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SEISMIC RESPONSE ANALYSIS OF EXISTING NON-DUCTILE BUILDINGS RETROTIFFED WITH BRBS

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Abstract. *The paper assesses the seismic performance of typical reinforced concrete (RC) existing framed structures designed for gravity loads only. Such structures exhibit high seismic vulnerability, i.e. low lateral stiffness, strength along with limited translation ductility; thus retrofitting strategies are employed to augment the seismic system capacity. Metallic dissipative braces, namely buckling restrained braces (BRBs), may utilized as cost-effective rehabilitation schemes for existing RC framed buildings. The braces can be conveniently installed along the perimeter frames of the multi-storey buildings to lower the seismic demand on the existing structure and regularize its dynamic response. The design approach assumed herein postulates that the global response of the inelastic framed structure is the sum of the elastic frame (primary system) and the system comprising perimeter diagonal braces (secondary system). Displacement-based approaches were employed to design the BRBs and the needs to improve existing code provisions and design guidelines are emphasized. Analysis and further design research needs, such as the effects of the effects of masonry infill panels and the beam-to-column joint modeling on the seismic performance of the retrofitted frames are also discussed.*

1 INTRODUCTION

Framed systems are extensively used for buildings structures in earthquake-prone regions because of their high capability of energy absorption and dissipation. However a large number of existing reinforced concrete (RC) framed building structures was designed in the last decades for gravity loads only and hence they do not possess satisfactory lateral stiffness and resistance; seismic detailing is also lacking. Surveys carried out in the aftermath of recent major earthquakes, especially in countries of Southern Europe, such as Greece, Italy [1, 2] and Turkey [3]; they have emphasized the widespread brittle failure of RC members, caused by inadequate reinforcement bar details especially in shear walls and deep columns, as for example shown in Figure 1.


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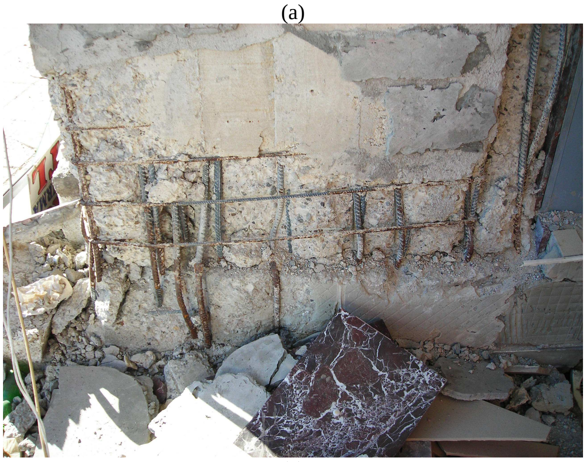
(b)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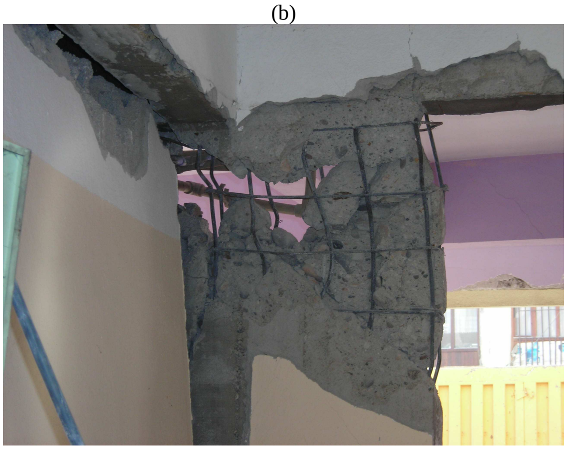

(d

Figure 1: Field surveys carried out in the aftermath of the 2011 Van (Turkey): (a) brittle failure of a typical shear wall (b) inset of the reinforcement details, (c) failure at the base and at the top (d) of deep RC columns in residential buildings.

The data collected in the earthquake reconnaissance investigations have pointed out that numerous existing RC framed buildings are not conforming as they exhibit inadequate earthquake resistance and hence require retrofitting or rehabilitation to conform to the current seismic design provisions. Seismic retrofitting of existing structures may result, however, not straightforward due to the complex response of the as-built structures, either in RC or in steel and composite steel and concrete. Innovative materials and technologies, such as base isolation and supplemental damping (e.g. [4, 5] among many others) tend to be highly beneficial to upgrade reliably the existing structures at an affordable cost [6].
In order to design properly the retrofit scheme and minimize the intervention cost, it is of paramount importance to determine accurately the actual capacity and characterize the failure mechanisms of structural systems. The seismic vulnerability of existing RC framed buildings

designed for gravity loads is significantly endangered by the lack of plan and elevation regularity, insufficient stiffness and strength of flooring systems, short column effects and inadequate structural detailing. As a result, the response of the structural system may possess insufficient local and global ductility. Additionally, the seismic vulnerability assessment of RC structures is a challenging task as it involves the interaction between several local and global mechanisms. Shear response, axial load-flexure-shear interaction, local buckling of steel reinforcement bars, bond slip and fixed-end mechanisms require sound models to predict reliably the inelastic static and dynamic response of RC framed systems. Reliable seismic performance assess is of paramount importance to select and design cost-effective intervention schemed for non-conforming RC framed buildings.

Concentrically braced frames (CBFs), which possess a lateral stiffness significantly higher than that of unbraced frames, e.g. moment resisting frames are efficiently used as lateral.resisting systems. Nevertheless, due to buckling of the metal compression members and material softening due to the Bauschinger effect, the hysteretic behaviour of CBFs with traditional steel braces is unreliable. Several recent experimental tests and numerical simulations (e.g. [7, 8, 9, 10, 11] among many others) have shown that multi-storey framed building structures may be efficiently retrofitted by using unbonded or buckling restrained braces (BRBs). A typical BRB consists of a steel ductile core designed to yield both in tension and compression. The core is placed within a hollow section member, filled with either mortar or concrete. The outer tube prevents the occurrence of the buckling of the brace. The confinement of the outer tube may also increase the compressive resistance of the braces. Such braces provide higher hysteretic energy dissipation than traditional metal braces due to the prevention of global buckling [5]. Stable hysteretic response is of vital importance in seismic design and/or re-design to absorb and dissipate large amount of earthquake-induced energy. The occurrence of plastic hinges in the existing RC frame is, indeed, prevented.

Buckling restrained braces are suitable for seismic applications in damage controlled structures [12] where the bare RC frame (existing system) responds elastically and the braces (added system) are the dissipative components of the system. The global response of the inelastic structural system can be assumed as the sum of the elastic frame (also termed primary structural system) and the system formed by the diagonal braces (secondary system) that absorbs and dissipates large amount of hysteretic energy under earthquake ground motion. The primary system is capable to withstand vertical loads and behaves elastically under earthquake loads. The secondary system includes the dissipative members and is thus designed to damp the seismic lateral actions and deformations. Dissipative members, such as BRBs, may be installed in the exterior frames of multi-storey buildings and can be thus easily replaced in the aftermath of a devastating earthquake. Primary and secondary systems act as a parallel system; the lateral deformation of the structure as a whole corresponds to the deformation of both primary and secondary systems.

The present work illustrates the design issues concerning the application of BRBs for the seismic retrofitting of typical non-conforming RC existing framed structures designed for gravity loads only. Two sample RC buildings, located in earthquake-prone areas with different risk, namely high and moderate, are selected as case studies; the BRBs are conveniently placed along the perimeter frames to limit the downtime for the occupancy of the buildings and lower the seismic demand on the existing structure and regularize its dynamic response. Nonlinear static (pushover) and dynamic (response history) analyses were carried out for both the as-built and retrofitted structures to investigate the efficiency of the adopted intervention strategy. The numerical models used to simulate the structural response of the bare and retrofitted systems were validated with respect to full-scale experimental test results of typical low-storey RC non-conforming frames. The outcomes of the inelastic analyses carried out on the sample structures demonstrate that, under moderate and high magnitude earthquakes, the damage experienced by the retrofitted structural system is concentrated in the added dampers and the response of the existing RC framed structure is chiefly elastic. Finally, analysis and further design research needs, such as the effects of the effects of masonry infill panels and the beam-to-column joint modeling on the seismic performance of the retrofitted frames are also discussed herein.

2 DESIGN OF BRBS FOR SEISMIC RETROFITTING OF RC STRUCTURES

The retrofitting of existing RC framed buildings with BRBs generally requires:

- The estimation of the optimum parameters for the dissipative braces, which may be conveniently performed by using simplified analysis methods;
- The application of capacity design checks for all members of the structure under the expected ultimate force induced by the dissipative braces, e.g. the yielding force of the BRBs;
- The compliance with the design performance requirements, which is preferably carried out through nonlinear response history analyses.

Numerous displacement-based design methods ofr BRBs have also been formulated but they refer primarily to steel structures, e.g. [13, 14], among many others. The design methodology typically employed within the framework of damage controlled structures is an iterative strategy based on response spectra and an equivalent viscous damping (ξ) used to quantify the effective hysteretic global response of the earthquake-resistant. The selected damping can be utilized to estimate both design spectral accelerations and displacements. A versatile design method has been recently formulated by employing an equivalent elastic static approach based on a mixed force- and deformation-based scheme employing. The step-by-step design procedure can be found in [5]. The aforementioned design method accounts for the energy dissipation capacity through the equivalent viscous damping; such damping is employed to reduce the acceleration and displacement response spectra. Alternatively, adequate response modification factors (R- or q-factors) may be employed; values of R ranging between 4.5 and 6.5 have been proposed in [15]. Values of R-factors have been recently investigated experimentally for existing RC structures retrofitted with BRBs (*see* [9]).

3 CALIBRATION OF NUMERICAL MODELS

3.1 Model description

Two full scale RC framed systems were employed to calibrate the numerical models used to investigate the effectiveness of BRBs as innovative retrofitting scheme for typical multi-storey non ductile frames. The benchmark structures include a bare system and a similar frame retrofitted with BRBs in the loading direction; their width is 5m, the depth is 6m and the roof height is 7.35m. The beams are 30x50cm deep and the columns employ square sections (30x30cm). The tested specimens employ typical details of gravity load design, i.e. smooth bars (fym=330MPa), intermediate concrete compression strength (fcm=19MPa), hooks and large spacing stirrups. Two types of BRBs were employed to retrofit one of the bare RC frame at first and second floor; both BRBs exhibit maximum strokes of ±20mm. They are connected to tubular pipe of diameter 80mm and a thickness of 7.2mm and 7.4mm, for the first and top floor, respectively. The yield force of the BRADs at base is Fy,b =75 kN, the maximum force is Fmax,,b = 90 kN; the displacement is dmax,b = ±15mm and the elastic axial stiffness kel,b = 90 kN/mm. For the top floor, Fy,t = 40 kN, the maximum force is

Fmax,t = 55 kN; the displacement is dmax,t = ±14mm and the elastic axial stiffness kel,t = 90 kN/mm. Further details on the layout, material properties and structural details of the sample RC buildings can be found in [9].

3.2 Model calibration

The sample frames were modelled with both lumped and fiber-based numerical discretizations; the finite element (FE) programs utilized are SAP2000 [16] and SeismoStruct [17]. The latter FE platform is capable of predicting the large displacement response of spatial frames under static or dynamic loading, taking into account both geometric and material nonlinearities. The spread of inelasticity along the member length and across the section depth is explicitly modelled, allowing for accurate estimation of damage distribution. In SAP2000, the inelasticity is lumped in zero-length plastic hinges placed at the both ends of the frame elements. Trilinear models were employed to define the inelastic response of beam-columns in SAP2000. Interaction between axial load and bending moment is accounted for in the columns. Non linear material modelling was utilized in SeismoStruct; the concrete was modelled with a nonlinear constant confinement. For the sample structures, values of the confinement factor k were assumed equal to 1.2 and 1.0 for confined (core) and unconfined (shell) concrete, respectively. A bilinear model with kinematic strain-hardening was utilized to simulate the inelastic response of steel longitudinal bars of the cross-sections of RC beams and columns. A strain hardening equal to 0.001 was assumed for the post-yield response. The distribution of material nonlinearity across the section area is accurately modelled in FE simulation due to the selection of 200 fibres employed in the spatial analysis of the sample structural systems. Two integration Gauss points per element are then used for the numerical integration of the governing equations of the cubic formulation (stress/strain results in the adopted structural model refer to these Gauss Sections, not to the element end-nodes). The spread of inelasticity along member length is accurately estimated because four 3D inelastic frame elements are utilized to model both beams and columns. At least two Gauss points were located in the inelastic regions in order to investigate adequately the spreading of plasticity in the critical regions and within structural members. Modelling of the local (beam-column effect) and global (large displacements/rotations effects) sources of geometric nonlinearity is carried out through the employment of a co-rotational formulation.

In the retrofitted system the dissipative buckling restrained braces (BRBs) were modelled using 3D inelastic truss elements. The BRBs employed for the retrofitting of the sample RC frame are connected in series with traditional steel hollow section braces. Equivalent mechanical properties were thus derived to replace the BRBs and the connected diagonal braces with equivalent steel inelastic truss elements. A bilinear model with kinematic strain-hardening was employed to model the structural steel of the braces.

The modal response analysis carried out using the FE models provide a close match of the frequencies estimated with both ambient noise and instrumented hammer, especially for translational modes of vibration. The values computed with Seismostruct are closer to those estimated experimentally. The discretization of the sample framed system with Seismostruct and the adopted formulation of the beam-column elements is more accurate than that implemented in SAP 2000. The values of the fundamental frequencies measured after the pushover tests, i.e. elongation of periods of vibrations of about 50-55%, demonstrate that the bare RC frames has experienced widespread damage in beams and columns. The numerical models used for the pre- and post-test analyses are sufficiently accurate and reliable for the seismic assessment of the sample building structures. Experimental and preliminary numerical results computed for the bare and retrofitted framed systems are shown in Figures 2 and 3. The results show the hysteretic response of the each floor and the global cyclic behaviour of the frames. High inelastic demand is concentrated at ground floor level. Soft storey and, in turn, global frame instability, was observed in the bare RC frame.

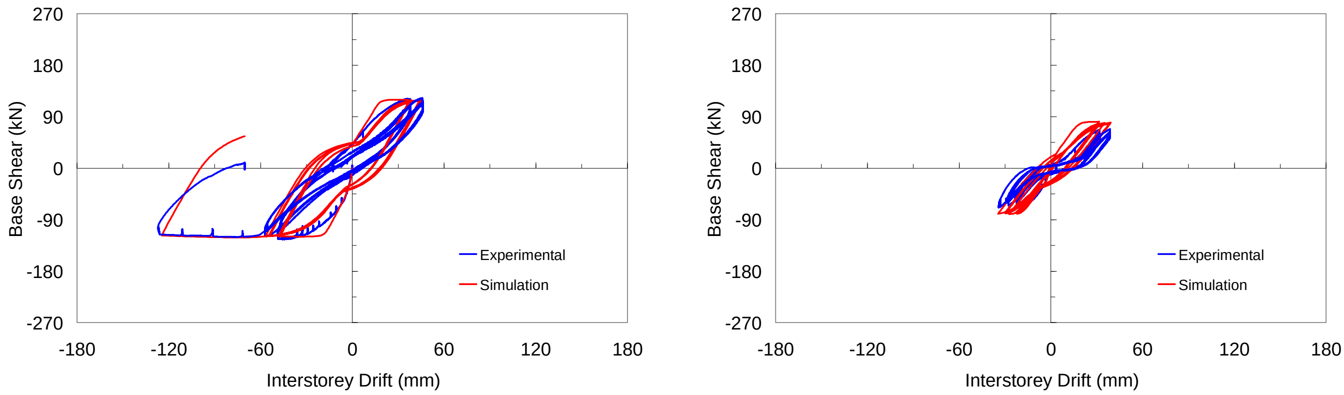


Figure 2. Experimental and simulation hysteretic response of the bare frame: 1st floor (*left*) and 2nd floor (*right*) response.

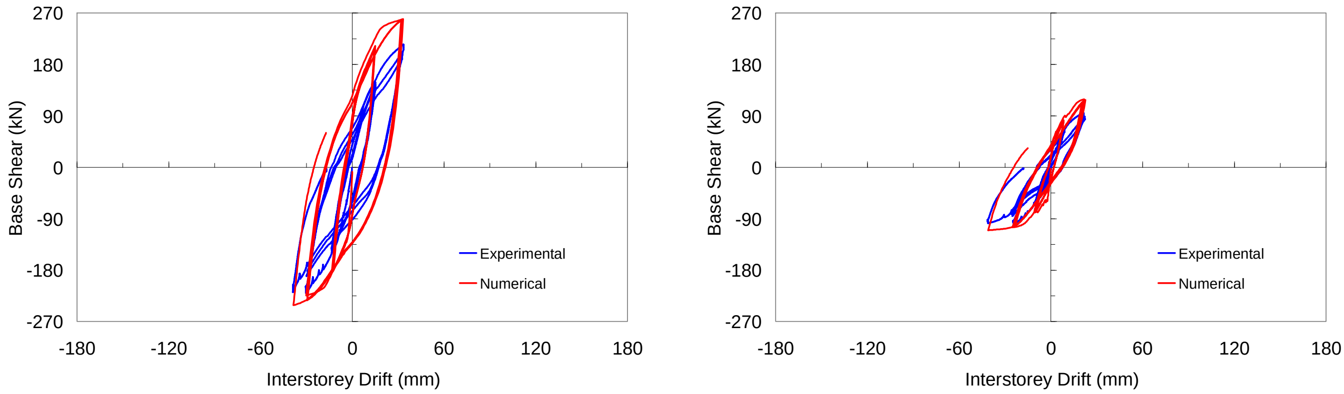


Figure 3. Experimental and simulation hysteretic response of the retrofitted frame: 1st floor (*left*) and 2nd floor (*right*) response.

The hysteretic response corresponds to the cyclic pushover loading applied to the buildings during the experimental tests. Pinching effects are not adequately modelled and further improvements, especially for concrete in tension, are deemed necessary. Notwithstanding, the simulated hysteretic loops provide close matches of the energy dissipation of the assessed systems.

4 SAMPLE BUILDING STRUCTURES

The first sample structure consists of a typical two-storey RC framed school building located in the South of Italy (area with high seismic hazard); it was designed in the late ‘60s to resist primarily gravity loads. The plan layout of the building is irregular; it consists of three main blocks: two T-shape block and a rectangular block. The T-shape unit is about 31m long, it has a width of 28.5m, the web thickness of 14.7m and two 7m-long offsets. Seismic joints were utilized to separate the three main blocks of the sample building. The ground floor of the structure is 3.08m high; the first and second floors are 3.65m high. The top floor has an inclined tiled roof: its height varies between 0.2m and 1.90m. Detailed fiber-based models were implemented in Seismostruct [17] to simulate the spreading of inelasticity within the structural members. Further details can also be found in [9].

The second sample building is an existing RC framed building which was built in the late 1930s in Tuscany, North-East of Italy, area of moderate seismic risk. The structural system frames located along a single direction only; the stairs are located in a slightly eccentric position. The 4-storey building has large interstorey heights in the range between 4.58 m and 5.10 m; the floors are placed at a height of 5.10 m, 9.86 m, 14.62 and 19.2 m. The floor slabs consist of 21 cm and 23 cm deep cast in situ concrete and brick decks at the first floor and all the other floors, respectively. The solid slab thickness is 5 cm at all floors; thus diaphragmatic behavior may be assumed for the assessed framed structure. The as-built framed system employs deep foundations consisting of plinths on piles, the piles are connected with tie-beams. Refined three-dimensional (3D) finite element models were employed to analyze the sample framed as-built and retrofitted structures under earthquake loading. The lumped plasticity models as implemented in SAP2000 code [16] were used to investigate the earthquake performance of the bare and retrofitted buildings. Further details can be found in [18].

5 EARTHQUAKE RESPONSE ANALYSIS

The seismic input was defined for the sample structures with reference to the 5% viscous damping acceleration response spectra evaluated for the four limit states compliant with the recent Italian code of practice [19], namely the operational (SLO), damageability (SLD), life safety (SLV) and collapse (SLC) limit states. Static (pushover) and dynamic (response history) nonlinear dynamic analyses were carried out on the refined 3D structural models to assess they earthquake elastic and inelastic response. The outcomes of such analyses are presented hereafter.

5.1 Framed Building located in high seismicity zone

The computed response (pushover) curves are provided in Figure 4 for the X and Y-directions. Two force distributions were considered: modal (or inverted triangular) and uniform distributions. The points corresponding to the onset of displacement demands at damage limit state (DL), life safety limit state (LS) and collapse prevention limit state (CP) are also included in the plots in Figure 4; such points are indicated with solid triangle, square and circle on the response curves. The results show that the existing frame exhibits a soft storey located at ground floor along the X-direction. The dimensionless global seismic resistance, i.e. ratio of the base shear and the seismic weight, of the as-built frame varies between 15% and 20%; the existing frame possesses similar global strength along X and Y directions. However, the seismic response is significantly influenced by the lateral load distribution along the X-direction. The modal response evidenced an irregular dynamic response along the latter direction. The maximum global displacement demand, expressed as roof drift, is 1.3%.

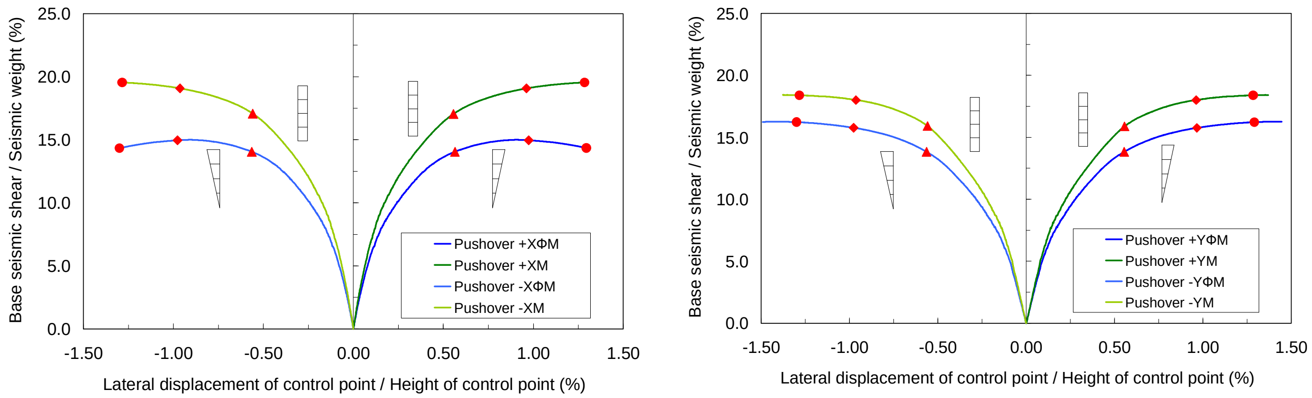


Figure 4. Response curve of the as-built structure: X-direction (*top*) and Y-direction (*bottom*)
Note: Triangle = DL; Square LS; Circle = CP.

For the retrofitted system, the computed results show a significant increase of the global over-strength of the structural system (about 30%) and a reduction of the displacement demand imposed on the structure at different limit states (Figure 5). The dimensionless global seismic resistance is about 45%; the displacement demand is lower than 1.0% (the estimated global drift is 0.8%). The post-peak stiffness and strength degradation observed along the X-direction of the as-built structure is also prevented thus enhancing the energy absorption and dissipate especially under high magnitude earthquake ground motions. The results of the pushover analyses provided in Figure 5 demonstrate that the retrofitted structure is not significantly affected by the lateral load pattern, especially with respect to the lateral strength. The variations between the results computed with the inverted triangular horizontal force distribution and those relative to uniform force distributions are lower than 10%.

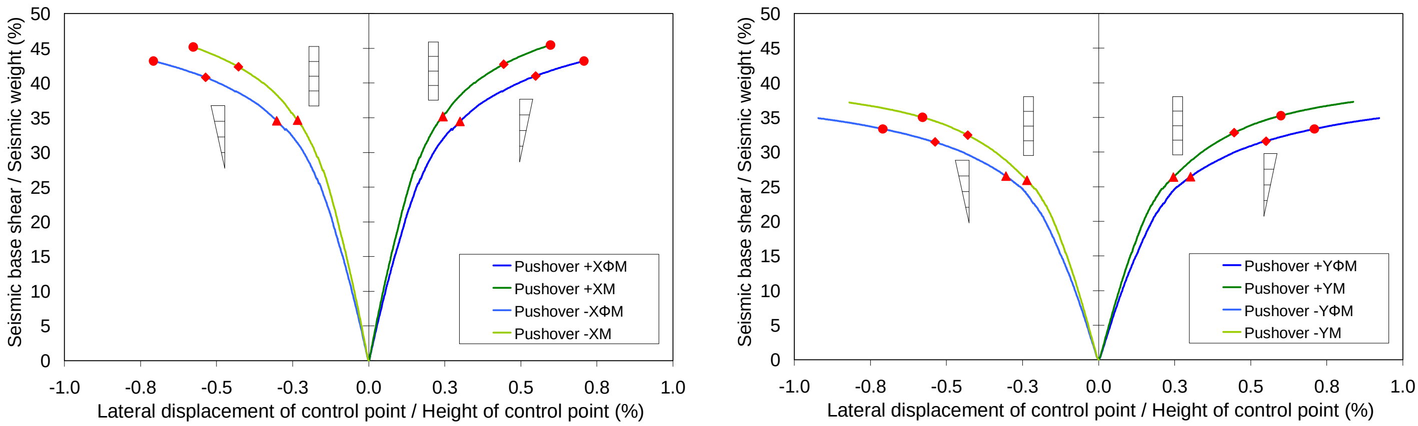


Figure 5. Response curve of the retrofitted structure: X-direction (*top*) and Y-direction (*bottom*)
Note: Triangle = DL; Square LS; Circle = CP.

The inelastic seismic performance of the as-built and retrofitted structures was further investigated through nonlinear dynamic analyses. Such analyses were conducted with respect to suites of seven different groups of earthquake natural records scaled linearly for each of the code-compliant limit states.

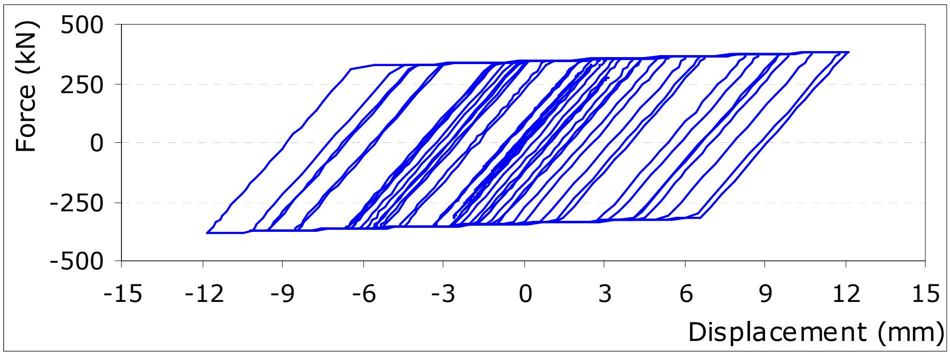
Table 1 summarizes the maximum interstorey drifts for the X- and Y-directions at damageability (serviceability) limit. The table provides also the average values of interstorey drift (σ), the standard deviations (δ) and coefficients of variation (COV).

Table 1. - Maximum interstorey drift at damageability limit state for existing and retrofitted buildings

		Existing Building				Retrofitted Building			
		Direction X		Direction Y		Direction X		Direction Y	
		1st Floor	2nd Floor	1st Floor	2nd Floor	1st Floor	2nd Floor	1st Floor	2nd Floor
$d_{r\,1}/h$	(%)	0.259	0.389	0.272	0.387	0.094	0.098	0.156	0.159
$d_{r\,2}/h$	(%)	0.189	0.320	0.346	0.452	0.095	0.108	0.115	0.111
$d_{r\,3}/h$	(%)	0.162	0.227	0.263	0.284	0.082	0.090	0.124	0.110
$d_{r\,4}/h$	(%)	0.288	0.373	0.197	0.221	0.148	0.143	0.118	0.130
$d_{r\,5}/h$	(%)	0.161	0.232	0.258	0.277	0.173	0.188	0.132	0.135
$d_{r\,6}/h$	(%)	0.210	0.291	0.260	0.334	0.127	0.142	0.149	0.148
$d_{r\,7}/h$	(%)	0.273	0.417	0.380	0.468	0.100	0.109	0.164	0.164
σ	(%)	0.220	0.321	0.282	0.346	0.117	0.125	0.137	0.137
δ	(%)	0.049	0.070	0.057	0.086	0.031	0.032	0.018	0.020
COV	(%)	22.30	21.80	20.20	24.90	26.50	25.40	13.20	14.60

The results provided in Table 1 demonstrate that the interstorey displacements estimated for the retrofitted structure are considerably lower than the counterparts values computed for the existing structure, especially at the second floor, where the storey mechanism is detected at ultimate limit state.

The time history of two typical devices is provided in Figure 6 with respect to the axial force and axial displacement response. The computed results demonstrate the large amount of energy dissipation and its cyclic stability under moderate-to-high magnitude earthquakes.



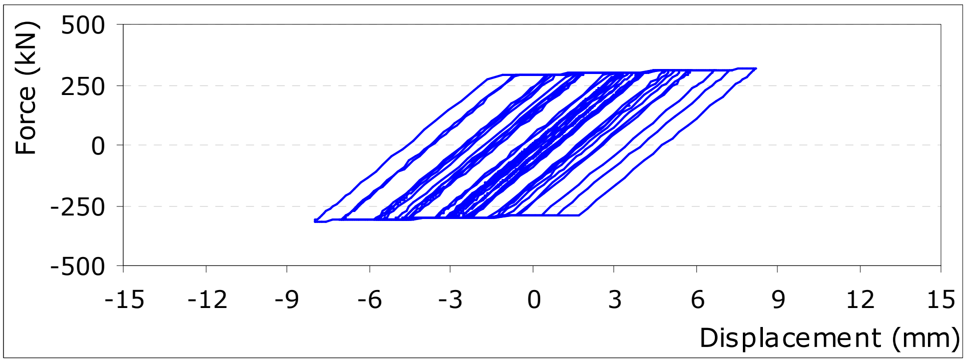


Figure 6 – Inelastic response history for typical hysteretic buckling restrained braces.

The maximum axial ductility of the BRBs is often a critical design parameter. For the sample structure located in the region with high seismicity, it can be assumed equal to 10 for both first and second floor. The computed value of maximum translation ductility is, however, compliant with BRBs available on the market.

5.2 Framed Building located in moderate seismicity zone

Modal and uniform load pattern distributions were employed to investigate the inelastic (static) response of the framed building located in the region with moderate seismic risk. Figure 7 provide the Acceleration Displacement Response Spectrum (ADRS) of the as-built and retro-fitted structures, respectively; they are calculated along the X- and Y- direction, for positive and negative directions of the lateral loadings. It is noted that conventional viscous damping coefficients equal to 4% and 10% have been assumed for the as-built and retrofitted structures, respectively. The performance points at operational life safety (LS) limit states with respect to both shear and moment beams and columns capacities are also included. The computed results showed that the as-built system is characterized by a low stiffness and ductility along X-direction, that is the weaker direction due to the lack of frames.

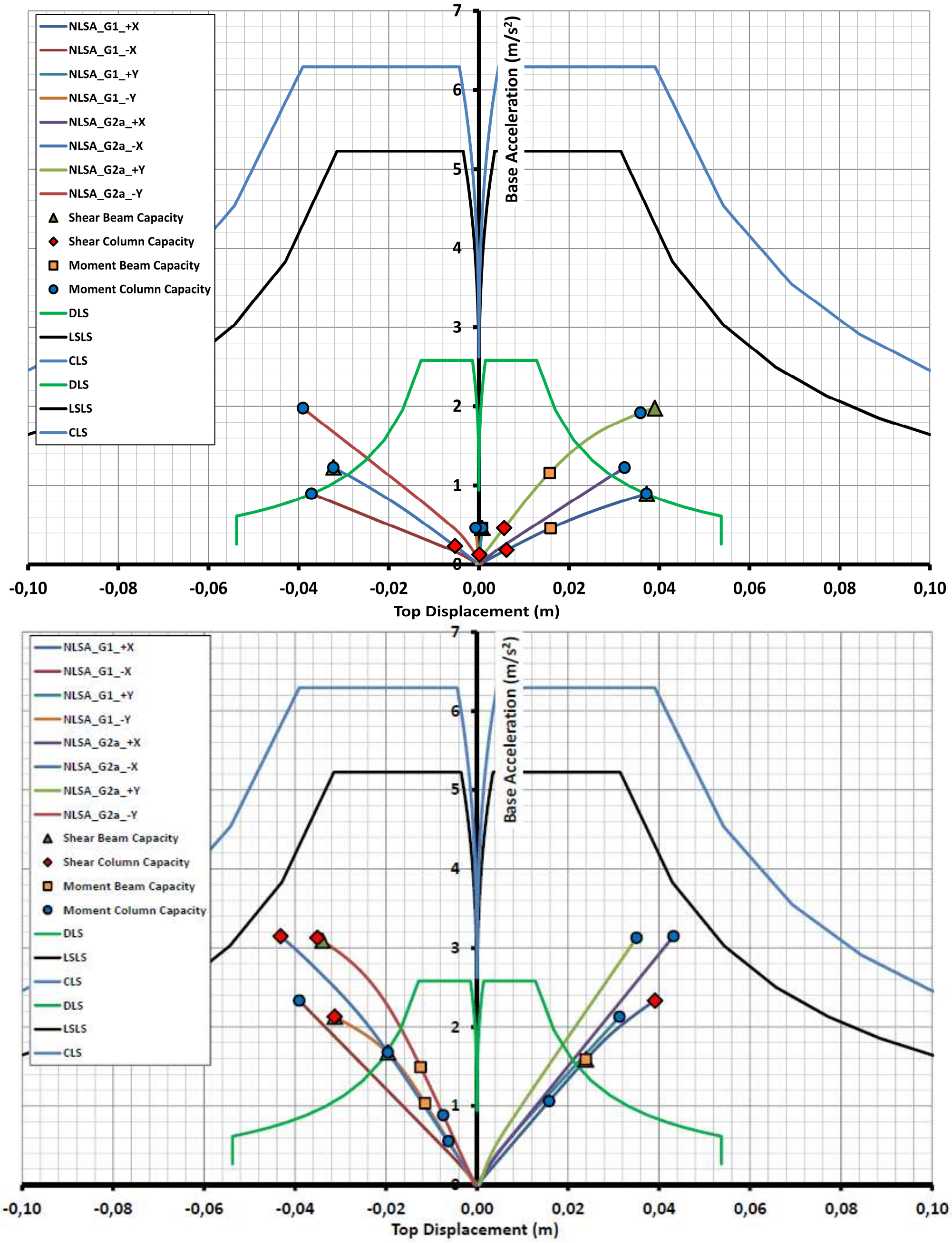


Figure 7. - Acceleration Displacement Response Spectrum (ADRS) of the as-built (*top*) and retrofitted (*bottom*) structure.

Fragility analyses of the as-built and retrofitted framed structure was also carried out. Additionally, a parametric analyses was performed to assess the influence of the angle of incidence of the earthquake ground motions on the structural response. Preliminary analysis results show that the angle of incidence may have a significant influence on the earthquake performance of a structure. For bare RC frames, the interstorey drifts (d/h) for weak storeys may be influenced by such an angle as shown in Figure 8 where the d/h has been plotted for the last floor (diagrams on the left side of Figure 8). However, when the BRBs are employed the systems tends to stabilize its response and, in turn, the effects of the angle of incidence of the earthquake input may be neglected. The latter response was also observed for the lower stories of the as-built structure, ie. the storeys with adequate lateral stiffness.

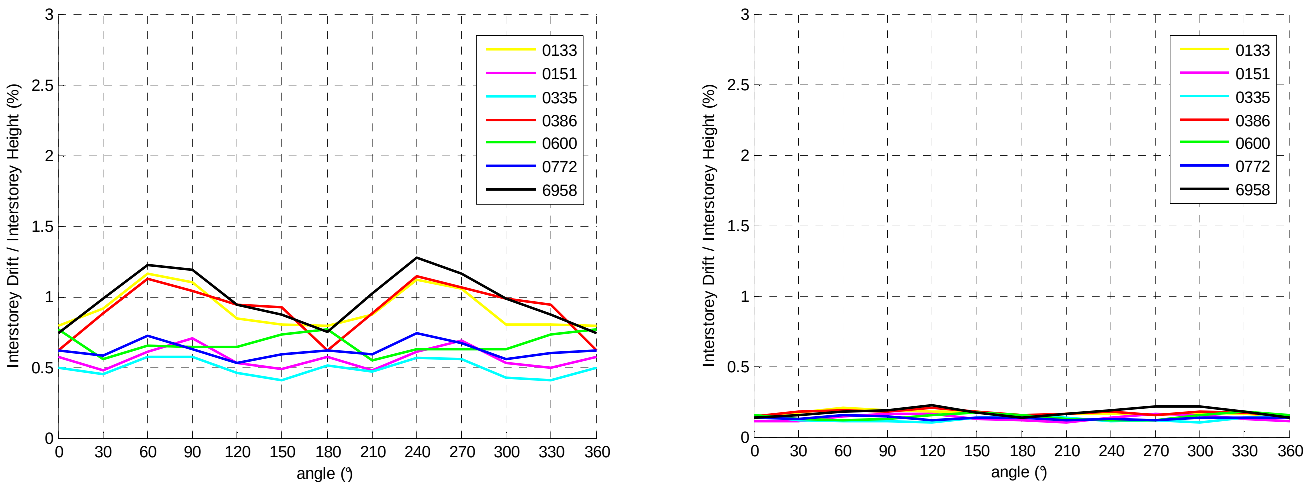


Figure 8. Effects of angle of incidence of the earthquake input on the structural response: response of the bare RC frame at the upper (*left*) and lower (*right*) floors.

The outcomes of the numerical investigations carried out on the inelastic response of the BRBs emphasize the effectiveness of such devices for seismic retrofitting of existing RC frames.

5. CONCLUSIONS

The present study has investigated the effectiveness of using buckling restrained braces (BRBs) to enhance the earthquake-induced energy absorption and dissipation of existing RC non-ductile framed buildings. The BRBs were placed along the perimeter frames of the structural systems, thus the dynamic response of the as-built RC frames was augmented and the seismic demand lowered. A displacement-based damage-controlled design procedure was employed to force the inelasticity within the added braces thus preventing the onset of the inelasticity within the existing RC frames. A numerical model has been calibrated on experimental test results of full-scale RC buildings retrofitted with BRBs. Such model was then applied to assess the earthquake response of two case study structures comprising existing non-compliant buildings located in regions with different seismic hazards. The results of the numerical investigation carried out demonstrate the effectiness of using BRBs to retrofit existing RC framed buildings. The hysteretic response of the BRBs remain stable even at large deformations and for a large number of cycles. The interstorey drifts of the retrofitted structures do not exceed 0.5%, which is generally employed as threshold values at serviceability limit state (or damage prevention). The maximum ductility demand on the diagonal dissipative braces is equal to 10 for both first and second floors.

There is an urgent need to further investigate the response of RC frames retrofitted with BRBs including also the effects of masonry infills. The presence of such infills may alter significantly the lateral stiffness and strength, especially at serviceability, thus endangering the onset of the yielding in the braces.

6. ACKNOWLEDGMENTS

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