Seismic strengthening of an existing building with innovative materials and devices

Luigi Di Sarno[1] and Gaetano Manfredi[2]

[1] University of Sannio, Benevento, Italy
[2] University Federico II, Naples, Italy

ABSTRACT: A large number of existing reinforced concrete (RC) buildings were designed mainly for gravity loads only and hence they do not employ adequate seismic details. As a consequence the ductility of such structures is rather poor and seismic retrofitting is deemed necessary to ensure that they will exhibit acceptable - structural and non-structural - performance. Structural designers may adopt traditional interventions, such as strengthening of members and/or connections or global strategies, or utilize innovative retrofitting schemes. The latter include base isolation or supplemental damping or, in same cases, a combination of them. Bracing systems have been found to be very cost-effective for seismic retrofitting of RC multi-storey frames. Innovative unbonded braces (UBs) are, indeed, a viable option to be used because of their stable energy dissipation capacity, especially under moderate-to-high magnitude earthquakes.

The present paper focuses on the seismic performance of a RC framed structure which was recently retrofitted by means of UBs and fiber reinforced plastic (FRP) wrapping for beam-columns and structural joints. The latter interventions enhance the lateral stiffness, strength and ductility of the RC structure designed for gravity loads only; they also increase significantly its energy dissipation capacity under earthquake loading. As a result, the seismic demand is lowered and the structural capacity is significantly augmented, which in turn minimizes the vulnerability of the structure. Advanced numerical analyses were carried out to estimate the earthquake vulnerability of the as-built structure before and after the seismic retrofitting. The results of inelastic static pushovers are discussed hereafter to prove the benefits in employing the innovative retrofitting scheme which combines UBs and FRPs.

1 INTRODUCTION

Recent severe earthquakes occurred in numerous regions world-wide, e.g. .g. L'Aquila (Italy, Mw=6.3) in 2009, Leogane (Haiti, Mw =7.0) and Maule (Chile, Mw =8.8) in 2010, showed that existing low-to-medium rise reinforced concrete (RC) framed buildings located in areas with high seismic risk exhibit inadequate lateral stiffness, strength and ductility to prevent either non-structural damage or structural failure. Surveys carried out in the aftermath of several destructive earthquakes worldwide demonstrated that many existing structures do not employ structural detailing as they were designed for gravity loads only; as a result their behaviour is inadequate. It is, therefore, of paramount importance to augment the earthquake performance of such vulnerable structures by employing efficient retrofitting strategies. In so doing, a number of intervention schemes, either traditional or innovative, have been suggested and applied worldwide (e.g. Di Sarno and Elnashai, 2005; Christopoulos and Filiatrault, 2006, among many others).

Several recent experimental tests and numerical simulations (e.g. Bozorgnia and Bertero, 2004; Mazzolani, 2006; among many others) have shown that multi-storey framed building structures may be efficiently retrofitted by using dissipative unbonded braces (UBs). A typical UB 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 (Iwata *et al*., 2000). Stable hysteretic response is of paramount 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. Consequently, UBs are suitable for seismic applications in damage controlled structures where the bare RC frame (existing system) responds elastically and the braces (added system) are the dissipative components of the system.

The present analytical paper illustrates the application of UBs and local interventions comprising fiber reinforced plastics (FRPs) for an existing RC buildings which was designed to resist gravity lads only. In so doing, detailed non linear static and dynamic analyses were carried out in order to investigate the inelastic performance of the framed system. The results of the pushover analyses presented hereafter prove that the use of UBs is extremely efficient for seismic retrofitting of existing RC framed structures. Local strengthening is however deemed necessary to ensure that concentrated actions do not endanger the structural performance of RC beams, columns and joints.

2 CASE STUDY

2.1 General description

The sample RC existing framed building is located near Naples, in South of Italy; the framed structure was built in the early 60s and it was designed for gravity loads only. The plan layout of the building comprises two T-shaped blocks (termed Building A and Building B) and a connecting rectangular block (named Building C) as pictorially shown in Figure 1. Buildings A and B are used for classrooms, while Building C is a sport hall. The total area of the building is about 1,400 sqm; the area of the Buildings A and B is about 610 sqm. The structural system consists of three stories used for classrooms, storage rooms and laboratories; the roof floor is utilized for insulation purposes. The ground floor is 3.08m high and includes laboratories; the first and second floors are 3.65m high. The top floor has an inclined tiled roof; its height varies between 0.2m (along the perimeter) and 1.90m (at the centre). The structural system of the sample school building consists of a multi-storey RC frame with deep beams. The column cross-sections vary between 35x40cm to 40x55cm at first and second floor, and 30x30cm and 40x40cm at third floor; the frame employs 30x65 cm deep beams. For the inclined roof, the deep beams are 30x50cm. The framed system employs shallow foundations with rectangular beam grid. The typical cross section of the foundation beams are T-shaped (inner beams, web thickness of 40cm, height equal to 90cm and 105cm, width varying between 120cm and 220cm) and rectangular (outer beams with 50x50cm cross-sections).

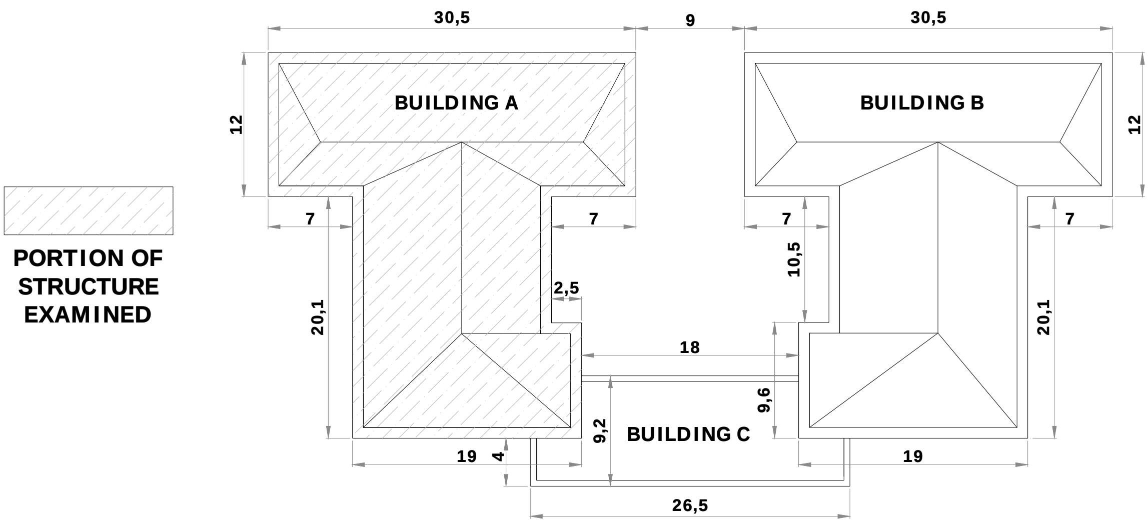

Figure 1. Plan layout of the structure of the school building retrofitted with unbonded braces (all dimensions are expressed in metres).

2.1.1 Material properties

An extensive experimental test program (in situ and in laboratory) was carried out to estimate the mechanical properties of the concrete and steel reinforcement in the existing RC building. Additional in situ tests were carried out on the structural system components, i.e. floor slabs and RC retaining walls of the underground level. Cylinder concrete samples with diameters of 100 mm and 60 mm were tested under compression to estimate the concrete strength (f_c). The latter is a function of the diameter (Φ) and the height (h) of the sample and the cylinder concrete compression strength ($f_{c,cyl}$) of the test specimens. To evaluate the concrete compression strength f_c the following relationship (BS 1881, 1983) was adopted.

$$f_c = 0.83 \cdot f_{c,cyl} \cdot \frac{2,5}{1,5 + \Phi / h} \quad (1)$$

The concrete strength of the cylinder specimens with diameter ϕ100mm was employed to determine the average value of $f_{c,mean}$ = 18.60 MPa and $f_{c,min}$ = 13.55 MPa. Similarly, the compression strength of the cylinder specimens with diameter ϕ60mm was employed to determine the average value of $f_{c,mean}$ = 22.42 MPa and $f_{c,min}$ = 19.89 MPa. Ultrasonic tests were carried out on structural members where the cylinders with ϕ100mm were drilled. The mean values $f_{c,mean}$ of the resistance may be derived from f_{ck} through the following relationship (CEN, 2006).

$$f_{c,mean} = f_{ck} + 8 \ \text{(MPa)} \quad (2)$$

The estimated mean value of the concrete cylinder compression strength is thus 18.8 MPa; the latter value is close to those evaluated earlier with the crushing of the cylinders. Variations of the computed strength are in the range of 10%. The mean value $f_{c,mean}$ of the concrete compression strength was also computed by utilizing the following expression (Masi, 2009)

$$f_{c,mean} = \left(C_{H/D} \cdot C_D \cdot C_s \cdot C_d\right) \cdot f_{c,cyl} \quad (3)$$

where $C_{H/D}$, C_D, C_s and C_d coefficients are as follows:

$$C_{H/D} = \frac{2}{1.5 + D/H} \quad \text{(MPa)} \tag{4}$$

C_D is a coefficient used for the cylinder diameters different from 100mm. The coefficient is 1.06, 1.00 and 0.98 for diameters D equal to 50mm, 100mm and 150mm. C_s is a coefficient utilized to account for the presence of steel reinforcement bars placed transversely to the axis of the cylinder. The coefficient is 1.0 if the steel rebars are not present and it varies between 1.03 for small diameter bars (e.g. ϕ10) and 1.13 for large diameter bars (e.g. ϕ20). C_d is a coefficient which accounts for the perturbation caused by the drilling and pull-out on the compression strength of the cylinders. A constant C_d-value is implemented in guidelines and standards; for instance, C_d=1.06 in ACI (2003), provided that the drilling and pull-out of the cylinders is operated by expert people. In the finite element modelling and performance assessment it is safely assumed that the characteristic concrete compression strength is $f_{ck} \cong 15.7\ \text{MPa}$.

Tensile tests were carried out on steel reinforcement smooth bars; the laboratory tests on ϕ20 mm straight bars showed yield strength f_y = 296 MPa and ultimate strength f_u = 435 MPa. The estimated material overstrength is f_u / f_y = 1.47 and the ultimate elongation is ε_{su} = 37.1%. The latter values demonstrated the high plastic redistribution and ductility of the steel reinforcement of the RC cross-sections of the structural system. For the model calibration of the smooth rebars in the spatial frame finite element discretization it is assumed that f_y = 285 MPa

2.1.2 Structural details

The structural details of the beams and columns of the sample framed structures do not comply with modern codes of practice for seismic regions. The steel reinforcement comprises smooth bars and the spacing of the transverse stirrups is insufficient to warrant adequate shear resistance to beams, columns and structural joints. The longitudinal steel reinforcement percentage is not appropriate to ensure ductile response of RC cross sections. The bar overlapping is not code-compliant and hence limited plastic deformations are expected under moderate-to-high magnitude earthquake loadings.

3 SEISMIC RETROFITTING STRATEGY

The sample school building was retrofitted by means of special dampers, i.e. unbonded braces. The selection of dampers, their location and number, their geometric and mechanic properties was based on the following:

- Dampers located along the perimeter of the structure to minimize the interruption of the building functionality and occupancy. The axial forces in the dampers are transferred to the RC walls along the perimeter of the lateral resisting system, at ground floor;
- The cross-sections of the dampers minimize the axial loads transferred to the foundation and are adequate for the installation within the infilled walls made of bricks;
- Dampers are installed within the existing infills to minimize the impact of the structural retrofitting elements on the facades of the building;
- The layout of the dampers is compliant with the large openings of the building facades;
- The layout of the dampers in elevation is aimed at regularizing the dynamic response of the retrofitted earthquake-resistant structural system;

- The design of the dampers is aimed at minimizing the level of tensile actions in the RC columns of the existing frame.

The layout of the UBs is displayed in Figure 2 for the sample T-shaped block of the building school, where the bays with braces are highlighted.

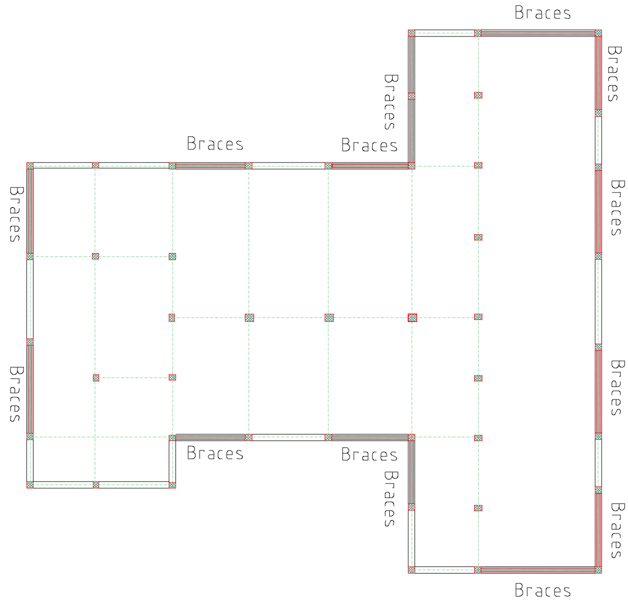

Figure 2. Layout of the dissipative braces along the perimeter of the T-shaped building block.

4 STRUCTURAL MODELLING AND ANALYSIS

Refined three-dimensional (3D) finite element (FE) models were employed to discretize the sample framed as-built and retrofitted structures and analyze the earthquake response. Bare frames were modelled as 3D assemblages of beam members. Shear deformability of beams and columns were also included in the structural model. Panel zone strengths and deformations were not considered. Figure 3 displays the FE models utilized for the response analyses of the buildings. Such FE models employ a refined fibre-based approach to estimate reliably the nonlinear response both at local and global level in the frames.

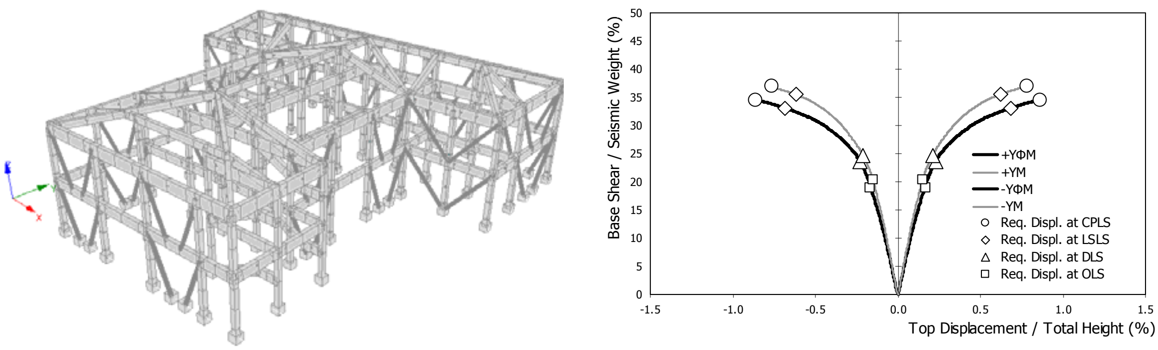

Figure 3. Finite element model (*left*) and capacity curves (*right*) of the retrofitted sample framed building.

The FE package utilized to assess the seismic performance of the sample structures is SeismoStruct (Pinho and Antoniou, 2009). Five inelastic space frame elements were used to model both beams and columns of the bare RC frames. Two elements with a length of 0.10L of the member clear span (L) are located at the beam ends; the remaining frame elements are 0.30L long. Rod elements connecting in-plane slab nodes were used to simulate the diaphragmatic action of the two slabs of the framed building. The cross-section of the floor rod elements was calibrated on the basis of the modal response of the system. The structural models utilized to perform the dynamic analyses employ masses lumped at structural nodes. The lumped masses were estimated by assuming the values of dead loads and part of the live loads in compliance with seismic code provisions.

To estimate the expected inelastic mechanisms and the distribution of damage in the sample framed buildings, non linear static (pushover) analyses were carried out both for the as-built and retrofitted structural systems. Two lateral load pattern were employed for the seismic structural assessment: modal and uniform force patterns. Additionally, non linear response history analyses were carried out by utilizing a suite of seven spectrum-compatible natural earthquake records. The details of the comprehensive seismic assessment of the sample structure can be found in Di Sarno and Manfredi (2010). Figure 3 provides the response curves of the retrofitted structure along the Y-direction; results were computed for positive and negative directions of the lateral loadings. The performance points at operational (OLS), damage (DLS), life safety (LSLS) and collapse prevention (CPLS) limit states are also included in the response curves.

5 GLOBAL AND LOCAL INTERVENTIONS

The seismic strengthening of the sample structures include the use of UBs and FRPs. The dissipative braces were placed along the perimeter of the as-built frame; V-shaped layouts were adopted to maximize the efficiency of the braces. The design of the UBs is based on the allowable interstorey drifts that are compliant with the maximum axial deformations of the dampers. As a result, UBs with 40 mm (= ± 20 mm) axial deformations were selected. The maximum storey lateral displacement is assumed equal to 10mm; this value is however very small for the ultimate limit state. A number of seismic details were designed to provide an efficient connection of the braces to the existing RC members of the sample frame. Due to the low shear reinforcement in the columns, , e.g. stirrups ϕ6/20, few members were reinforced with additional structural steel angle profiles located at the cross-section corners. Additionally, carbon fiber reinforced polymers were utilized to wrap the zones of the beams connected to the UBs. A single layer of 300g uniaxial carbon fiber was utilized. Beton plaque was used to strengthen the top of the beams and to facilitate the construction of the brace-to-beam joint. Figure 4 provides, for example, the seismic details for the bays of the frame incorporating UBs. Columns with and without additional corner angles are also shown in the figure. The design of all seismic details was based on capacity-design rules and was dimensioned in such a way to minimize the cost of the strengthening of the existing multi-storey frame.

6 CONCLUSIONS

A typical reinforced concrete (RC) existing building structure designed for gravity loads only was assessed; it exhibits high seismic vulnerability and hence a retrofitting scheme based on the use of innovative materials (fiber reinforced plastics, FRPs) and devices (unbonded braces, UBs) was considered. Extensive nonlinear analyses demonstrate that the proposed retrofitting method enhances significantly the global energy dissipation capacity and in turn lower the seismic vulnerability of the as-built RC framed system. The results of the nonlinear static response presented herein prove the enhancement of global lateral stiffness, strength and ductility due to the use of unbonded braces and FRPs. It is, however, of paramount importance to achieve augmented energy absorption and dissipation to design the structural details by employing capacity-design rules.

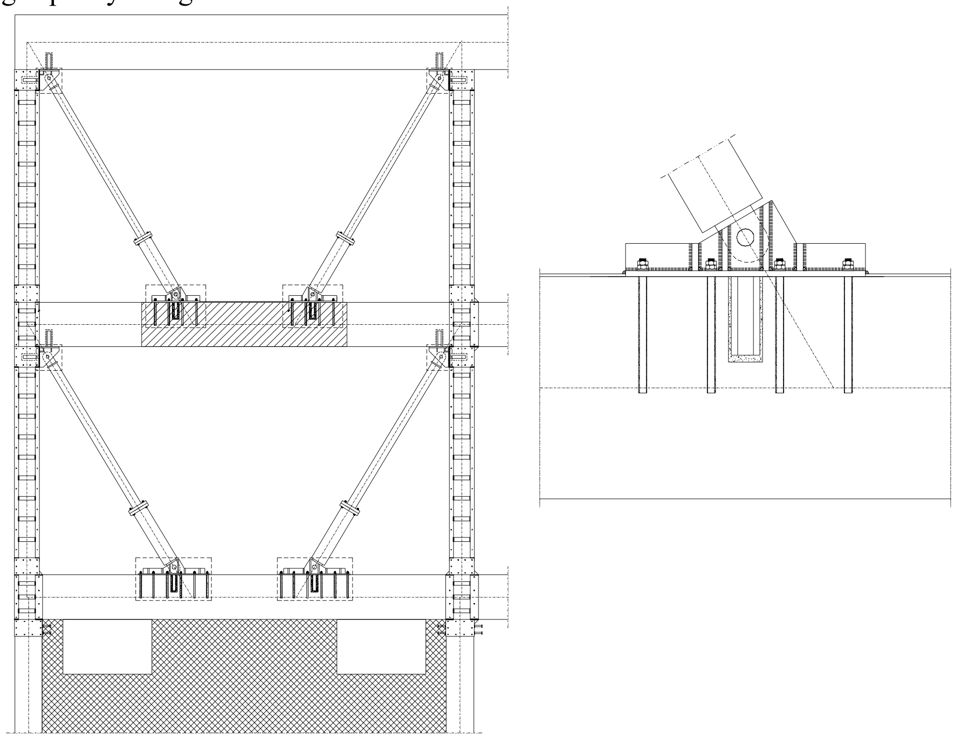

Figure 4. Seismic details for the bays of the frame incorporating unbonded braces.

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