Seismic Performance of Existing RC Structures retrofitted with Hysteretic Devices

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Keywords: seismic reliability, BRBs, performance point, ductility, reinforced concrete, infill walls.

ABSTRACT
Hysteretic devices represents one of the best techniques for retrofitting or upgrading the numerous existing reinforced concrete framed buildings in areas with high seismic hazard. These passive control devices are usually installed in braces that are connected to the existing structures with the purpose of increasing their stiffness and providing additional energy dissipation capacity. This study deals with the influence of masonry infill walls on the performance design and assessment of buckling restrained braces (BRBs) for building seismic retrofit. First, an advanced nonlinear three-dimensional model of an existing building in L'Aquila is developed in OpenSees, by accounting for the effect of infill walls, and a widely employed procedure based on pushover analysis is employed to design the braces, by controlling the maximum inter-storey drift under the design seismic input. Subsequently, the seismic performance of the retrofitted buildings is checked by performing both nonlinear static analysis and incremental dynamic analysis under a set of real ground motion records. The study results demonstrate the effectiveness of the design procedure and shed light on the influence of the infill walls on the performance of the system retrofitted with BRBs.

1 INTRODUCTION

Several and different earthquake protective systems have been proposed over time as well as have been used in designing or retrofitting structures. Numerous experimental tests and numerical simulations have shown that one some the best solutions for retrofitting or upgrading multi-story framed RC existing building are dissipative unbounded or buckling restrained braces (Di Sarno and Manfredi 2009). For this reason, this work focuses on the buckling restrained braces (BRBs) that are metallic dampers. These steel braces are composed by a steel core placed inside a steel tube filled with a concrete material. The confinement provided by the concrete prevent the buckling of the steel core in compression so the damper can yield both in tension and in compression with similar behavior. According to numerous experimental tests BRB exhibit stable hysteretic behavior, and so a high energy dissipation capacity, reaching maximum ductility ratios higher than 20 (Iwata et al. 2000). Various mathematical models can describe the hysteretic behavior of BRBs, such as the Bouc-Wen model but more sophisticated constitutive models have been developed in the last years taking into account all the particularities of the BRBs' behavior investigated in numerous experimental tests. A model that addresses several requirements for the BRB has been developed by Zona and Dall'Asta (Zona and Dall'Asta 2011).

The aim of this work is to evaluate the efficiency of the retrofitting of an existing RC building by means of the BRBs also considering the influence of the infill walls. In particular, an existing reinforce concrete (RC) building located in L'Aquila, damaged by the 2009 earthquake, is used as case study. First, an advanced non-linear three-dimensional model of the existing RC building is defined in OpenSees (McKenna et al 2006), by accounting also for the effect of the infill walls, and a widely employed procedure based on pushover analyses is employed to design the braces. Specifically, the bracing system is designed in order to obtain a retrofitted bare structure that is able to withstand the seismic demand associated to the life limit state design spectrum (NTC 2018) showing a maximum interstorey drift of 1.5%. Successively, the seismic performance of the retrofitted bare/infilled building is evaluated by performing non-linear static analyses, demonstrating the effectiveness of the design procedure and shed light on the influence of the infill walls on the performance of the system retrofitted with BRBs.

2 DESIGN OF THE BRBs

The last configuration of the buckling restrained braces BRB of reduced length consists in a brace divided into two members placed in series. One is the proper BRB that shows plastic deformations in tension and compression and the other is an over-strengthened brace designed in order to remain into elastic field. The overall characteristics of the dissipative brace depend on the characteristics of both components placed in series, of the damper and of the over-strengthened steel brace. The properties of the overall dissipative brace having a length L_c are the stiffness K_c, the yielding force F_c and the ductility μ_c. The properties of the proper BRB with length L_0 are herein indicated as K_0, F_0, μ_0, whereas, the property of the elastic part of the brace with length L_b and cross section is denoted as K_b, F_b, μ_b. Since the steel tube has to remain into the elastic field it is necessary to design its transverse section in order to guarantee a certain overstrength with respect to the yielding strength of the proper BRB, introducing a safety coefficient (usually equal to 1.2). Choosing the ductility μ_0 of the dissipative devices it is possible to derive the stiffness of the BRB and of the elastic connecting arm in order to achieve the desired behavior as follows:

$$K_0 = K_c \frac{\mu_0 - 1}{\mu_c - 1} \tag{1}$$

$$K_b = \frac{K_0}{K_0 / K_c - 1} \tag{2}$$

in compliance with a method based on the comparison of the capacity curve of the equivalent SDOF system with the seismic code demand in the acceleration-displacement space (Dall'Asta et al., 2009). In fact, in the hypothesis of regular behavior of a bare building along its height in elastic field, it is reasonable to assume as the objective displacement also for a coupled system (bare frame equipped with BRB system) the deformed shape of the first vibration mode of the bare frame. Once that the displacements of the first vibration mode of the bare frame at *i*-th floor U^i and the corresponding relative interstorey displacements $\Delta^i = U^i - U^{i-1}$ are known, it is possible to normalize U^i with respect to the displacement of the last floor U^n, usually assumed as control point in the push-over analysis, obtaining:

$$u^i = U^i / U^n \tag{3}$$

It follows that the distribution of the shear forces at the *i*-th level of the structure can be obtained from the equilibrium:

$$V^i = V^{i+1} + \omega^2 m^i u^i \tag{4}$$

where ω is the circular frequency of the first vibrational mode. A distribution of the stiffness along the floors applies:

$$K^i = V^i / \Delta^i \tag{6}$$

Normalizing these values with respect to the base shear V_f^1 and stiffness provides:

$$v^i = V^i / V^1 \tag{5}$$

$$k^i = K^i / K^1 \tag{7}$$

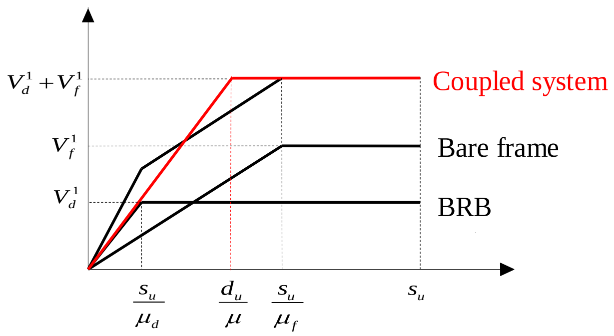

Figure 1. Equivalent elastic-perfectly plastic SDOF systems: bare frame, BRB and coupled system.

The approach implies that the shear and stiffness distribution related to the BRB system should be the same in order to obtain a coupled system with the same modal shape. For this reason the shear and stiffness of the BRB system have to be proportional to v_i and k_i, respectively, as follows:

$$V_d^i = V_d^1 v^i \tag{8}$$

$$K_d^i = \frac{\mu_d V_d^1}{s_u} k^i \tag{9}$$

where V_d^1 and μ_d are respectively the base shear and the ductility of the BRB system and s_u is the ultimate displacement of the bare frame. The dissipative bracing system may be represented by an equivalent elastic-perfectly plastic SDOF system, as well as the bare frame, characterized by a base shear V_d^1 and a ductility μ_d . The coupled system is still a an elastic-perfectly plastic SDOF system but the base shear is $V^1 = V_f^1 + V_d^1$ where V_f^1 is the base shear of the bare frame and the ductility μ is obtained by applying the areas equivalence criterion as shown in Figure 1 and applies:

$$\mu = \frac{\mu_d \mu_f \left(V_t^1 + V_d^1\right)}{V_t^1 \mu_d + V_d^1 \mu_f} \tag{10}$$

where μ_f is the ductility of the bare frame, the terms V_d^1 and μ_d are chosen in order to obtain a retrofitted bare structure whit a capacity curve able to reach the performance point intersecting the inelastic response spectrum according to the N2 method proposed by Fajfar (Fajfar 2000). After that V_d^i and K_d^i for each floor are known, it is necessary to proceed with the repartition of these values for each brace inside the single plane choosing the number of braces and their position in order to minimize the torsional effects that can rise. Once that the shear forces and the stiffness provided by each brace are defined, it is possible to evaluate the yielding force and the stiffness of each brace and then proceed with the design of the characteristics of the two components: the dissipative BRB and the elastic connection arm.

3 NUMERICAL MODEL OF THE CASE STUDY

The case study consists of a building built in 1984 that presents some typical problems of the RC structures built before the introduction of modern seismic codes. The building is composed of five stories and the plan configuration is depicted in Figure 2. The resisting mechanism of the frames is parallel to the shorter side. The material parameters are summarized in Tables 1 and 2. The building is and ordinary structure having a lifetime of 50 years, located in L'Aquila (Italy) with geographical coordinates Lon. = 13.394° and Lat. = 42.36°, on a soil of class D and topographical category T1, according to NTC 2018. The fibre model of the building and the nonlinear analysis was defined in the open source software OpenSees (McKenna et al., 2006). The constitutive law of the concrete is modelled by means of a uniaxial concrete material object (Concrete02) with tensile strength set to $0.1f_{cm}$ and a linear tension softening. In the numerical model the confinement of the core concrete of the beams and of the columns was taken into account modified the concrete constitutive law as suggested by Mander (Mander et al., 1988). Using the function "MinMax material" of OpenSees it is possible to simulate the fail of the material after the reaching of the of the crushing strength setting the stress to 0 once a certain strain threshold value is reached.

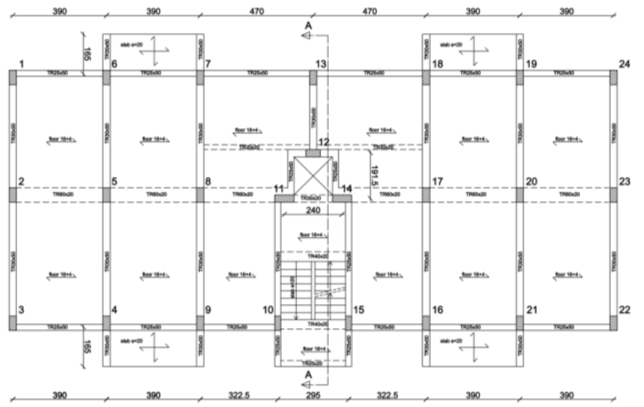

Figure 2. Schematic plan configuration of the building.

Table 1. Concrete parameters.

f_{cm} [N/mm²]	E_c [N/mm²]	$E_{c,fess}$ [N/mm²]
21.6	27717.80	20788.35

Table 2. Steel parameters.

f_{ym} [N/mm²]	E_s [N/mm²]	f_u [N/mm²]
430.7	206000	540

Regarding the reinforcement steel, a uniaxial bilinear constitutive law with kinematic hardening (Steel01) is used. The rupture of the reinforcement bars, with a drop of the stress to 0, both in tension and compression, occurs at a strain of 0.075 under a safety assumption. All the mechanical nonlinearities are taken into account using a fiber model of the structure. The model is realized using a particular type of force-based finite element with the plasticity concentrated over specified hinge lengths L_{pi} and L_{pj} at the two ends. The lengths of the plastic hinges are obtained according to (Panagiotakos and Fardis 2001):

$$L_p = 0.12 L_V + 0.014 \alpha_{sl} f_y d_b \tag{11}$$

where L_V is the shear span, d_b is the diameter of the longitudinal bar and α_{sl} depends on the slippage of the reinforcement. During the analysis the P-delta effects are also considered in order to not overestimate the member strength and underestimate the deflections. Successively, the numerical model of the building has been improved taking into account the presence of the infill walls that are modelled in line with Decanini model (Liberatore and Decanini 2011). The dissipative bracing system is modelled in OpenSees dividing the brace in the two parts. The connecting arm is modelled as an elastic beam while the BRB is modelled as a truss element assigning a material with the constitutive law of Zona and Dall'Asta (steel BRB material): the elastic modulus is 210000 N/mm^2 and the yielding strength is 250 N/mm^2. The parameters that influence the elasto-plastic model can be calibrated in order to obtain a numerical approximation of the results of experimental tests.

4 DESIGN AND MODELLING OF THE HYSTERETIC DEVICES (BRBS)

The bracing system is designed only along X direction because is the weak direction of the structure. The design procedure of the BRB system requires the evaluation of the system capacity curve by means of a nonlinear static (pushover) analysis. The lateral load pattern for the pushover analysis is determined in order to have a distribution of the loads proportional to the first vibration mode of the structure and to the mass of each floor. The control node is the gravity center of the top floor. The design parameter chosen is the maximum interstorey drift (ID). An interstorey drift of 1.5% corresponds to a limit of μ_f=2.64 to the ductility offered by the structure. Reducing the value of μ_f also influences the seismic demand represented by the inelastic spectrum and for this reason the performance point will not be reached, as can be seen in Figure 3. Therefore, it is necessary an upgrading of the structure by means of hysteretic devices (i.e., BRBs). To design the BRB system it is necessary to define the characteristics of the coupled system μ_d , V_d^1, μ_0 . A pushover analysis is performed on the retrofitted bare structure, obtaining the capacity curve until an interstorey drift of 1.5% with a maximum ductility μ=3.22. This value of ductility is referred to the coupled system, while the ductility of the only frame remains the same obtained before (μ_f=2.64). Applying the N2 method it is possible to observe that the performance point is reached confirming that the retrofitted structure can withstand the seismic action corresponding to the life limit state with a ductility demand of 3.13 (Figure 5(a)-(b)).

Table 3. Dissipative braces: yield force and stiffness at each floor.

Floor	F_c^i [kN]	K_c^i [kN/m]
5	-	-
4	152.0	91404
3	235.6	91793
2	299.0	95200
1	338.0	105238
0	343.8	188593

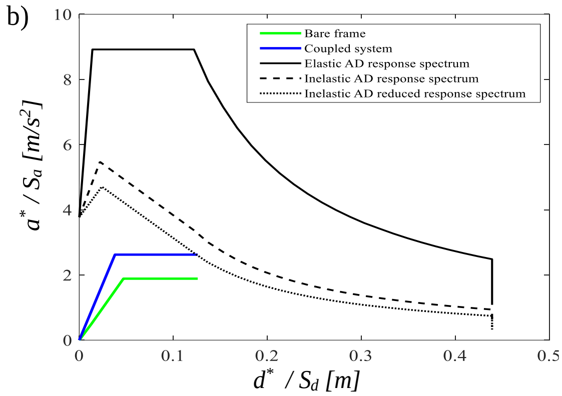

Figure 3. Performance point assessment in line with the N2 method for the bare frame under the imposed design displacement to design the BRBs.

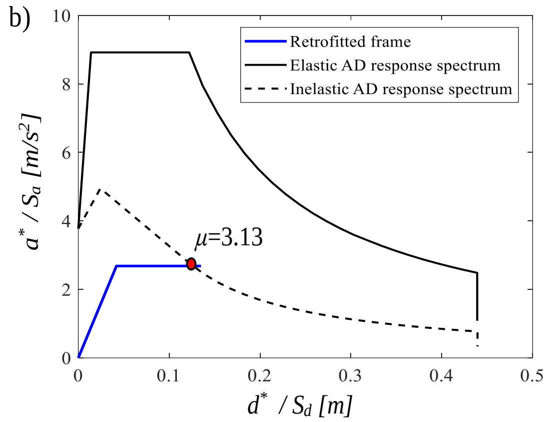

Figure 4. Performance point assessment in line with the N2 method for the retrofitted bare frame.

Choosing a value of μ_0 equal to 15 and μ_d equal to 10 (because the ratio between μ_d and μ_0 should be lower than 0.7-0.8) leads to a value of the base shear V_d^1 =900 kN in order to obtain a capacity curve of the coupled system that intersect the inelastic spectrum (Figure 4). The design of the characteristics of the BRB system at each floor follows the procedure explained in Section 2. The characteristics of the braces at each floor are given in Table 3. In order to obtain reasonable values of yielding forces and axial stiffness it was necessary to place four brace for each floor, two for each external frame, placed symmetrically in the external spans of the frame in order to respect the regularity hypothesis. This designed BRB system was also added also to the model of the infilled structure to investigate the influence provided by the nonstructural elements on the response of the retrofitted structure. In compliance with the N2 method, the performance point is reached with a ductility demand of 3.18, as shown in Figure 5, confirming that the used design procedure is suitable for the purpose.

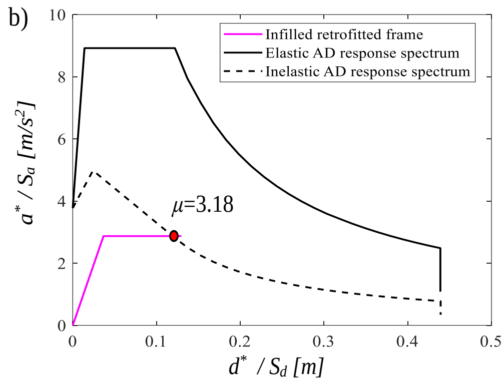

Figure 5. Performance point assessment in line with the N2 method for the infilled frame with BRBs.

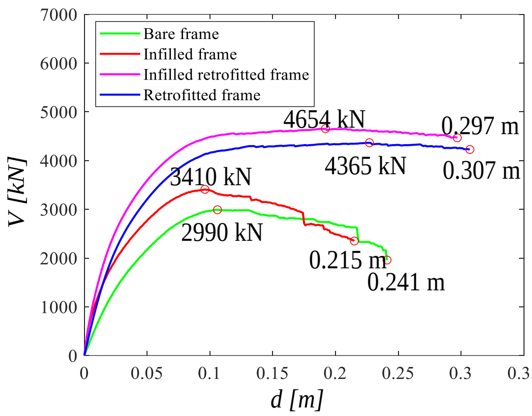

Figure 6. Comparison between the pushover curves.

Figure 6 illustrates a comparison between the pushover curves defined for the bare frame with and without BRBs and for the infilled frame with and without BRBs. V is the base shear of the structure and d is the displacement of the control node. The additional BRB system increases the maximum strength of the capacity curve with respect to the unretrofitted structure as well as the presence of the infills. It can be seen that the increase of maximum resistance, given by the infill walls with respect to the bare frame is equal to 14%. The increase of resistance of the infilled retrofitted structure with respect to the infilled frame (37%) is lower than the case without taking into account the infill walls (46%) because the BRBs positioned in the external spans of the frame requires the elimination of the infill walls and therefore the loss of their contribution.

5 CONCLUSIONS

This work evaluated the efficiency of the retrofitting of an existing RC building by means of the BRBs also considering the influence of the infill walls. In particular, considering an existing RC building located in L'Aquila, an advanced non-linear three-dimensional model is defined in OpenSees by accounting also for the effect of the infill walls. A widely employed procedure based on pushover analyses is employed to design the braces. The study results demonstrate the effectiveness of the design procedure and shed light on the influence of the infill walls on the performance of the system retrofitted with BRBs.

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