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RESEARCH ARTICLE / НАУЧНАЯ СТАТЬЯ

Case study on structural health assessment for existing reinforced concrete building

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Abstract. Retrofitting is a method of renovating/repairing and strengthening the weak structure that was affected due to the excessive load on structure during any uncertainty load like earthquake or due to end of service life of the infrastructure. The objectives of this paper are to design reinforced concrete and fiber-reinforced polymer jacketing of failed columns of an existing building, after addition of two more storey in previous design and to compare suitability of before mentioned methods of retrofitting. The presented work also describes design procedure of reinforced concrete, carbon fiber reinforced polymer jacketing for strengthening existing columns. This study is fruitful to gauge suitability of the two retrofitting methods for weakened structural members. The existing buildings in Nepal designed as using Mandatory Rules of Thumb are most vulnerable types of building; to mitigate further crack in structural members with appropriate type of retrofit will be considered with proper management of construction related to post-earthquake activity. After analysis and design of existing building its extremely necessary to plan construction management for economic and safety concern. Most cases of such projects will lead improper work without proper construction management leading uneconomic and prolonging of completion of project.

Keywords: concrete jacketing, fiber-reinforced polymer jacketing, structural health assessment, retrofitting

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Оценка состояния конструкций существующего железобетонного здания и способы его укрепления

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Аннотация. Модернизация – это метод, связанный с обновлением, ремонтом и укреплением слабой конструкции, пострадавшей из-за дополнительной нагрузки на нее, такой как землетрясение, а также из-за истечения срока службы. Цель исследования – спроектировать железобетонную обшивку и обшивку из стеклопластика для вышедших из строя колонн существующего здания из-за пристройки еще двух этажей и сравнить эффективность методов модернизации. Также описывается процедура проектирования железобетонной, армированной углеродным волокном полимерной оболочки для усиления существующих колонн. Исследование полезно для оценки эффективности двух методов модернизации ослабленных элементов конструкции. Существующие здания в Непале, спроектированные с использованием стандартных эмпирических правил, являются наиболее уязвимыми типами зданий. Для уменьшения развития трещин в модернизированных конструктивных элементах рассмотрен вопрос о надлежащем контроле над строительством, связанный с изучением зданий после землетрясения. После анализа и проектирования здания важно спланировать управление строительством с учетом экономики и безопасности. В противном случае это приведет к экономическим потерям и затягиванию завершения проекта.

Ключевые слова: бетонная оболочка, оболочка из стеклопластика, оценка состояния конструкции, модернизация

Introduction

Cities located in Nepal of high seismic hazard have large numbers of buildings, which are constructed of reinforced cement concrete resisting moment frames with infill walls that share common characteristics and seismic vulnerabilities. Collapses of such structures during recent earthquakes have killed about 3000 people. The main reason of collapse of such buildings is constructing illegal additional storeys for business purpose. All cities in Nepal are categorized for type of buildings and legality of maximum floors that should be constructed within range of cities by government, but lack of supervision of government, monopoly of contractor and using of low-quality materials several buildings are constructed within Kathmandu valley and in other major cities. Secondly, the strong column and weak beam principle is not followed in mostly constructed RC building being one of the causes of damage and collapse of buildings during earthquakes.

Structures get dilapidated with time for which repairs and reconstruction are not feasible so, retrofitting is the efficient approach which can be adopted to combat the defiance [1]. Retrofitting is a process of regaining the strength of deteriorated structural components of existing structures to the sufficient level of safety and protection against seismic hazards. It is carried out to reduce vulnerability of damage to the existing structure due to any natural disaster or seismic activity [2].

The inadequacy in strength of structural elements may be result of higher design load, poor workmanship, design errors or construction deficiencies, deterioration and corrosion or modification of structural system. Also,

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various findings show that old engineering structures do not correspond to the new seismic codes resulting difference on design requirements now and then. Proper solution implying retrofitting of concrete and masonry structures can be carried out by following techniques:

1. Previously building had been modeled by Pranay Ranjan and Poonam Dhiman – 4 storey and approximately 2000 sq. feet building in STADD PRO Software to design RC, FRP and SFRC Jacketing of failed columns of an existing building and to compare suitability of these three methods of retrofitting. Alexander Sichko, Halil Sezen had studied twelve experimental columns of differing interface conditions and compared across various coefficient values to determine which value best matches the observed performance. Basically, fiber-reinforced polymers (FRP), RC jacketing using high-performance concrete (HPC) is also highlighted [3]. Catalin Baciu et al. presented classic and modern retrofitting technologies for industrial buildings. They also explains the single storey industrial building retrofitting, using four different intervention options and concluded that all the retrofitting methods presented in paper lead to a more resistant structure, reducing the seismic risks: lateral displacements decrease, while ductility, bending moment and shear force capacities significantly increase and so on [4]. Shamim A. Sheikh and Jingtao Liu presents fiber-reinforced polymer (FRP) jackets research on square and circular column of size 305 and 356 mm respectively with its length 1473 mm. They explain brief results on the evaluation of the seismic behavior of reinforced concrete columns laterally confined by FRP. Here, the specimens were tested under lateral cyclic displacement excursions also at the same time it is subjected to a constant axial compression to simulate seismic forces and the results include the evaluation on amount of FRP-confinement.

2. Different types of retrofitting techniques can be illustrated as follows.

Concrete jacketing (Figure 1). By placing reinforcing steel rebar around its periphery, concreting is widely adopted, called concrete jacketing. It is for the enlargement of existing structural members like columns and beams. This method increases the member stiffness and its size [5].

Steel jacketing (Figure 2). Using various steel angles, channels, and bands, jacketing of columns and beams is done by this technique.

Fiber reinforced polymer jacketing (Figure 3). It is a modern technique for enhancing strength, and this technique base on composite materials such as carbon and glass fiber reinforced polymer. Using these technique high-strength sheets retrofitting of structures can be done easily [5].

Figure 1. Concrete jacketing

Figure 2. Steel jacketing

Figure 3. Fiber reinforced polymer jacketing

Using the above different technique of retrofitting, following advantages and disadvantages can be obtained:

Advantages:

– higher sale price and lower operational cost;
– better return on investment and better rental income;
– improves building quality and reduces risks;
– greater building durability, survivability and functionality;
– improves indoor environmental quality and save energy.

Disadvantages:

– increase in dead load and chances of erosion are high;
– high installation cost;
– if any indication of corrosion in the reinforcement, this technique is not useable;
– bonding between concrete and steel plates may not be proper;
– the production of dust causes health hazards to the public (Figure 4).

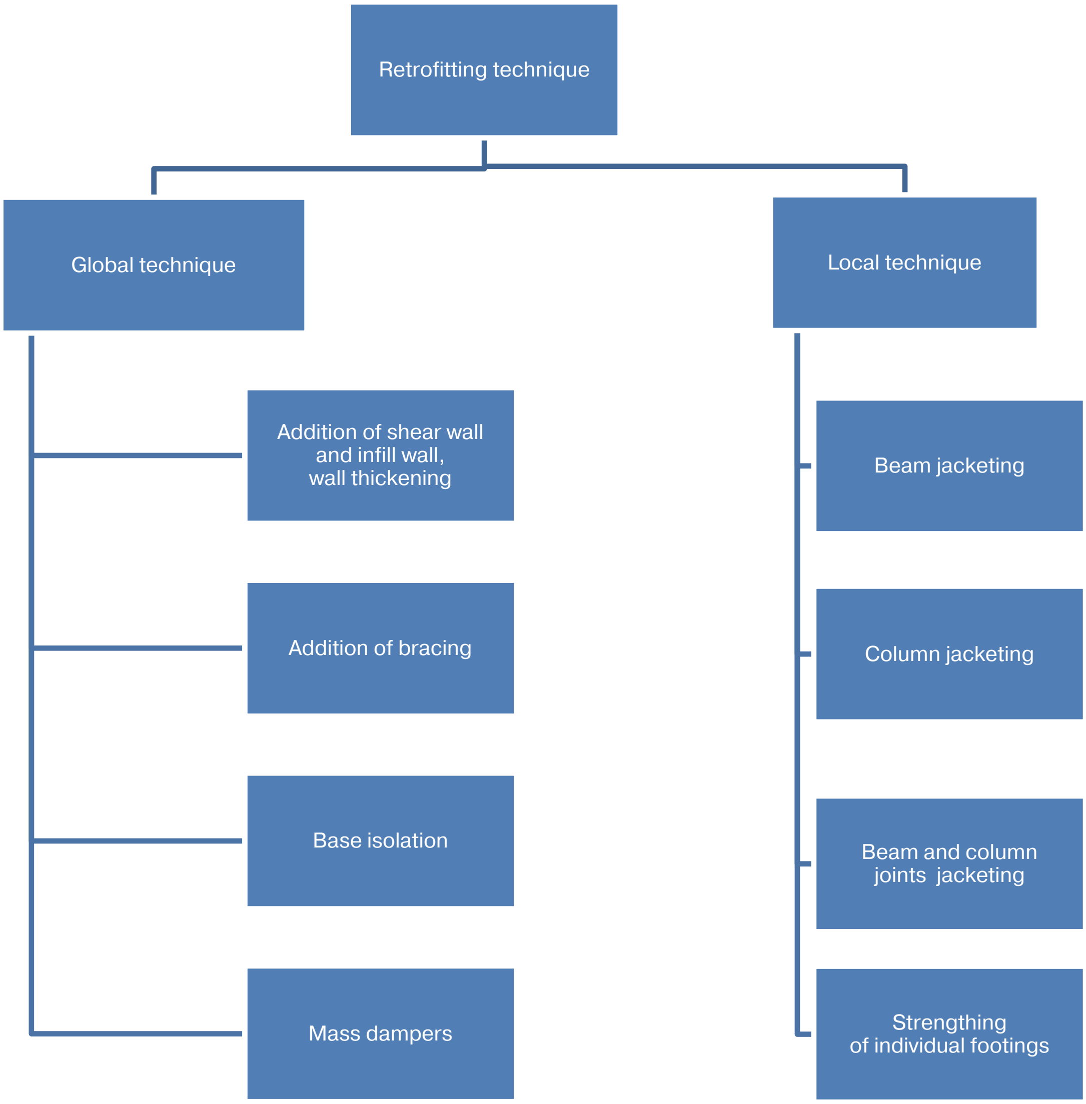

Figure 4. Different techniques of retrofitting [6]

Statement of the problem and objectives

The commercial building considered for this research is situated in Biratnagar, Nepal. This building was initially designed to be built up to G+3 storey in approx. 328.63 m^2 and building have 3 bay in Y direction and 5 bay in X direction. The foundation is 6 feet below the soil and isolated footing is taken in account. The model building has a staircase and lift system with size 1.6 m by 2.5 m. There are altogether 24 columns in every floor with rooms having size 4.5 m by 4.7 m, 4.0 m by 4.7m and so on. Seminar hall, lobby, and guest room occupy other space of the building. The dimensions of columns are 0.5×0.5 m, where as that of beams are 0.30×0.55 m and secondary beam are 0.3×0.4 m. Slab has a thickness of 6-inch, i.e. 0.15 m. For the initial purposes, (G+3) storey building with storey height 3 meter for all floor, with plan 24×13 m is taken and load was applied as per IS code 456:2000 to show that no column failed for 4 storey, i.e. the building passed the design from ETABS 2017.

As the construction phase grows client changes the initial design idea and thus 2 storeys are need to be added over the G+3 storey building and construct a new G+5 storey building. Thus new G+5 storey building was then modeled in ETABS 2017 with initial considerations resulting 52 number of columns failed the design due to increase in load with added storey thus where retrofitting comes in account.

The main aims of this paper are:

– to identify different types of retrofitting technique that are suitable for the structures by studying the nature of failure on structures;

– to assess a building for its structural data types like grade of concrete used, reinforcement details and dimensions etc.;

– to analyze the structure according to IS 1893:2016 and to check its functionality, and its structural behavior;

– to design the structure with proper retrofitting options for satisfying the design codes and serviceability;

– to identify the deficiency in structural elements such as beams and columns.

Methodology

The six-storied existing commercial building including 2 more stories after previous design was modelled on ETABS 2017 with load patterns and cases as per IS 875 and IS1893:2016 for a building with commercial purposes for the study (Tables 1–3). Structure analysis of the structure was carried out using ETABS 2017. Also, three dimensional models were prepared and the existing building was designed as per the client requirements. The deficient in reinforcement was calculated for columns that need to be reinforced. Over stressed (o/s) columns were used for the design of RC jacketing whereas columns with reinforcement deficient were used in design of CFRP. Furthermore IS 15988[1]; 2013 code was used for the design of RC column jacketing and ACI 440.2R-08/ACI-318-05[2] was used design of CFRP for strengthening of RCC column due to deficiency in longitudinal steel reinforcement. The methodology we used can be shown in Figure 5.

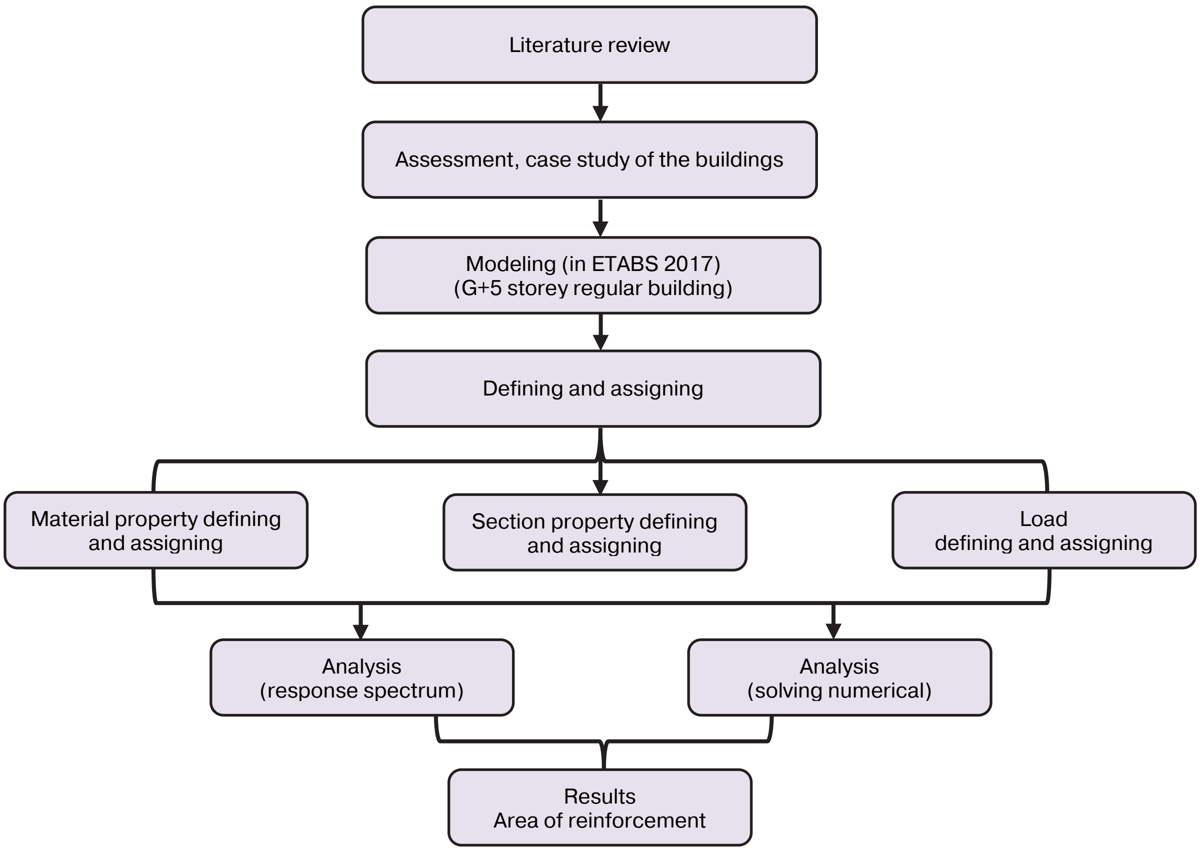

Figure 5. Methodology flowchart

The 3D model diagram of building in ETABS can be seen in Figure 6 whereas the plan of first floor and the layout of column is shown in Figures 7 and 8 respectively.

[1] IS 15988. *Seismic evaluation and strengthening of existing reinforced concrete building – guidelines*. New Delhi: Bureau of Indian Standards; 2013.

[2] ACI 440.2 R-08. *Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures*. American Concrete Institute; 2008.

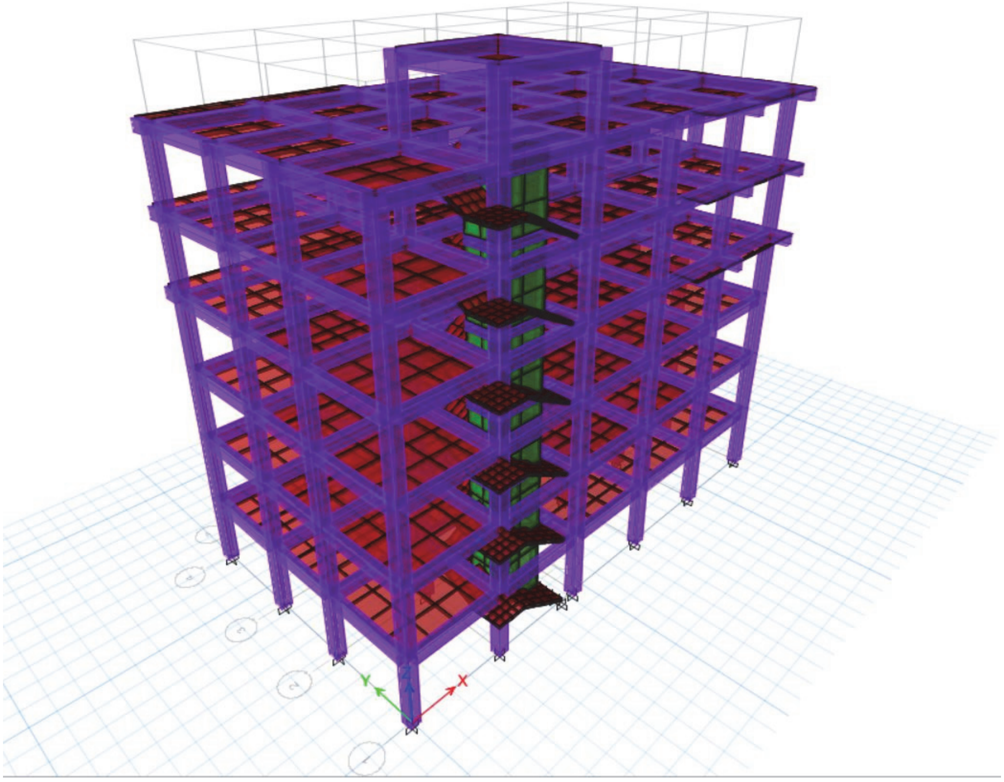

Figure 6. 3D modelling of building in ETABS

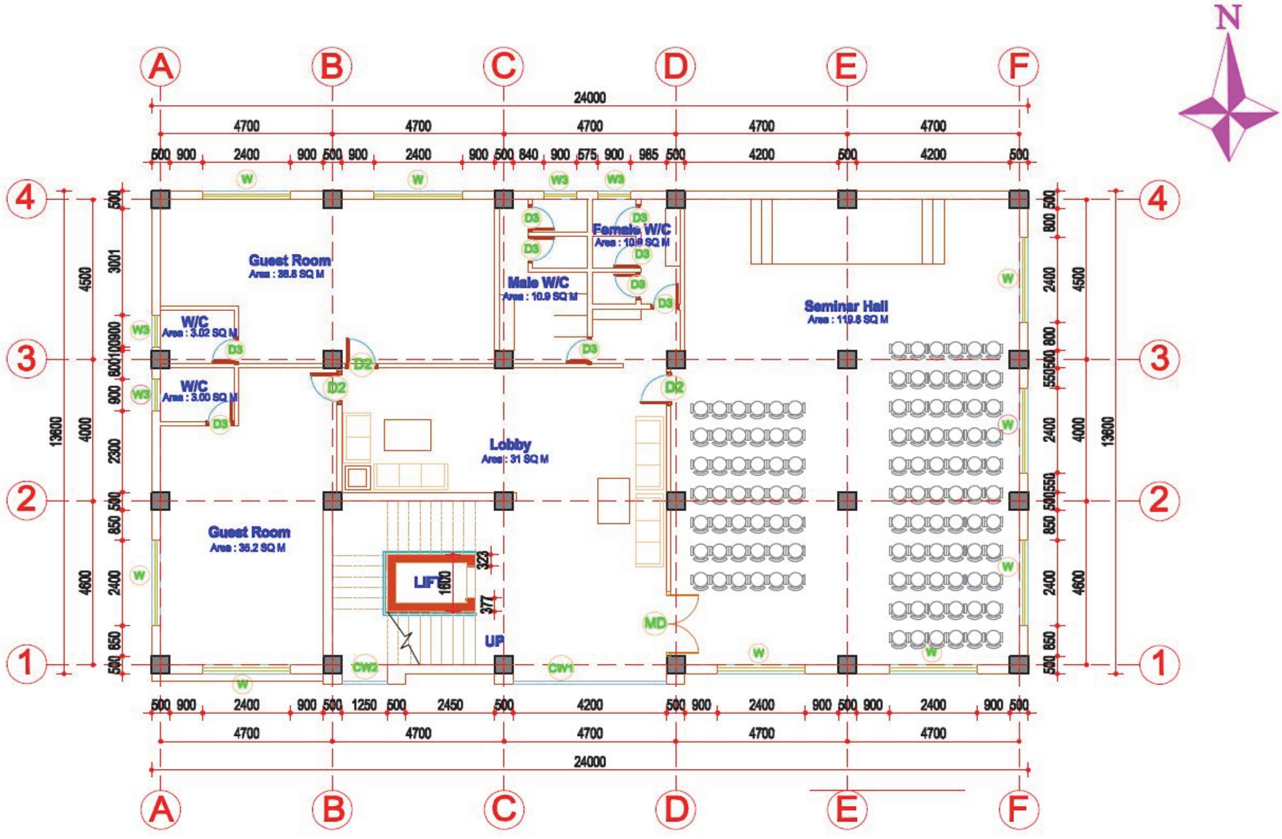

Figure 7. First floor, plan of building

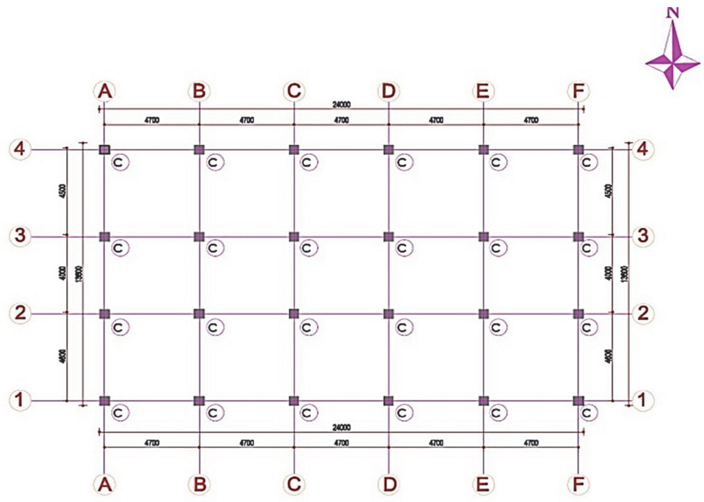

Figure 8. Column layout of building

Table 1

Silent features of building, description of model buildings

Parameters	Data	Unit	Remarks
Building type			Commercial
Plan			Regular
Number of storey	G+5		
Storey height	3	m	
Footing type			Isolated
Footing depth	6	feet	
Infill wall thickness	230	mm	
Imposed load on roof	1	KN/m^2	
Imposed load on regular floor	3	KN/m^2	
Floor finish load	1	KN/m^2	
Lift load	10	KN/m^2	
Staircase load	4	KN/m^2	
Wall load	8.4	KN/m^2	
Size of column	500×500	mm×mm	
Size of beam	300×550	mm×mm	
Secondary beam	300×400	mm×mm	
Slab depth	150	mm	
Grade of concrete, f_{ck}	25	MPa	IS 456:2000
Grade of steel	500	MPa	IS 456:2000
Specific weight of RCC	25		
Soil type	Soft		IS 456:2000
Seismic zone	V		IS 456:2000
Zone factor	0.36		IS 456:2000
Importance factor (I)	1.5		IS 456:2000
Response reduction factor, R	5		IS 456:2000
Time period of vibration	0.655	sec	IS 1893:2016, $T = 0.075h^{0.75}$
Spectral acceleration coefficient S_a/g	2.50		IS 1893:2016
Horizontal seismic coefficient A_h	0.135		
Poisons ration concrete	0.2		
Modulus of elasticity infill, E_m	5310	MPa	
Modulus of elasticity concrete, E_c	25 000	MPa	IS 456:2000, $E_c = 5000\sqrt{fck}$
Time history ground motion	Elcentro		
Damping ratio	5	%	
Shear wall	250	mm	Lift
Angle of friction of soil	30	degree	
Specific weight of soil	18	KN/m^3	

Table 2

Load combinations as per IS 1893:2016

S.N	Load combinations
1	1.5(DL + IL)
2	1.2(DL + IL ± EL)
3	1.5(DL ± EL)
4	0.9DL ± 1.5EL

Note: DL – dead load; IL – imposed load; EL – earthquake load.

Table 3

Unit load of materials used

S.N	Type	Value
1	Reinforced concrete	25 KN/m^3
2	Brick masonry	19 KN/m^3
3	Screed	21.0 KN/m^3
4	Marble	26.7 KN/m^3
5	Mosaic finish	23.1 KN/m^3
6	Plaster	20.4 KN/m^3
7	Steel rebar	78.6 KN/m^3

Imposed loads are taken as per their function and services as per IS 875:2016 (part 3).

Self-weight of structure components is atomically included in ETABS software[3].

Design parameters

A total of 9 columns were needed for the RC jacketing which was carried out by Indian Standard 15988:2013 whereas 43 others were suitable for CFRP design which was carried out by American Concrete Institute 440.2R-08/ American Concrete Institute-318-05. Design example for one column by each method is given below.

Design of RC column jacketing of failed column using Indian Standard Code 15988:2013

Depth of column (D) = 500 mm.

Width of column (B) =500 mm.

Characteristic strength of concrete (f_{ck}) = 25 N/mm^2.

Strength of steel (f_y) = 500 N/mm^2.

Axial load (Pu) = 4790.92 kN.

Moment about X-axis (Mx) = 273.10 kN-m.

Moment about Y-axis (Mx) = 251.04 kN-m.

From IS 456:2000 Clause 8.5.1.2 (a) concrete strength shall be at least 5 MPa greater than the strength of the existing concrete.

Thus, characteristic strength of concrete (f_{ck}) = 30 N/mm^2.

Assuming 0.8% of reinforcement we have A_{sc} = 0.8% of Ac.

From Indian Standard 456:2000 Clause 39.3 in Indian Standard Code 15988:2013

$$Pu = 0.4 f_{ck} Ac + 0.67 f_y A_{st}.$$

So, Ac = 326 356.9 mm^2.

According to Indian Standard 15988:2013 Clause 8.5.1.1 (e)

$$A'c = 1.5 \times Ac.$$

Thus, $A'c$ = 489 535.4 N/mm^2

Assuming the cross section details as B = 700 mm and $D = Ac/2$ = 700 mm.

Jacketing details of cross section are: B = (700 – 500) / 2 = 100 mm, D = (700 – 500) / 2 = 100 mm.

According to Indian Standard 15988:2013 Clause 8.5.1.2 (c in Indian Standard Code 15988:2013) minimum jacket thickness shall be equal to 100 mm.

Thus, new size of column is B = 500 + 100 + 100 =700 mm and D = 500 + 100 + 100 = 700 mm.

Now new concrete area = 490 000 mm^2 > Ac = 326 356.9 mm^2.

Area of steel $A's$ = 0.8% × 700 × 700 = 3920 mm^2.

According to Indian Standard 15988:2013 Clause 8.5.1.1 (e) Indian Standard Code 15988:2013

$$As = 4/3A's = 5226.677 \text{ mm}^2.$$

Thus, we provide 4–25Ø and 12–20Ø, i.e. 5733.416 mm^{2}for the new jacketed section of 700×700 mm.

[3] SP 16. *Design aids for reinforced concrete to IS.* 1980.

***Design of CFRP using American Concrete Institute 440.2R-08/ACI-318-05 for strengthening of RCC column*[4]**

Overall depth of column D = 500.00 mm.
Width of column B = 500.00 mm.
Characteristic strength of concrete f_{ck} = 25.00 N/mm^2.
Strength of steel f_y = 500 N/mm^2.
Area of steel As = 2000.00 mm^2.
Gross area of concrete $A_g = BD$ = 250 000.00 mm^2.
Area of longitudinal reinforcement A_{st} = 14 515.00 mm^2.
Calculations:

Design of ultimate tensile strength
From Eqn. 9–3 in American Concrete Institute 440.2R-08 we have
f_{fu}=$C_e f_{fu^*}$, where C_e= 0.95 and f_{fu^*}= 3200 MPa,
f_{fu} = 3040 MPa.

Design of rupture strain
$\varepsilon_{fu} = C_e \varepsilon_{fu^*}$, where C_e= 0.95 and ε_{fu^*}= 0.0155.
ε_{fu} = 0.14725 MPa.

Determination of required axial compressive strength
As per Clause 10.3.6.2 in American Concrete Institute 318-05

$$\varphi P_n = 0.8\varphi\ [0.85fc'(A_g - A_{st}) + f_y A_{st}],$$

where φ =0.7 (as per Clause C.3.2.2 in American Concrete Institute-318-05)

$$fc' = 0.8fck = 20 \text{ MPa}.$$

So, φP_n =5839.439 kN.

Determination of maximum confining pressure due to the FRP jacket, FL (R&M C-Fiber)
From Eqn. 12–4 in American Concrete Institute 440.2R-08

$$f_l = \frac{2E_f n t_f \epsilon_{fe}}{D},$$

where E_f = 220 GPa (modulus of elasticity of carbon fiber),
n = 1 no (number of plies of carbon fiber wrap),
t_f = 1.5 mm (thickness of one carbon fiber layer).

From Eqn. 12–5 in American Concrete Institute 440.2R-08 we have
$\varepsilon_{fe} = K_\varepsilon \varepsilon_{fu}$ = 0.00809875 (effective strain level in FRP),
where K_ε = 0.55 (FRP strain efficiency factor).
From Eqn. 12–8 in American Concrete Institute 440.2R-08 for non-circular column cross section we have

$$D = \sqrt{b^2 + h^2} = 707.1068 \text{ mm}.$$

Thus, f_l = 0.007559 = 7.559219 MPa.

[4] Wight J.K., Rabbat B.G. *Building code requirements for structural concrete and commentary (ACI 318M-05).* American Concrete Institute; 2005.

Determination of maximum compressive strength of confining concrete, fcc'
From Eqn. 12–3 in ACI 440.2R-08 we have

$$f_{cc'} = f'_c + \Psi_f 3.3 K_a f_l,$$

where Ψ_f = 0.95 (as per Clause 12.1 Pg.35 in American Concrete Institute 440.2R-08)

$$K_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2.$$

From Eqn. 12–11 in American Concrete Institute 440.2R-08 we have

$$\frac{A_e}{A_c} = \frac{1 - \dfrac{\left[\left(\dfrac{b}{h}\right)(h-2r_c)^2 + \left(\dfrac{h}{b}\right)(h-2r_c)^2\right]}{3A_g} - \rho_g}{1-\rho_g},$$

r_c = 25 (min radius at corners), ρ_g = 0.03 (existing longitudinal steel reinforcement ratio).
Therefore
$\frac{A_e}{A_c}$ = 0.443298969
K_a =0.443298969,
Thus $f_{cc'}$ = 30.50536613 MPa.

Verification of ultimate axial strain of the confined concrete $\varepsilon_{ccu} \le 0.01$
From Eqn. 12–6 in American Concrete Institute 440.2R-08

$$\varepsilon_{ccu} = \varepsilon'_c\left(1.5 + 12K_b\frac{f_l}{f'_c}\left(\frac{\varepsilon_{fe}}{\varepsilon'_c}\right)^{0.45}\right),$$

where $\varepsilon_{c'} = \frac{f'_c}{Ec}$ = 0.000952.
Now as per American Concrete Institute-318-05Ec = 4700√*f'c* = 21019.03899.
Also, from Eqn. 12–10 in American Concrete Code 440.2R-08:
Shape factor, $Kb = \frac{A_e}{A_c}\left(\frac{h}{b}\right)^{0.5}$ = 0.443299.
Thus, ε_{ccu}= 0.006441948<= 0.01 from Eqn. 12–7 in ACI 440.2R-08.
Hence it is safe.
Now, $\frac{f_l}{f'_c}$ = 0.377960949
Hence as per Clause 12.1 Pg.35 in American Concrete Institute 440.2R-08 since it is >0.08 it is safe [7].

Axial compressive strength in column after confinement with FRP
From Eqn. 12-1b in American Concrete Institute 440.2R-08 we have

$$\varphi P_n = 0.8\varphi\left[0.85 f'_{cc}\left(A_g - A_{st}\right) + f_y A_{st}\right].$$

$\varnothing P_n$ = 7025.62068 MPa.
Since it is greater than required capacity i.e. 5839.439 MPa Hence OK.
Thus, provide 1 ply of 600 Gsm R&M Carbon-Sheet on periphery with anchor fastener for anchorage.

Summary

The outcomes of all the columns which required retrofitting either by RC jacketing or CFRP jackets from the above design example are illustrate in Tables 4, 5 and Figure 9.

Table 4

Detailing of RC jacketing for columns

Column grid	Storey	Design *Pu*, kN	*Mux*	*Muy*	Jacketed C/section	Reinforcement provided	Jacket rebar	Lateral ties
1C	Ground	4523.44	229.78	218.21	700×700	5733.416	4–25φ 12–20φ	8 mm φ at the rate of 100 mm *c/c*
2C	Ground	4790.92	273.1	251.04	700×700	5733.416	4–25φ 12–20φ	8 mm φ at the rate of 100 mm *c/c*
2C	First	3635.72	284.73	347.83	700×700	5733.416	4–25φ 12–20φ	8 mm φ at the rate of 100 mm *c/c*
2E	Ground	2477.38	419.24	210.25	700×700	5733.416	4–25φ 12–20φ	8 mm φ at the rate of 100 mm *c/c*
2F	Ground	1992.31	483.93	193.72	700×700	5733.416	4–25φ 12–20φ	8 mm φ at the rate of 100 mm *c/c*
3E	Ground	2452.98	416.45	258.62	700×700	5733.416	4–25φ 12–20φ	8 mm φ at the rate of 100 mm *c/c*
3F	Ground	1962.27	483.19	237.52	700×700	5733.416	4–25φ 12–20φ	8 mm φ at the rate of 100 mm *c/c*
4E	Ground	2404.31	372.51	307.76	700×700	5733.416	4–25φ 12–20φ	8 mm φ at the rate of 100 mm *c/c*
4F	Ground	1777.81	430.67	284.21	700×700	5733.416	4–25φ 12–20φ	8 mm φ at the rate of 100 mm *c/c*

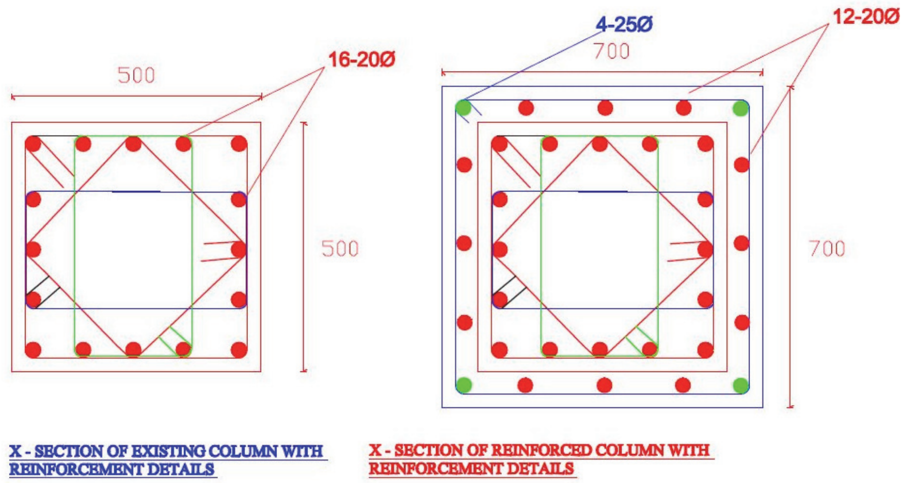

Figure 9. X-section of existing and reinforced column with reinforcement details

Table 5

Detailing of CFRP sheets for columns

Column grid	Storey	A_{st} required	CFRP provided
1B	1st	8226	1 ply of 600 Gsm R&M Carbon-Sheet on periphery with anchor fastener for anchorage
1C	1st	11 964	
1C	2nd	9292	
1D	Ground	9846	
1E	Ground	11 575	
1E	1st	8579	
1F	Ground	11 331	
2A	Ground	9128	
2B	Ground	10 344	
2B	1st	9655	
2C	2nd	12 144	
2D	Ground	11 578	
2D	1st	10 937	
2D	2nd	10 319	
2E	1st	12 178	
2E	2nd	10 796	
2F	1st	10 921	
2F	2nd	9529	
3A	Ground	9816	
3B	Ground	10 603	
3B	1st	10 438	
3B	2nd	9029	
3C	Ground	10 974	
3C	1st	10 927	
3C	2nd	9700	
3D	Ground	12 757	
3D	1st	12 064	
3D	2nd	10 537	
3E	1st	12 790	
3E	2nd	11 197	
3F	1st	11 337	
3F	2nd	9939	
4A	Ground	9375	
4B	Ground	10 375	
4B	1st	8790	
4C	Ground	10 919	
4C	1st	9320	
4D	Ground	12 509	
4D	1st	10 096	
4D	2nd	9131	
4E	1st	10 214	
4E	2nd	8905	

Discussion

The design for retrofitting techniques can be implemented as per the building code that is in practice for the nation and the retrofitting techniques can also vary as per site situation, available materials and properties of those available materials. For further research, using different methods and techniques of retrofitting, with different codes and practices is recommended from this paper.

Conclusion

This research primarily was conducted to assess the structural elements and their strength, properties for a commercial building, which was found to be deficient for its serviceability. Thus, retrofitting measures for strengthening the structure were implemented in which column concrete jacketing and fiber wrap polymers were adopted in such deficient column to enhance the strength. The following points are concluded from this research:

1. The structural parameters of the building were assessed by performing non-destructive tests and rebar detection equipment's to find out the grade of concrete and rebar diameters and number to verify the in-built structural drawings.

2. After structural health assessment, extracted data were used for reanalyzing the structure using Finite Element Program, ETABS 2017, to check whether the structural elements can carry out the desired performance or not. Most of the columns in ground floor and first floor were found to be deficient in carrying service loads, thus, retrofitting for those columns was recommended.

3. Concrete jacketing and FRP sheets were two retrofitting techniques that were defined as best suited for the building structure where columns were subdivided for using a particular retrofitting technique as per their demand capacity.

4. The design for retrofitting techniques were carried out as per IS codes.

5. For column jacketing, micro concreting with calculated rebar percentage, stirrups size and spacing, anchorage was used whereas 600 Gsm R&M Carbon-sheet on column periphery was used for FRP retrofitting technique.

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