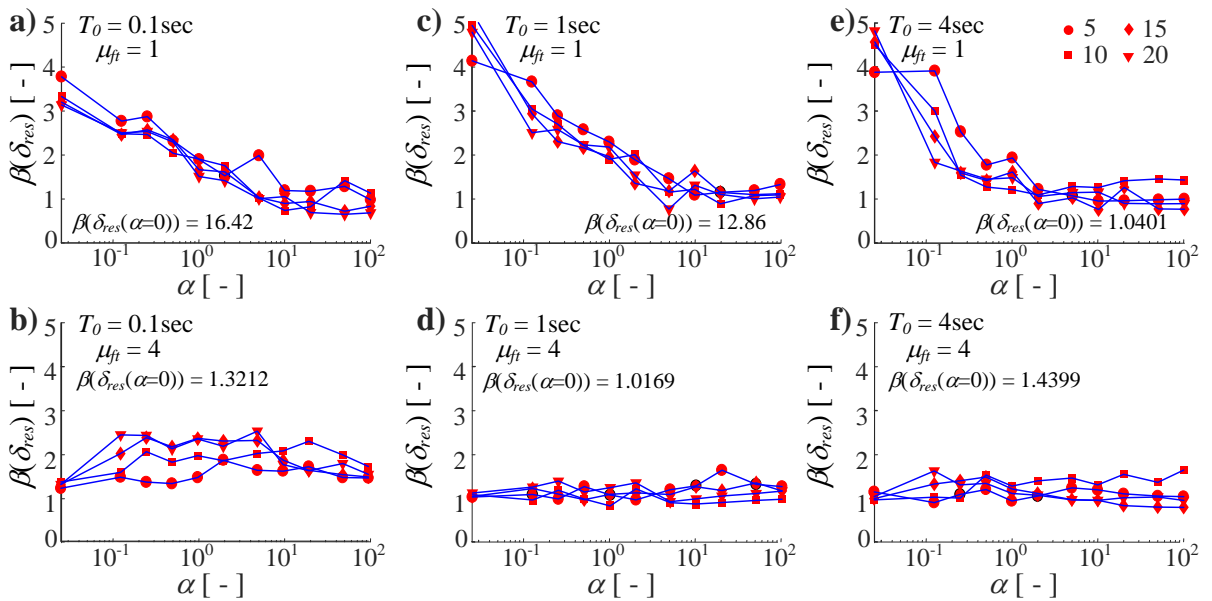

Figure 6. Dispersion of the normalized residual displacement demand δ_{res} vs the base shear ratio α, for different values of T_0 (0.1, 1 and 4 sec), of μ_{ft} (1 and 4) and of μ_{bt} (5, 10, 15 and 20)

The trends of variation of the normalized absolute acceleration α_{abs} are not shown due to space constraint. The GM values of α_{abs} are equal to one for the linear system, and reduce by increasing the level on nonlinearity of the system, *i.e.*, by increasing the values of α, of μ_{bt}, and of μ_{ft}. For very short period systems, α_{abs} increases as period decreases because the peak absolute acceleration eventually approaches the peak ground acceleration as T tends to zero (Karavasilis and Seo 2011). It is noteworthy that for values of α increasing beyond 1, the absolute acceleration does not decrease significantly.

Figure 7 shows the GM of the cumulative plastic ductility demand in the BRBF $\mu_{b,cum}$ vs. the base shear ratio α, for different values of the target BRBF ductility μ_{bt}. The different figures refer to different values of T_0 and of the target frame ductility μ_{ft}. In general, the cumulative ductility demand reduces by increasing α. This can be explained by observing that the system becomes more nonlinear by increasing α, and this generally results in fewer cycles at the maximum deformation and less ductility accumulation under an earthquake history, as it can be seen in Figure 7 for a specific case and earthquake record. 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 Choi and Kim (2006), showing that the accumulated ductility ratios are nearly constant in BRBFs with $T_0 > 0.1$ sec Moreover, there is an almost linear relation between $\mu_{b,cum}$ and μ_{bt}. Thus, the curves $\mu_{b,cum}/\mu_{bt}$ collapse into a single master-curve. These trends suggest that higher α values permit to control better the cumulative ductility demand in the BRBs. However, the decrease is higher for low α values, whereas for $\alpha > \alpha_d$ the cumulative ductility does not decrease significantly, similar to the normalized accelerations.

The trends of variation of the dispersion are not shown due to space constraint. In general, the values are between 0.4 and 0.6, do not change significantly with the period, with μ_{ft}, and with μ_{bt}, and in most of the cases they slightly increase for increasing α values.
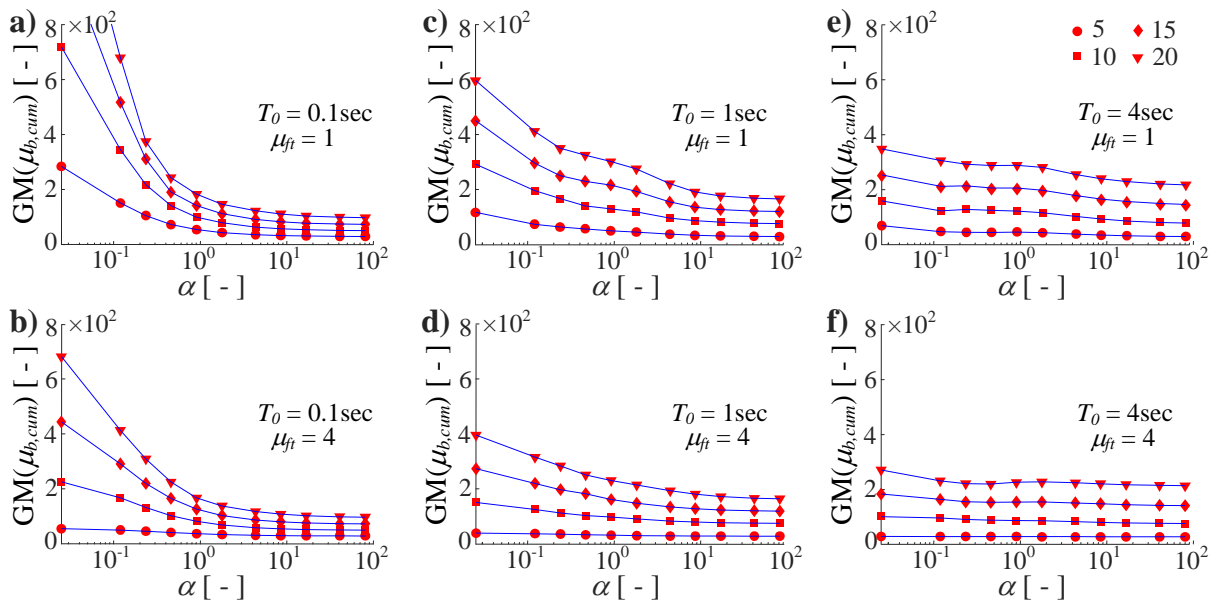

Figure 7. Geometric mean of the BRBF's normalized cumulative ductility demand $\mu_{b,cum}$ vs the base shear ratio α, for different values of T_0 (0.1, 1 and 4 sec), of μ_{ft} (1 and 4) and of μ_{bt} (5, 10, 15 and 20)

5. CONCLUSIONS

This paper presented the results of a study on the seismic performance of dual systems consisting of BRBFs coupled with MRFs, designed according to a criterion which aims to control the maximum ductility demand on both the resisting systems. A single degree of freedom system assumption and a non-dimensional problem formulation allow estimating the response of a 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 BRBF and the MRF, affect the median demand and the dispersion of the normalized displacements, residual displacements, and cumulative BRB ductility.

Based on the results of the study, the following main conclusions are drawn: *i)* adding a very ductile BRBF in parallel to the MRF may result in excessively high residual displacements, particularly for high values of α. The limit $\alpha_d = 3$ posed by SEI/ASCE 7-10 on the maximum values of α in dual systems yields values of the median residual-to-peak displacements of the order of 0.15-0.20, which may be excessive in some situations. In fact, for a maximum inter-storey drift ratio of 4%, the expected residual drift would be of the order of 0.60%-0.80%, higher than the limit of reparability. *ii)* the dispersion of the residual displacements is very high, and this should be taken into account when assessing the probability of repairing a structure after an earthquake. *iii)* The median cumulative ductility demand of the BRBFs has an opposite trend of variation with α compared to the residual displacement, *i.e.*, it decreases by increasing α. This result has also an impact on the choice of α in the design, since excessive accumulation of plastic deformations affect the safety of the BRBs and their capability to withstand aftershocks and multiple earthquakes.

6. ACKNOWLEDGMENTS

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