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Structural Health Monitoring And Repairs: A Case Study From Mumbai

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Abstract:
This paper presents a case study of a two story (G+2) institutional building, it is framed structure made of RCC columns, beams & slabs. Age of the building is in the range of 47 to 50 years as per the construction. Structural audit was conducted for proposed repairs, rehabilitation, and retrofitting of an existing building. The structural health monitoring was conducted using visual inspection, detailed distress mapping, and non-destructive tests. The structural health monitoring is a crucial tool for assessing the condition, serviceability, and safety of the structure. It helps in identifying risk areas, critical areas, and the need for immediate attention. The structural health monitoring also investigates the impact of changing the building's use from residential to commercial or industrial on its performance. The purpose of the audit is to save life and property, assess the extent of distress, estimate the residual life of the structure, highlight critical areas, advise residents/owners/users about the problems' seriousness, comply with statutory requirements, and select an effective remedy. This paper emphasizes the importance of conducting a structural audit before undertaking any repair or retrofitting work to ensure the structure's safety and durability and then the repairing work is taken care.

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I. Introduction:

The building considered Library building located in Mumbai. The A & B Wing of the building was constructed in 1973, while the C & D Wing was constructed in 1976. The A & B Wing has an approximate age of 45 years, while the C & D Wing is approximately 42 years old. The building is currently used as a library, with the ground floor and mezzanine floor serving as lending sections. It is an RCC framed structure with a total of four wings.

The building consists of a ground floor and two additional stories. The floor heights are as follows: Ground Floor - 2.45m, Mezzanine Floor - 3.15m, 1st Floor - 3.35m. The building has an X-shaped layout with re-entrant corners. The plinth level of the building ranges from 0.2m to 0.3m above ground level. Previous repair history includes painting and petty/patch repair work. There are no reported incidents of flooding in the building's history. There is no history of water logging in the area. No adjoining construction or excavation has been noticed. The building is located approximately 5 kilometres away from the sea. There is no significant level difference with the adjoining plots.

Building was checked for design according to Indian Codes IS 456:2000 - Plain and Reinforced Concrete

Visual Inspection and Critical Observations:

Visual examination of structure was the most effective and qualitative approach to evaluate the structural soundness and to identify the typical distress symptoms together with the associated problems. With experience in condition assessment, Structural Audit and Rehabilitation Engineering, the symptoms of distress allowed a reasonably sufficient understanding of the cause of distress, as these are related with the age of the structure.

This provided following valuable information concerning its workmanship, structural serviceability and material deterioration mechanism. It gave a quick scan of the structure to ***assess*** its status of general health.

Building common areas

1. **Overall Condition of Plinth***:* *Flooring is found to be levelled except at few locations, C wing flooring was observed to be uneven. Plinth is 0.2m to 0.3m above ground level.*
2. **Settlement:** *No settlement in foundation has been observed.*

Note: Even though no settlements in foundation are specifically noticed, the same cannot be ruled out.

External faces

1. *The building is a framed structure made of RCC columns, beams & slabs.*

2. *Overall plaster is in distress condition with bulging, cracking & delamination on all faces of building.*
3. *All faces show weathering effect in terms of leakages/seepages & exposed reinforcement at most of the locations.*
4. *Dampness has been observed on brick masonry wall due to leakages / seepages through toilets & drainage pipes.*
5. *External faces show deterioration due to weathering at many locations.*
6. *External beams and columns have been observed to be cracked at reentrant corners of the building due to corrosion activity present inside structural members.*
7. *Heavy vegetation growth has been observed at Chajjas & on plinth protection in external periphery of building.*
8. *Elevation pardi has been observed to be cracked at few locations.*
9. *Moss collection & formation of fungus on external walls has been observed at south east portion of building.*
10. *Reinforcement exposure in beams, columns & Chajjas due to corrosion & weathering effects was observed at south east portion of building resulting in sagging of beams and lintels above windows.*

Masonry & Plaster

1. *Dampness to the external and internal masonry walls has been observed due to seepage / leakage.*
2. *Cover concrete have been fallen and reinforcement found to be exposed / corroded at few locations.*

3. Plumbing

1. *Leakages have been observed at few locations of plumbing lines which leading to vegetation growth, dampness to masonry walls and delamination of plaster.*
2. *Conduit pipes were missing at few locations.*

4. Staircase & Passages

1. *Cover concrete has been fallen at few locations of the common passage with exposed reinforcement of few beams & slabs.*
2. *On tapping with ebonite hammer, hollow sound can be heard at few locations in passage.*
3. *Overall Staircase (Waist) slab is in good condition.*
4. *Vertical cracks due to corrosion of rebar have been observed throughout the length of few column in common passage area.*
5. *Separation crack between Masonry walls & RCC members has been observed at many locations.*

Terrace

1. *Bituminous overlay has been observed on junctions/ joints of wings & at internal periphery of terrace over IPS water proofing layer was observed. Damages and cracks have been observed on bituminous over layer, IPS water proofing layer also found to be damaged and cracks at few locations results in leakages / seepage to top floor.*
2. *Skylights were provided on terrace floor and it has been covered with bituminous overlay to prevent leakage/seepage.*

Over Head Water Tank

1. *The RCC Water Tank has been observed to be provided on all 4 wings of terrace.*
2. *Leakages through bottom slabs of water tanks causing vegetation growth on terrace floor.*
3. *Deterioration of RCC tank pardi has been observed with exposure reinforcement of RCC pardis and bottom slabs.*

Internal observation

1. *Seepages through slabs have been observed.*
2. *Bulging / Cracking of plaster have been observed at few locations of beams and columns in C wing & D wing area.*
3. *Delamination of cover concrete and corroded reinforcement has been observed at many locations of beams, columns and slabs in C wing & D wing area.*
4. *C wing & D wing is affected by corrosion of structural members due to weathering effects.*
5. *At most of the location, RCC slab gives hollow after tapping with ebonite hammer. Further, delamination of cover concrete and exposed reinforcement has been observed at few locations.*
6. *Most of the distress & cracks to structural members are due to the corrosion of reinforcement.*
7. *Separation cracks has been observed between the masonry and RCC element at many locations.*
8. *Formation of moss and fungus on walls was also observed at common passage area.*

9. *Dampness has been observed on external masonry walls at most of the locations.*
10. *It has been observed that lintels in south east portion of the structure has wide corrosion cracks.*
11. *Overloading: in few columns at C wing crack pattern indicates signs of overloading which may be due to deterioration of column or due to long column effect.*
12. *Mezzanine/ lofts : Yes, mezzanine floor was present.*
13. *Vibration : Vibration not felt.*
14. *Termites : Yes, Termite present at few locations in structure.*
15. *Existing propping : Not observed.*

Chajjas

1. *Exposure reinforcement, bulging and spalling of cover concrete of Chajjas has been observed at many locations mainly due to weathering effects & corrosion.*

NON-DESTRUCTIVE TEST

The test performed on existing structure to check the current structural condition and material uniformity is Rebound Hammer Test, Ultra Sonic Pulse Velocity (USPV) Test, Half Cell Potentiometer Test and Carbonation Test.

Rebound Hammer Test

The test is performed as per guidelines given by IS: 13311 (Part 2): 1992 & BS 1881: Part 202: 1986 to estimate the in-situ strength of concrete based on the correlation established between in-situ strength at the particular location & rebound numbers.

When the plunger of rebound hammer is pressed against the surface of concrete, a spring-controlled mass with a constant energy is made to hit concrete surface to rebound back. The extent of rebound, which is a measure of surface hardness, is measured on a graduated scale. This measured value is designed as Rebound Hammer (a rebound index). A concrete with low strength and low stiffness will absorb more energy to yield in a lower rebound value. The results are significantly affected by the following factors:

a. Mix characteristics:
   i. Cement type,
   ii. Cement content,
   iii. Coarse aggregate type:
b. Angle of Inclination of direction of hammer with reference to horizontal
c. Member characteristics:
   i. Mass,
   ii. Compaction,
   iii. Surface type,
   iv. Age, rate of hardening and curing type,
   v. Surface carbonations,
   vi. Moisture condition,
   vii. Stress state and temperature

Comparison of Rebound numbers, which indicate the near surface hardness of the concrete, will help to identify relative surface weaknesses in cover concrete and also can be used to determine the relative compressive strength of concrete. Locations possessing very low rebound numbers will be identified as weak surface concrete.

Steps to carry out Rebound Hammer Test:

1. The plaster is removed at test locations (patch of min 6”x6”).
2. The test location selected shall be smooth, clean, dry without any defect like Honeycombing cracks and without hollow sound is selected.
3. The patch is scrubbed with carborandum stone to remove loosely adhered scales, and remains of plaster mortar,
4. By holding the rebound hammer at right angles to surface of the concrete member, 7 readings are taken with random distribution over the entire patch.
5. Of these readings, abnormally high & abnormally low results are eliminated & average of the balance readings is worked out.
6. Taking into consideration the factors influencing hardness of the concrete surface like moisture condition of the surface, carbonation, test location within the member, direction of test etc. corrected rebound number is worked out.
7. Apparent compressive strength of concrete against corrected rebound number is obtained from graph.
8. The statistical analysis is carried out for this set of values of compressive strengths obtained by above

method if required.
Table 1 is showing results of rebound hammer test.

Table 1: Results of Rebound Hammer Test

REBOUND HAMMER TEST READINGS										
Sr. No.	**R.C.C. MEMBER**	**LOCATION**	**R1**	**R2**	**R3**	**R4**	**R5**	**AVERAGE REBOUND No.**	**COMP. STRENGTH (MPa)**	**DIRECTION OF TEST**
			Ground Floor							
1	Column	C1	39	35	37	36	37	37	35.0	Horizontal
2	Column	C2	40	39	37	35	39	38	37.0	Horizontal
3	Column	C3	39	38	35	40	37	38	37.0	Horizontal
4	Column	C16	39	33	40	30	42	37	35.0	Horizontal
5	Column	C15	32	27	31	24	28	28	20.0	Horizontal
6	Column	C5	31	29	32	31	29	30	35.0	Horizontal
7	Column	C6	38	38	35	39	33	37	33.5	Horizontal
8	Column	C7	38	38	33	35	38	36	33.5	Horizontal
9	Beam	B1	36	35	30	33	30	33	28.0	Horizontal
10	Beam	B3	20	22	30	28	20	24	15.0	Horizontal
11	Beam	B4	22	24	22	20	26	23	13.5	Horizontal
			Mezzanine Floor							
12	Column	C12	29	25	25	31	32	28	20.0	Horizontal
13	Column	C14	44	35	32	30	34	35	31.5	Horizontal
14	Beam	B2	22	24	22	20	26	23	13.5	Horizontal
15	Slab	S1	38	38	40	36	34	37	28.0	Vertical U
16	Slab	S2	28	24	30	24	25	26	11.0	Vertical U
17	Slab	S3	39	39	38	42	39	39	31.5	Vertical U
			First Floor							
18	Column	C8	38	34	35	34	32	35	31.5	Horizontal
19	Column	C9	29	24	34	32	34	31	25.0	Horizontal
20	Column	C10	26	24	28	27	28	27	19.0	Horizontal
21	Column	C11	30	32	32	32	36	32	26.5	Horizontal
22	Column	C13	36	50	40	38	32	39	38.5	Horizontal
23	Slab	S4	30	30	30	38	44	34	23.0	Vertical U
24	Beam	B5	30	35	36	34	28	33	28.0	Horizontal
25	Beam	B6	36	30	30	32	34	32	26.5	Horizontal
								Average=	**27.0**	
Average apparent concrete strength based on rebound hammer test is 27.0 N/mm2										

Ultra Sonic Pulse Velocity Test

Being a recognized non-destructive evaluation test to qualitatively assess the homogeneity and integrity of concrete, the Ultrasonic scanning was proposed to assess the following.

1. Qualitative assessment of strength of concrete, its gradation in different locations of structural members and plotting the same.
2. Any discontinuity in cross section like cracks, cover concrete delamination etc.

Though pulse velocity is related with crushing strength of concrete, yet no statistical correlation can be applied. The pulse velocity in concrete may be influenced by:

1. Path length
2. Lateral dimensions of the specimen tested
3. Presence of reinforcing steel
4. Moisture content of the concrete

The influence of path length will be negligible provided, it is not less than 100 mm, when 20 mm size aggregate is used. Pulse velocity will not be influenced by the shape of the specimen, provided its least lateral dimension (i.e. its dimension measured at right angles to the pulse path) is not less than the wavelength of the pulse vibrations. For pulse of 50 Hz frequency, this corresponds to a least lateral dimension of about 80 mm. The velocity of pulses in a steel bar is generally higher than they are in concrete. For this reason, pulse velocity measurements made in the vicinity of reinforcing steel may be high and not representative of the concrete.

Table 2 below shows guidelines for qualitative assessment of concrete based on UPV results.

Table 2: Guidelines for qualitative assessment of concrete based on UPV results.

Pulse Velocity	Concrete Quality	**Quality of Concrete**
> 4.0 km/s	Very good to excellent	Excellent
3.5-4.0 km/s	Good to very good, slightly porosity may exist	Good
3.0-3.5 km/s	Satisfactory but loss of integrity is suspected	Medium
<3.0 km/s	Poor and loss of integrity exist	Doubtful

To make a more realistic assessment of the condition of surface concrete of a structural member, the pulse velocity values is combined with rebound number. For Indirect transmission i.e. Surface probing in general gives lower pulse velocity than in case of cross probing and depending on number of parameters, the difference could be of the order of about 1 km/sec. Results are mentioned in Table 3.

Table 3: Results of Ultra Sonic Pulse Velocity

UPV TEST READINGS						
Sr. No.	**R.C.C. MEMBERS**	**LOCATION**	**VELOCITY (Km/Sec.)**	**VELOCITY (Km/Sec.)**	**AVERAGE VELOCITY (Km/Sec.)**	**METHOD OF TESTING**
		Ground Floor				
1	Column	C1	3.54	2.02	2.78	ID
2	Column	C2	3.54	3.94	3.74	ID
3	Column	C3	4.00	2.72	3.36	ID
4	Column	C5	1.61	1.70	1.66	ID
5	Column	C6	5.84	6.08	5.96	ID
6	Column	C7	5.84	6.00	5.92	ID
7	Column	C15	4.95	6.00	5.47	ID
8	Column	C16	4.49	4.09	4.29	ID
9	Beam	B1	4.5	4.5	4.50	SD
10	Beam	B3	1.4	1.4	1.37	D
11	Beam	B4	2.40	2.42	2.41	SD
12	Slab	S2	5.84	6.08	5.96	ID
		Mezzanine Floor				
13	Column	C12	3.27	2.03	2.65	ID
14	Beam	B2	2.29	2.28	2.29	ID
15	Slab	S1	3.05	3.91	3.48	ID
16	Slab	S3	3.46	2.94	3.20	ID
17	Column	C14	2.15	2.00	2.07	ID
		First Floor				
18	Column	C8	4.0	4.0	4.00	SD
19	Column	C9	4.3	4.0	4.15	SD
20	Column	C10	5.7	5.6	5.63	SD
21	Column	C11	3.9	3.9	3.93	SD
22	Column	C13	3.21	2.64	2.92	ID
23	Slab	S4	2.43	3.44	2.93	ID

24	Beam	B5	3.85	3.72	3.79	ID
25	Beam	B6	3.54	2.29	2.91	ID
			Average=		**3.66**	
Average Ultra Sonic Pulse Velocity is **3.66 km/s**, which indicates that apparent quality of concrete is Medium-Good.						

Notations:
D = Direct; ID = Indirect; SD = Semi direct
UPV result summary is as shown in Table 4

Table 4: UPV Result Summary

UPV Results Summary		
Criteria	**Concrete Quality**	**No. of readings**
Above 4.5 km/s	Excellent	7
3.5 to 4.5 km/s	Good	5
3.0 to 3.5 km/s	Medium	3
Below 3.0 km/s	Doubtful	10

Half Cell Potentiometer Test

The instrument as shown in Figure 1, measures the potential and the electrical resistance between the reinforcement and the surface to evaluate the corrosion activity as well as the actual condition of the cover layer during testing. The electrical activity of the steel reinforcement and the concrete leads them to be considered as one half of weak battery cell with the steel acting as one electrode and the concrete as the electrolyte. The name half-cell surveying derives from the fact that the one half of the battery cell is considered to be the steel reinforcing bar and the surrounding concrete. The electrical potential of a point on the surface of steel reinforcing bar can be measured comparing its potential with that of copper – copper sulphate reference electrode on the surface. Practically this achieved by connecting a wire from one terminal of a voltmeter to the reinforcement and another wire to the copper sulphate reference electrode. Then readings taken are at grid of 1 x 1 m.

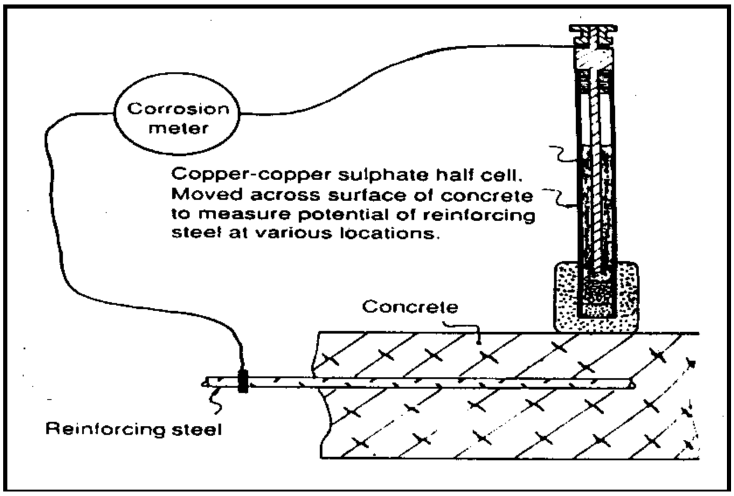


Fig. 1: Half-cell Potential Test

The risk of corrosion is evaluated by means of the potential gradient obtained, the higher the gradient, and the higher risk of corrosion. The test results can be interpreted based on the following table.

Table 5: Half Cell Potential Corresponding to Percentage Chance of Corrosion Activity

Half-cell potential (mv) relative to Cu-Cu sulphate Ref. Electrode	% chance of corrosion activity
Less than -200	<5%
Between -200 to -350	50% (uncertain)
Above -350	>90%

This method may be used to indicate the corrosion activity associated with steel embedded in concrete. This method can be applied to members regardless of their size or the depth of concrete cover. This method can be used at the any time during the life of concrete member.

Reliability and Limitation:

The test does not give corrosion rate or whether corrosion activity has already started, but it indicates the probability of the corrosion activity depending upon the actual surrounding conditions. If the concrete surface has dried to the extent that it is dielectric, then pre wetting of concrete is essential. Result of half Cell potentiometer Test is as shown in Table 6.

Table 6: Results of half Cell potentiometer Test

HCP Results Summary		
Criteria	**Probability of corrosion**	**No. of readings**
Less than -200 mV	<5%	2
-200 mV to -350 mV	50%	2
More than -350 mV	>95%	5

Half-cell potentiometer indicates the probability of corrosion ranging from Moderate to High level. From visual inspection & Half-cell potentiometer test it is evident that moderate to high corrosion activity is present.

Carbonation Test

Carbonation of concrete occurs when the carbon dioxide, in the atmosphere in the presence of moisture, reacts with hydrated cement minerals to produce carbonates, e.g. calcium carbonate. The carbonation process is also called depassivation. Carbonation penetrates below the exposed surface of concrete extremely slowly.

Equipment for Carbonation Depth Measurement Test

If there is a need to physically measure the extent of carbonation it can be determined easily by spraying a freshly exposed surface of the concrete with a 1% phenolphthalein solution. The un-carbonated portion of concrete changes to pink color while the carbonated portion does not change color.

Table 7: Results of Carbonation Test

CARBONATION TEST RESULTS						
Sr. No	**R.C.C MEMBER**	**DEPTH OF HOLE (mm)**	**COLOUR INDICATION**			**DEPTH OF CARBONATION**
			0-10	**11-20**	**21-40**	**(mm)**
1	At ground floor, Column C2	40	NCC	NCC	CCFP	30
2	At ground floor, Column C3	40	NCC	CCFP	NCC	20
3	At ground floor, Column C4	40	NCC	NCC	CCFP	40
4	At ground floor, Beam B1	30	NCC	CCFP	NCC	15
5	At ground floor, Beam B2	30	NCC	NCC	CCFP	30
6	At ground floor, Slab S1	25	NCC	NCC	CCFP	25
7	At First floor, Beam B3	30	NCC	NCC	CCFP	30
8	At First floor, Slab S2	25	NCC	NCC	CCFP	25
9	At First floor, Slab S3	25	NCC	NCC	CCFP	25
Average depth of carbonation =						**26.67**

Notations: NCC = No colour change; CCFP = Colour changed to faint pink; CCDP = Colour changed to dark pink

Corrosion of concrete surface is associated with the carbonation of concrete surface as noted probability of **Corrosion** is found to be 50% to >95% at most of the locations, Average carbonation has almost exceeded half the limiting value for column while exceeded limiting value for beam & Slab.

DISTRESS MAPPING

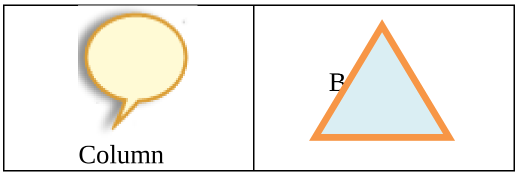
Distress mapping has been carried out and the following levels of distress are assigned to each of the building element.

Levels of distress:

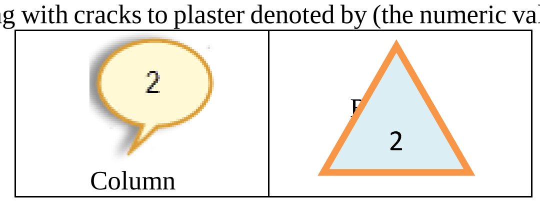
1 - Minor cracks to plaster.
2 - Minor corrosion cracks to structural member along with cracks to plaster.
3 - Major corrosion cracks to structural member / cover concrete spalled in patches
4 - Cover concrete spalled & reinforcement exposed at few locations.
5 - Cover concrete spalled & reinforcement exposed/corroded at majority of locations.
6 - Structural member broken, cover concrete fallen & reinforcement broken also.
7 - Bulging of column/ sagging of beam/ sagging of slab.
8 - Leakages, dampness, seepage etc.
9- Hollow sound / air pockets present

Sign Convention

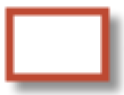
Distress in beam or column with level of distress.



e.g. Minor cracks to beam along with cracks to plaster denoted by (the numeric value denotes the level of distress)



2) Distress in slab



3) Distress in RCC element other than Column, Beam and Slab

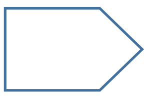


Figure 2 shows distress mapping on plan.

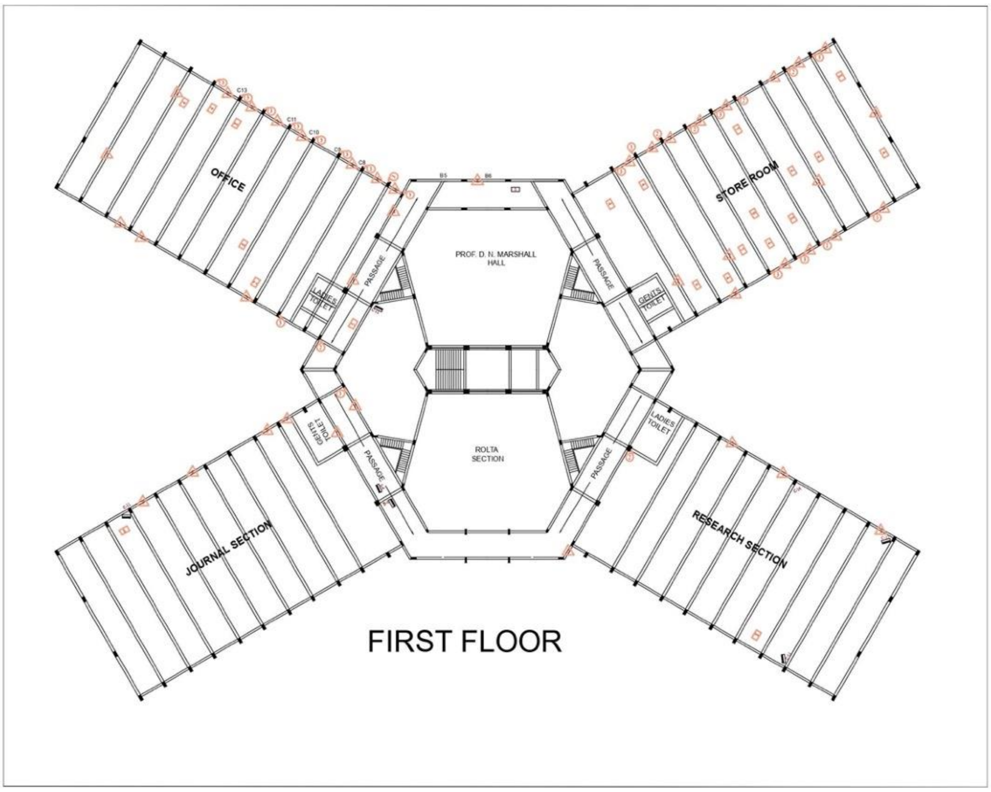


Fig.2 Distress Mapping on Plan for First floor

Concluding Remarks and Repairing :

The building is a G + 2 storied RCC framed structure, Wings A & B constructed and commissioned in year 1973, Wings C & D in 1976 & i.e. the building structure is around 45 & 42 years old respectively. External faces show deterioration due to weathering. The detailed inspections along with Non-Destructive Tests have been performed to assess the condition of the building.

The column, beams and slabs are deteriorated showing delamination of cover concrete and corroded reinforcement. RCC slabs gives hollow sound after tapping with ebonite hammer at many locations. Wide corrosion cracks have been observed on soffit of beams and column throughout their length. Leakages, seepage / dampness resulting in spalled / fallen cover concrete with exposed and corroded reinforcement. RCC elements projection out of building face (weather shade / chajja / fins / architectural features) is in distress condition with delamination of cover concrete. Leakage/Seepage present through walls, slab at most of the location. Severe deterioration of structural members (beam, column, and slab) has been observed near staircase, passage, C wing & D Wing area at Ground & 1st floor also at water tank. The deterioration/distresses observed in the RCC elements are primarily due to corrosion of reinforcement steel.

The external plaster has been observed with cracks, bulging and delamination at few locations. Plumbing lines has been observed in working condition with minor leakages near junctions resulting in leakages dampness & moss collection.

Results of the various NDT tests and the visual inspection survey are combined to conclude the quality of the concrete. The on-site experimental investigation revealed signs of loss of strength as well as loss of integrity of a few structural elements. **Rebound hammer test** results indicate reduction in in-situ strength of concrete. **Ultrasonic pulse velocity** also shows that the in-situ concrete is of uncertain quality with loss of integrity in few RCC elements. **Carbonation** has reached to an average depth of **26.67 mm** ranging from **20-40 mm**. **Half-cell potentiometer** indicates the probability of corrosion is **50% to >95%**. However visual inspection indicates that the corrosion in RCC members is of **moderate to severe** level.

It can be concluded that the building structure is not in dilapidated condition. However, few RCC elements primarily beams, columns, slab needs urgent structural repairs. If adequate structural repair, strengthening & retrofit measure are undertaken then enhancement in service life of the building structure can be achieved. To prevent mishaps and/or casualties Vertical props should immediately be provided at C & D wing on 1st floor where the slabs & beams are observed in severely deteriorated condition (Refer Distress mapping plan).

The seepage of water (rain water / water from bathrooms or toilets, damaged terrace waterproofing near expansion joints, leakage from plumbing lines) into the RCC elements is the primary cause for corrosion of reinforcement bars and hence deterioration of RCC members. RCC beams, columns and slabs which shows corrosion of reinforcement bars and associated deterioration should be repaired / strengthened on priority basis.

The loose delaminated plaster, cover concrete, should be removed in order to avoid any injury or casualty due to falling off of chunks of delaminated concrete.

All leakages / seepage should be attended by adapting adequate waterproofing measures. Damaged plumbing lines should be repaired / replaced. Damaged portion of plinth protection should be repaired.

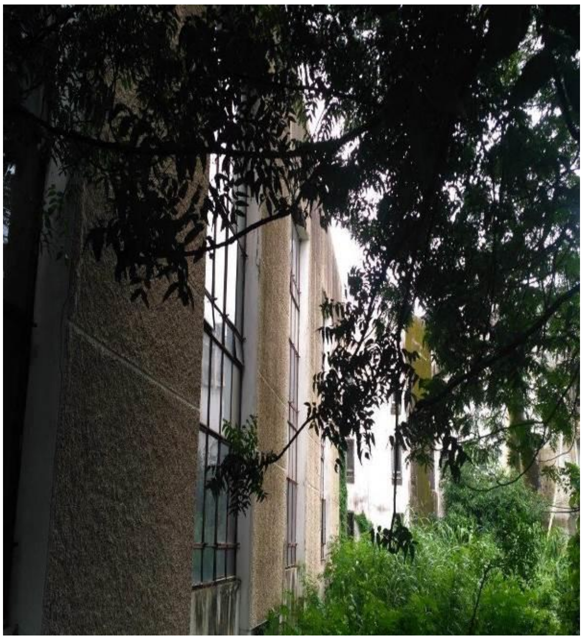
Wherever old external plaster is bulged / delaminated, shall be removed and re-plastered using river sand and appropriate waterproofing admixtures, and the entire external surface of the building shall be painted using cement based waterproofing paint. Internal re-plastering should be carried out wherever necessary. The vegetative growth on building faces shall be removed from the roots. Further, it is recommended to carry out repairs and maintenance on regular basis to maintain serviceability of the building. The repair/rehabilitation shall be carried out under the supervision of experienced repair consultant.

Table 8: Distress in Structural Elements

EXTERNAL & INTERNAL PHOTOGRAPHS

Face A: Front view; External plaster is in distress condition with minor cracks, algae, moss formation.	
Face B: Full view	Face B: Minor cracks in columns & Vegetation growth observed at plinth protection.
	
Face C: Minor cracks on wall plaster, cracks on elevation pardis with moss formation	Face C: Beam is in damage condition with exposed reinforcement & wide crack.
	
Face D: vegetation growth on plinth protection, columns damaged with fallen cover concrete, exposed and corroded reinforcement.	

	
Face G Minor plaster cracks on walls, Vegetation growth on plinth protection.	Exposed reinforcement at ground beam.
	
Face H, I: Moss & black mold formation on wall with vegetation growth on plinth protection	Roof: Spalled cover concrete and exposed Reinforcement of columns at few locations

	
Face N: Heavy vegetation growth on plinth & near plumbing lines & reinforcement exposure of column at 1st floor	

	
C wing: Flooring Upheaval at ground floor	Wide Corrosion Crack in Lintel Beams at Ground floor

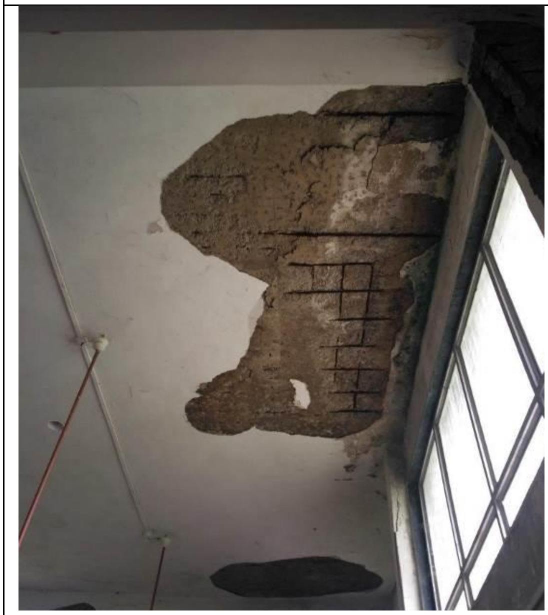
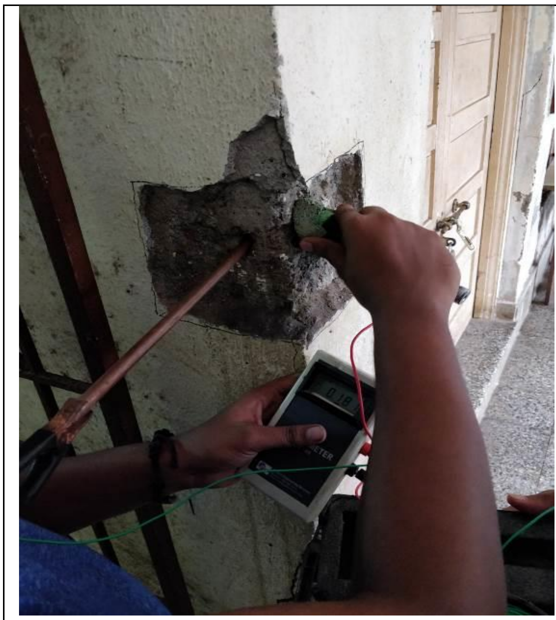
<table>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Ground Floor Common Passage: Reinforcement exposed and corroded of slab with delamination of cover concrete and formation of fungus</td></tr>
<tr><td></td><td></td></tr>
<tr><td>C Wing Ground Floor: R/f exposed and corroded with fallen cover concrete of Slab</td><td>Passage Ground Floor: Termite Attack on RCC beam</td></tr>
</table>

Table 9: Non-Destructive Test Photographs

	
C Wing Ground Floor: At few location concrete cover fallen, R/f exposed and corroded of Column	Common Passage slab at Ground Floor: Concrete cover fallen with exposed and corroded reinforcement
	
Wide corrosion crack in columns throughout its length at D wing, First Floor	D wing: Leakage/ seepage from wall at 1st Floor

	
D Wing First Floor: Spalled cover concrete with exposed and corroded reinforcement	D Wing First floor: Delaminated cover concrete with exposed and corroded reinforcement of lintel
	
Surface preparation for ND test	Rebound Hammer Test



Corrosion Test by Half Cell Potentiometer

<table>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Moss Formation on walls at 1st floor in common passage area</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Cover concrete fallen and exposed/corroded reinforcement of beam at at C Wing 1st Floor</td><td>Wide corrosion crack in RCC beam through its span at few locations</td></tr>
</table>

	
Wide vertical corrosion crack in RCC column through its length in Common Passage at few locations on 1st floor	Separation Crack in RCC Column and Wall at main Staircase
	
	Leakages from RCC Tank on Terrace

Recommendations for Repair And Rehabilitation:

1. To restore the strength decreased with the time
2. To address the Environmental effects
3. To avoid major repairs in future
4. To prevent Leakages, Seepages and Dampness
5. To minimize the cracks in non-structural elements
6. To minimize the Annual maintenance cost

Material selection:

Based on Visual Inspection and Interpretation of Non-destructive Test Results following parameters for materials were considered besides their compatible properties. Low shrinkage properties, Requisite setting / hardening properties, Workability Good bond strength with existing sub–strata, Compatible coefficient of thermal expansion, Compatible mechanical properties, Accommodates relative movement, Minimum curing, Alkaline character, Low water permeability, Aesthetics to match with surroundings, Cost, Durable, non–degradable or non–biodegradable due to various forms of energy like ultra violet rays, heat, etc., Non–hazardous / non–polluting.

RCC Repaires:

Materials selection is carefully done. Main task before repair of RC members is the adoption of a proper load releasing system from the RCC members under repair. Safety should be the matter of paramount importance. Next general step is the eradication of cause of damage to the RCC i.e. making the concrete in the surrounding of steel metal alkaline. This would be possible by removing the rust product and chiseling out the contaminated concrete. Chloride extraction is possible but the extraction system is cumbersome and expensive; hence, we can adopt easier and cheaper system of Cathodic Protection of Zinc Rich Epoxy Primer Sacrificial Coating in general and Sacrificial Anodic Protection at vital spots in particular. Such protection will push the deterioration countdown period at least 10 years further.

Next major task is to bond the old matured concrete and new repair material. Surface conditioning shall be done mechanically and by rotary brush which will open the micro pores of old concrete matrix and make the same conditioned to receive the new repair material by maintaining the continuity of cement matrix. Depending upon the level of deterioration the repair material shall be selected. Common repair materials we proposed are Latex Modified Cement Mortar / Concrete, Polymer Fibre Reinforced Thixotropic Mortar, Non-shrink Super Fluid Micro-Concrete, Fibre Wrap. For repair of cold joints and structural cracks in vital RCC member high pressure grouting at 2.0 to 2.5 kg/cm^2 of solvent free and low viscosity epoxy is proposed.

Plastering scheme:

a) Plastering against RCC:

RCC being the vital element in the framed structure, an external cover is required apart from the concrete cover to the embedded reinforcing steel. For proper adhesion of concrete and plaster cement mortar a Latex Modified bonding agent will be applied before plastering. Plaster will be modified by Acrylic Polymer at a very nominal dose of 2.5%. This will eliminate the inherent impurities of mortar like silt content, which could not be removed even after washing of sand.

b) Plaster at Delam Joint:

Delam joints of RCC and masonry are most suspected spot of leakage / dampness / seepage. At such joints a suitable filler material has to be used which can accommodate the thermal movement of two different materials. Also, such filler will not allow the regular plaster against the delam joint to develop the cracks in future.

c) Plaster against Masonry:

Wherever the plastering is required to be done in patches, utmost care has to be taken to match the old saturated plaster and new plaster. Filler material should be used after plastering to accommodate the shrinkage movement of interface joint. Also, the adhesion of filler material has to be ensured to both old and new plaster.

d) Plaster on Dead Walls:

There are many dead walls without any opening. The plastering on these dead walls requires a great attention. Due to single continuous height of more than 70feet, the plaster will have a tendency to buckle under its own weight and liable to de-bond from the wall. It is proposed to create RCC false band at every floor.

Waterproofing of Terrace:

For terrace water proofing, Brick-bat coba with mosaic tile or membrane waterproofing shall be carried out.

Plumbing & Drainage

Seeing the age of existing GI pipes for fresh water supply and being the chlorine treated water, the inside damage level will be very high. Rust might have reduced the thickness to a substantial level. It should not be expected that a majority portion of pipes can be saved and reused after cleaning. The drainage and waste water pipes has to be changed from time to time. However; these pipes cannot be saved during retrofitting.

Repair Scheme

After thorough deliberations, the methodology of the rehabilitation work has been finalized. The repair scheme is as follows**.**

Steps involved in Repairs of Buildings

Step 1: Vacate the building totally or the part thereof eliminating from the routine functions
Step 2: Tapping of RCC members with hammer
It shall be carried out to identify the distress/damage/deterioration in RCC members not visible to naked eyes.
a) Tap each of the structural members using single piece small metal hammer.
b) Mark hollow sound areas as distress portion
c) Remove plaster / concrete cover and delaminated portion of concrete.
Step 3: Grouting of RCC structural elements:
All the structural members with distress D3 to D7 should be grouted.
a) Slab: cement grout with polymer admixture for non-shrinkage.
b) Beams and columns: low viscosity epoxy grout.
Step 4: Repair of Columns
Step 5: Repair of beams
Step 6: Repair of slab

Recasting of Slab

Step 7: Providing External Plaster (in the location where plaster is not done in last 10 years and plaster can be chipped of easily)
Step 8: Providing Terrace / Toilet waterproofing:
Step 9: Flooring
Step 10: Pressure Grouting
Step 11: External Plastering
Step 12: Dash Coat Plaster
Step 13: Internal Plastering

Step 14: Brick Work / Block Work:
Step 15: Plumbing & Sanitary Piping
Step 16: Painting

Detail methodology for repair of Columns:

The following scheme is recommended for the corroded columns. A typical photograph of the damaged column after removal of old concrete is shown in the Fig. 3.
Step 1) Prop the beams on all the sides of the columns. The props shall be capable of taking the total load coming on to the column.
Step 2) For column chip open the cover concrete until all the corroded steel rods are exposed or all the concrete affected by carbonation is removed whichever is deeper. Clean the steel rods with steel wire brush to remove the rust completely.
Step 3) Chip the spallen surface of concrete to remove all loose materials. Then brush it with steel wire brush to remove all loose particles. Wash the surface with potable water.
Step 4) Measure the net diameter of corroded steel bars and assets the net area of steel available using a Vernier caliper.
Step 5) The area of steel originally provided can be determined from the drawings / assessed from the physical observation of the rods existing in the columns.
Step 6) Apply coat of anticorrosive coating like manufactured by leading co. and of approved brand to all the existing reinforcements. It shall be ensured that the anticorrosive is applied/ coated all throughout the surface of the rods including all crevices.
Step 7) If the difference between the area of steel originally provided and the measured net area is more than 5 to 10% provide extra steel. The extent of taking the steel below floor level shall be decided at the site depending on the area affected by corrosion. If the steel in the column above the foundation is not corroded and sufficient length (lap length) is available then the extra steel provided can be tied to the existing rods for a length of lap length as

shown in Fig 4. If the existing steel in the column is corroded up to the top of the foundation new bars have to be anchored by drilling holes in the foundation for a length of development length in tension as shown inFig.3, bonded with the concrete using polymer-based epoxy. Anticorrosive coating can be applied to the new longitudinal bars before placing. But to the ties this coating has to be applied after placing in position in order to avoid crack in the coating. New longitudinal bars have to be tied using new column ties as shown in Fig.6, if the additional bars are provided only at the corners and also if the number of new bars is less than 12 numbers with the spacing of the corner bar and adjacent bar less than 75mm. In case more than 12 rods are provided then the ties have to be anchored into the concrete by drilling holes in the concrete and inserting the ends of the ties into the holes as shown in Fig. 7. The depth of drilling shall be such that length of the ties from the centre of new longitudinal bar is 8 times the diameter of tie. The ends of the tie rods are bonded with the concrete using polymer-based epoxy grout. The arrangement of fixing the column bars at top is shown in Fig. 7.
Step 8) Leak proof form work which should not deform or leak due to pressure of micro concrete shall be fabricated and erected in position. The form work should be coated with approved mould release agent, prior to the final fixing in position. Proper supporting arrangements are to be made for keeping the shutter in correct line and length.
Step 9) The cover for the longitudinal steel has to be provided just to accommodate the funnel for pouring micro concrete. The funnel for pouring micro concrete is lifted up as the concreting proceeds.

Fig.3. Damaged column a) and b) Before removal of cover concrete and c) After removal of cover concrete

The new longitudinal steel can be drilled into the foundation or lapped to the existing steel. It may be noted that lot of local site decision have to be taken depending on the site conditions.

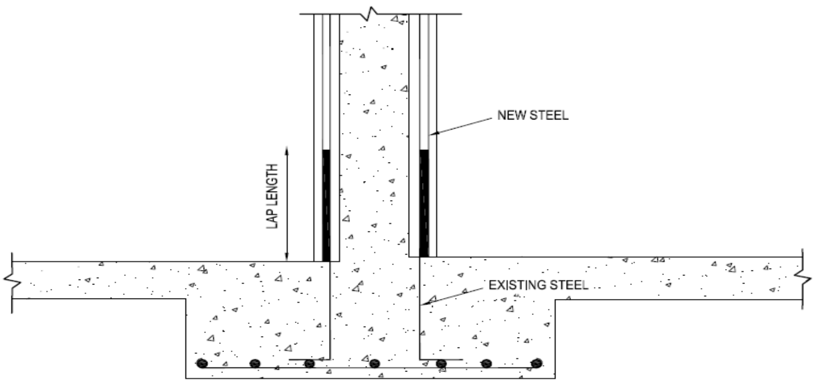


Fig. 4: Tying of the extra steel to the existing rods for a length of lap length

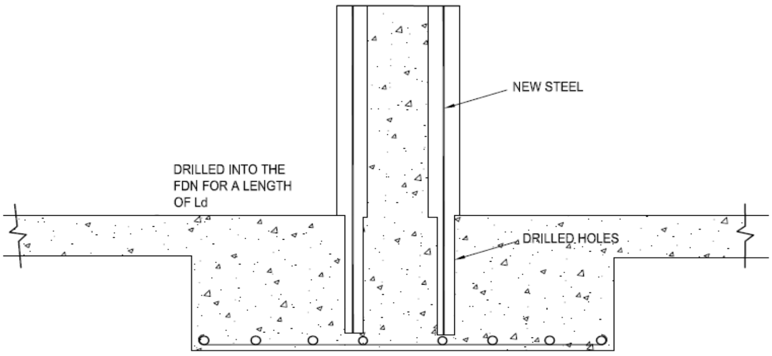


Fig. 5: Anchoring of extra steel by drilling holes in the foundation for a length of development length in tension.

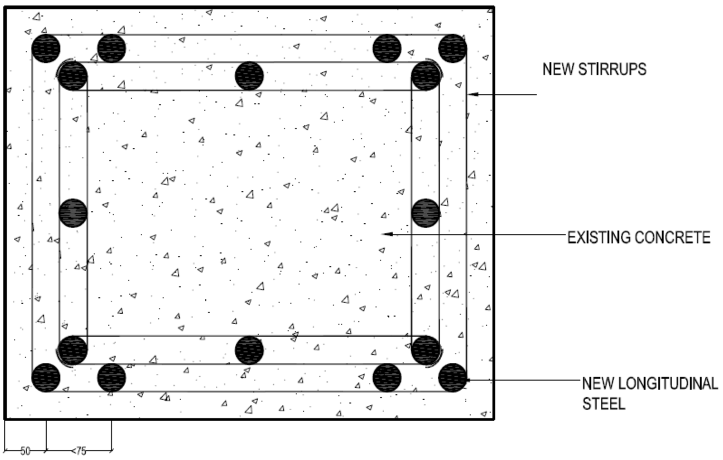


Fig. 6: New column ties in case of number of new bars are less than 12 numbers with the spacing of the corner bar and adjacent bar less than 75mm.

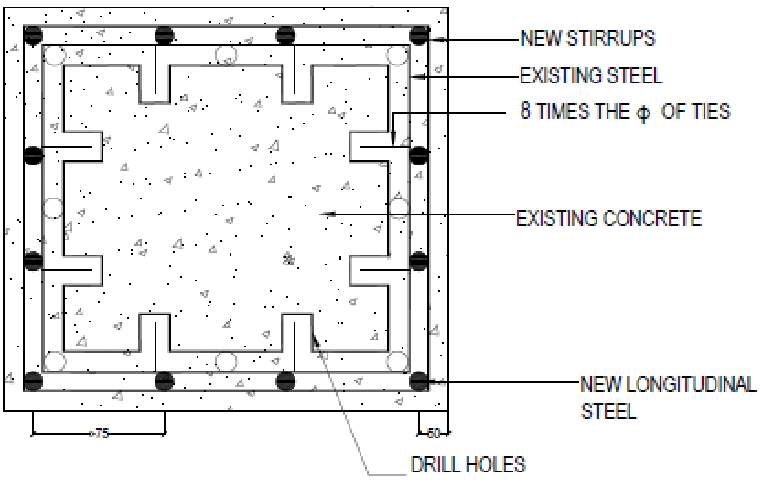


Fig. 7: New column ties with bar anchors in case of number of new bars is more than 12 numbers

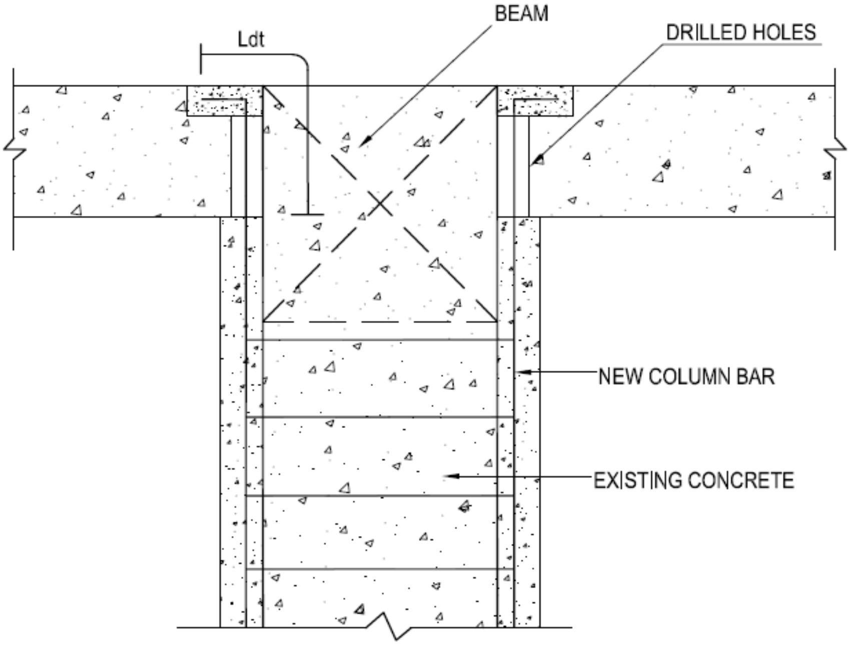


Fig. 8: Arrangement of fixing the column bars at top- discontinuous edge.

Detail methodology for repair of Beams:

The following Fig 9 and 10 depict the damage to some of the beams in the technological structure. The following repair scheme is recommended. The repair scheme is same for all the structures in general. Basic steps involved in the repair of beams are almost the same as that of columns.

Step 1) Prop the slabs with a runner on sides of the beam so that even if the beam is removed the slab shall be safe. Steps indicated for columns from (2) to (6) to be followed for beams.

Step 7) If the additional area required is coming to be more than about 5-10% of the original area provided, provide extra steel. Tie the steel to the existing steel. The details shown in Fig.10 are adopted when the vertical leg of the stirrups is also corroded. In case the longitudinal steel and bottom leg of the ties alone are corroded without much damage to the vertical leg of the stirrups, then the following details shown in Fig.11 are adopted. Ties can be anchored by drilling holes through the slab and bonded with polymer-based epoxy grout. Anticorrosive coating can be applied to new longitudinal bars before placing. But to the ties this coating has to be applied after placing in position in order to avoid crack in the coating.

Step 8) Leak proof form work which should not deform or leak due to pressure of micro concrete shall be fabricated and erected in position. The form work should be coated with approved mould release agent prior to the final fixing in position. Proper supporting arrangements are to be made for keeping the shutter in correct line and length.

Step 9) Encasement is done using approved micro concrete, with 50% aggregate (washed / cleaned) by weight of size of 6.4mm and down size. It shall be ensured that clear cover to the new steel is 40mm. The curing has to be done immediately after stripping the formwork with approved curing and bonding agent (1:1 by volume of water) at a coverage if 8-10 sq.m/lt. It may be noted that a lot of local site decision have to be taken depending on the site conditions.

Step 10) Faces of all repaired beams shall be coated with anticarbonation painting.

Fig: 9 Damaged Beam

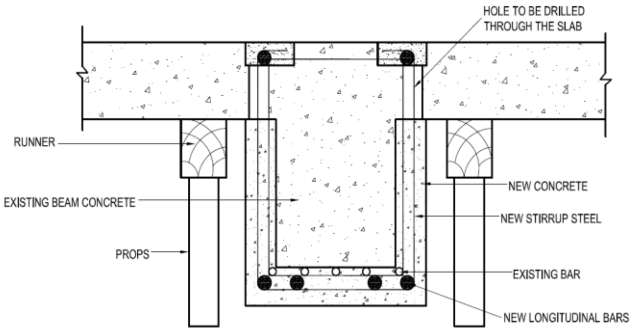


Fig:10 Typical Strengthening of Beam and propping of slabs with a runner on sides of the beam

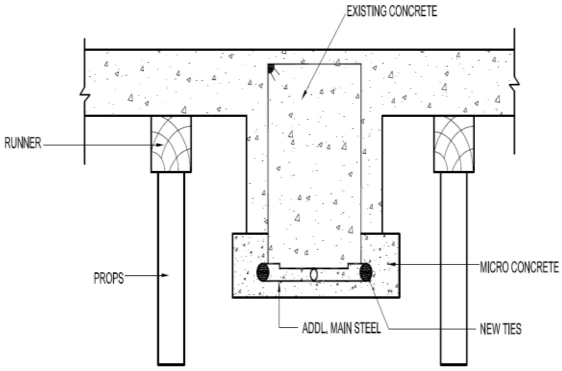


Fig: 11 Alternative Strengthening scheme for Beam

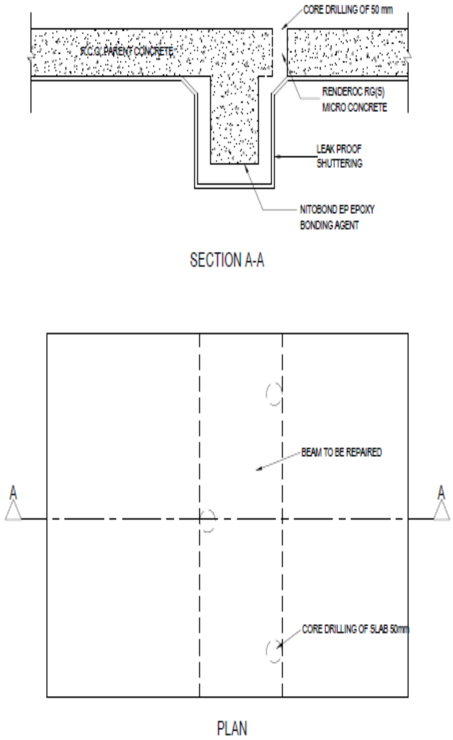


Fig: 12 Scheme for pouring of Micro-concrete for strengthening of Beams.

Detailed methodology for repair of Slabs:

The following Fig 13 indicate the damage to some of the slabs in the technological structures. The scheme to repair the slabs is as follows:

Step 1) Prop the slabs at intervals at about 1.5m. Propping at the center is to be avoided. Steps indicated for Columns (2) to (6) to be followed for slabs.

Step 7) If the difference between the area of steel originally provided and the measured net area is more than 5 to 10% provide extra steel. Additional bars thus introduced are anchored to the beam for a length of Ldt/3, where Ldt is the development length in tension. These additional bars are bonded to the beam by using polymer-based epoxy grout. The details are shown in Fig. 11. Additional steel shall be tied to the existing steel or anchored using anchors drilled into the slab.

Step 8) Leak proof form work which should not deform or leak into the concrete of the slab due to pressure of micro concrete shall be erected in position. The form work should be coated with mould release agent prior to final fixing in position. Proper supporting arrangements are to be made for keeping the shutter in correct line and length.

Step 9) The micro concrete, with 50% aggregate of size 6.4mm and down is poured by funnels by drilling holes of about 50mm ϕ at about 2m intervals in both directions. It shall be ensured that clear cover to the new steel is 30mm.

Step 10) Apply two coats of a high build solvent free epoxy resin of 500 μ DFT, after all the floor surface are cleaned thoroughly using a concrete cleaning and etching agent. It may be noted that lot of local site decision have to be taken depending on the site conditions. The Fig (14) indicates the slab after inclusion of new reinforcement: The above procedure has been followed with a meticulous planning and rehabilitation work had been carried out with great care under expert supervision and skilled and specialized workers when the units are in operating condition. However, certain areas, where permit could not be obtained, due to safety of the plant work was carried out during shutdowns. The slabs after repair were intact and looking newly built. Thus, the life is enhanced. The fig. 16 depict the slab after repair.

Fig: 13 Damaged Slab

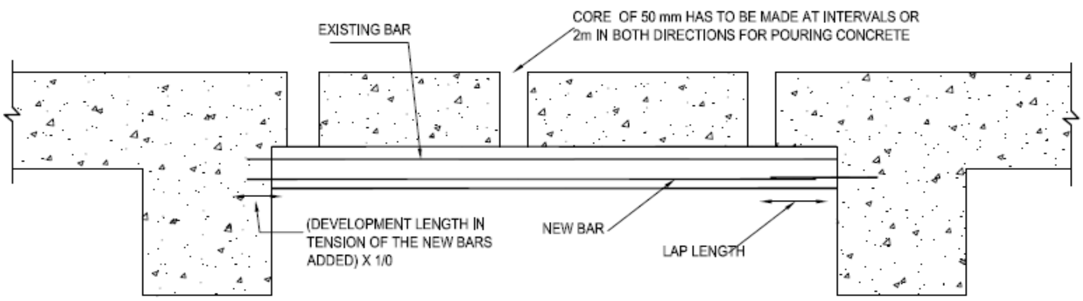


Fig: 14 Typical Strengthening of Slab

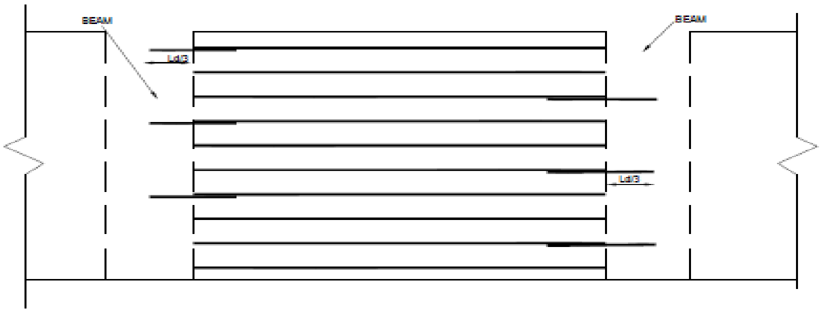


Fig: 15 Arrangement of new reinforcement (bottom) for slab

Fig: 16 Slab view from bottom after rehabilitation

References:

Indian Standards (IS Codes):
[1]. IS 456:1978 and IS 456: 2000 - Plain and Reinforced Concrete - Code of Practice (Bureau of Indian Standards)
[2]. IS 13311(Part 1):1992 - Non-destructive Testing of Concrete - Methods of Test (Bureau of Indian Standards)