ANALYTICAL POST EARTHQUAKE DAMAGE ASSESMENT OF RC BUILDING AND ITS RETROFITTING: A CASE STUDY

M. B. Sharif, A. U. Qazi, A. Hameed, N. M. Khan, and S. Jabeen*

Department of Civil Engineering, University of Engineering and Technology, Lahore.
*Strucrual Division Nespak House, Lahore
Corresponding author emai: burhansharif@uet.edu.pk

ABSTRACT: Majority of earthquake damaged buildings can be safely used by employing retrofitting measures after systematic post earthquake damage assessment. The study considers evaluation of structural performance under earthquake using empirical and analytical approach. The subject building in this research is Abbas Institute of Medical Sciences (AIMS) Muzzafarabad. It is a three story RC frame structure with masonry infill walls and a lift well which is located at one corner of the building. This institute was in operation at the time of October 08, 2005 earthquake. After earthquake no significant damage was observed in the structural members. However, infill walls suffered minor damages at some locations. Seismic evaluation was carried out in three phases. First phase was the screening phase in which evaulation was performed by an emperical approach. Second phase was the analytical evaluation phase in which modal and linear static analysis (LSA) are performed. Third phase was the detailed evaluation phase in which pushover analysis was carried out on the existing and retrofitted building models to access performance of the building by using capacity spectrum method. The first phase concluded that building can be used after the earthquake with minor repairs but the results of Linear static and nonlinear pushover analysis revealed that the building was weak not only under seismic but also under gravity loading. This was due to the absence of mathematical modeling of infill walls in the computer model made with ETABS. After modeling of retrofitted building, results showed that strength and stiffness was increased along both orthogonal directions. However, ductility was little affected in strong direction but a significant gain occurred in weak direction.

Key words: Retrofitting, Nonlinear Analysis, Earthquake.

INTRODUCTION

The aftermath of an earthquake manifests great devastation due to unpredicted seismic motion which causes extensive damage to a number of buildings with varying degree. Damage to structures causes irreparable loss of life with a large number of causalities. It has been observed that majority of earthquake damaged buildings may be safely used, if they are converted into seismically resistant structures by employing retrofitting measures after systematic post earthquake damage assessment.

The majority of Reinforced concrete existing structures are aging. These structures are either gravity load designed or lacking detailing which improves their performance under sesimic loading (Sasmal et al. (2011)). Aycardi et al. (1994) studied the seismic performance of gravity load design sub-assemblages (designed according to ACI 318-89) by changing the parameters such as axial load level, lap splice etc. The author attempted to analytically model the seismic behaviour and to identify the parameters which play the key role under seismic loading. Seismic performance evaluation of RC multi-storey building structures, primarily designed for gravity loads, indicates that these gnererally suffer from weak column strong beam behavior (Bracci et al. (1995)). El-Attar et al. (1997) studied the seismic behaviour of gravity load desing for RC buildings designed on ACI 318-89. He found that vulnerability (deformation and stiffness degradation) of the gravity load design based buildings without infill. Simulated seismic load tests on RC interior and exterior beam-column joints were conducted by Hakuto et al. (2000). He studied an existing RC building in New Zealand built in 1950's designed on previous New Zealand code which does not conform with the lates code. He attributed poor structural detailing for poor performance of buildings during an earthquake. Dhakal et al. (2005) carried out an experimental study on dynamic response of RC connections of gravity load design according to British Standard BS8110. He finally concluded that although the connection in RC buildings are very important zones in dissipating the energy however in gravity load design majority of the connections are weak hence they fail in shear.

Retrofitting of a building improves the capacity of the building and its usability after the earthquake. There are many techniques which may be used for retrofitting, e.g; introduction of shear walls or columns in the existing buildings, steel jacketing of the critical concrete regions etc. Various researchers around the globe studied different materials for retrofitting purpose. Biddah et al. (1997) and Ghobarah et al. (1997) suggested a seismic upgradation technique for existing RC frame connections using corrugated steel jacketing. Aboutaha et al. (1999) also suggested rehabilitation schemes for shear critical concrete columns by using rectangular steel jackets to evaluate the effectiveness of thin rectangular steel jackets for seismic retrofit of large rectangular RC columns with inadequate shear strength. He conducted an experimental investigation of seismic repair of lap splice failures in damaged concrete columns using steel jackets with adhesive anchor bolts or through rods. Bligh et al. (2005) used concrete jackets as a replacement to the confinement that would be provided to framing members on all four sides of the joint. Due to the concrete jacketing, the clear span of beams and columns were reduced which led to increase in shear demand in beam and column. Hence, the shear strength of the retrofitted structural components was re-checked. The use of all such retrofitting methods were very useful in structural updration and performance of RC building during earthquakes.

MATERIALS AND METHODS

Building description: Abbas Institute of Medical Sciences (AIMS) is situated in Muzzafarabad, Azad Kashmir, Pakistan. This institute is located near the fault. According to Building code of Pakistan 2007 this area is categorized as sesimic zone-4.It was completed in the mid of year 2005 and was in operation at the time of Oct, 2005 earthquake. The building mainly comprises of four blocks which are separated by expansion joints. Among these blocks, New Block is selected for study because of structural irregularities or details. The New Block building is presently a three story structure. However, originally the building was designed as four story structure but due to lack of funds the construction was stopped at third story level. Column dowels for future vertical extension of the building are provided.

On physical inspection after the October 08, 2005 earthquake little or no damage has been observed. Beams, Columns and their joints are intact without any signs of cracking or spalling. However, the infill walls have suffered minor diagonal shear cracks at some locations.

Structural system: The structural system of AIMS building is an essentially RC space frame with masonry infill walls. The scrutiny of design calculations and structural drawings indicates that the new block of AIMS was not designed for seismic forces as prescribed in the Pakistan Building Code–Seismic Provisions (2007) (PBC-07). Infill to the moment resisting frame of the building comprises of burnt clay bricks. The floor and roof slabs were constructed using reinforced concrete and consists of mostly two-way slab system.

A lift-well is eccentrically located at one corner of the building. Foundation system of the building comprises of combined footings. The entire building is tied by plinth beams at the plinth level. AIMS building is modeled for three stories only. Future extension is ignored and only existing structure at the time of Oct, 2005 earthquake is studied.

Story Data: Table -1 provides story heights and levels at different stories.

Table-1. Story Heights

Storey ID	Height (m)	Elevation (m)
1st	1.65	1.65
2nd	3.50	5.15
3rd	3.65	8.80
4th	3.65	12.45

Frame Section Properties: Table - 2 provides section properties for beams and columns at ground, first and second floor slabs.

Table – 2. Frame Section Properties

Cross-Section	Section Type	Section Shape	Section Depth (mm)	Section Width (mm)
B225X450	Beam	Rectangle	450	225
B225X525	Beam	Rectangle	525	225
C450X225	Column	Rectangle	225	450
C225X450	Column	Rectangle	450	225
C450X450	Column	Square	450	450
C375	Column	Circular	375Ø	
EQ1	Column	Square	3000	3000
EQ2	Column	Rectangle	2600	2600

Shell Element Property Data: Table - 3 provides section properties for ground, first and second floor slabs.

Table – 3. Shell Element Section Detail

Section ID	Section Type	Thickness mm
Slab125	Slab	125
Slab150	Slab	150

Reinforcing Steel*:* The yield strength of the reinforcing steel used is taken as 300MPa (40,000 psi) for existing concrete and same is considered for retrofitted concrete.

Concrete Strength*:* The compressive strength of existing reinforced concrete used is taken as 17MPa (2400 psi) and 28MPa (4,000 psi) for retrofitted concrete to avoid much bigger X-Sections for retrofitted structure.

Dead loads: Dead loads are the gravity loads due to the self weight of all permanent structural and non-structural components of a building, such as partition walls, floors and finishes, which are calculated from known specific weights of the materials used.

Table – 4. Dead Loads

Description	Load
First Floor Finishes:75mm (3") finishes i.e. Concrete, screed and marble	1.44 kN/m^2 (30 psf)
Second Floor Finishes:75mm (3") finishes i.e. Concrete, screed and marble	1.44 kN/m^2 (30 psf)
Roof Finishes:150mm (6") finishes 112.5mm (4.5") mud and 37.5mm (1.5") thick brick tiles	2.87 kN/m^2 (60 psf)

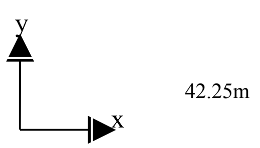
Live loads: Live loads are assigned as uniform area loads on the slab elements. For the subject building, floor live loads as per occupancy and intended use requirements, are as given in Table - 5.

Table – 5. Live Loads

Area	Load
Operating rooms and laboratories	2.87 kN/m^2 (60 psf)
Patient rooms	1.92 kN/m^2 (40 psf)
Corridors above first floor	3.83 kN/m^2 (80 psf)
Office for General use	2.39 kN/m^2 (50 psf)

Seismic loads: The area of the project corresponds to Zone 4 of Pakistan Building Code–Seismic Provisions–2007 (PBC-07). The following Seismic factors are considered in the analysis and design.

- Seismic Zone factor Z = 0.4
- Importance factor I = 1.25



- Soil Profile Type = Sc (very dense soil and soft rock)
- Seismic Zone type = A (due to faults of producing high range of seismic activity)

The value Na and Nv will be used for a source located at a distance of 2 km from the site.

Screening Phase: During the screening phase the design professional gets familiarized with the building, its potential deficiencies and its expected behavior, so that one can quickly decide whether the building complies with the provisions. This screening phase helps to provide evaluation statements for structural, non-structural and foundation aspects in the form of checklists for the chosen level of performance and given region of seismicity as per ASCE/SEI 31-03.

The general purpose of the screening is to identify potential weak links associated with structures of a specific types that have been observed in past significant earthquake.

Following are the observations noticed in the screening phase.

a) Insufficient clear distance between two portions of building.
b) Cracks in infill walls.
c) Infill walls not isolated from main reinforced concrete moment resisting frame.
d) Shear stress more than specified.
e) Axial stress more than specified.
f) Inadequate columns and foundation dowels.
g) Strong column/week beam behavior absent
h) Improper detailing of reinforcing bars.
i) Inadequate infill.
j) Stirrup and tie hooks not properly anchored
k) Unbraced masonry partitions.

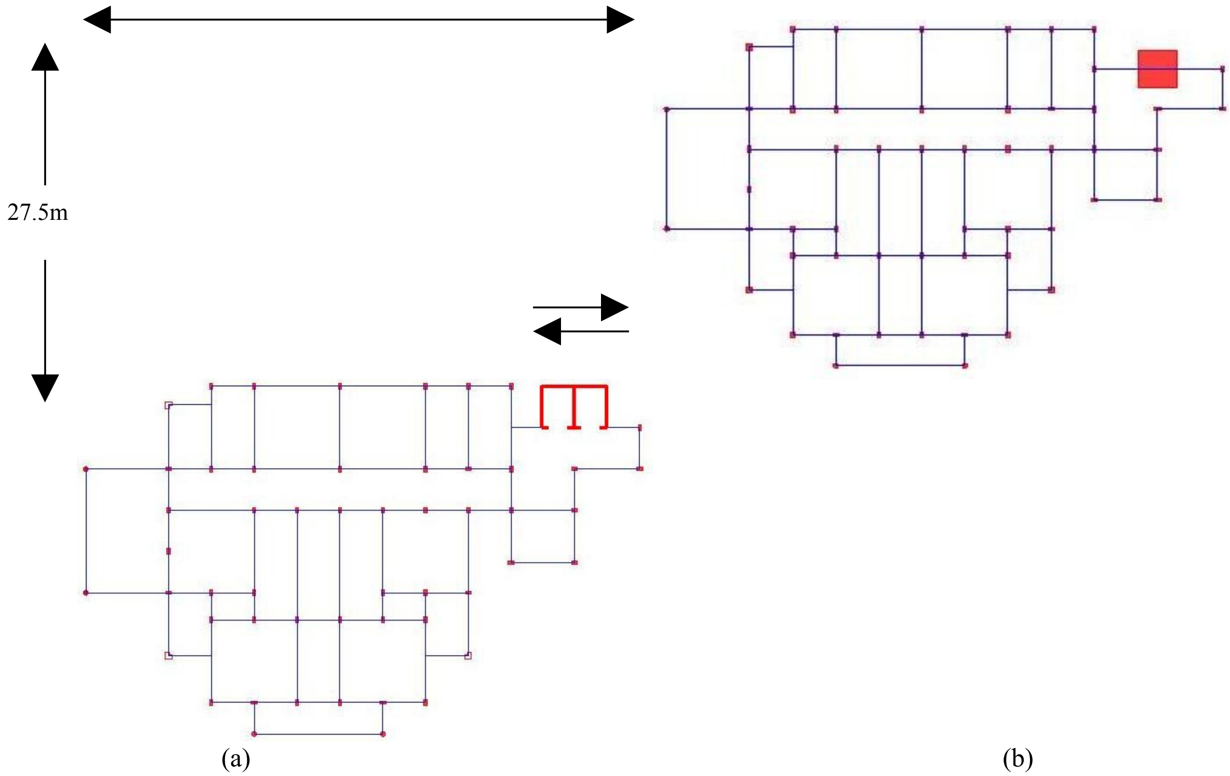


Figure - 1 Plan of a building and equivalent column for retrofitting

Table - 6 Types of analysis and their nomenclature

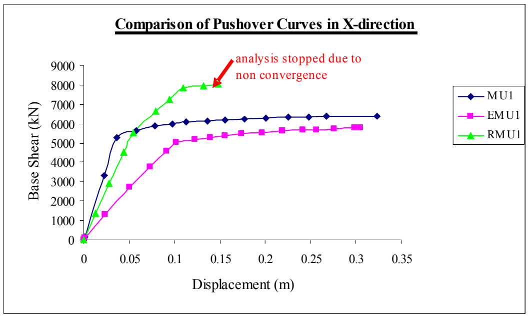
Model	Description
MU_1	3D model of original building is pushed by applying a lateral load based on fundamental mode in **x-direction** and displacement is monitored.
EMU_1	3D model of existing building is pushed by applying a lateral load based on fundamental mode in **x-direction** and displacement is monitored.
RMU_1	3D model of retrofitted building is pushed by applying a lateral load based on fundamental mode in **x-direction** and displacement is monitored.
MU_2	3D model of original building is pushed by applying a lateral load based on fundamental mode in **y-direction** and displacement is monitored.
EMU_2	3D model of existing building is pushed by applying a lateral load based on fundamental mode in **y-direction** and displacement is monitored.
RMU_2	3D model of retrofitted building is pushed by applying a lateral load based on fundamental mode in **y-direction** and displacement is monitored.

In screening phase it was found that although the building is weak against the lateral loads but it may be utilized after minor repairs. However, the detailed evaulation is essential to estabilish the serviceability of the building for its long term usability especially regarding it susceptibility for future earthquakes.

Analytical modeling: The building was modeled using Sap 2000 version 14.0.0. The plan of the building is shown in the figure-1. Since the pushover analysis was used for the non linear analysis of the building. It uses plastic hinges within the columns therefore during the modelling process lift well walls have been replaced by equivalent column. The stiffness of columns, walls, beams and slabs have been reduced for the inclusion of second order effects. The research is divided into various categories as presented by table – 6. The computer model for each variation was developed and results were analyzed before reaching to the final conclusion.

RESULTS AND DISCUSSION

The different analysis options which are shown in Table-1 were analyzed on separate computer model based on the parameters which have also been mentioned in the previous sections. The main considerations were given on the story drifts and drift ratios because the divergence of these values during different analysis options can comment on the status of the structure.



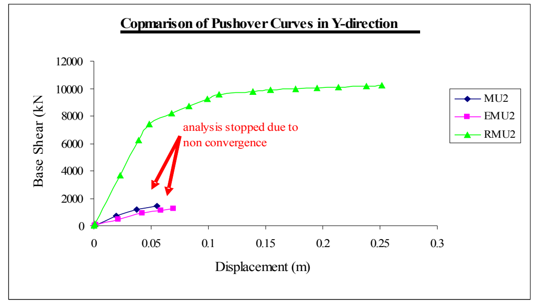


Figure -2 Push over analysis for cases 1 to 6 in x and y direction

Fig. 2 shows the comparison of pushover curves for the original, existing and retrofitted buildings in x & y directions. For retrofitted buildings the analysis stopped before approaching its collapse stage. The analysis stopped earlier due to non convergence, even by using a higher value of 0.1 for "Iteration Convergence Tolerance" and "Event Lumping Tolerance" instead of using their default values of 0.0001 and 0.01 respectively.

It is observed that gain in strength and stiffness from existing to retrofitted building is 37.93% and 90.91% respectively. However, ductility remains the same i.e. 3. The ductility is determined based on the available information which is incomplete as analysis for retrofitted building stopped before approaching the target displacement. In y-direction, there is remarkable increase in strength and stiffness after retrofitting. But for the existing and damaged buildings analysis stopped before approaching its collapse stage due to non convergence of the analysis even by using a higher value of 0.1 for "Iteration Convergence Tolerance" and "Event Lumping Tolerance". Therefore ductility in original and existing buildings may be underestimated.

Figure – 3 shows (color zone of plastic hinges) that the damage is relatively less in retrofitted structure as compared to original and existing structures shown in Figure - 4 and Figure – 5.

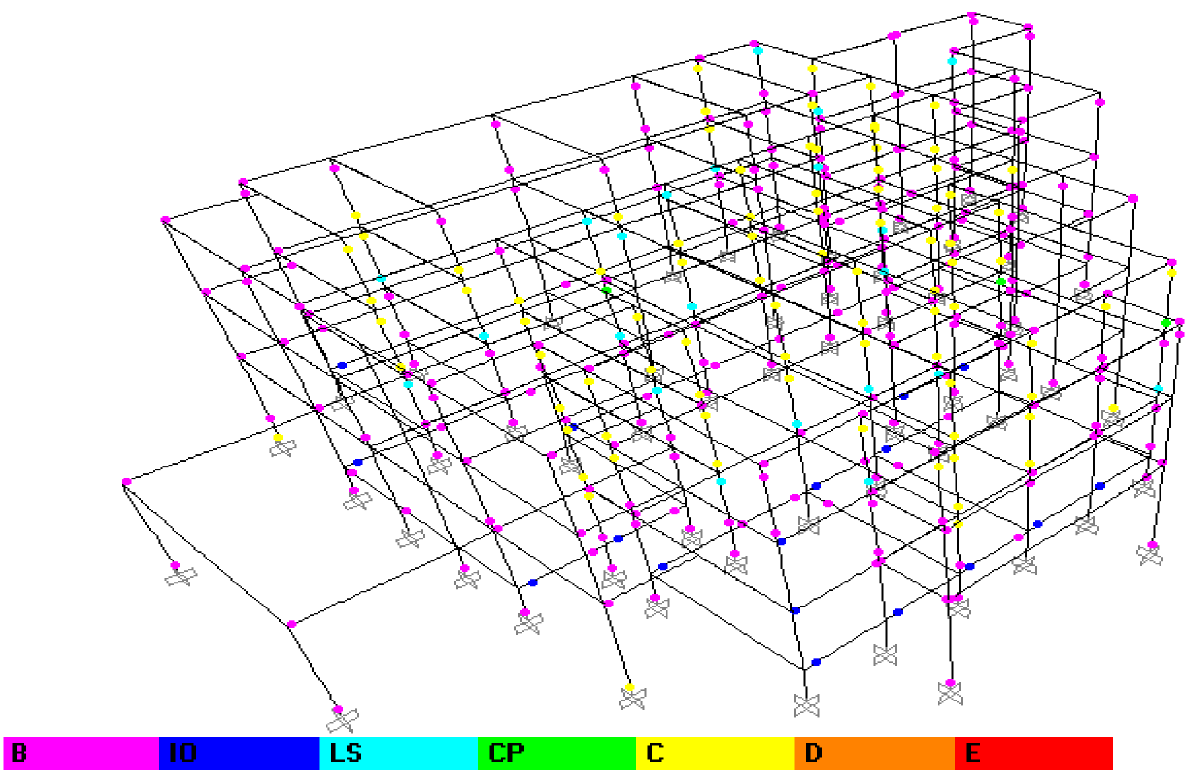


Figure -3. Damage Degree at End of Analysis of Retrofitted Building in X-Direction

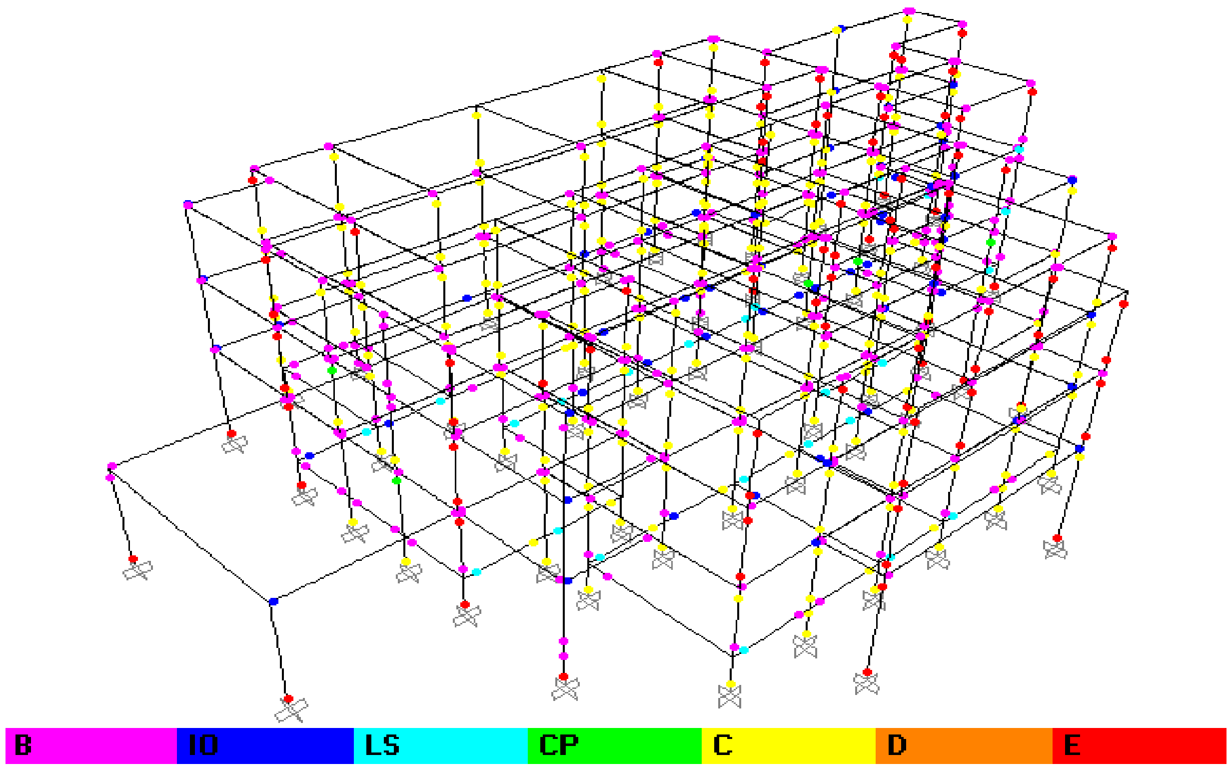


Figure – 4. Damage Degree at End of Analysis of Original Building in X-Direction

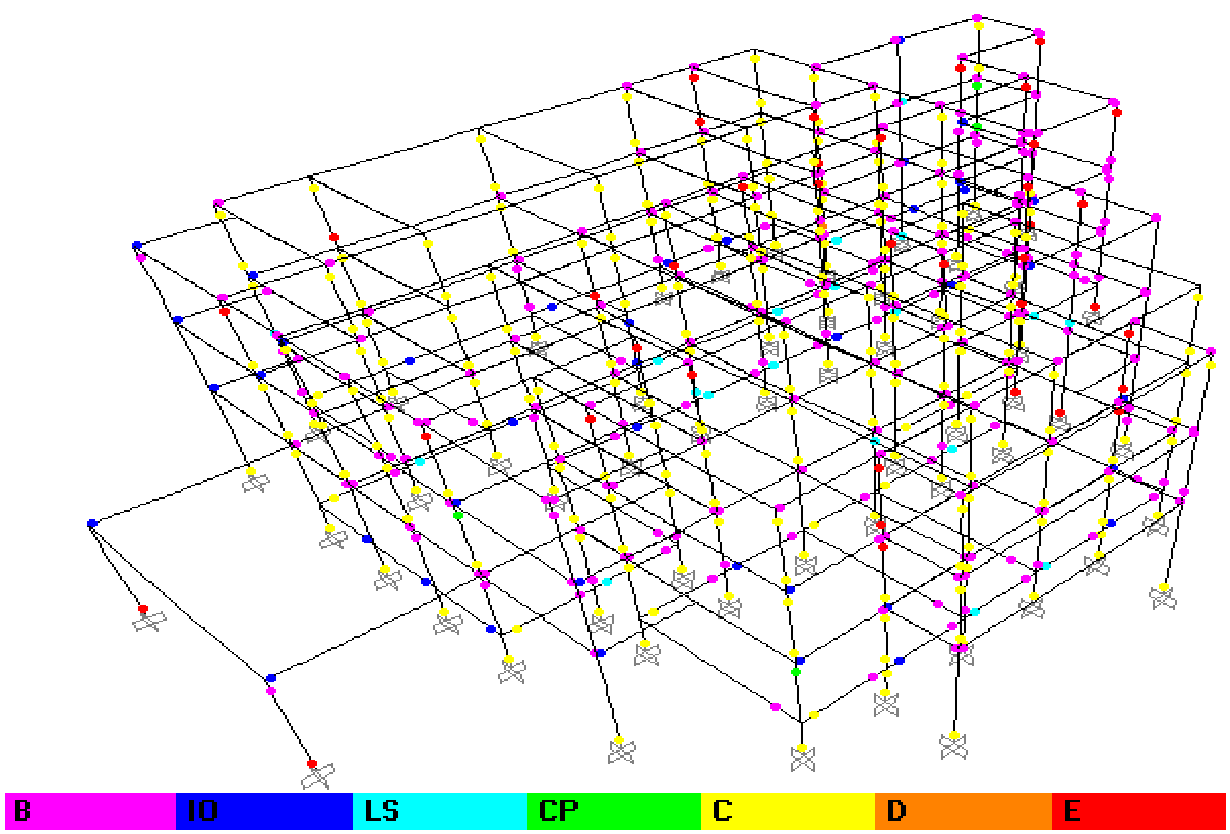


Figure – 5. Damage Degree at End of Analysis of Existing Building in X-Direction.

The maximum dispalacement observed in x – direction were 148 mm. Keeping the same displacement, different options were tested (case 1 to 3) and results are shown in figures 6 – 8..

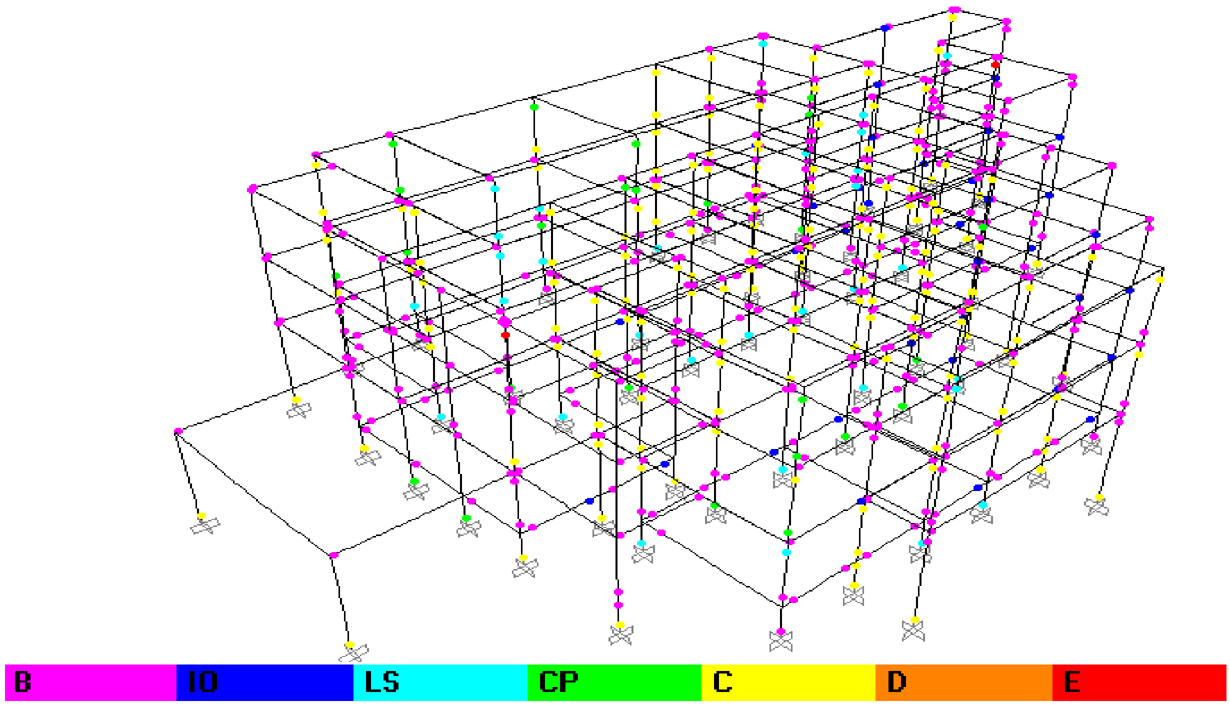


Figure – 6. Damage Degree of Original Building at a Displacement of 148mm in X-Direction

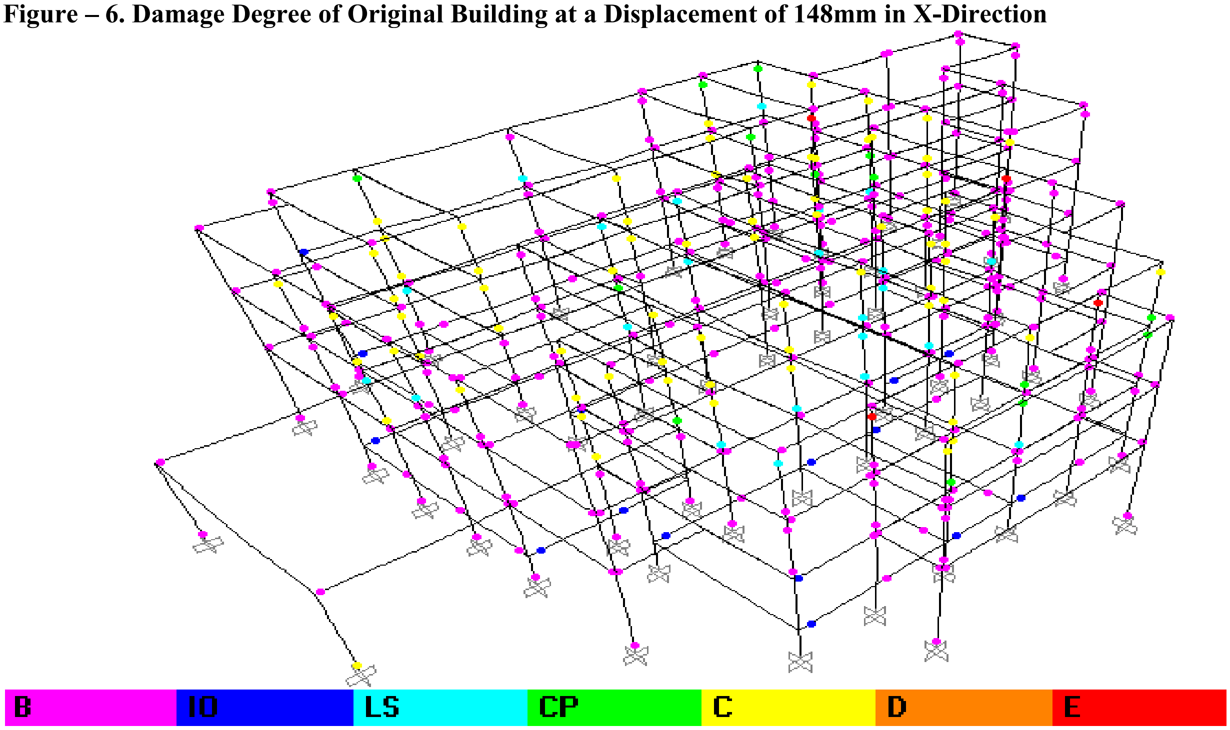


Figure – 7. Damage Degree of Existing Building at a Displacement of 148mm in X-Direction

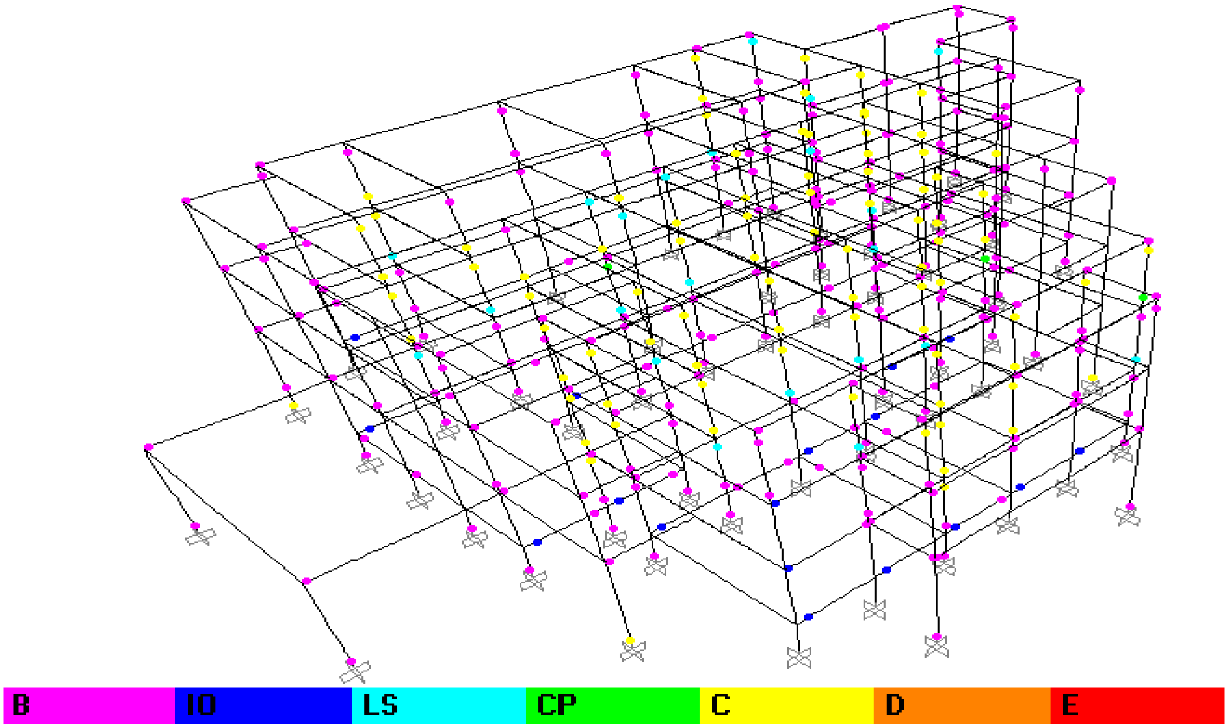


Figure – 8. Damage Degree of Retrofitted Building at a Displacement of 148mm in X-Direction

The above figures clearly demonstrates that retrofitted structure shows least damage and existing structure shows most severe damage when pushed to the same displacement. Similarly the same model was tested in y – direction (cases 4 to 6) and similar resutls i.e. retrofitted structure showed less damage than that of the exisiting structure.

Capacity spectrum is a representation of the capacity curve in Acceleration-Displacement Response Spectra (ADRS) format (i.e., S_a versus S_d). In order to develop the capacity spectrum from the capacity curve, it is necessary to do a point by point conversion to first mode spectral coordinates. Any point V_i, Δ_{roof} on the capacity curve is converted to the corresponding point S_{ai}, S_{di} on the capacity spectrum using the equations:

$$Sai = \frac{Vi/W}{\alpha_1} \quad \ldots\ldots(1)$$

$$Sdi = \Delta roof / (PF_1 \times \phi_1, roof) \quad \ldots\ldots(2)$$

Where α_1 and PF_1 are respectively the modal mass coefficient and participation factors for the first natural mode of the structure and φ_1, roof is the roof level amplitude of the first mode.

Table-7 presents the base shear and other information for three states of the building. The displacement at performance point is maximum for the existing building as compared to other buildings which is found to be 0.294m. The base shear is maximum for the retrofitted building therefore the displacement at the performance point of the building is minimum among all three buildings in x-direction. After earthquake time period of the building is lengthened from 1.603sec to 1.877sec and after retrofitting due to gain in stiffness, it is decreased to 0.960sec. Similarly along y-direction, the displacement at performance point is 109mm for the retrofitted building and 42mm for the original building which is given inside table – 8.

Table – 7. Results for X-Direction

Case	V (kN)	D (m)	Sa	Sd	Teff	Beff
Original Building	6341.028	0.238	0.226	0.145	1.603	0.285
Existing Building	5759.907	0.294	0.201	0.176	1.877	0.259
Retrofitted Building	7979.79	0.136	0.433	0.099	0.96	0.205

Table - 8. Results for Y-Direction

Case	V (kN)	D (m)	Sa	Sd	Teff	Beff
Original Building	1269.086	0.042	0.55	0.116	0.916	0.114
Existing Building	1047.938	0.053	0.469	0.152	1.139	0.096
Retrofitted Building	9551.334	0.109	0.534	0.081	0.784	0.202

Conclusions: Based on this analytical study on Post Earthquake Damage Assessment and its Retrofitting by using Pushover Analysis, following conclusions are drawn:

1. The original structure is designed for service gravity loads while some columns overstressed when analyzed under factored gravity loads. Moreover, under service lateral loads, majority of the structural members overstressed. Capacity spectrum results also indicate that the existing building is at collapse at the performance point. But, why the building survived during 2005 earthquake and remained at Immediate Occupancy level, is because masonry infill walls provided increased lateral resistance to the structure, which although ignored and not considered in the mathematical model.
2. Most of the columns are at collapse stage, while few beams are at Immediate Occupancy performance level which clearly indicates that the existing building is having strong beam and weak columns.
3. From pushover analysis in x and y directions (for both existing & retrofitted buildings) it is found that after retrofitting gain in stiffness and strength in x-direction is 90.91% and 37.93% respectively but the ductility remains the same. However, for y-direction there is remarkable increase in stiffness, strength and ductility. Since the analysis of retrofitted building in x-direction and original and existing buildings in y-direction stopped before approaching the target displacements. Therefore, ductility for these structures may be underestimated.
4. The result of retrofitting are very favourable which resulted in stronger building along weak (y-axis) direction.
5. The presence of lift well at one corner of the existing building increases the eccentricity between center of mass and center of rigidity, and induces torsional effects in the building as a result of which fundamental building mode is having less than 60% modal participating mass ratio in x and y directions which may also affect the accuracy as the results of pushover analysis are based on first mode only.
6. At performance point, the damage is relatively less in retrofitted structures as compared to original and existing structures in both orthogonal directions.

REFERENCES

Aboutaha, R. S. M. D. Engelhardt, J. O. Jirsa and M. E. Kreger. Rehabilitation of shear critical concrete columns by use of rectangular steel jackets. ACI Structural Journal. 96(1):68–78 (1999).

ASCE/SEI 31-03. Seismic Evaluation of Existing Buildings, American Society of Civil Engineers (2003).

Aycardi, L. E. J. B. Mander and A. M. Reinhorn. Seismic resistance of reinforced concrete frame structures designed only for gravity loads: experimental performance of subassemblages. ACI Structural Journal. 91(5):552–63 (1994)

Biddah, A., A. Ghobarah and T. S. Aziz. Upgrading of nonductile reinforced concrete frame connections. Journal of Structural Engineering ASCE. 123(8):1001–10 (1997).

Bligh, R. A., S. Fischer and S. K. Ghosh. Structural retrofit of special moment-resisting frames of concrete. Concr Int. 27(6):47–53 (2005).

Bracci, J. M. A. M. Reinhorn and J. B. Mander. Seismic resistance of reinforced concrete frame structures designed for gravity loads: performance of structural system ACI Structural Journal. 92(5):597–609 (1995).

Building Code of Pakistan. Section 5. Seismic design parameters:(2007).

Dhakal, R. P., T-C. Pan, P. Irawan, K-C. Tsai, K-C. Lin and C-H. Chen. Experimental study on the dynamic response of gravity-designed reinforced concrete connections. Eng Struct.27(1):75–87 (2005).

El-Attar, A. G., R. N. White and P. Gergely. Behaviour of gravity load designed reinforced concrete buildings subjected to earthquakes. ACI Structural Journal. 94(2):133–45 (1997).

Federal Emergecny Management Agency. NEHRP Guidelines for Seismic Rehabilitation of Buildings, FEMA 273. Weidlinger Associates (1997)

Ghobarah, A., T. S. Aziz and A. Biddah. Rehabilitation of reinforced concrete frame connections using corrugated steel jacketing. ACI ACI Structural Journal. 94(3):282–94 (1997)

Hakuto, S., R. Park and H.Tanaka. Seismic load tests on interior and exterior beam column joints with substandard reinforcing details. ACI Structural Journal. 97(1):11–25 (2000)

Sasmal, S., K. Ramanjaneyulu, N. Balthasar; V. Srinivas; K. S. Kumar, C. Korkowski, C. Roehm, N. Lakshmanan and N.R. Iyer. Seismic retrofitting of nonductile beam-column sub-assemblage using FRP wrapping and steel plate jacketing. Construction and Building Materials. 25: 175–182 (2011).