IACSIT International Journal of Engineering and Technology, Vol. 4, No. 5, October 2012

Seismic Performance Improvement of a Plan-Asymmetric RC building Designed for Gravity Loads

Marco Valente

***Abstract*—A mixed retrofitting intervention including both FRP wrapping and RC jacketing applied to selected columns was proposed and investigated by numerical analyses with the aim of improving the seismic performance of a four-storey plan-asymmetric RC building designed for gravity loads. Retrofitting was aimed at both reducing the torsional component of the seismic response and improving the local and global ductility of the building. A displacement-based procedure using nonlinear static pushover analyses was adopted to assess the seismic performance of the structure in the original configuration and to select the retrofitting intervention. Due to the asymmetry of the investigated structure, appropriate correction factors were computed in order to take into account the effects of torsion. Nonlinear dynamic analyses were carried out to verify the effectiveness of the retrofitting intervention strategy. Demand-to-Capacity Ratio (DCR) values were used to evaluate the damage level of columns and to identify the most critical columns affecting the seismic performance of the structure.**

***Index Terms*—Displacement-based procedure, FRP wrapping, plan-asymmetric building, RC jacketing, seismic retrofitting.**

I. INTRODUCTION

The majority of existing structures in southern Europe has not been designed according to modern seismic codes and is, thus, inherently vulnerable to earthquakes. In recent years, innovative techniques along with traditional solutions have been proposed and applied in order to satisfy the structural goals of seismic retrofit, either enhancing the seismic capacity or reducing the demand, [1]-[3]. This study investigates the effectiveness of a seismic retrofitting strategy for improved strength and ductility of a non-ductile plan-asymmetric reinforced concrete (RC) building. A displacement-based procedure using nonlinear static pushover analyses was performed and appropriate correction factors were computed in order to take into account the effects of torsion due to the asymmetry of the investigated structure. The retrofitting intervention strategy was based on the decrease of the torsional component highlighted in the seismic response of the original structure by means of the reduction of the eccentricity of the centre of stiffness (CR) with respect to the centre of mass (CM). The strength and stiffness relocation was achieved using the traditional technique of RC jacketing, limited to selected columns. The mixed retrofitting intervention included FRP wrapping applied to the other columns with the aim of improving the local and global ductility of the structure.

II. BUILDING UNDER STUDY

The case study is a four-storey RC building designed for gravity loads without the application of specific earthquake-resistant provisions. Fig. 1 shows the plan and the elevation of the RC building. The materials used were concrete C20/25 and steel S400 for longitudinal and transverse reinforcement. Storey masses included dead loads and a percentage of live loads (30% according to Eurocode 8 for common residential and office buildings). The columns presented square cross-sections of dimensions 30cm x 30cm, except the large column C2 with a rectangular cross-section of dimensions 30cm x 80cm. The rectangular column C2 provided the structure with more stiffness and strength in the x direction than in the y direction. The beam cross-section dimensions were 30cm x 50cm. The eccentricities between the centre of mass (CM) and the centre of stiffness (CR) amounted to 0.22 m and 3.92 m (about 1.5% and 26% of the plan dimensions) in the x and y directions, respectively. The RC building was modelled by using the computer code SeismoStruct, [4]. The spread of the inelastic behaviour along the length of any member and within its cross-section was described by means of a fibre model that made it possible to accurately evaluate the damage distribution. Fig. 1 shows a three-dimensional view of the numerical model of the RC building.

III. SEISMIC PERFORMANCE ASSESSMENT

A simplified assessment procedure [5] was adopted for the seismic verification of the global structural behaviour of the RC building. The seismic assessment of the structure was performed by comparing seismic demand and capacity. The seismic demand was evaluated with reference to Eurocode 8 response spectrum (Type 1, subsoil class C) with $a_g = 0.25g$. The seismic capacity was achieved once a specific chord rotation was attained in one of the members of the structure. The expressions of the specific chord rotations are reported in Eurocode 8 Part 3, [6]. According to the code, in this study the most critical member was conservatively assumed to control the behaviour of the structure. Nonlinear static pushover analyses were performed using the computer code independently in the two horizontal directions and a load in the positive and negative direction was taken into account.

Manuscript received April 5, 2012; revised September 4, 2012.

Marco Valente is with the Department of Structural Engineering, Politecnico di Milano, Milan, Italy (e-mail: valente@stru.polimi.it).

DOI: 10.7763/IJET.2012.V4.455

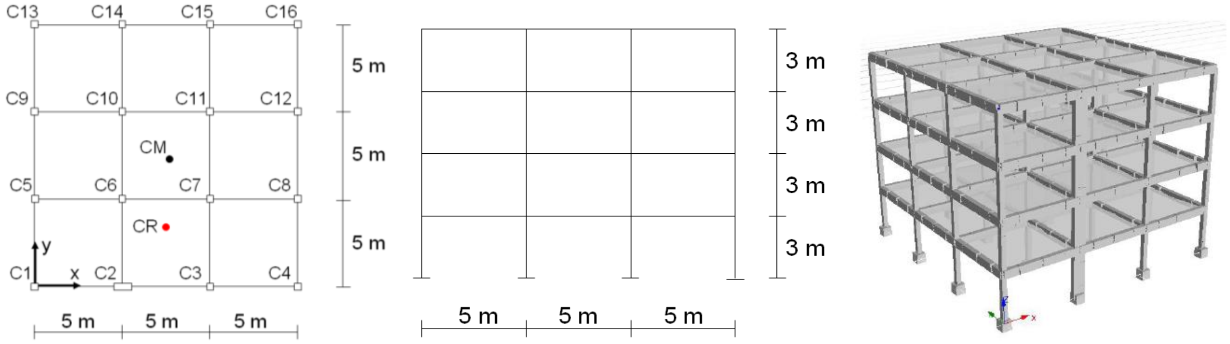

Fig. 1. Schematic plan and elevation of the RC building under study and three-dimensional view of the developed numerical model.

The bilinear idealization of the pushover curve with zero post-yield stiffness was defined on the basis of the “equal-energy” concept. The target displacement was computed as the intersection between the bilinear capacity curve and the inelastic demand spectrum characterized by the relevant ductility. Due to the asymmetry of the investigated building, appropriate correction factors were used in order to take into account the effects of torsion for plan-asymmetric structures. The results obtained by pushover analysis were combined with the results of a linear dynamic (spectral) analysis. The target displacements and the distribution of deformations along the height of the building were determined by means of the simplified procedure, which is based on pushover analysis, whereas the torsional amplifications were determined by linear dynamic analysis in terms of correction factors to be applied to the relevant results of pushover analyses. The correction factor was defined as the ratio between the normalized roof displacements (the roof displacement d at an arbitrary location divided by the roof displacement d_{CM} at CM) obtained by linear dynamic analysis and by pushover analysis. Displacement reductions due to torsion were neglected. Torsional amplifications were taken into account for the columns of the flexible sides of the structure. Fig. 2 presents the normalized roof displacements of the structure for linear dynamic and nonlinear static pushover analyses at the Limit State of Significant Damage (LSSD) in the x and y directions.

Fig. 3 shows that the bare structure was unable to satisfy the demand in both directions at a peak ground acceleration of Sa_g = 0.29g (S = soil factor) at the LSSD. The displacement demand and capacity in Fig. 3 refer to the equivalent SDOF system. The displacement demand and capacity of the MDOF system were obtained by multiplying the SDOF system demand and capacity by the transformation factor Γ. The difference between the seismic demand and the displacement capacity was 3.6 cm (15.1 cm *vs* 11.5 cm) in the x direction and 3.7 cm (16.5 cm *vs* 12.8 cm) in the y direction. The comparison of the bilinear idealized capacity curves of the structure in the x and y directions shows an increase of strength and stiffness in the x direction due to the orientation of the rectangular column C2. The simplified assessment procedure established that the critical columns were the internal columns C6, C7, C10, C11 with high axial load and the perimeter columns C14, C15, C16, C12 of the flexible edges with high torsional amplifications.

IV. DESIGN STRATEGY FOR RETROFITTING INTERVENTION

A retrofitting intervention using both RC jacketing and glass-fibre-reinforced polymer (GFRP) laminates was carried out in order to improve the seismic performance of the structure. Fig. 4 presents a schematic view of the proposed retrofitted structure, hereafter named as “RS1”. The perimeter columns C5, C9, C14, C15, C12 and C8 were strengthened at all storeys with 20 cm-thick jackets, longitudinally reinforced with 12∅16 bars. The ductility of these columns was increased by adding ∅10 stirrups, spaced by 100 mm. At all storeys, the remaining square columns were confined at the top and at the bottom by means of GFRP uniaxial laminates (thickness = 0.7 mm; modulus of elasticity = 72 GPa; tensile strength = 2000 MPa; ultimate strain = 0.035) in order to enhance structural ductility. The ultimate chord rotation of the retrofitted columns increased by about 70% with respect to the original columns. Quadriaxial GFRP laminates were used for the rectangular column C2, wrapped for the entire height at all storeys, in order to increase its shear capacity.

The combination of the two approaches (RC jacketing and FRP wrapping) applied to selected columns aimed at improving the seismic performance of the structure. The selection of the retrofitting intervention was based on the deficiencies underlined by numerical analyses performed on the bare structure. The retrofitting strategy was focused on two main objectives: 1) relocating the centre of stiffness (CR) in order to reduce the torsional component of the response and increasing the strength and stiffness of the structure; 2) increasing the local deformation capacity of columns and thus the global deformation capacity of the structure. In the retrofitted structure the eccentricity of CR with respect to CM was significantly reduced compared to the bare structure and amounted to 0.06 m and 0.51 m in the x and y directions, respectively. Such a retrofitting intervention turned out to be very effective, since a sizable reduction of the torsional response was achieved in a rather simple way.

The capacity curves and the demand spectra for the retrofitted structure RS1 are presented in Fig. 5. The retrofitting intervention reduced the irregularities of the structure and the global response could be more accurately captured by pushover analyses. Numerical outcomes pointed out that the retrofitted structure RS1 was able to withstand the displacement demand due to seismic action of Sa_g=0.29g and thus to satisfy the LSSD. In the x direction the seismic

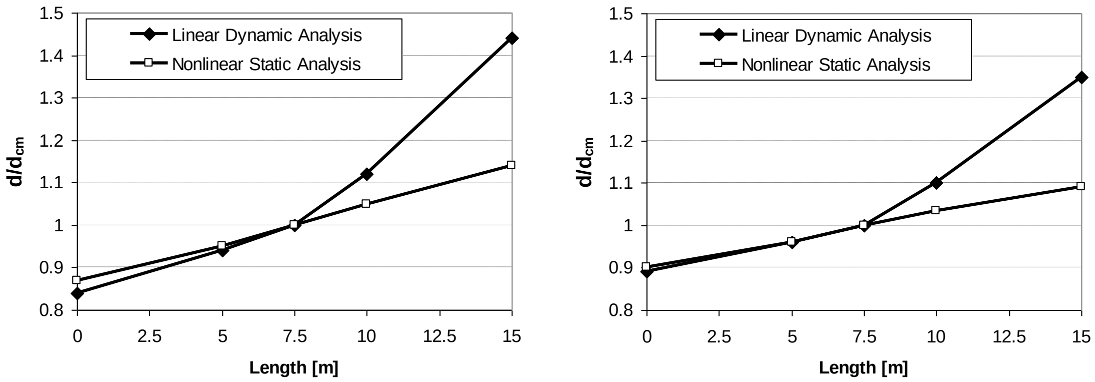

Fig. 2. Normalized displacements at the top of the bare structure for linear dynamic and nonlinear static analyses: x direction (left) and y direction (right).

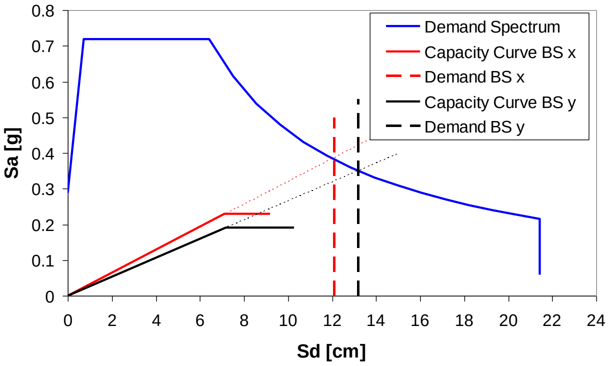

Fig. 3. Demand spectrum and capacity curves in AD format at LSSD (Sa_g = 0.29g) for the bare structure in the x and y directions.

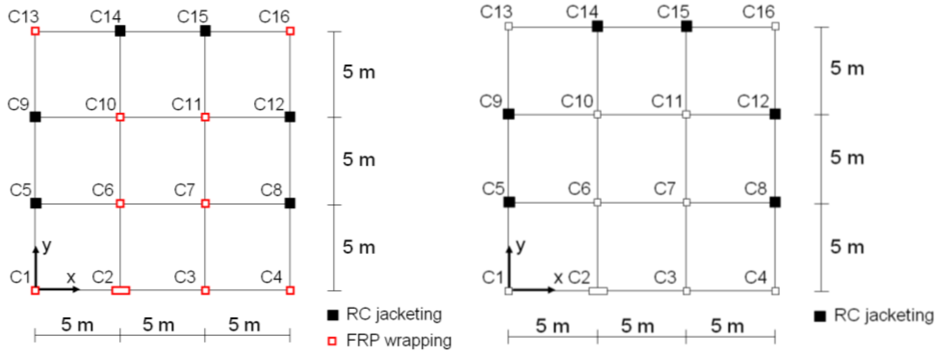

Fig. 4. Schematic plan of the retrofitted structures RS1 (left) and RS2 (right).

demand in terms of displacement, transformed to actual MDOF system, was reduced to 13.1 cm (15.1 cm for the bare structure), while the capacity of the structure was increased up to 13.7 cm (11.5 cm for the bare structure).

In the y direction the seismic demand in terms of displacement was reduced to 13.3 cm (16.5 cm for the bare structure), whereas the capacity of the structure was increased up to 15.2 cm (12.8 cm for the bare structure). According to the simplified procedure based on nonlinear pushover analyses, the perimeter columns C14, C15 were detected as critical columns.

V. NONLINEAR DYNAMIC ANALYSES

Nonlinear dynamic analyses were carried out to verify the validity of the simplified displacement-based design procedure and the effectiveness of the retrofitting intervention strategy. Bidirectional artificial accelerograms were generated using the computer code SIMQKE in order to match the Eurocode 8 response spectrum (Type 1, subsoil class C). The retrofitting intervention increased the stiffness of the structure and reduced the maximum inter-storey drift at all levels with respect to the bare structure. A considerable decrease of the storey rotation at all levels, in particular at the second level, was observed for the retrofitted structure compared to the bare counterpart. The intervention based on RC jacketing of selected columns of the structure was effective in reducing the effects of torsion and the global behaviour of the structure was improved.

The Demand-to-Capacity Ratio (DCR), i.e. the ratio of the chord rotation demand to the chord rotation capacity, was used to evaluate the damage level of columns. The maximum chord rotation demand was obtained by numerical analyses and the chord rotation capacity was computed according to Eurocode 8 Part 3.

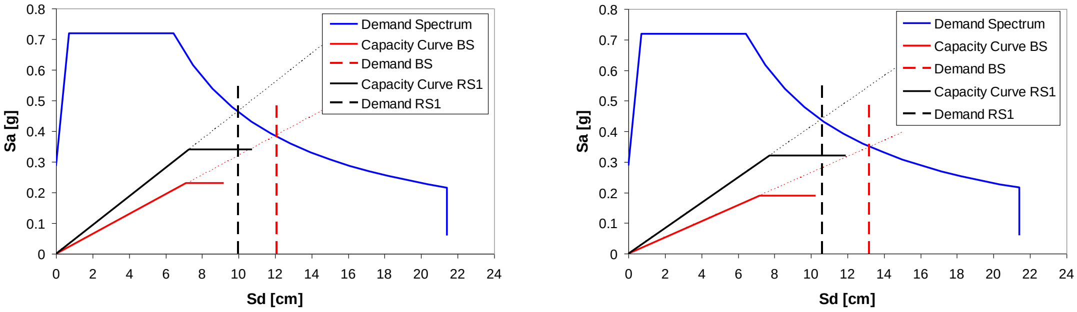

Fig. 5. Demand spectra and capacity curves in AD format at LSSD (Sa_g = 0.29g) for the retrofitted structure RS1: x direction (left) and y direction (right).

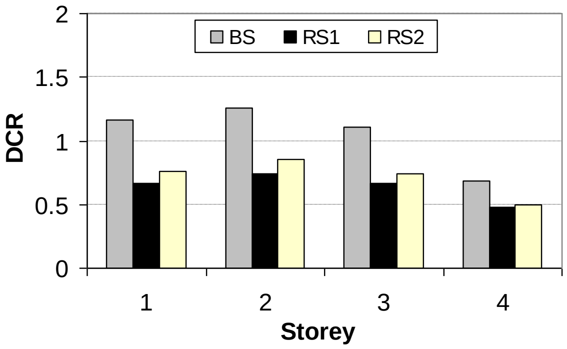

Fig. 6. Maximum DCR values for the columns of each storey of the three investigated structures (BS, RS1 and RS2) at Sa_g = 0.3g seismic intensity level.

The comparison of the maximum DCR values was carried out considering also another retrofitted configuration, named as “RS2”. The structure RS2 was strengthened by using only RC jacketing for the same columns as the retrofitted structure RS1, without applying FRP wrapping to the remaining columns, as shown in Fig. 4. Fig. 6 provides the maximum DCR values registered for the columns of each storey of the bare and retrofitted models under ground motion intensity of Sa_g=0.3g. For all the numerical models, the maximum DCR values were computed for the columns of the second storey. A significant reduction of the DCR values was observed for the columns of both the retrofitted structures. The maximum DCR value was registered for column C14 of the bare structure. For the retrofitted structures RS1 and RS2, the maximum DCR value was computed for column C2 and column C11, respectively. The results reported for the models RS1 and RS2 pointed out the effectiveness of the retrofitting intervention. Smaller values of deformation demand were registered for the columns of both the retrofitted models compared to the bare counterpart. Moreover, in case of model RS1, the remaining columns were detailed for ductility due to high level of confinement provided by FRP wrapping. A considerable improvement in deformation capacity was obtained and a significant decrease of the DCR values was observed for the retrofitted model RS1.

VI. CONCLUSION

A displacement-based procedure using nonlinear static pushover analyses was applied in this study: 1) to assess the seismic performance of a non-ductile plan-asymmetric RC building; 2) to select the seismic retrofitting intervention. The use of appropriate correction factors allowed to predict the torsional response due to the asymmetry of the investigated building. The critical columns affecting the seismic performance of the structure were identified by the procedure. The retrofitting design strategy was capable of both reducing the torsional component of the seismic response and improving the local and global ductility of the structure. A considerable decrease of the DCR values was registered for the retrofitted model compared to the bare counterpart, because the deformation demand was reduced and the columns were detailed for ductility due to high level of confinement provided by FRP wrapping.

REFERENCES

[1] M. Valente, “Seismic assessment and selective retrofitting of an underdesigned RC frame,” *Studies and Researches*, Starrylink., vol. 28, pp. 211-243, 2008.
[2] M. Valente, “Seismic rehabilitation of a three-storey R/C flat-slab prototype structure using different techniques,” *Applied Mechanics and Materials*, vol. 193-194, pp. 1346-1351, 2012.
[3] M. Valente, “Displacement-based seismic design of steel frames strengthened by buckling-restrained braces,” *Applied Mechanics and Materials*, vol. 217-219, pp. 1114-1118, 2012.
[4] S. Struct, *A Computer Program for Static and Dynamic Nonlinear Analysis of Framed Structures*, 2007.
[5] P. Fajfar, “A nonlinear analysis method for performance-based seismic design,” *Earthquake Spectra*, vol. 16, pp. 573-592, 2000.
[6] CEN European Standard EN 1998-3. Eurocode 8: Design of structures for earthquake resistance. Part 3: Assessment and retrofitting of buildings. European Committee for Standardization, Brussels, 2005.