Condition assessment and strengthening of aged structures: Perspectives based on a critical case study

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Abstract

This article presents a concise overview on condition monitoring and retrofitting/ strengthening of structures including a practical case study of strengthening for an existing historical building. Condition assessment of an existing structure is required mainly to check serviceability and safety requirements of the structure after short term events like earthquake or long term degradation of the structure with time. It is carried out to assess the ability of a structure to perform its intended operations under changed loading conditions with time or modification in its structural system as per newly imposed requirements. The condition assessment and strengthening may also be required for integrated extension of an existing structure. After assessing the condition of the structure, either it is retrofitted (or strengthened) or it is demolished according to the severity of the damage. In this article, such a critical condition assessment for an existing historical masonry building is presented and appropriate strengthening schemes are suggested by following two separate measures (concrete jacketing and fiber reinforced polymer strengthening). Subsequently, the relative advantages and disadvantages of the strengthening measures are discussed from a practical engineering perspective. Aim of this article is not to propose any new method for condition assessment and strengthening of structures, rather we take a systematic approach to demonstrate our experience. Critical case studies on condition assessment and strengthening of historical buildings with adequate technical insights are very scarce to find in scientific literature. This article would serve as a valuable reference for the practicing engineers and the concerned scientific community.

Keywords: structural health monitoring; condition assessment; FRP strengthening; retrofitting; concrete jacketing

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Introduction

Civil engineering structures are always subjected to considerable amount of risk factor due to their continuous depreciation under time-driven operating and service environments. The condition assessment of an existing structure is required mainly to check serviceability and safety requirements of the structure after short term events like earthquake and fire or long term degradation of the structure with time. Civil engineering structures are constantly subjected to geophysical and human-induced loads during their service life. Such structures are likely to be damaged when loads exceed the capacity of the structures. As construction of a new structure in place of the damaged structures is not often possible due to economic reasons (three-fold economic criteria involved with demolition of the damaged structure, construction of new structure and loss of revenue for the interruption in important functions/ operations of the structures), a decision to repair and strengthen the existing structure can be made at appropriate level. These situations may warrant retrofitting of the structure to continue its intended operations. The decision for strengthening/ retrofitting is taken on the basis of condition assessment. Condition assessment and subsequent strengthening may also be required for integrated extension of an existing structure to investigate its capability to bear additional loads. The purpose is to assess the ability of a structure to perform its intended operations under changed loading conditions with time or modification in its structural system. After assessing the condition of the structure, either it is retrofitted (/strengthened) or it is demolished according to the severity of the damage. Plenty of studies have been reported in the scientific literature on damage modelling (Skrzypek et al. 1998; Nichols and Murphy 2016; Naskar et al. 2017) and damage identification (Mukhopadhyay 2018; Naskar and Bhalla 2015; Mukhopadhyay et al. 2015, 2016a) in structures.

The local strengthening of reinforced concrete members by concrete jacketing is a common mode of retrofitting/ strengthening (Hamid et al. 1994; Bracci et al. 1997; Lakshamanan 2006; Lee et al. 2006). The jacket generally consists of added concrete and longitudinal cum transverse reinforcement around the existing structural member. Such type of strengthening improves the axial and shear strength for a column while the flexural strength of the column and the strength of beam-column joint remain mostly unchanged. Chipping away of concrete cover of original member and roughening its surface is required in this method to improve the bond between the old and new concrete. Fibre reinforced composites have attracted wide attention in the last two decades for an alternative and efficient way of strengthening/retrofitting structural elements (JBDPA 1999; ACI 440, 2000; TCSUK 2000). Application of fibre reinforced polymers (FRP) as reinforcement for structures has gained rapid popularity and appeal due to several advantages like affordability of such materials compared to conventional steel reinforcement or concrete encasements, light weightiness, high strength-to-weight ratio and better quality control (Dey et al. 2017, 2018a, 2018b; Naskar et al. 2018, 2019; Karsh et al. 2018). Moreover, the ease of handling, lack of requirement for heavy lifting and handling equipment and corrosion resistance are some other factors which are advantageous in the repair, retrofitting and rehabilitation of civil engineering structures. Due to continuous research and development on new composite materials (Dey et al. 2015, 2016a, 2016b, 2016c, 2016d, 2016e, 2016f; Mukhopadhyay et al. 2016b), the use of such materials is found to be advantageous in terms of weight-sensitivity and cost-effectiveness. The confinement of reinforced cement concrete (RCC) columns by FRP jackets enhances their strength and ductility. Several researches have been carried out around the world on this issue concerning the enhancement of structural performance by means of FRP (Teng et al. 2000; Antonopoulos and Triantafillou 2003; Bacque et al. 2003; Choi and Xiao 2010; Minicelli and Tegola 2007; Sundarraja and Rajamohan 2009; Smith and Kim 2009; Bank 2006; Kezmane et al. 2016) and it is expected that the design criteria will continue to enhance as the results of these research and development become known in the coming years based on optimal utilization of available resources.

In general, long-term field data are required to accurately predict the life of FRP strengthening systems. The respective design guidelines can be benchmarked to account for environmental degradation and long-term durability by suggesting reduction factors for various working environments. The load-carrying capacity of the existing structure is required to be assessed based on the information gathered in the field investigation, the review of design calculations and drawings, and as determined by analytical or other suitable methods. Load tests or other methods can be incorporated into the overall evaluation process if deemed appropriate. However, due to variety of structural conditions during the construction and operational phase, it is not easy to develop general rules for retrofitting. Every strengthening/ retrofitting process for building needs to adopt specific approaches depending upon the structural deficiencies. In the detail retrofitting scheme, it must comply with the latest building codes. The results generated by adopting retrofitting techniques should fulfil the minimum requirements prescribed by the building design codes such as deformation, detailing strength etc. Practical case studies on condition assessment and strengthening of civil engineering structures (particularly buildings) are very scarce to find in literature (Teworte et al. 2015; Bergamo et al. 2014; Livina and Perry 2017; Hadianfard et al. 2017; Alessandri and Turrioni 2017; Cosenzo and Ivervolino 2007; Valluzzi et al. 2005; Verma et al. 2016), even though such studies can be valuable references for practicing engineers and the concerned scientific community. The present article provides a case study on structural condition assessment of an existing building including comprehensive technical discussions. Thereby detail strengthening schemes based on two different approaches are presented for the deficient structural members. Aim of this article is not to propose any novel methodology for structural retrofitting; rather we focus on rendering a practical perspective on this subject. The paper hereafter is organized as: I. brief overview on the technical details of strengthening structural members; II. description of the problem considered for practical case study; III. details of computer modelling of the building; IV. results of structural condition assessment and subsequent strengthening schemes; V. conclusion and outlook.

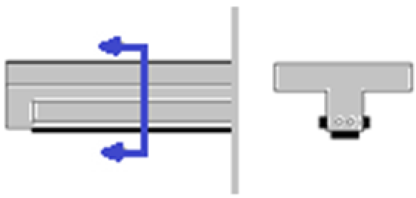
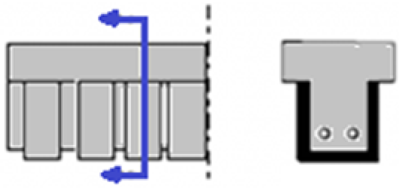
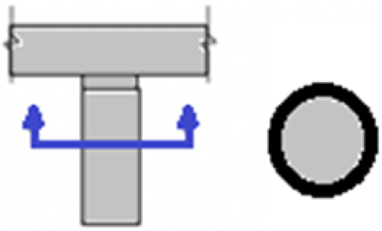
Type	Schematic diagram	Application
Flexural		Tension and/or side face of beam (along long axis of beam)
Shear		Side face of beam (U-wrap) (Perpendicular to long axis of beam)
Confinement (Axial load)		Around column (Circumferential)

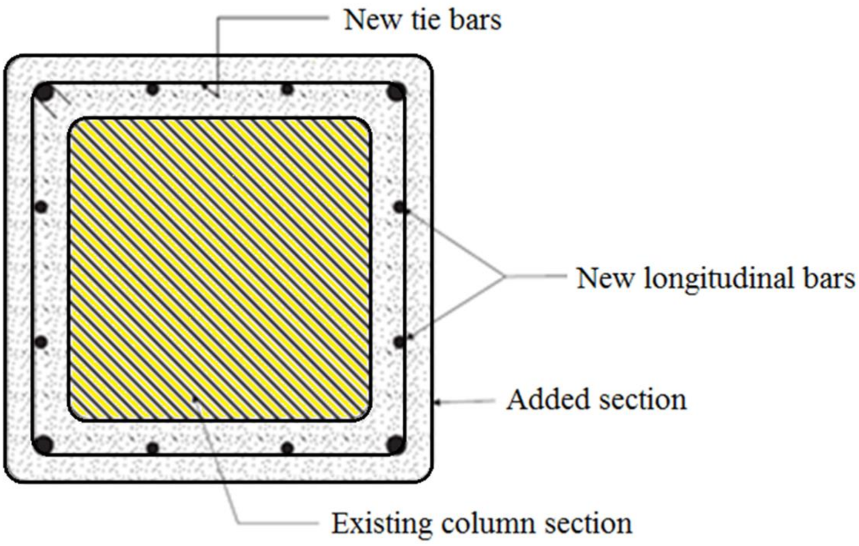
Fig. 1 FRP strengthening applications

Strengthening of structural elements

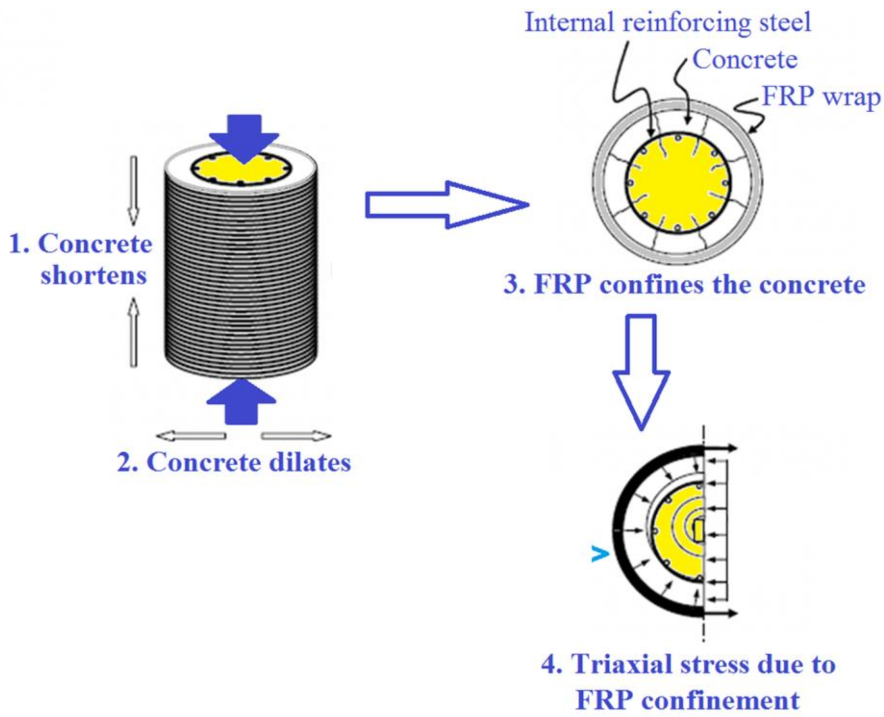
The strengthening through repair, retrofitting and rehabilitation of civil engineering structures is of paramount significance to reduce the risk and ensure the reliability during service life. Based on assessment of the present condition of an existing building, prudent strengthening schemes can be suggested. Two widely used approaches of structural strengthening are: concrete jacketing and FRP confinement. In both the methods, the space optimization and cost component are needed to be taken into account based on the structure under consideration. Schematic diagrams corresponding to strengthening schemes for deficiencies in different types of load carrying capacities for the common structural elements are explained in figure 1. The figures clearly indicate the position of FRP placement for three different types of load carrying deficiencies.

The strategy followed for concrete jacketing to strengthen a structural element is straight forward. First structural analysis is carried out for a structural member to find out its load carrying capacity. Thereby computer simulation is performed to calculate the loads that different members of a building experience. Comparing the imposed loads on a particular member and its capacity, the deficiency in load carrying capacity is calculated. Based on the deficiency, extra reinforcement (Ø) is provided (refer to figure 2(a)) to satisfy the design requirements (Pillai and Menon 2009; Punmia et al. 2006; IS 456 2000; IS 875 1987; IS 1893 2002; IS 13920 1993; ACI 318-05; ACI 440.2R-08). However, for FRP strengthening, a relatively more complex design procedure is needed to be followed (Kezmane 2016, ACI 440.2R-08). As it is found that most of the columns are deficient in load carrying capacity (detailed results are provided later in this paper) in the present problem of strengthening an existing building, a representative strengthening scheme for a column based on FRP confinement is briefly discussed here. The FRP confinement mechanism for a column section is depicted in figure 2(b). For the purpose of demonstration, it is assumed that design forces on a particular column are: P_u (axial force), M_{ux} (moment with respect to x-direction) and M_{uy} (moment with respect to y-direction), while the corresponding load carrying capacity of the column are: P_{uc}, M_{uxc} and M_{uyc}, respectively. If the load carrying capacity is less than the design forces, the column needs to be strengthened to carry the additional loads. For this purpose FRP wraps can be utilized (ACI 440.2R-08). A bilinear interaction curve is considered for the case of combined axial force and bending to optimize the number of layers for FRP wraps as shown in figure 3. The values of ϕP_n and ϕM_n are calculated corresponding to the three different points A, B and C as (ACI 440.2R-08)

$$\phi P_{n(A)} = \phi 0.8\left[0.85 f_{cc}^{'}\left(A_g - A_{st}\right) + f_y A_{st}\right] \quad (1)$$



(a)



(b)

Fig. 2 Strengthening of column sections using (a) Concrete jacketing for strengthening of column sections (b) Strengthening mechanism of FRP confined concrete columns

$$\phi P_{n(B,C)} = \phi\left[A(y_t)^3 + B(y_t)^2 + C(y_t) + D\right] + \sum A_{si} f_{si} \quad (2)$$

$$\phi M_{n(B,C)} = \phi\left[E(y_t)^4 + F(y_t)^3 + G(y_t)^2 + H(y_t) + I\right] + \sum A_{si} f_{si} d_i \quad (3)$$

Here the Points A, B and C correspond to three zones of a column section with pure compression caused by a uniform axial compressive strain of unconfined concrete (ε_{ccu}),

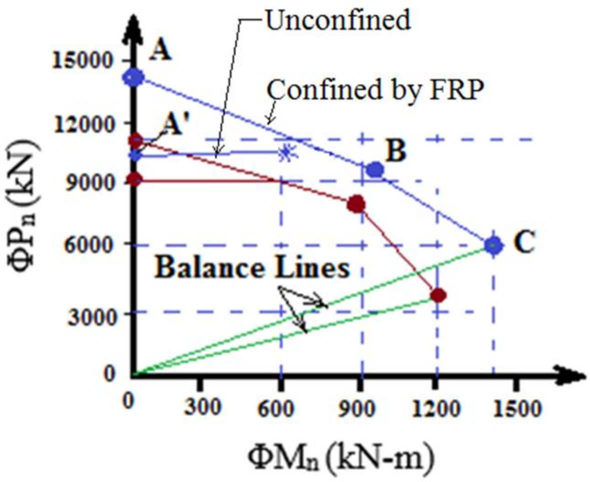
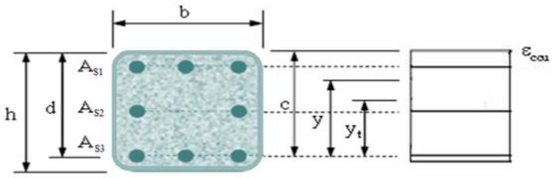
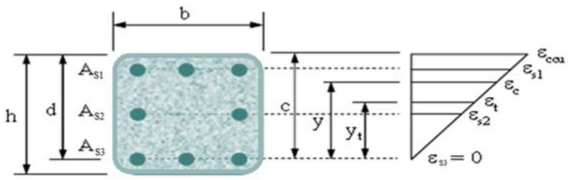


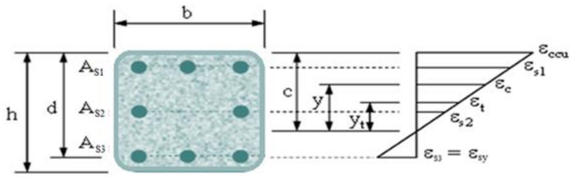
Fig. 3 Typical representation of bilinear interaction curve



(a) Strain distribution corresponding to Point A



(b) Strain distribution corresponding to Point B



(c) Strain distribution corresponding to Point C

Fig. 4 Strain distributions corresponding to the three points of bilinear interaction curve shown in figure 3

strain distribution corresponding to zero strain at the layer of longitudinal steel reinforcement nearest to the tensile face and compressive strain ε_{ccu} on the compression face and strain distribution corresponding to balanced failure, respectively (refer to figure 4) (ACI 440.2R-08). A, B, C…H in equation (1) - (3) are the constant coefficients depending on the properties of FRP materials used and can be obtained from expressions provided in ACI 440.2R-08. If the condition of design force and moment interaction point lies in the zone between the bilinear interaction curves corresponding to the unconfined and confined columns, the column is designated as safe. A case study of condition assessment and subsequent strengthening for a building is presented in the following sections.

Problem description

Assessment of the present condition and accordingly strengthening measures were required to be taken for an existing historical library building situated at Uttarakhand, India. The unique G+1 storey building with historical significance was designed and constructed in early 1900s and subsequently one more storey was required to be added due to requirement of expansion of the library building. The building was constructed as RCC framed structure with load bearing brick masonry walls in the periphery. For condition assessment and strengthening of the building, supplied structural drawings of the building have been studied in detail and a separate analysis/design of the building was carried out using ETABS (ETABS 2012) and SAFE (SAFE 2012). To ascertain different parameters used in the aforementioned analysis and design, a site visit was also conducted. This report aims to assess the present condition of the existing library building and to suggest necessary measures of strengthening according to the requirement.

Computer modelling

The entire building except the foundation has been modelled in ETABS, wherein the beam and columns are modelled using line element as frame (refer to figure 5). Beams and columns provided in the building have different dimensions and orientations. Dimension of the beams and columns are shown in Table 1. The modelling of slabs has been done using shell elements. Shell element is used because the purpose of modelling slab was to transfer loads as well as to provide stiffness to the floor. Shell element helps in analysing the bending behaviour of slabs under various loads. The outer walls of the building are load bearing walls and they have been modelled using shell element for normal elastic analysis. Thickness of slabs, ramps and walls are 75 mm, 150 mm and 250 mm, respectively. Material properties

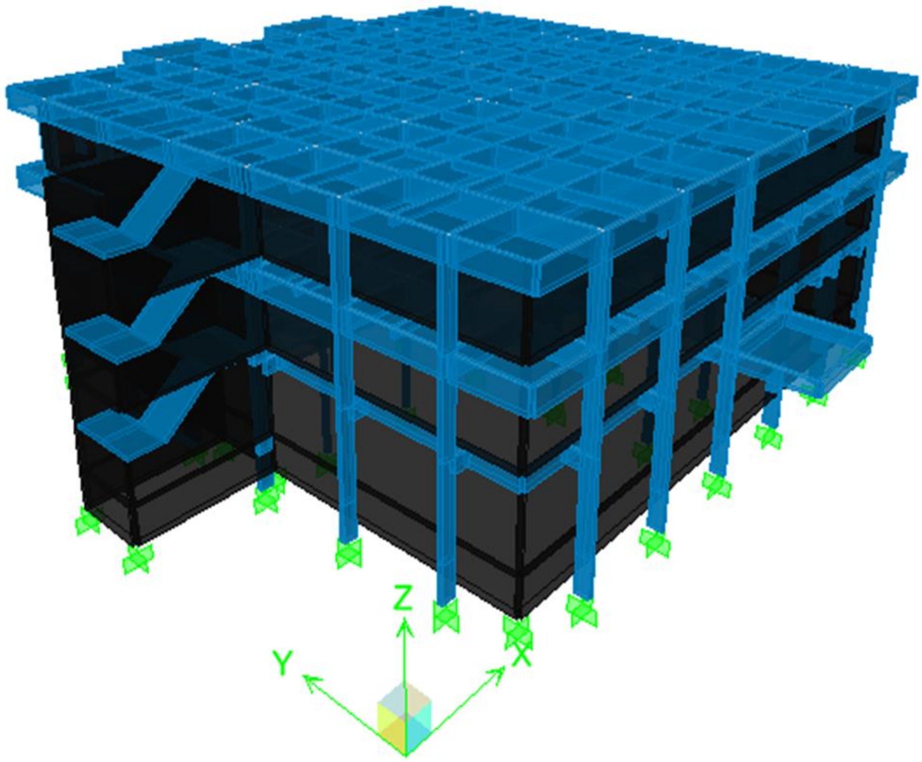


Fig. 5 Typical three dimensional view of the building model

used in the analysis are shown in Table 2. Reinforcements (Ø) have been modelled as per existing drawings. The support conditions at the base have been assigned as no translation and no rotation in any direction, which resembles a fixed support.

Column locations at base level are shown in figure 6. Figure 7 presents the location of beams at the first and second floor level including position of slabs and load bearing walls. To access the requirement of strengthening in the existing structural components of first and second floor level for adding one more storey to the building, the third storey has been modelled in this study as a replica of the second story. Thus beam locations for the roof level are same as figure 7(b). The only difference adopted in computer modelling of the third storey is that no load bearing wall is designed following present construction practices. It should be noted that the existing building was designed and constructed in early 1980s, when framed building structures were not very common. Thus it is expected that the columns in the third storey will need extra reinforcement compared to second storey to balance the effect of

Table 1 Dimension of beams and column sections (refer to figure 6 and 7)

Structural element	Type	dimension	Colour code
Beam	Rectangular	200x750(mm)	Beam Type I
	Rectangular	200x500(mm)	Beam Type II
	Rectangular	120x300(mm)	Beam Type III
Column	Rectangular	500x200 (mm)	Column Type I
	Rectangular	230x230 (mm)	Column Type II
	Circular	230 Ø (mm)	Column Type III

Table 2 Material Properties

Material	Concrete	Masonry
Compressive Strength	20000 KN/m^2	-
Mass/Volume	2.4007 g/m^3	-
Weight/Volume	24KN/m^3	16 KN/m^3
Modulus of Elasticity	22360679.8 KN/m^2	4200000 KN/m^2
Reinforcement Yield Stress	415000 KN/m^2	-
Poisson's Ratio	0.2	0.2
Shear Modulus	9316949.9 KN/m^2	1750000 KN/m^2

removing load bearing walls. The requirement of extra reinforcement can be taken care of effectively while designing the new storey.

Results and discussion

The dead load and live load considered as per codal provisions (IS 875 1987) in this study are shown in Table 3. For considering earthquake loading as per IS 1893 2002 (Part 1), different parameters used are as follows: zone factor: 0.24 (seismic zone IV), response

Table 3 Static loads considered in the design

Super Imposed Dead Load	Roof	0.22 KN/m^2
	2^{nd} Floor	0.20 KN/m^2
	1st Floor	0.20 KN/m^2
Live Load	Roof	1.5 KN/m^2
	2^{nd} Floor	3 KN/m^2
	1st Floor	6 KN/m^2
	Ramps and landing of staircase	4 KN/m^2

Table 4 Different loading combinations considered in the analysis with appropriate factor of safety (DL: Dead load; SD: Super imposed dead load; LL: Live load; EQX and EQY: Earthquake loadings in two perpendicular directions)

Sl. No.	Design combinations
1.	1.5(DL+SD)
2.	1.5(DL+SD+LL)
3.	1.2(DD+SD+LL+EQX)
4.	1.2(DD+SD+LL-EQX)
5.	1.2(DD+SD+LL+EQY)
6.	1.2(DD+SD+LL-EQY)
7.	1.5(DL+SD+EQX)
8.	1.5(DL+SD-EQX)
9.	1.5(DL+SD+EQY)
10.	1.5(DL+SD-EQY)
11.	0.9(DL+SD)+1.5EQX
12.	0.9(DL+SD)-1.5EQX
13.	0.9(DL+SD)+1.5EQY
14.	0.9(DL+SD)-1.5EQY

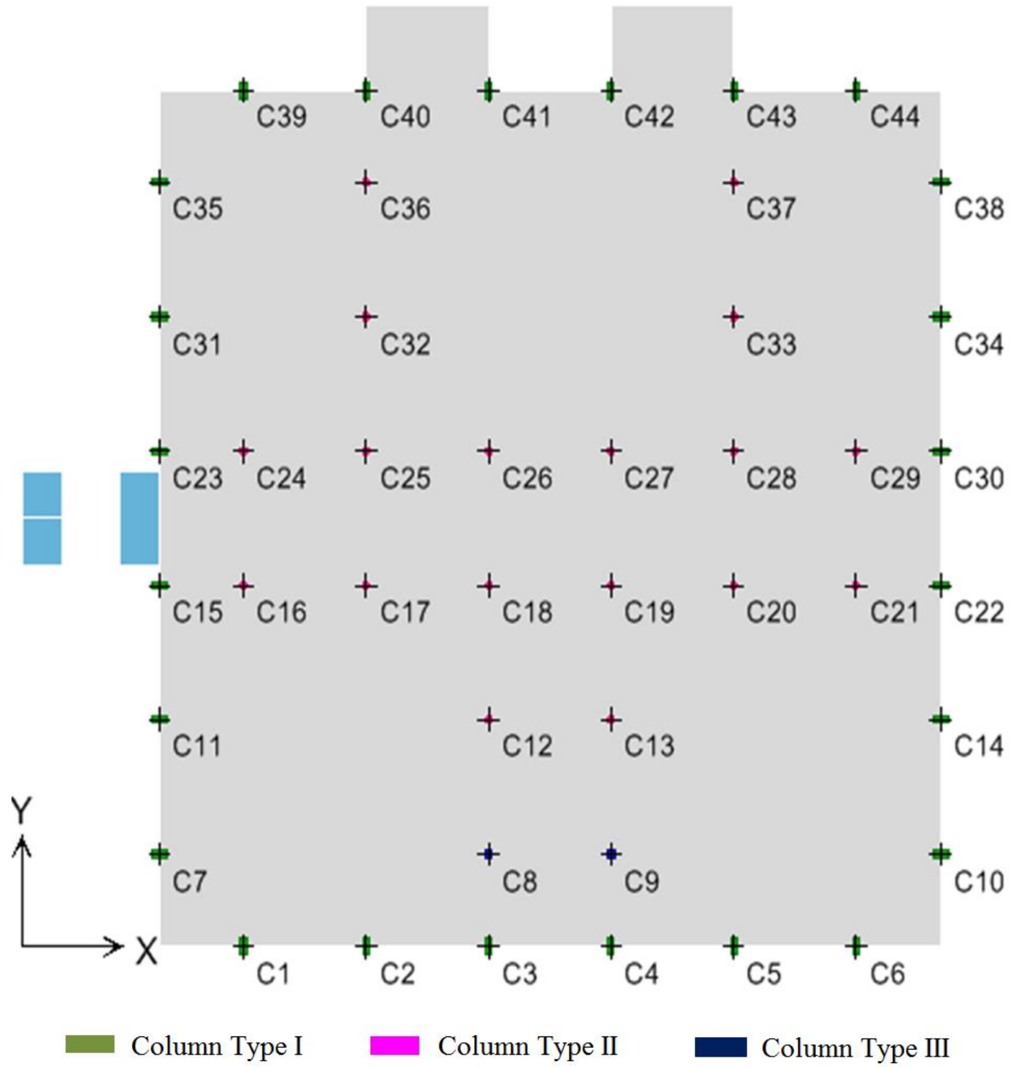


Fig. 6 Plan View of building including column positions (refer Table 1 for colour codes)

reduction factor: 3 (OMRF), importance factor: 1.5 (important service and community building), damping factor: 0.05 (RCC structures), soil type: medium. As the problem under consideration is not of high rise building, effect of wind loading has not been accounted in the analysis. Different loading combinations that have been analysed to access performance of the structural components are shown in Table 4 including the factor of safety values as per codal provisions. A particular structural component is considered as 'failed' if it fails in any one of the loading case. For analysing the foundations, allowable bearing pressure considered at a depth of 2 m below the ground surface is 8 t/m^2, as per soil testing report.

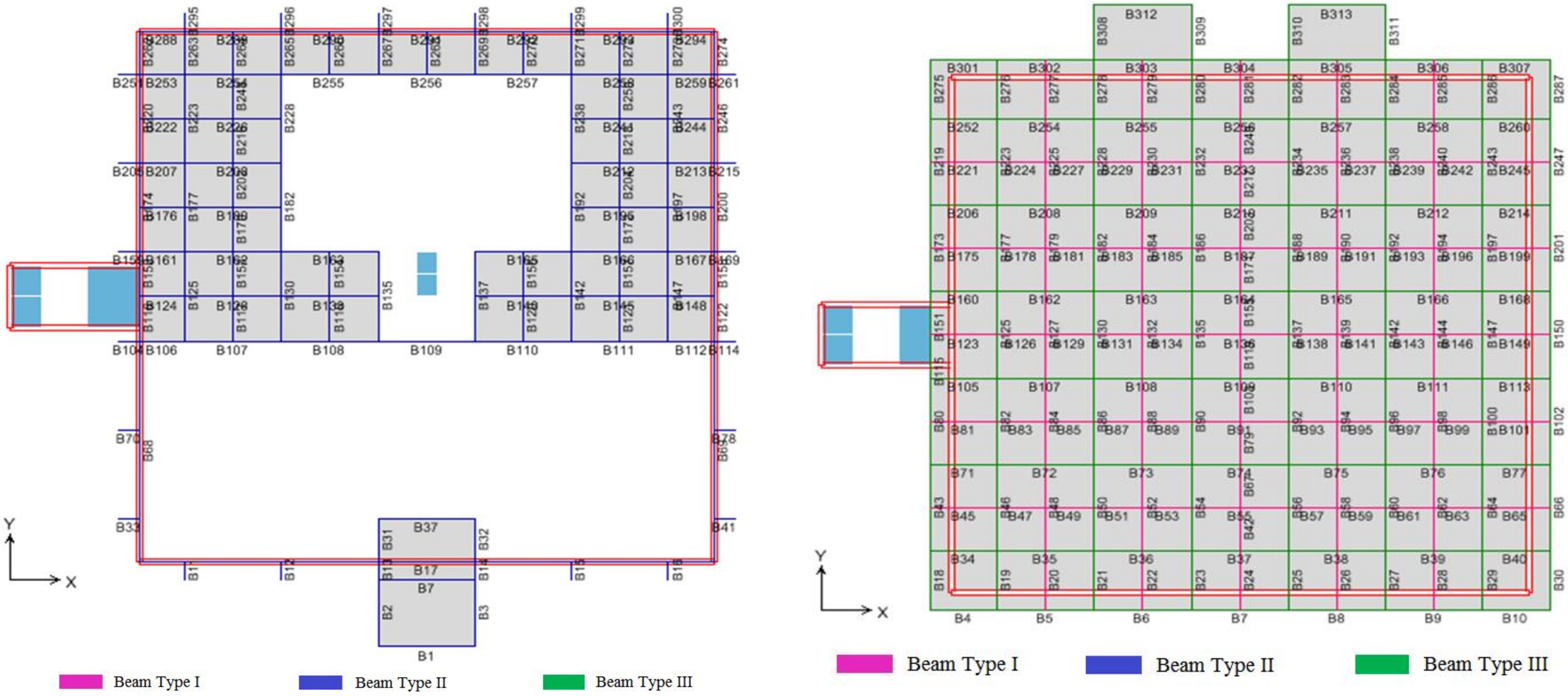
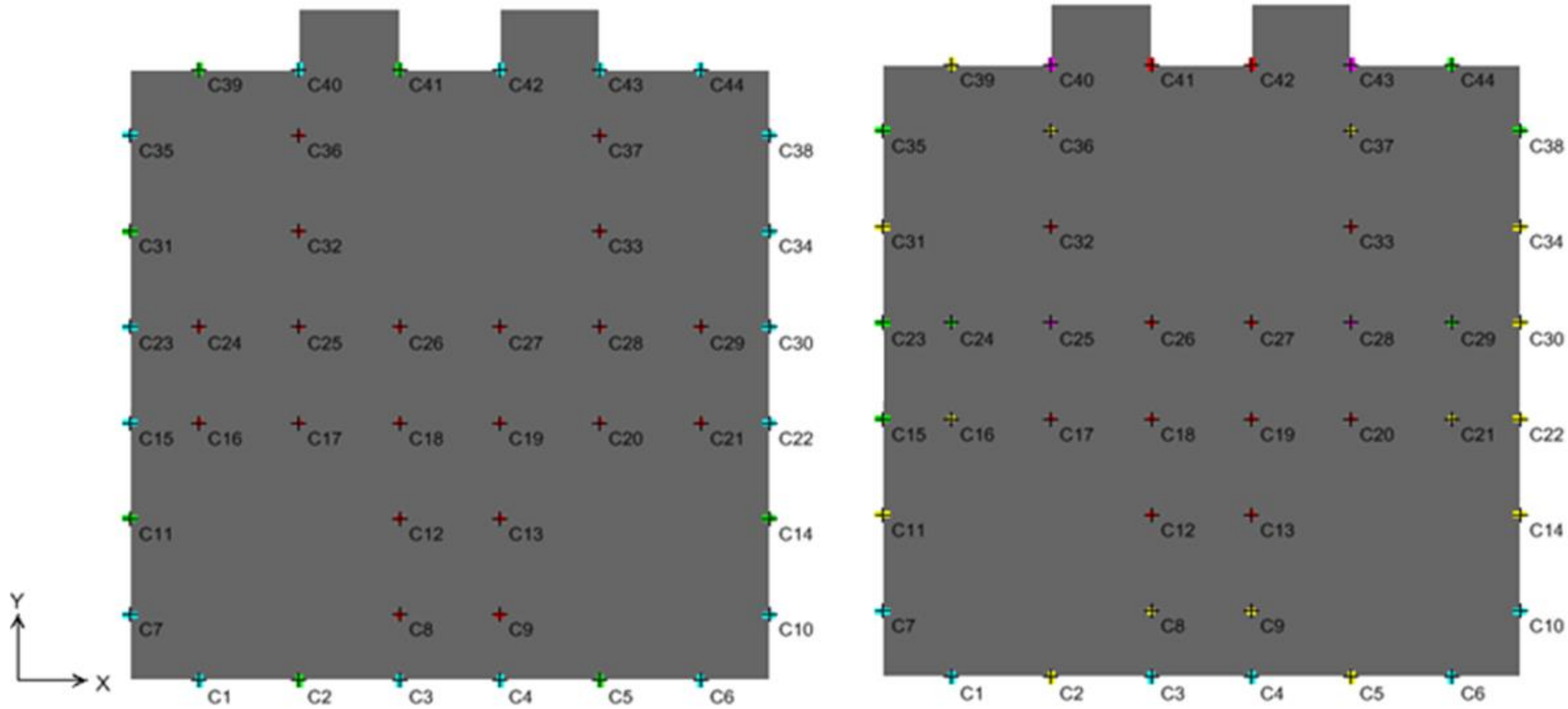


Fig. 7 Location of beams with different dimensions (refer Table 1) in (a) first floor level and (b) second floor level. The rectangular areas in sky blue colour show position of the landing slabs of staircase and double lines in red colour at the periphery indicate location of load bearing brick masonry walls. Filling in grey colour indicates location of slab.



(a)

(b)

Fig. 8 Location of failed columns at (a) third storey (b) second storey. Failed columns are indicated in red colour (these columns are strengthened). Other colours indicate different levels of safety as per design requirements (green being the safest, followed by blue, yellow and pink). The grey colour indicates the position of slabs in a particular floor.

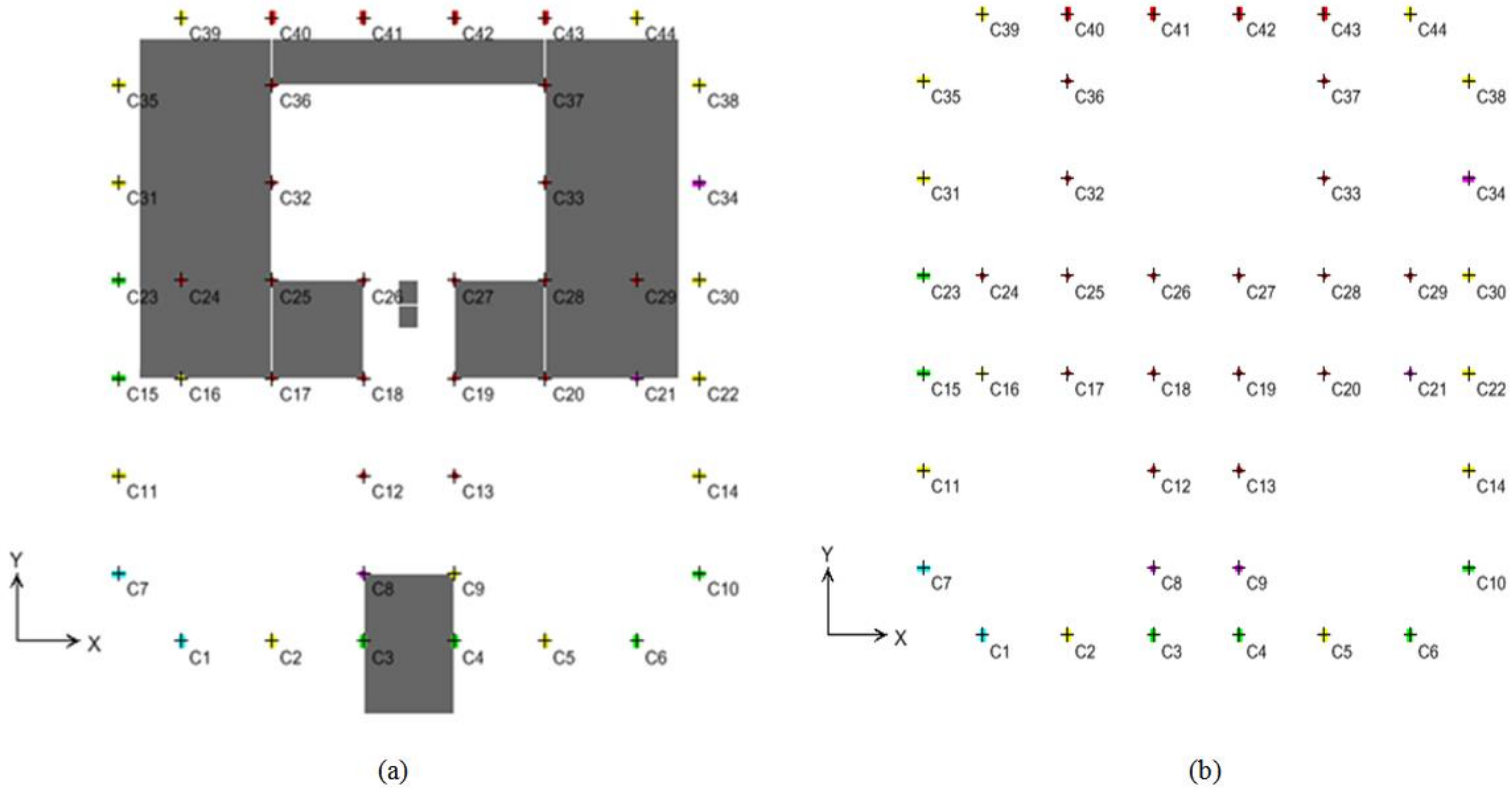


Fig. 9 Location of failed columns at (a) first storey (b) base level (Ground). Failed columns are indicated in red colour (these columns are strengthened). Other colours indicate different levels of safety as per design requirements (green being the safest, followed by blue, yellow and pink). The grey colour indicates the position of slabs in a particular floor.

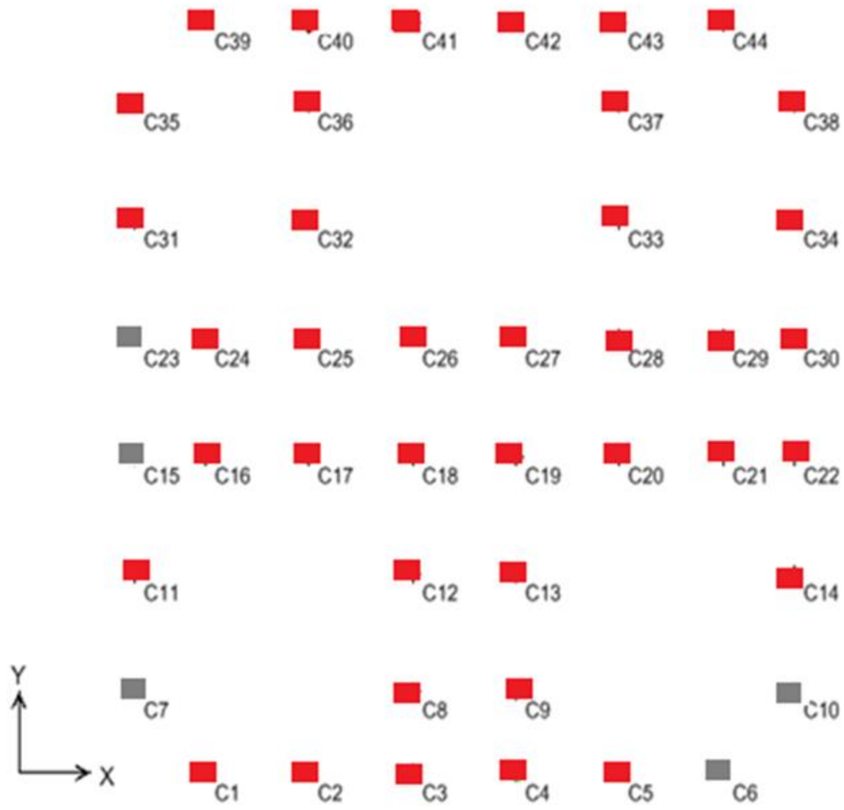


Fig. 10 Location of failed foundations (indicated in red colour)

Condition assessment

In the present analysis, it is observed that beams and slabs remain safe after the addition of extra storey. This is quite expected as the extra static loads are supposed to be transferred through the columns of first and second floor to the foundations. Several columns at different levels (refer to figure 8 and 9) and foundations (refer to figure 10) are found to be unsafe after the proposed expansion. The foundations failed due to gross bearing pressure of soil.

Strengthening schemes

For the strengthening of the columns, two different schemes (concrete jacketing and FRP strengthening) have been explored in this project. The adopted strengthening measures using concrete jacketing (increase in dimension and reinforcement, as required; refer to figure 2(a)) for the failed columns at different sections are presented in Table 5 (detailed results are shown in APPENDIX: Table A1- A4). It should be noted here that the requirement for

Table 5 Proposed strengthening schemes for the failed columns of first storey (detailed results are shown in APPENDIX: Table A1- A4)

Column number	Existing Size (mm^2)	Proposed Size (mm^2)	Existing Reinforcement (mm^2)	Rebar Percentage	Reinforcement Required (mm^2)	Additional Reinforcement Required (mm^2)	Extra Bars
C12	230 Ø	330 Ø	1205.76	0.95	812.1	0	
C17	230 Ø	330 Ø	1205.76	1.94	1658.4	452.6	4-12 Ø
C20	230 Ø	330 Ø	1205.76	1.92	1641.3	435.5	4- 12Ø
C24	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C25	230 Ø	330 Ø	1205.76	1.18	1008.7	0	
C26	230 Ø	330 Ø	1205.76	2.01	1718.2	512.5	4- 16Ø
				•			
				•			
				•			
C43	500x200	600x300	1440	0.8	1440	0	

Table 6 Manufacturer's reported FRP system properties

Thickness of ply (t_f)	0.33 mm
Ultimate tensile strength (f_{fu})	3792 MPa
Rupture strain (ε_{fu})	0.017
Modulus of elasticity (E_f)	227.523 MPa

Table 7 Capacity of the column before (n = 0 plies) and after (n = 6 plies) FRP strengthening

Points	n = 0 (plies)		n = 6 (plies)	
	ΦP_n (kN)	ΦM_n(kN-m)	ΦP_n(kN)	ΦM_n(kN-m)
A	9133.54	0	10331	0
B	6998	196	7856	359
C	3127	378	5639	489

increased dimension and reinforcement for third storey (new addition) can be taken care of during new construction.

Representative results for FRP strengthening is presented for column C41 as per the guidelines of ACI 440.2R-08. From the structural analysis results, the design forces

Table 8 Proposed strengthening schemes for foundations (detailed results are shown in APPENDIX: Table A5)

Column	Existing Size	Remarks	Proposed size	Depth	
				existing	Proposed
C1	2500x980	Valid Design			
C2	2500x980	Fails on GBP	2500x1065	450	450
C3	2500x980	Fails on GBP	2500x1255	450	450
C4	2500x980	Fails on GBP	2500x1270	450	450
C5	2500x980	Fails on GBP	2500x1170	450	450
			•		
			•		
			•		
C44	2500x980	Fails on GBP	2500x1135	450	450

obtained for the column are: P_u = 7321.55 kN ; M_{ux} = 170.25kN-m and M_{uy} = 2.295kN-m (negligible). However, capacity of the column is: P_{uc} = 6000 kN and M_{uxc} = 156 kN-m. So it is required to increase the load demand by 22% at constant eccentricity. The properties of FRP used in this study are given in Table 6. A wrapping system composed of 6 plies has been used for the strengthening by constructing the bilinear curve (refer to figure 3). Typical results for 6 plies are shown in Table 7, wherein it is clear that if six plies are used for the purpose of strengthening, the column becomes safe under the applied loading conditions. However, the design can be optimized further by trying lesser number of plies. Due to addition of the extra storey, several footings are found to be unsafe as indicated in figure 10. As the foundations fail due to gross bearing pressure (GBP), it has been recommended to increase dimension of the foundations as per requirements (refer to Table 8 and Table A5).

Discussion

In this paper we have discussed a critical study concerning the strengthening of an aged building. It can be noted that the intension of this article is not to propose any new methodology; rather we have adopted some of the well-established techniques here. The building was actually designed for G+1 storey and it was mentioned in the structural drawings that no further storey should be constructed over the existing building. However, due to requirement of vertical expansion owing to the purpose of capacity enhancement, one extra storey is proposed to be added leading to a requirement of strengthening the existing structure. The library building being a monumental structure with historical significance, demolition and subsequent reconstruction of a new building is not an option in this case. In general, such masonry buildings share a large percentage of the current building stock in most parts of the world. The use of unreinforced masonry (URM) for load bearing walls in these buildings is a common practice. The URM walls are normally prone to failure under seismic in-plane and out-of-plane deformations. The in-plane behaviour of URM walls is crucial, as it provides the primary load path for transfer of seismic loads. However, URM has also very low tensile strength and hence, the URM walls are highly vulnerable to out-of-plane flexure. The contemporary design guidelines, which were followed during construction of the buildings, were not very sophisticated to account for the effect of earthquake loading. Thus to ensure the modern safety and serviceability requirements, these buildings are often needed to be strengthened as per the latest codal provisions. Due to sustained policies of several governments worldwide, old structures are encouraged to be strengthened/ retrofitted according to modern design guidelines for economic benefits and to preserve monumental structures of historical significance (Power 2010; Fernandez 2017). Computer modelling of the present G+2 storey library building reveals that several columns and footings fail to satisfy the design requirement as per latest codal provisions. In most of the cases, the size of the columns are increased with minor or no change in the area of longitudinal reinforcements for concrete jacketing (Pillai and Menon 2009, IS 15988 2013). Most of the footings fail due to soil bearing pressure. Mostly the depth and size of the column footings are suggested to be increased without significantly changing the area of the reinforcements so as to make the strengthening work feasible (refer to figure 11) (Thermou and Elnashai 2006; Website 2019). No major action of strengthening is required to be taken for beams and slabs. Though here the columns are strengthened by following two different schemes: concrete jacketing and FRP strengthening, future investigations can be carried out to investigate other potential

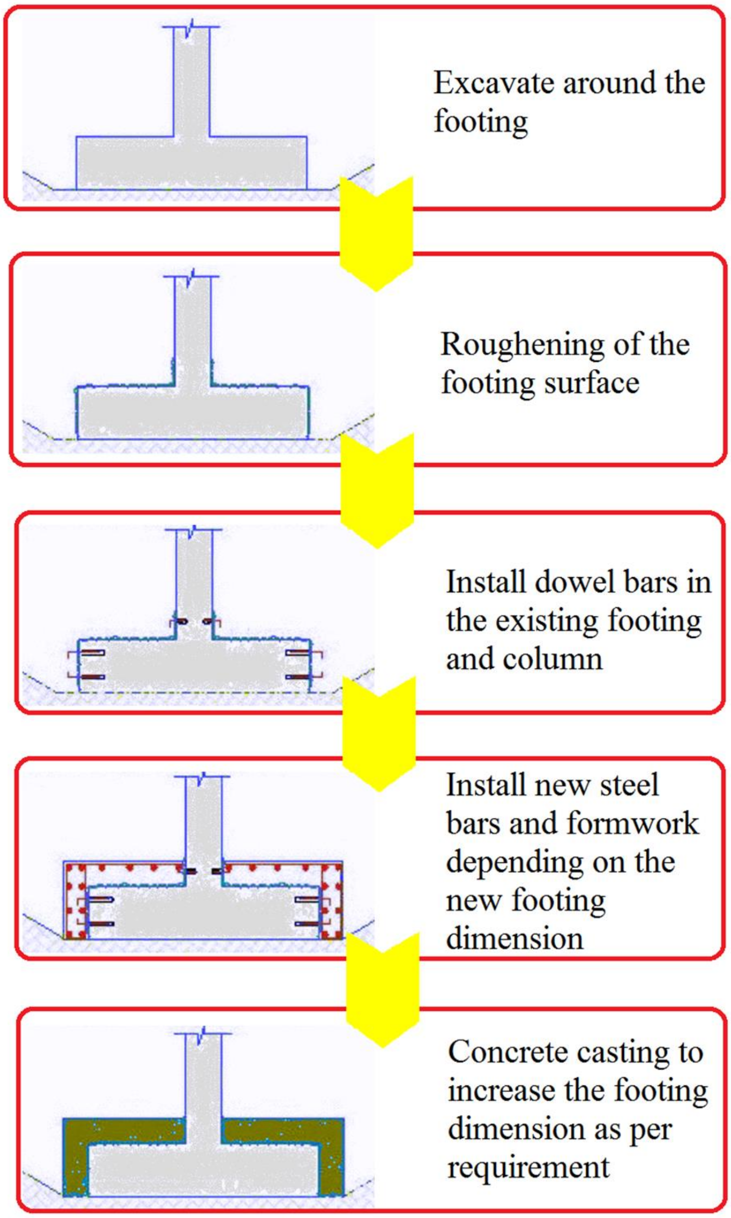


Fig. 11 Strengthening scheme for column footings

methods of strengthening such as steel-jacketing (Campione et al. 2017; Ferrotto et al. 2018).

In view of the above discussion, it is observed that most of the columns and footings are required to be strengthened for the safety of the library building. From a construction point of view, though the columns can be easily strengthened either by using FRP or by concrete jacketing, but strengthening the footings by increasing their size is difficult due to involvement of excavation. FRP strengthening may be a superior choice than concrete jacketing for strengthening of columns form the viewpoint of space optimization. A direct comparative economic assessment on the basis of the cost of materials can be carried out based on the detailed strengthening scheme presented in this article considering the concrete jacketing and FRP strengthening. The issue of cost effectiveness of the two prospective methods should be accounted before choosing the most suitable option for strengthening of a particular structural element. The execution of such strengthening works should be decided at appropriate level based on economical and constructional feasibility.

Conclusion

A brief overview of condition assessment and strengthening for existing structures has been presented in this article. To illustrate the topic further a practical problem has been considered concerning strengthening the structural elements of a historical library building, which is examined for the purpose of prospective vertical expansion. Even though the beams and slabs do not need any major strengthening measure due to addition of an extra storey, several columns and footings are found to fail as per the existing structural configuration. For strengthening the columns, two different schemes (concrete jacketing and FRP strengthening) have been explored and detail results are presented. The footings are found to fail due to gross bearing pressure of soil and therefore, to strengthen the footings, their dimensions have been increased in most of the cases. Monumental structures with historical significance are often required to be strengthened or retrofitted, instead of a complete demolition and subsequent reconstruction. Moreover, due to sustained policies of several governments worldwide, old structures are encouraged to be strengthened/ retrofitted according to modern codal provisions ensuring various safety and serviceability criteria, after appropriate condition assessment instead of constructing a new structure in place of the old one. As practical case studies on condition assessment and strengthening of civil engineering structures with adequate technical insights are very scarce to find in published literature, this article on the critical aspects of structural health monitoring of historical old buildings is expected to serve as a valuable reference for practicing engineers and the concerned scientific community.

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APPENDIX

Table A1 Proposed strengthening schemes for the failed columns of third storey

Column number	Existing Size (mm^2)	Proposed Size (mm^2)	Existing Reinforcement (mm^2)	Rebar Percentage	Reinforcement Required (mm^2)	Additional Reinforcement Required (mm^2)	Extra Bars
C8	230x230	330x330	803.84	0.8	871.2	68	4-12 Ø
C9	230x230	330x330	803.84	0.8	871.2	68	4-12 Ø
C12	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C13	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C16	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C17	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C18	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C19	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C20	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C21	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C24	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C25	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C26	230 Ø	330 Ø	1205.76	0.9	769.3	0	
C27	230 Ø	330 Ø	1205.76	0.9	769.3	0	
C28	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C29	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C32	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C33	230 Ø	330 Ø	1205.76	0.8	683.	0	
C36	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C37	230 Ø	330 Ø	1205.76	0.8	683.8	0	

Table A2 Proposed strengthening schemes for the failed columns of second storey

Column number	Existing Size (mm^2)	Proposed Size (mm^2)	Existing Reinforcement (mm^2)	Rebar Percentage	Reinforcement Required (mm^2)	Additional Reinforcement Required (mm^2)	Extra Bars
C12	230 Ø	330 Ø	1205.76	0.87	743.7	0	
C13	230 Ø	330 Ø	1205.76	0.88	752.2	0	
C17	230 Ø	330 Ø	1205.76	1.18	1008.7	0	
C18	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C19	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C20	230 Ø	330 Ø	1205.76	1.17	1000.1	0	
C26	230 Ø	330 Ø	1205.76	1.37	1171.1	0	
C27	230 Ø	330 Ø	1205.76	1.37	1171.1	0	
C32	230 Ø	330 Ø	1205.76	2.19	1872.1	666.3	4- 16 Ø
C33	230 Ø	330 Ø	1205.76	2.07	1769.5	563	4- 16 Ø
C41	500x200	600x300	1440	0.8	1440	0	
C42	500x200	600x300	1440	0.8	1440	0	

Table A3 Proposed strengthening schemes for the failed columns of first storey

Column number	Existing Size (mm^2)	Proposed Size (mm^2)	Existing Reinforcement (mm^2)	Rebar Percentage	Reinforcement Required (mm^2)	Additional Reinforcement Required (mm^2)	Extra Bars
C12	230 Ø	330 Ø	1205.76	0.95	812.1	0	
C13	230 Ø	330 Ø	1205.76	0.96	820.6	0	
C17	230 Ø	330 Ø	1205.76	1.94	1658.4	452.6	4-12 Ø
C18	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C19	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C20	230 Ø	330 Ø	1205.76	1.92	1641.3	435.5	4- 12Ø
C24	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C25	230 Ø	330 Ø	1205.76	1.18	1008.7	0	
C26	230 Ø	330 Ø	1205.76	2.01	1718.2	512.5	4- 16Ø
C27	230 Ø	330 Ø	1205.76	2.04	1743.9	538.1	4-16 Ø
C28	230 Ø	330 Ø	1205.76	1.16	991.6	0	
C29	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C32	230 Ø	330 Ø	1205.76	2.79	2385	1179	4-20 Ø
C33	230 Ø	330 Ø	1205.76	2.67	2282.4	1076	4-20 Ø
C36	230 Ø	330 Ø	1205.76	1.04	889	0	
C37	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C40	500x200	600x300	1440	0.8	1440	0	
C41	500x200	600x300	1440	0.8	1440	0	
C42	500x200	600x300	1440	0.8	1440	0	
C43	500x200	600x300	1440	0.8	1440	0	

Table A4 Proposed strengthening schemes for the failed columns at base level (ground)

Column number	Existing Size (mm^2)	Proposed Size (mm^2)	Existing Reinforcement (mm^2)	Rebar Percentage	Reinforcement Required (mm^2)	Additional Reinforcement Required (mm^2)	Extra Bars
C12	230 Ø	330 Ø	1205.76	1.01	863.4	0	
C13	230 Ø	330 Ø	1205.76	1.02	871.9	0	
C17	230 Ø	330 Ø	1205.76	1.98	1692.6	486.8	4- 16Ø
C18	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C19	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C20	230 Ø	330 Ø	1205.76	1.97	1684	478.3	4- 16Ø
C24	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C25	230 Ø	330 Ø	1205.76	1.23	1051.4	0	
C26	230 Ø	330 Ø	1205.76	3.49	2983.4	1777	4- 20Ø
C27	230 Ø	330 Ø	1205.76	3.6	3077.5	1871	4-20 Ø
C28	230 Ø	330 Ø	1205.76	1.21	1034.3	0	
C29	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C32	230 Ø	330 Ø	1205.76	2.74	2342.3	1136	4-20 Ø
C33	230 Ø	330 Ø	1205.76	2.61	2231.1	1025	
C36	230 Ø	330 Ø	1205.76	1.09	931.8	0	
C37	230 Ø	330 Ø	1205.76	0.8	683.8	0	
C40	500x200	600x300	1440	0.8	1440	0	
C41	500x200	600x300	1440	0.8	1440	0	
C42	500x200	600x300	1440	0.8	1440	0	
C43	500x200	600x300	1440	0.8	1440	0	

Table A5 Proposed strengthening schemes for foundations

Column	Existing Size	Remarks	Proposed size	Depth	
				existing	Proposed
C1	2500x980	Valid Design			
C2	2500x980	Fails on GBP	2500x1065	450	450
C3	2500x980	Fails on GBP	2500x1255	450	450
C4	2500x980	Fails on GBP	2500x1270	450	450
C5	2500x980	Fails on GBP	2500x1170	450	450
C6	2500x980	Valid Design		450	450
C7	2500x980	Valid Design			
C8	1600x1600	Fails on GBP	1650x1650	450	450
C9	1600x1600	Fails on GBP	1660x1660	450	450
C10	2500x980	Valid Design		450	450
C11	2500x980	Fails on GBP	2500x1030	450	450
C12	1600x1600	Fails on GBP	1880x1880	450	450
C13	1600x1600	Fails on GBP	1880x1880	450	450
C14	2500x980	Fails on GBP	2500x1225	450	450
C15	2500x980	Valid Design			
C16	1600x1600	Fails on GBP	1675x1675	450	450
C17	1600x1600	Fails on GBP	2175x2175	450	460
C18	1600x1600	Fails on GBP	1870x1870	450	450
C19	1600x1600	Fails on GBP	1870x1870	450	450
C20	1600x1600	Fails on GBP	2170x2170	450	450
C21	1600x1600	Fails on GBP	1715x1715	450	450
C22	2500x980	Fails on GBP	2500x1225	450	450
C23	2500x980	Valid Design			
C24	1600x1600	Fails on GBP	1815x1815	450	450
C25	1600x1600	Fails on GBP	2225x2225	450	500
C26	1600x1600	Fails on GBP	2465x2465	450	600
C27	1600x1600	Fails on GBP	2475x2475	450	610
C28	1600x1600	Fails on GBP	2215x2215	450	500
C29	1600x1600	Fails on GBP	1845x1845	450	450
C30	2500x980	Fails on GBP	2500x1340	450	450
C31	2500x980	Fails on GBP	2500x1390	450	450
C32	1600x1600	Fails on GBP	2365x2365	450	570
C33	1600x1600	Fails on GBP	2325x2325	450	550
C34	2500x980	Fails on GBP	2500x1510	450	450
C35	2500x980	Fails on GBP	2500x1155	450	450
C36	1600x1600	Fails on GBP	2040x2040	450	450
C37	1600x1600	Fails on GBP	1925x1925	450	450
C38	2500x980	Fails on GBP	2500x1100	450	450
C39	2500x980	Fails on GBP	2500x1145	450	450
C40	2500x980	Fails on GBP	2500x1600	450	450
C41	2500x980	Fails on GBP	2500x2130	450	530
C42	2500x980	Fails on GBP	2500x2170	450	550
C43	2500x980	Fails on GBP	2500x1680	450	450
C44	2500x980	Fails on GBP	2500x1135	450	450