Evaluation of Seismic Behavior of RC Frame Retrofitted with Different Configuration of FRP

Rishath Sabrin, Mohammad Al Amin Siddique

Abstract— ***For the requirement/need of retrofitting, in recent years, Fiber Reinforced Polymers (FRP) become engineer's choice to increase strength and ductility of reinforced concrete (RC) beams, columns and beam-column joints because of its' light weight, higher strength, and ease of applications to the existing members. To attain better performance, better configuration of retrofitting should be selected. In this paper, nonlinear static pushover analysis has been carried out with the commercial software ETABS v.9.6.0 to investigate seismic performance criteria i.e. ductility, over-strength, response modification factor of moment resisting RC frames retrofitted with different level of FRP additions and compared with the bare frame. From the analyses in general, both the load carrying capacity and displacement at failure is enhanced. In comparison to the bare frame, inter-story drift index at any floor level of the retrofitted frame is decreased for the same level of base shear capacity. Proper retrofitting scheme can be adopted from the analysis as per the requirement criteria of the project/design engineer.***

Key words - Fiber Reinforced Polymer (FRP), Pushover analysis, Response Modification Factor, Retrofitting

I. INTRODUCTION

Structural safety: withstanding of infrastructure both in higher permissible loads and in environmental hazards during their service life are always the most important concern of Structural engineers. Retrofitting, the renovation process of existing structures to improve their strength can be done by concrete jacketing, steel jacketing, steel plating, external pre-stressing, fiber reinforced polymer wrapping etc. To ensure desired safety to a great extent and successfully strengthen the vulnerable structures to withstand seismic damage as well as ultimate failure of a structure, retrofitting of existing structures has become much popular due to their higher ultimate strengths, lower density, lesser self-weight as well as faster, easier and economic installation and higher durability. These composite materials can be added to any of the structurally deficient members such as beams, columns, slabs, beam-column joints etc. of a reinforced concrete building structure. Previous research works include assessment of flexural behavior of RC T-beams retrofitted with Carbon Fiber Reinforced Polymer (CFRP) plates and bonding effect both analytically and experimentally [1], flexural capacity of mechanically fastened FRP strengthened RC beams [2], axial strength, axial strain, hoop strain and ductility of reinforced and nonreinforced columns confined with Steel- Fiber Reinforced Polymer (SFRP) and CFRP [3], both bare and retrofitted beam-column joints with FRP subjected to cyclic loading [4], slender reinforced concrete columns strengthened with 2 ways: CFRP sheet jacketing and near surface mountain CFRP sheet [5], shear capacity of RC both rectangular and T-beams retrofitted with 1, 2 and 3 layers of CFRP composites [6]. All these cases a significant improvement is found compared to the control one (without retrofitted member).

This paper focuses on the retrofitting of RC beams and columns using different FRP retrofitting schemes to evaluate and compare the seismic performance levels of both the existing RC building (bare one) and retrofitted RC frames with FRP composite.

II. METHODOLOGY: NONLINEAR PUSHOVER ANALYSIS AND SEISMIC PERFORMANCE ASSESSMENT

Existing structures which require retrofitting should be assessed properly so that it can be accomplished in a cost-effective manner. A global pushover curve generated through a pushover analysis of bare frame structure [7], [8]. ATC-40 [9] and FEMA-356 [8] documents provide a guideline of modeling parameters, acceptance criteria and procedures of pushover analysis and the actions followed to determine the yielding of frame members. Using multiple load patterns does not improve the accuracy of pushover analysis significantly [10].

In the present study, a single lateral load pattern [11] based on the first mode shape of 2D frame of an existing structure is used. During earthquake loading, plastic hinges usually form at the end of beams and columns. To perform pushover analysis, flexural moment hinges and frame hinges are assigned to the ends of the beams and columns of the frame respectively. The moment-rotation behavior of frame members simulates the plastic hinge properties. Yield and ultimate curvature and rotation capacities for both beam and column can be determined analytically. In ETABS, moment hinge properties, M3 is usually added or modified for concerned member (actual hinge property). According to the cross-section and material properties of the fame element, individual nonlinear hinge is assigned at both ends of the individual beam or column. Flexural strength may be calculated by using the rectangular stress block [12] with the condition that maximum concrete strain, ε_{cu} 0.005 and maximum stress in concrete compression zone taken equal to 85% of the expected compression strength.

Manuscript received February 9, 2018
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The maximum moment capacity is assumed considering post-yield slope of 3% that of the slope of elastic curve. The material property and sectional analysis are used to calculate the moment capacities at yield and ultimate conditions for user-defined hinge cases. Analysis of Park & Dai [13], Maghsoudi & Sharifi [14] and Inel & Ozmen [15] are used to calculate the moment-rotation behavior of RC frame members. Moment-rotation (M–θ) behavior for a member section consists of plastic rotation and corresponding moments as ratio of yield moment as shown in Fig. 1. Five points, define the force deflection behavior of the hinge labeled A to B – Elastic state, B to C- post yielding stage, C to D – post maximum capacity, D to E- residual strength [16].

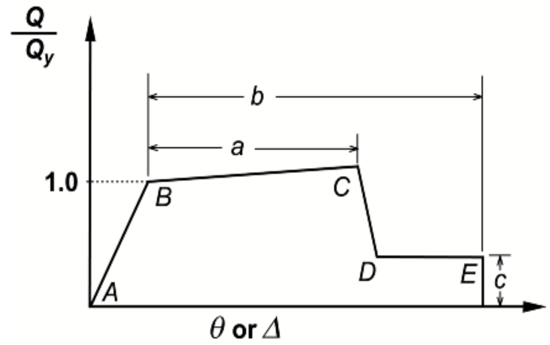


Fig. 1. Force-deformation behavior of frame members.

Plastic hinges are assigned at the end of columns considering both Moment-rotation behavior and P-M-M interaction surface for the user defined cases. Using ETABS v.9.6.0 section designer module, P-M interaction surface is calculated for a given section geometry and materials [12].

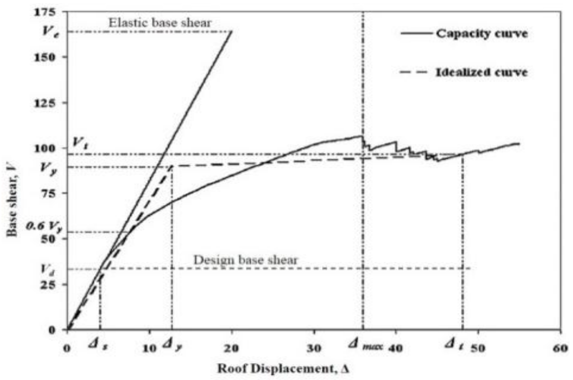
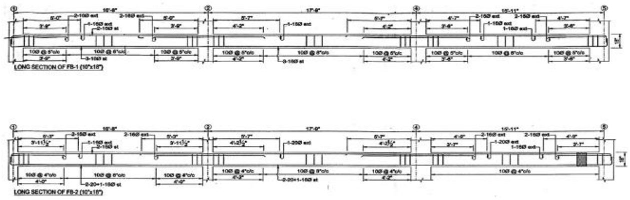


Fig. 2. Description of over-strength and ductility factor for a structural response [10].

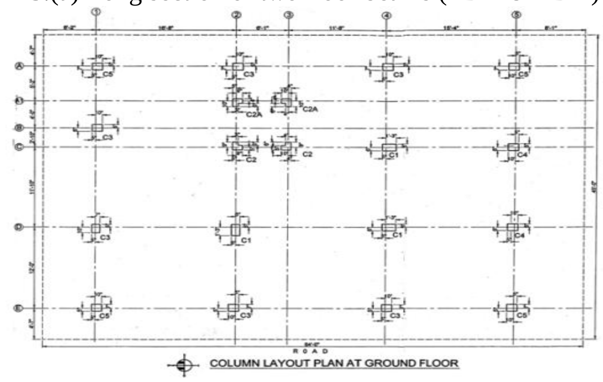
Following FEMA 273 [19], obtained pushover curve from the analysis is idealized to evaluate seismic performance parameters. Actual lateral strength (V_y) corresponding yield displacement (Δ_y) of the frame is determined by idealizing pushover curve (Fig. 2) as a bilinear curve considering the same energy under the actual curve. For RC structure, FEMA 356 [8] specify inter-story drift index thresholds of 1%, 2% and 4% for the immediate occupancy (IO), life safety (LS) and collapse prevention (CP) performance levels, respectively. Condition of existing building is first checked and subsequently seismic performance of different retrofitting scheme is evaluated.

III. EVALUATION OF EXISTING STRUCTURE: CASE STUDY

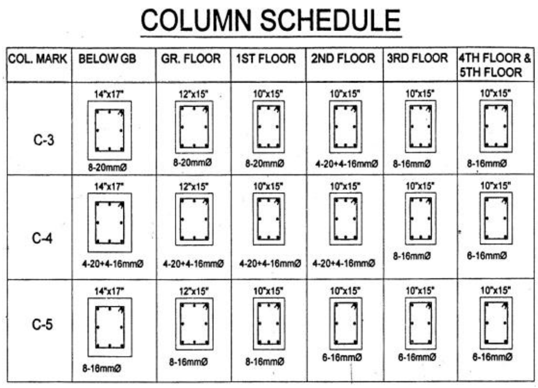
Total height of the 6-storied existing building is 20.42 m where typical floor height is 3.05 m and below ground floor column height (to foundation) 2.13 m. Concrete compressive strength is 24 MPa and 17 MPa for columns and beams respectively, yield strength 414 MPa is used for both transverse and longitudinal reinforcements. Among 5 frames, 2D frame E is taken into account for pushover analysis. A detail description of beams and columns (both layout and schedule) are shown in Fig. 3 (a),(b) and (c).



3.(a) Long section of two floor beams (FB-1 & FB-2)



3.(b) Column layout plan at ground floor



3.(c) Column Scheduling

Fig. 3. Information of the building

Gravity loads (dead loads: self-weight, partition walls, floor finishing and live loads: 25% of dead load i.e. 1.92 KPa equivalent to seismic weight is applied first on the beams of the frame. In ETABS, default hinges at the ends of different frame members are assigned. Then, the lateral force distribution (Table. I) on different floor level is applied gradually until the failure of the frame is occurred. For frame E, gravity loads applied are used 7.09 kN/m on roof, 16.93 kN/m on different floors except the ground floor and 10.03 kN/m on the ground floor.

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Table. I. Lateral force distribution at any floor level of the considered frame.

Story No.	Height (m)	Vertical (gravity) load (kN)	Horizontal Load on the building (X dir) (kN)	Horizontal Load (kN) for frame E
Roof	20.43	644.29	109.15	27.31
F5	17.38	1278.62	81.40	20.46
F4	14.33	1278.62	67.16	16.90
F3	11.28	1278.62	52.84	13.21
F2	8.23	1278.62	38.70	9.79
F1	5.18	1278.62	24.46	6.23
GF	2.13	1278.62	10.01	2.67
Sum	---	8316.03		

Deflected Shape of the Bare Frame and plastic hinge formation at Maximum Load Carrying Capacity in the bare frame is presented in Fig. 4. From idealized and actual pushover curves for the bare RC frame (Fig. 5), yield shear capacity, yield roof displacement and maximum displacement is determined. Following BNBC-93, design base shear is determined as 132.96 kN for this frame and other determined parameters are presented in Table. II. The inter-story drift index (Fig. 6) of different floor levels of the bare frame at maximum lateral load capacity are compared with the acceptable performance levels and found to be within the Life safety performance level (2%) [18].

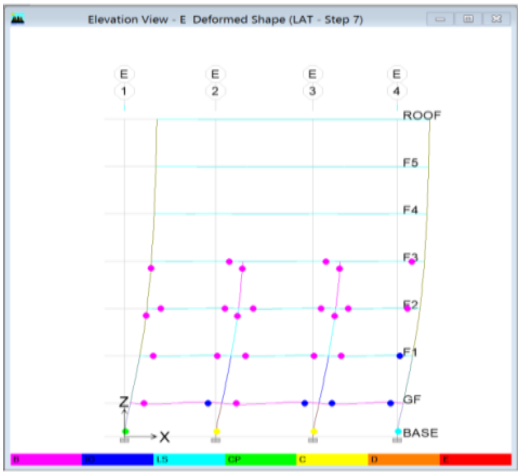

Fig. 4. Hinge formation on different frame elements of the bare frame (maximum load) [18]

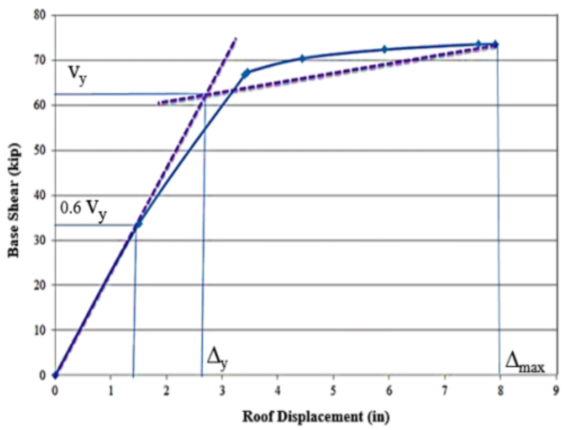

Fig. 5. Pushover curves of the bare frame [18]

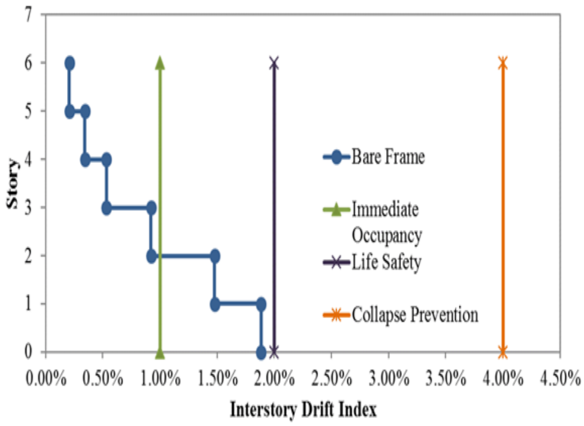

Fig. 6. Inter-story drift index of the bare RC frame [18]

IV. SEISMIC BEHAVIOR OF DIFFERENT RETROFITTED SCHEMES OF FRAMES

In partial retrofitting schemes, only column below grade beams and floor level F1, both beams and columns at the ground floor level; in full retrofitting schemes all the beams and columns are retrofitted with FRP composites with increased moment capacity ranges from 5% to 25%. Moment-rotation behavior of RC frame members is evaluated first by using the sectional analysis. Considering level of retrofitting increases with the yield and ultimate moment capacities, enhanced moment-rotation behavior obtained from moment-curvature analysis is used in pushover analysis of retrofitted frames keeping the other parameter constant. In first case of partial retrofitting analysis, only the columns below grade beams and floor level F1 are retrofitted with different level of FRP composites by changing the plastic hinge properties of only columns below GB and F1. Pushover curves (Fig. 7(a)) show that overall frame behavior is improved slightly in comparison to the bare frame under seismic loads. In 2nd case: only the columns below grade beams and beams at grade location, retrofitted with different level of FRP composites (Fig. 7(b)) load carrying capacity of the frames is also increased but displacement at failure is drastically reduced for 25% retrofitting level. Fig. 8 shows the pushover curves for the retrofitted beams and columns of the frames with different level of FRP composites where at the 25% retrofitting level, roof displacement capacity is also decreased although overall frame behavior is improved than bare frame. The formation of hinges on various frame members of the retrofitted frames with 5% and 25% FRP additions are shown in Fig. 9(a) and (b), Fig. 10(a) and (b) and Fig. 11(a) and (b) respectively. The idealized and actual pushover curves for the retrofitted frame with 5% and 25% FRP additions for all beams and columns are presented in Fig. 12(a) and (b) respectively.

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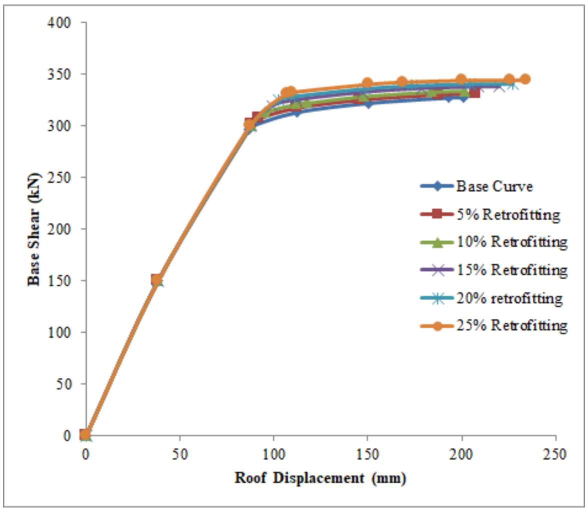
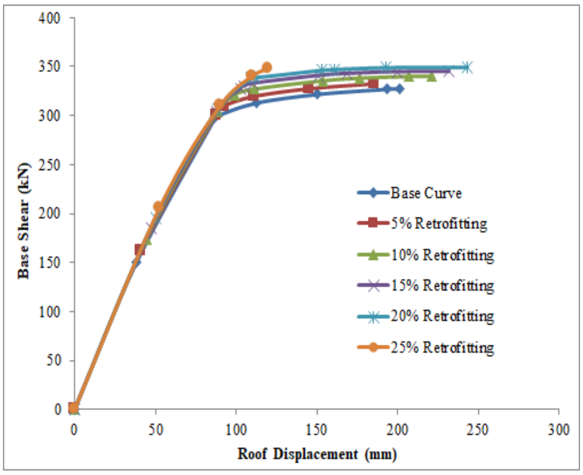


7.(a)



7.(b)

Fig.7. Pushover curves for partially retrofitted frames (a) at columns below GB and below F1 (C3 and C5); (b) at columns and beams at grade beam location.

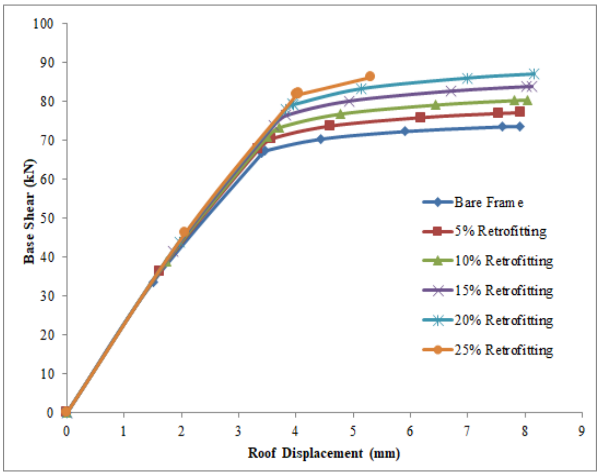
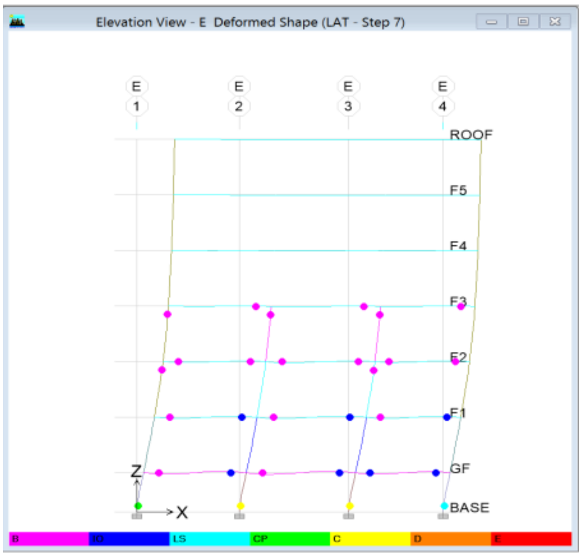
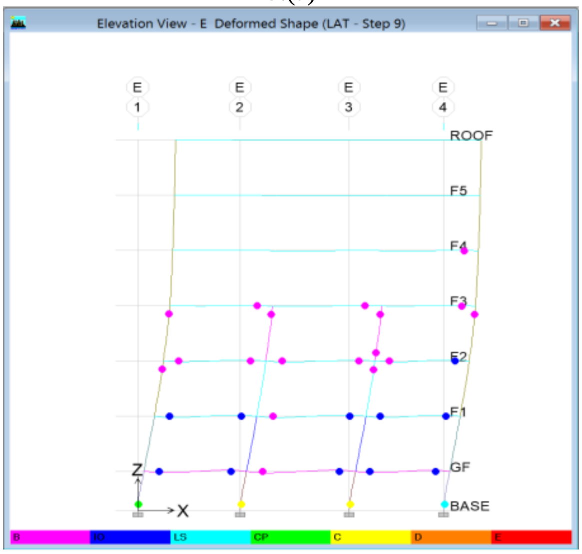


Fig. 8. Pushover curves for fully retrofitted beams and columns.

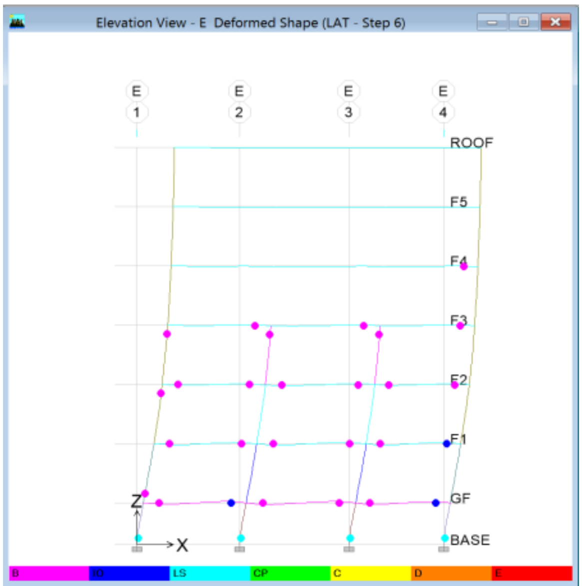


9.(a)



9.(b)

Fig. 9. Deflected shape of the frame retrofitted in columns below GB and F1 (C3 and C5); (a) for 5% retrofitting; (b) for 25% retrofitting.



10.(a)

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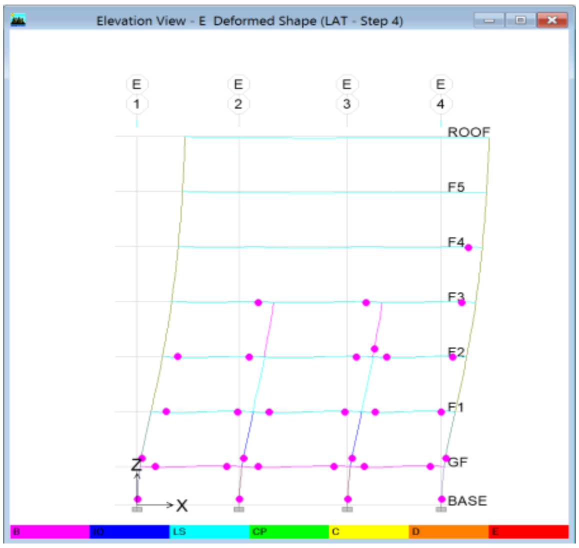
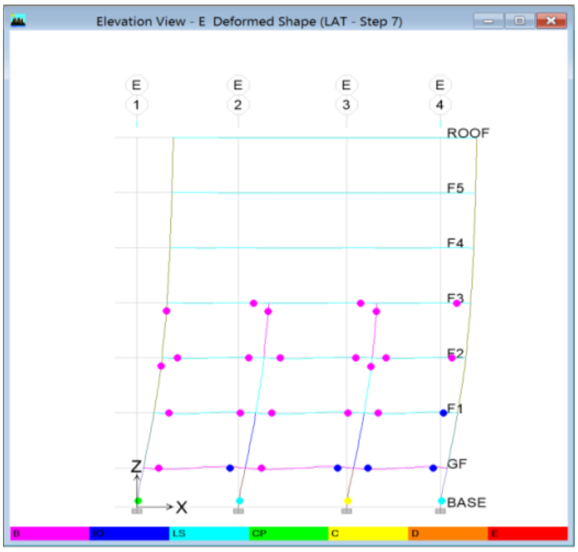
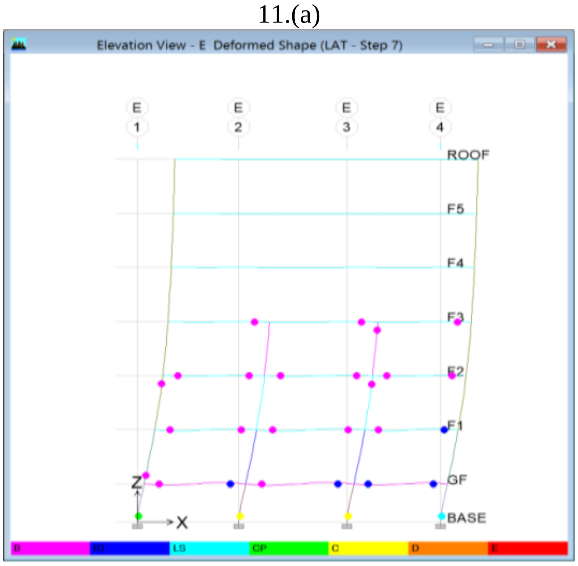


10.(b)

Fig. 10. Deflected shape of the frame retrofitted in columns and beams at grade beam location; (a) for 5% retrofitting; (b) for 25% retrofitting.

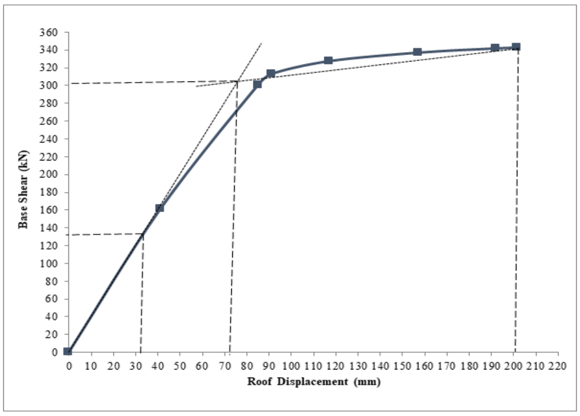


11.(a)

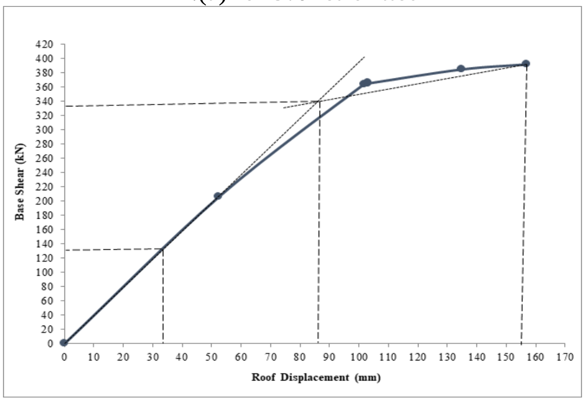


11.(b)

Fig. 11. Deflected shape of the frame retrofitted in all beams and columns; (a) for 5% retrofitting; (b) for 20% retrofitting.



12.(a) for 5% retrofitted



12.(b) for 25% retrofitted

Fig. 12. Actual and idealized pushover curves for fully retrofitted beams and columns.

Table. II illustrates the results of pushover analyses in terms of ductility, over-strength, and response modification factors of retrofitted frames with 5% and 25% FRP additions and is compared with the bare frame. Here both the load carrying capacity and displacement at yield are increased with 25% FRP addition. However, displacement at failure is drastically reduced. This may occur due to improper strengthening case.

Table. II. Ductility, over-strength, and response modification factor for the retrofitted frames with 5% and 25% FRP on all beams and columns.

Frame	Bare frame	5% Retrofit	25% Retrofit
Yield displacement, Δ_y mm (in)	66.3 (2.61)	71.63 (2.82)	87.88 (3.46)
Maximum displacement, Δ_{max} mm (in)	200.91 (7.91)	201.42 (7.93)	156.97 (6.18)
Yield capacity, V_y kN (kip)	276.71 (62.21)	303.04 (68.13)	333.6 (75)
Design base shear, V_d kN (kip)	132.91 (29.88)	132.91 (29.88)	132.91 (29.88)
Ductility factor, $\mu=\Delta_{max}/\Delta_y$	3.03	2.81	1.79
Over-strength factor, $\Omega_d=V_y/V_d$	2.08	2.28	2.51
Response factor, $R=\mu\,\Omega_d$	6.31	6.41	4.48
%		1.58	-29

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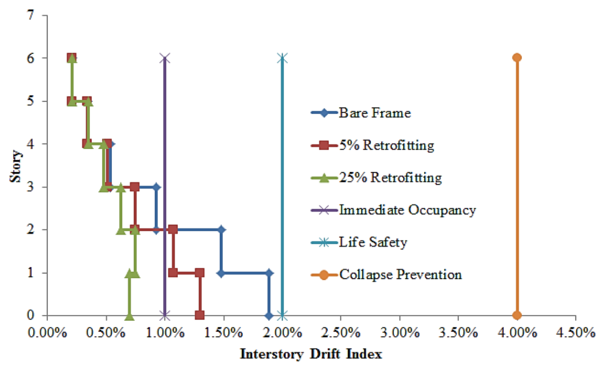
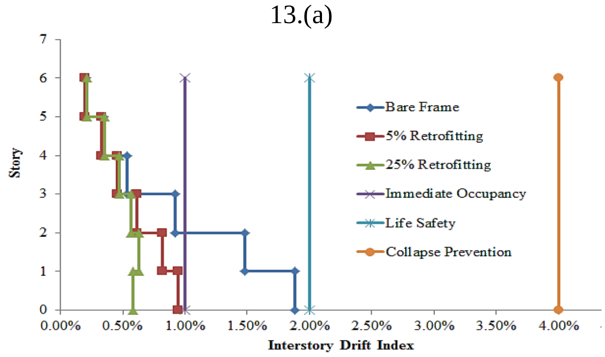
Fig. 13 (a), (b) show the inter-story drift index of the retrofitted frames (at the same base shear capacity of the bare frame) in comparison to acceptable performance levels. It is observed that inter-story drift index decreased with additions of FRP composites and this reduction of drift is prominent in 25% FRP addition in comparison to that of the 5% FRP addition.



13.(a)



13.(b)

Fig. 13. Inter-story drift index for retrofitted frame with retrofitted (a) beams and columns at grade only; (b) all beams and columns.

V. CONCLUSIONS

Following observations can be made from the analysis of the retrofitting schemes with different pattern and different FRP additions (from 5% to 25%).

- Generally, both the load carrying capacity and displacement at failure is increased with increasing FRP additions.
- For the frame with different stiffness of columns at different floor levels, some localized failure reduces the overall displacement capacity at failure drastically. Therefore, the retrofitting scheme should be chosen such a way that it will not trigger localized collapse of any member.
- Inter-story drift indexes are within the Life safety performance level for all the frames with different FRP additions. However, inter-story drift index at any floor level is reduced to a great extent at the same base shear capacity of the bare frame.

Before taking any decision, engineers should evaluate different retrofitting schemes to figure out the better performance of the frame. By using the commercial software ETABS v.9.6.0, nonlinear static pushover analysis can easily/simply be carried out.

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