Seismic Retrofitting of Reinforced Concrete Structures under Different Retrofitting Schemes

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***Abstract*—The buildings that were designed and constructed according to old codes may not satisfy the requirements of the presently used seismic codes and design practices. Therefore, it is crucial to reassess these buildings. Buildings, which were damaged in past earthquakes or the existing buildings which are deficient at resisting seismic forces need to be retrofitted for better performance. Seismic evaluation is a necessary step before the retrofitting procedure to identify the most vulnerable components of a building during an expected earthquake. The seismic rehabilitation process aims to correct these deficiencies by increasing strength, stiffness or deformation capacity, and improving connections. The present study deals with the seismic retrofitting of two structures located in diverse seismic zones i.e. New Delhi and Mexico City. Each structure was retrofitted under two different schemes and the results were compared to identify the better method of retrofitting.**

***Index Terms*—seismic damage, retrofitting, reinforced concrete**

I. INTRODUCTION

Earthquakes are considered the more dangerous among natural calamities due to their relatively high unpredictability. To prevent excessive structural damage during earthquakes, the serviceability of structures together with the failure prevention aspects ought to be considered with the ultimate objectives of down time reduction, minimum repair budgets and, most importantly, prevention of the loss of life [1]. If a building fails such an evaluation, corrective measures are required to make it safer. To render a RC building earthquake resistant, three levels of improvement of existing frame buildings are possible: (1) Repair, wherein only visual or cosmetic modifications are made; (2) Restoration, wherein structural modifications are made so as to restore the original performance of the building; (3) Retrofitting, wherein structural modifications are carried out to ensure higher performance of the building than that of the original structure [1, 2, 3].

Seismic Evaluation is the necessary initial step towards seismic retrofitting. It is the process of assessment and comparison between additional resistance requirements as demanded by the earthquake scenarios and the current readiness of the structure to meet such challenges [4]. Any retrofitting strategies can be decided only after calculating the Demand-Capacity Ratio (DCR) for each structural member of the building. Any deficient members are further evaluated for retrofitting. The present study carries out such seismic assessment of two RC buildings located in diverse seismic zones. Two different retrofitting schemes have been evaluated and their suitability has been determined. The present analysis used FEMA 273 for structure-01 and IS1893:2002 for structure-02. Code specified lateral loads were applied to the structure modelled with an elastic linear stiffness. Response spectrum dynamic analysis was used to ensure better distribution of forces.

II. SEISMIC RESISTANCE AND VULNERABILITY:

A probable earthquake is first characterized by means of a Design Spectrum which depends on the energy dissipation capacity through the Structure Behavior Factor. If the seismic resistance of a structure is greater compared to the one demanded by the design earthquake, it is categorized as an over-resistant structure and therefore is not vulnerable to collapse during a sudden earthquake [3, 4, 5]. This case is showcased as the longer ordinate on Fig. 1. Such a structure is well capable of withstanding an earthquake with an anchoring acceleration larger than that associated with the design earthquake. On the other hand, if a structure has less seismic resistance than the design earthquake demand, such a structure is said to be vulnerable and needs retrofitting [5, 6, 7].

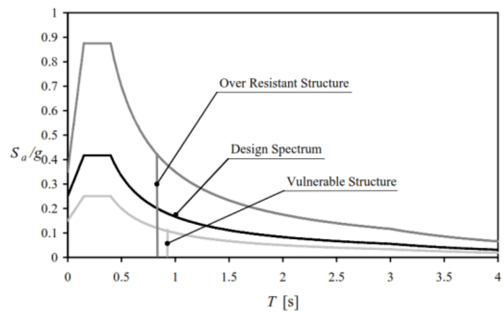

Figure 1. Comparison between seismic demand and seismic resistance

III. STRATEGIES OF SEISMIC RETROFITTING

To achieve the optimal combination of stiffness, ultimate resistance and deformation capacity needs to be the aim of any seismic retrofitting strategy. The most

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important consideration in retrofitting is that the connection between the new features and the existing structures should invariably be seamless. A retrofitting strategy can be focused on ‘Improving Regularity’, which fits additional structural members in a way so as to create a regularity of the structural system. ‘Strengthening’ is another strategy that enhances the existing structural system with new elements or by doubling the elements of the existing building. Additionally, strengthened concrete walls or steel trusses could be used [8]. With this method, the resistance and the toughness of the structure is enhanced while retaining the deformation capacity. Enhancing the structural ductility is another retrofitting strategy. Usage of additional bonded strips makes brittle structural elements like masonry walls more ductile [3,4].

IV. Retrofitting Techniques

The retrofitting program for a building is decided on the basis of a properly carried out seismic evaluation. Visual inspection of the drawings and the structure itself are critical for the seismic retrofitting schemes and processes. Capacity and demand of each member in the structure is identified for assessment and capacity by demand ratio is calculated. The following are some of the very common retrofitting techniques used [8, 9, 10]:

A. *Addition of New Shear Walls*

Adding a new shear walls is one of the most common methods to increase the lateral strength of a reinforced concrete building. It also helps in controlling drift. Therefore, it is the optimum approach for improving the seismic performance of non-ductile reinforced concrete frame buildings. The newly added shear walls can either be precast or cast-in-place. Addition of a shear wall is mostly preferred in the exterior of the buildings, which may hinder the windows and balcony layouts. Despite that, new shear walls are not preferred in the interiors so as to avoid interior moldings. The addition of new shear walls to an existing structure can present many technical challenges. Some of which are: Transferring diaphragm shear to the newly built shear walls with the dowels, adding new collector and drag members to the diaphragm, and increasing the weight and concentration of shear by the addition walls which may affect the foundation. Location of shear walls is also important. It is desirable to locate the new shear wall adjacent to a beam between columns so that minimum slab demolition is required with connections made to beams.

B. *Addition of New Steel Bracings*

Another common method of strengthening a seismically damaged structure is the addition of cross steel bracings on the exterior of the structure. One of the main benefits of steel bracings is that the windows, balconies etc. will not be hindered. Some of the other advantages of using steel bracings compared to other retrofitting schemes are: it provides higher strength and stiffness; bracing will not increase the weight of the structure to a great extent, and the foundation cost can be minimized. Since some of the retrofitting works can be pre-fabricated, much less disturbance is caused to the occupant. Steel bracing retrofitting techniques can be used with both concrete and steel structures. The installation of steel bracing members can be an effective solution when large openings are required [11,12].

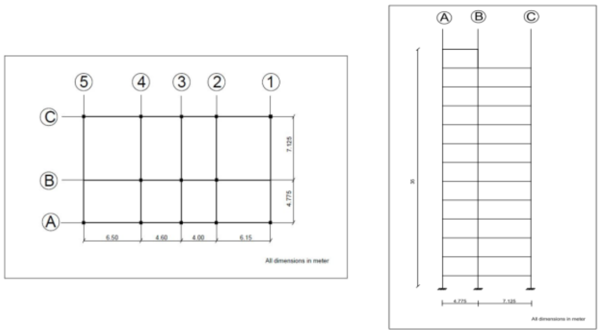
Newly added bracings always require vertical columns at both ends to resist overturning forces similar to the chords of a cantilever truss. Bracing should have low slenderness ratio so as to function effectively during compression. Skilled labour is crucial for steel bracing construction. Careful considerations of connections of strengthening elements to the existing structures and to the foundations have to be cautiously designed to ensure proper shear transfer.

V. Methodology

The present study evaluates the effectiveness of different retrofitting schemes in different seismic zones. Two buildings were selected for this purpose, each retrofitted with two different schemes followed by the seismic evaluation. These steps have been elaborated below.

A. *General Description of the Buildings*

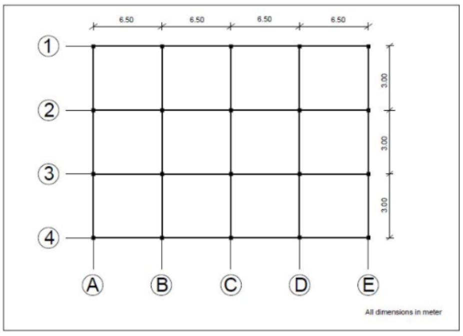
The structure-01 is a 12 storey hotel building made of reinforced concrete located in New Delhi, India. The building consists of cast-in-place reinforced concrete columns and beams. The typical plan of the existing building is shown in Fig. 2. The supports of all the frames in this building were considered fixed with respect to translation and rotation. The floor system for the structure-01 is cast-in-place concrete joint beam construction with 2.5 inch concrete slab. The sizes of all beams are 400mm X 400mm and those of all columns are 600mm X600mm. The structure has no plan irregularity such as re-entrant corners, diaphragm discontinuity, out of plane offsets, or torsional irregularity.



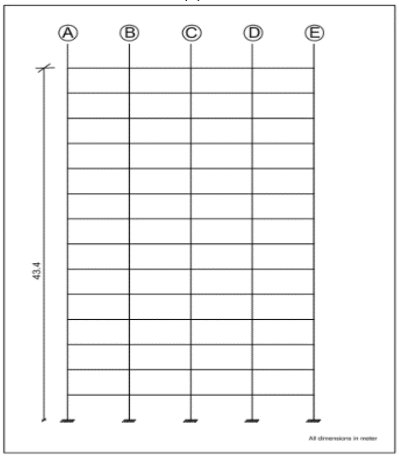
(a) Plan (b) Elevation

Figure 2. Plan and elevation of Structure-01

The structure-02 is 14 storeys (G+13) hospital building located in Mexico City. The building consists of cast-in-place reinforced concrete columns and beams. The typical plan of the existing building is shown in Fig. 2. The building consists of five reinforced concrete framed blocks (i.e. B1, B2, B3, B4 and the central block). The frames of the block B2 were considered in this study. Ordinary moment resistant concrete frames were expected to resist lateral forces including earthquakes. The supports of all the frames were considered fixed with respect to translation and rotation. The floors of the buildings have 200mm thick, monolithically cast reinforced concrete slabs, with beams and columns. The sizes of the beams of are 500mm X 500mm and those of all the columns are 700mm X 700mm. The structure is considered to have no plan irregularity.



(a) Plan

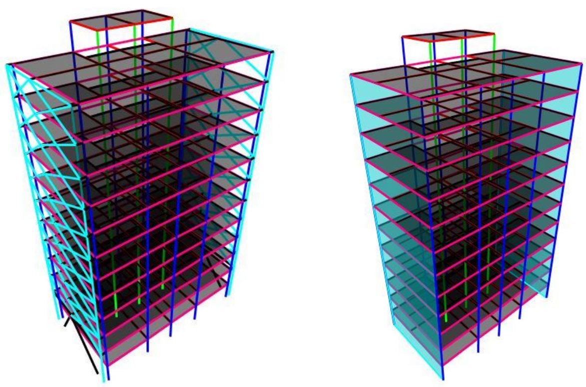


(b) Elevation

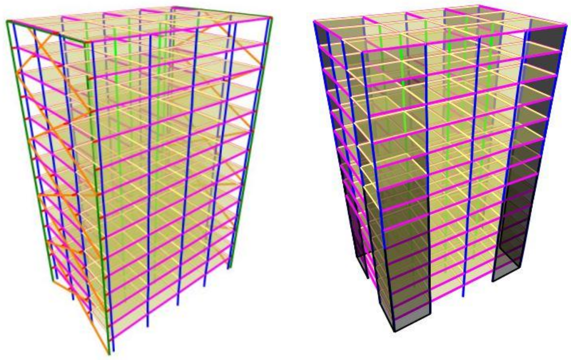
Figure 3. Plan and elevation of Structure-02

B. Retrofitting Schemes

The seismic evaluations of both the structures were carried out with two retrofitting schemes. The structure-01 was initially retrofitted with Steel cross bracings (scheme-01, Fig. 4a) followed by reinforced concrete ductile shear walls (scheme-02, Fig. 4b). Whereas the structure-02 was initially retrofitted using ductile reinforced concrete shear walls (scheme-03, Fig. 4c), followed by steel cross bracing (scheme-04, Fig. 4d).



(a) (b)



(c) (d)

Figure 4. Various retrofitting schemes

C. Seismic Evaluation

The process of seismic evaluation was carried out in three stages as explained below.

1) Estimation of the capacity of the member

The capacity of the beams and columns are estimated under both schemes for structure-01 and structure-02. For determining the capacity of the existing columns and beams, Microsoft excel sheets are used to calculate the moment of resistance and shear capacity of beams, and the axial load capacity and moment capacity of the columns. The sheets are developed according to the limit state method. In all the beams the bending moment capacities are computed at the start of the section; end of the section and on the middle of the span. Shear capacity is calculated only for the beginning and end of the section.

2) Estimation of demand of the member

The seismic demands of beam and columns are computed from the dynamic analysis of structure-01 and structure-02 under two schemes each using SAP-2000 software. Response spectrum method is adopted using UBC-97 for rock site with 5% damping. CQC combination was used to get peak response for dynamic analysis. Demand of beams and columns are thereby estimated from their capacity by demand ratios.

3) Identification of deficient members

After calculating the capacity (C) as explained from section 4.3.1 and the demand (D) from the above section, the capacity by demand ratios are calculated. If the C/D ratio calculated is less than one, this means member is deficient and retrofitting is a requisition.

VI. Selection of the Retrofitting Scheme

The structure-01 was retrofitted and strengthened after the 1979 earthquake using steel bracing in one direction on two frames and new infill reinforced walls in the other direction. The floor plans of the structure-01 are shown in Appendix A (Fig. 01) while the elevation views of frames 2, 3 and 4 are shown in Appendix A (Fig. 02) and the frame 1 and 5 in Fig. 03 in Appendix A.

In the study of structure-01, all efforts are made to retrofit the same building by addition of ductile reinforced concrete shear walls at strategic location and the results compared under various factors. Seismic Evaluation was done on the structure to calculate the capacity by demand ratio of each member and conclude if they are safe to resist the loads or not. Three types of beam reinforcement arrangement are considered.

Scheme-01: Structure initially retrofitted using Steel Bracing. (Scheme-01, Fig. 4a)

Scheme-02: Structure retrofitted using ductile reinforced shear walls. (Scheme-02, Fig. 4b)

In the study of structure-02, almost the same procedures were adopted. The structure-02 was initially retrofitted and strengthened by the addition of ductile reinforced concrete shear walls on the exterior frames along grids 1, 4 between A-B and D-E and along grids A and E between 1-2 and 3-4. The floor plan of the structure-02 is shown on figure-04 in Appendix A.

Scheme-03: Retrofitted Structure using ductile reinforced shear walls. (Scheme-03, Fig. 4c)

Scheme-04: Structure initially retrofitted using Steel Bracing. (Scheme-04, Fig. 4d).

In the present study, the efforts are made to retrofit the same building by the addition of steel bracing in one direction on two frames on grids A and E and new infill reinforced walls on the grids 1 and 4.

This study involves the retrofitting of the same building with two different retrofitting schemes and comparing the results of structure under both schemes with regard to their time periods, modal participating mass ratios, base shears, bending moments and shear forces for beams, axial forces and moment of columns and story drifts.

For the dynamic analysis of structure-01 and structure-02, response spectrum analysis is used. There are no vertical irregularities in both structures like stiffness irregularity (soft storey effects), mass irregularity, vertical geometric irregularity, unsymmetrical bracings and in plane discontinuity and there are no horizontal irregularities like torsion irregularity, re-entrant corners, diaphragm discontinuity, out of plane offsets irregularity and non-parallel system irregularity.

After the retrofitting procedures for all the schemes, capacity demand ratios of the members are again calculated to verify the safety of the members. The results of time periods, Modal participating mass ratios, Base shears, bending moments and shear forces for beams (at beginning, midspan and end of the beams), axial forces and moment of columns (at the start and end) are calculated for the structures under two schemes are compared. The story drifts for both the structures are calculated under both the schemes and compared to check which scheme for a particular structure has lower story drift compared to the other scheme.

VII. Discussion of Results of Structure-01

The following results are obtained from the dynamic analysis of the retrofitted models under both schemes for structure-01.

Scheme-01: Structure initially retrofitted using Steel Bracing

Scheme-02: Structure retrofitted using ductile reinforced shear walls

1) *Dynamic characteristics*

Time periods of 12 modes of vibrations after retrofitting the structure-01 with the schemes-01 and scheme-02 are presented in Table I

TABLE I. Time Periods after the Retrofitting Schemes of Structure-01

Modes	Time Period after Retrofitting by Scheme -01 (Sec.)	Time Period after Retrofitting by Scheme -02 (Sec.)
1	1.9011	2.099
2	1.338	1.0933
3	0.9832	0.9794
4	0.6154	0.677
5	0.4445	0.5362
6	0.3490	0.4762
7	0.3265	0.3841
8	0.2557	0.363
9	0.247	0.3302
10	0.2442	0.281
11	0.2352	0.2664
12	0.1837	0.2631

The time period of Structure-01 under scheme-01 is less compared to the time periods under scheme-02. The value of time periods largely depends on the flexibility and mass of the structure. Larger time periods in the structure gives more flexibility to the structure. Flexible structure can undergo large relative horizontal displacements which may result in the damage of the structure. Thus seismic retrofitting under scheme-01 is considered more effective as compared to retrofitting under scheme-02. The Modal Participation mass ratios calculated for structure-01 under scheme-01 is 96% while for scheme-02, the result is 95%. In both the schemes, ratios are greater than 90%.

2) *Base shear*

Base shear (V_S) calculated from the dynamic analysis carried out using SAP-2000 software on the structure-01 under scheme-01 and scheme-02 are shown in Table-02. Base shear for scheme-02 is higher compared to scheme-01. Therefore, scheme-02 is more effective as compared to scheme-01. The base shear calculated from the response spectrum load case is 1211.95 kN for scheme-01 while it is 1307.521 kN for scheme-02. Therefore, the combined response for the modal base shear is less than 85 percent of the calculated base shear.

TABLE II. Comparison of the Base Shear Calculated from Dynamic Analysis of the Structure-01 under Scheme-01 and Scheme-02

Base Shear After Retrofitting in kN	
Retrofitted using Steel Bracing (Scheme-01)	Retrofitted using Ductile Reinforced Shear Walls (Scheme-02)
1407.527	1525.209

3) *Bending moments*

The bending moment demands and hence their capacity-demand ratios for the structure-01 under scheme-01 and scheme-02 are graphically shown on Figure-08 and Figure-09. Before retrofitting, most of the beams and columns were deficient to withstand the bending moment demands as their capacities by demand ratios were less than one. But after retrofitting under both schemes, all the beams and column sections became safe for the bending moment demands as they have obtained capacity by demand ratios to be greater than one.

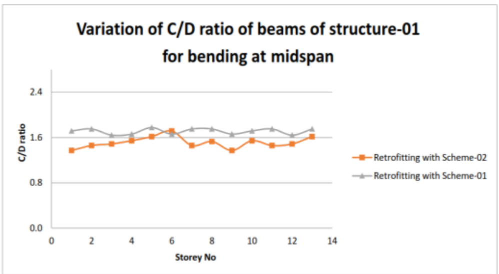


Figure 8. Variation of the C/D ratio of the beams of structure-01 for bending moment at midspan after retrofitting with two schemes

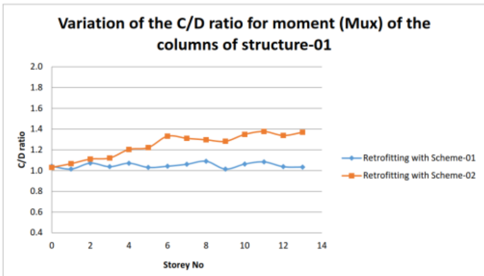


Figure 9. Variation of the C/D ratio for moment (Mux) of the columns of structure-01 after retrofitting with two schemes

4) *Shear forces*

Shear force demands (Sx) of the beams with their capacity by demand ratios of structure-01 after retrofitting under scheme-01 and scheme-02 are shown below. Before retrofitting, most of the beams were deficient to withstand shear forces and obtained capacity by demand ratios less than one. After retrofitting under both schemes, capacity by demand ratios comes out to be greater than one which makes them safe to withstand shear forces.

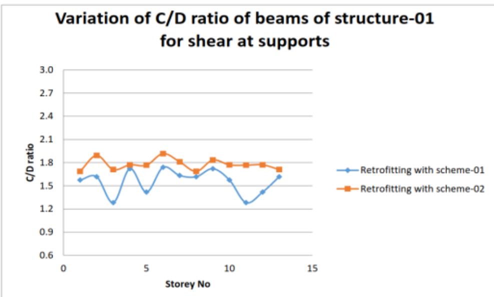


Figure 10. Variation of the C/D ratio of the beams of structure-01 for shear force after retrofitting with two schemes

5) *Axial forces*

Axial forces capacity by demand of the columns of the structure-01 after retrofitting under scheme-01 and under scheme-02 are graphically shown below. All the columns have become safe after the retrofitting procedure under both schemes since their capacity demand ratios are greater than one. During seismic evaluation two types of column reinforcement arrangement are considered for interior and exterior columns

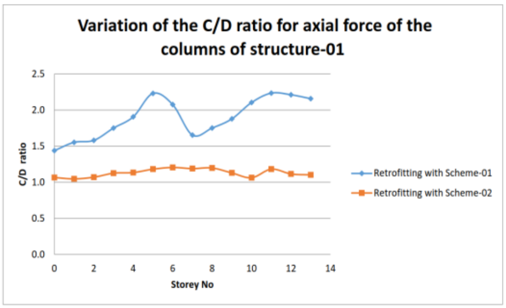


Figure 11. Variation of the C/D ratio for axial force of the columns of structure-01 after retrofitting with two schemes

6) *Storey drift*

The storey drift (Δs) for the structure-01 under scheme-01 and scheme-02 are plotted graphically below. Storey drifts calculated under scheme-01 is less compared to scheme-02.

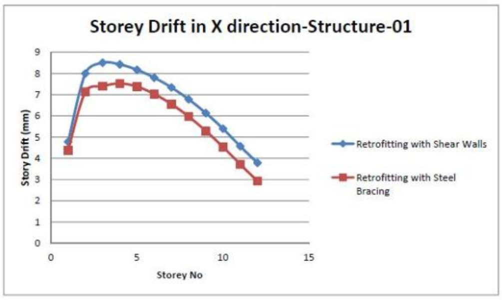


Figure 12. Story drift of structure-01 in X-direction

VIII. Discussion of Results of Structure-02:

The following results are obtained from the dynamic analysis of the retrofitted models under both schemes for structure-02.

Scheme-03: Retrofitted Structure using ductile reinforced shear walls.

Scheme-04: Structure initially retrofitted using Steel Bracing

1) *Dynamic characteristics*

Time periods of 12 modes of vibrations after retrofitting the structure-01 with the schemes-01 and scheme-02 are presented in Table-01

TABLE III. Time Periods after the Retrofitting Schemes of Structure-02

Modes	Time Period after Retrofitting by Scheme -03 (Sec.)	Time Period after Retrofitting by Scheme -04 (Sec.)
1	1.3462	1.6827
2	1.3402	1.5501
3	1.2288	1.3904
4	0.4318	0.5468
5	0.43037	0.4977
6	0.3968	0.4456
7	0.3672	0.3104
8	0.2984	0.2833
9	0.2807	0.2573
10	0.2411	0.2088
11	0.2284	0.1969
12	0.1972	0.1811

The time period of structure-02 under scheme-03 is less compared to the time periods under scheme-04. Larger time periods in the structure gives more flexibility to the structure. Flexible structure can undergo large relative horizontal displacements which may result in the damage of the structure. Thus seismic retrofitting under scheme-03 is considered more effective as compared to retrofitting under scheme-04. The Modal Participation mass ratios calculated for structure-02 under scheme-03 is 94% while for scheme-04, the result is 95%. In both the schemes, ratios are greater than 90%.

2) Base Shear

Base shear (VS) calculated from the dynamic analysis carried out using SAP-2000 software on the structure-01 under scheme-03 and scheme-04 are tabulated in table-00. Base shear for scheme-03 is higher compared to scheme-04. Therefore, scheme-03 is more effective as compared to scheme-04. The base shear calculated from the response spectrum load case is 3746.193 kN for scheme-01 while it is 2667.476 kN for scheme-02. Therefore, the combined response for the modal base shear is less than 85 percent of the calculated base shear.

TABLE IV. COMPARISON OF THE BASE SHEAR CALCULATED FROM DYNAMIC ANALYSIS OF THE STRUCTURE-02 UNDER SCHEME-03 AND SCHEME-04

Base Shear After Retrofitting in kN	
Retrofitted using Ductile Reinforced Shear Walls (Scheme-03)	Retrofitted using Steel Bracing (Scheme-04)
4464.997	3184.592

3) Bending moments

The bending moment demands and hence their capacity-demand ratios are calculated for the structure-02 under scheme-03 and scheme-04. Before retrofitting most of the beams and columns were deficient to withstand the bending moment demands as their capacity by demand ratios was less than one. But after retrofitting under both schemes, all the beams and column sections became safe for the bending moment demands as they have obtained capacity by demand ratios to be greater than one.

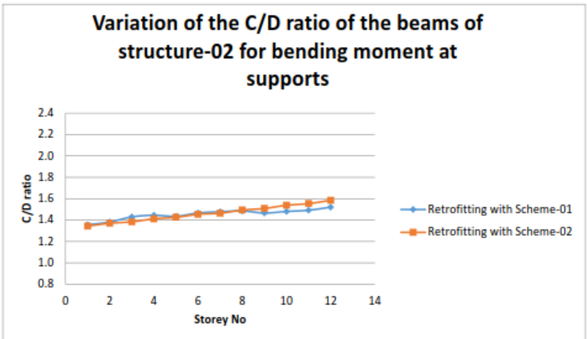


Figure 13. Variation of the C/D ratio of the beams of structure-02 for bending moment at supports after retrofitting with two schemes

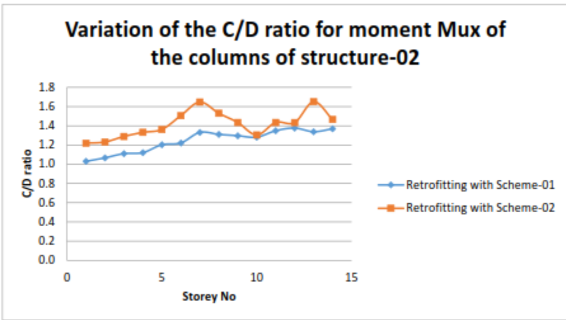


Figure 14. Variation of the C/D ratio for moment Mux of the columns of structure-02 after retrofitting with two scheme

4) Shear force

Shear force demands (S_x) of the beams with their capacity by demand ratios after retrofitting under scheme-03 and scheme-04 are shown graphically below. Before retrofitting, most of the beams were deficient to withstand shear forces and obtained capacity by demand ratios less than one. After retrofitting under both schemes, capacity by demand ratios comes out to be greater than one which makes them safe to withstand shear forces.

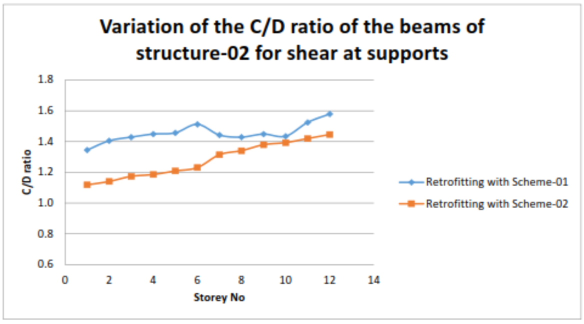


Figure 15. Variation of the C/D ratio of the beams of structure-02 for shear force after retrofitting with two schemes

5) Axial force

Capacity by demand calculated for the axial force of the columns after retrofitting under scheme-03and under scheme-04 are shown below graphically. All the columns have become safe after the retrofitting procedure under both schemes since their capacity demand ratios are greater than one.

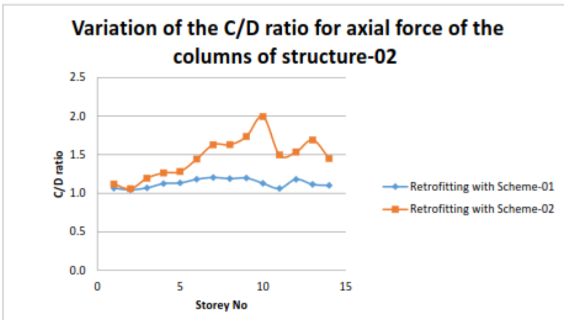


Figure 16. Variation of the C/D ratio for axial force of the columns of structure-02 after retrofitting with two schemes

6) Storey drifts

The storey drift (Δs) for the structure-02 under scheme-03 and scheme-04 in X direction are plotted graphically. Storey drifts calculated under scheme-04 is less compared to scheme-03.

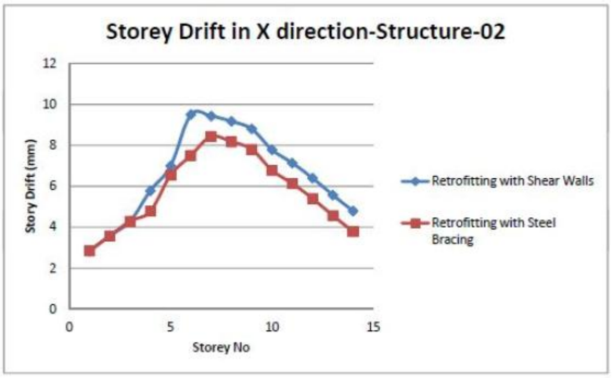


Figure 17. Story drift of structure-02 in X-direction

IX. CONCLUSION

- The case study conducted on Structure-01 and Structure-02 invariably leads to the following conclusions:
- The seismic evaluation of both structures depicts most of the beams and columns in both the Structures to be deficient to resist design earthquake forces and in serious need of seismic retrofitting.
- The initial retrofitting scheme having been found inadequate in resisting the design earthquake forces, augmentation of retrofitting was envisaged in both structures, with new retrofitting schemes, and a comparison of the results.
- The comparison of time periods of Structure-01 under Scheme-01 (addition of steel bracings) and Scheme-02 (addition of ductile reinforced shear walls) substantiated the following:
  - The time period under Scheme-01 is less than that for Scheme-02.
  - Larger the time period in the Structure, higher the flexibility to the Structure and, flexible Structure can undergo large horizontal displacements.
  - Whereas similar comparison of Structure-02 under Scheme-03 (addition of ductile reinforced shear walls) and Scheme-04 (addition of steel bracings) indicated the time periods of Scheme-03 to be less than that in Scheme-04.
- The comparison of the results of base shear for Structure-01 showed the base shear to have increased in Scheme-02 when compared to Scheme-01. While for Structure-02, the base shear for Scheme-03 is much higher when compared to Scheme-04.
- The computation of the Mass Participation Ratios for Structure-01 and Structure-02 under both the Schemes indicated excellent ratios exceeding 90% in all the four cases.
- The calculation of the Shear Forces and Bending Moment for all beams and axial forces as well as Moment Capacity of all columns in all the four Schemes proved most of the members to be resistant to withstand the design earthquake forces.
- The result of Story drift has shown that for Structure-01, Scheme-02 has larger story drift as compared to Scheme-01 while for Structure-02, Scheme-03 has larger story drift as compared to Scheme-04.

APPENDIX - A:

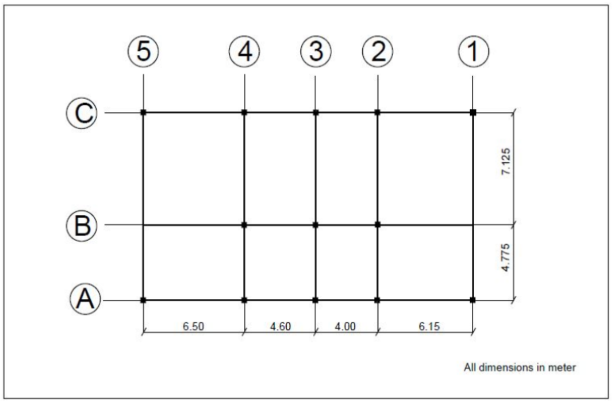


Figure 01 . Typical floor plan with column layout

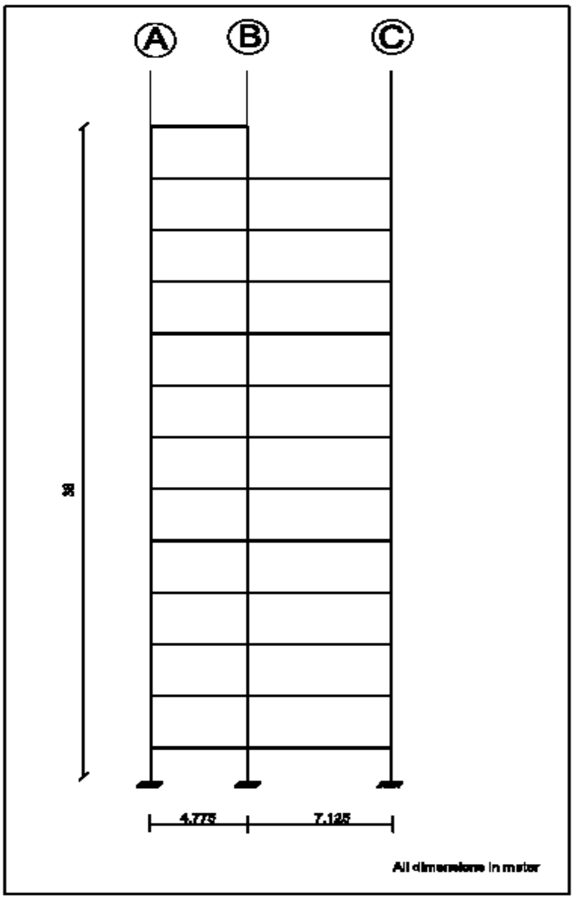


Figure 02. Elevation view of frame 2, 3 and 4 (Structure-01)

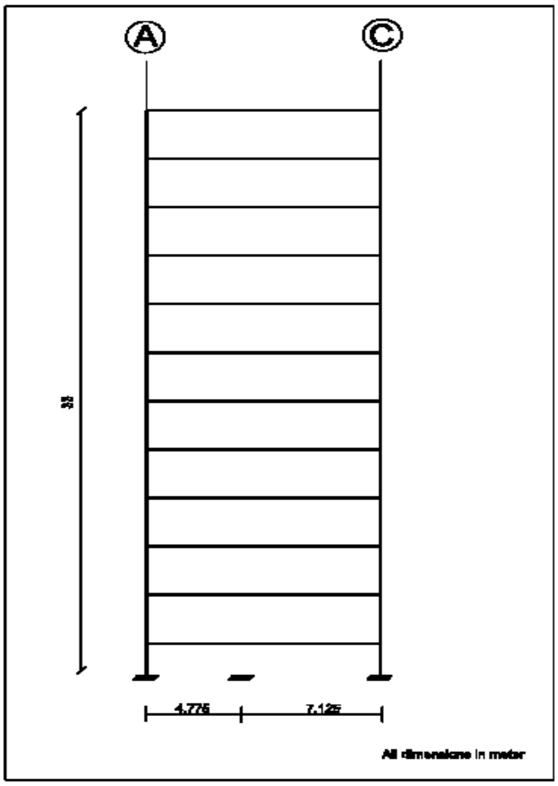


Figure 03. Elevation view of frames (Structure-02)

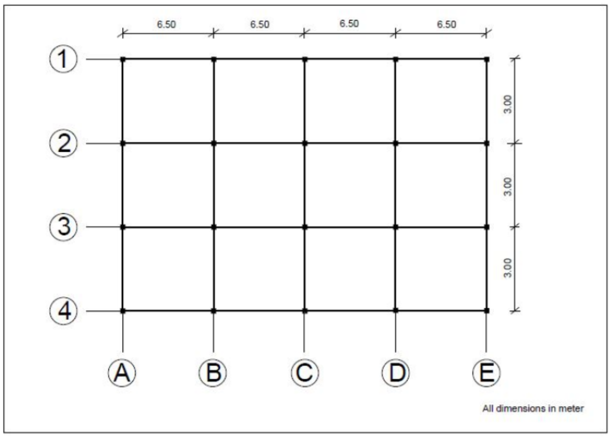


Figure 04. Typical floor plan with column layout

Conflict of Interest

The submitted work was carried out without any conflict of interest.

Author Contributions

Archana analyzed the data and wrote the paper, Abid helped devise the methodology and conclusions, Gul contributed to data analysis and conclusions. All the authors approve the final version.

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