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Improving Structural Stability: Non-Destructive Evaluation in Building Maintenance

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Abstract: **Amidst the rapid advancement of technology, there is a growing demand for Structural Health Monitoring (SHM) and the application of Non-Destructive Testing (NDT). These methodologies are becoming indispensable for evaluating and preserving the integrity of structures. This project delves into the synergistic relationship between NDT and SHM, where innovation and precision converge to address the critical need for assessing, safeguarding, and prolonging the lifespan of essential infrastructure. The primary objective is to explore and implement various NDT techniques within the framework of SHM, focusing on an industrial facility and a Civil hospital. By applying NDT in real-world scenarios, this project enhances sustainability and enables structural enhancements where needed. Overall, this research paper provides valuable insights for professionals and stakeholders involved in preserving the structural integrity of built environments, including engineers, researchers, and other stakeholders invested in ensuring the stability and safety of constructed structures.**

Keywords: **non-destructive testing, structural health monitoring, structures, techniques.**

1. Introduction

In civil engineering, the construction and maintenance of buildings represent not just feats of engineering, but also enduring symbols of human progress and achievement. However, as our cities grow taller and our structures become more intricate, ensuring their safety and longevity becomes an increasingly complex challenge. The foundation of any enduring structure lies in the meticulous effort put into its construction. Longevity demands not just skilled craftsmanship but also adherence to rigorous quality standards. However, even the most meticulously constructed buildings are subject to the relentless forces of time, weather, and changing usage patterns. Consequently, ongoing vigilance and proactive measures are essential to safeguard these investments in infrastructure [1]-[4] Central to the integrity of many modern buildings are concrete—a material that forms the backbone of our urban landscapes. Yet, despite its ubiquity, concrete is not impervious to the passage of time and environmental stressors. The strength and durability of concrete structures are influenced by many factors, from the composition of the mix to the conditions of curing and environmental exposure. To ensure that these structures remain safe and reliable, non-destructive testing (NDT) methods emerge as indispensable tools. These methods allow engineers to assess the quality and integrity of concrete without compromising its structural stability [5]-[8]. Among the challenges faced by concrete structures, incidents such as fires pose particularly grave threats, especially in high-rise buildings, tunnels, and industrial installations. The extreme temperatures generated during fires can wreak havoc on concrete, leading to irreversible damage and compromising the structure's safety. The importance of early detection and intervention cannot be overstated in such scenarios, underscoring the critical role of reliable monitoring techniques. Moreover, the significance of NDT extends beyond immediate safety concerns to encompass broader considerations of sustainability and environmental impact. By optimizing resource utilization and reducing carbon emissions associated with concrete production, NDT contributes to the broader goal of sustainable infrastructure development [9]-[11]. In this context, structural health monitoring (SHM) emerges as a comprehensive approach to safeguarding the integrity and performance of civil infrastructure. SHM encompasses a range of NDT techniques, from ultrasonic pulse velocity testing to rebound hammer assessments, aimed at evaluating structural conditions, predicting service life, and guiding maintenance strategies [3], [12]-[14]. As we navigate the complexities of modern urban environments, adopting advanced NDT methods and SHM practices becomes imperative. By leveraging innovation and technology, we can ensure that our built environments are not just safe and durable but also sustainable and resilient in the face of evolving challenges and aspirations [15]-[20] In conclusion, the exploration of structural health monitoring using NDT methods serves as a testament to our commitment to building a safer, more sustainable future—one where our cities stand as beacons of progress and resilience, built to withstand the tests of time and nature.

A. Leveraging NDT for Effective Structural Health Monitoring

Leveraging NDT for Effective Structural Health Monitoring exposes how non-destructive testing (NDT) methods can be strategically employed to boost monitoring structure health and integrity over time. To ensure that the structures we construct are safe and will serve us in the long run, they must be regularly monitored. This exercise is known as structural health monitoring (SHM). In this process, NDT techniques are

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essential because they enable the assessment of various structural components without damaging the structure itself. By using the term "leveraging," means making maximum use of or exploiting SHM practice concerning NDT. The following points explain how to apply NDT for effective structural health monitoring: Early Detection of Defects: Early-stage defects, deterioration, or damage in structures can be detected using non-destructive testing methods. Such an approach would prevent catastrophic failures and minimize the cost of repair. Comprehensive Assessment: Another advantage of non-destructive testing techniques is that they give a comprehensive idea of elements such as steel, concrete, or composite materials used in construction. By looking into characteristics like strength, integrity, and internal flaws among others; NDT provides an inclusive perspective.

Fig. 1. Working with NDT methods

Fig. 2. Site virtual inspection

B. Objective of the Present Work

a) Quantifying Internal Defects: Utilizing Ultrasonic Testing for Detailed Analysis This objective centers on employing ultrasonic testing methodologies to meticulously quantify and characterize internal defects, voids, and anomalies within structural elements. By generating precise, quantitative data, the aim is to offer a thorough analysis of the internal condition of the structures under examination, moving beyond mere detection to provide specific measurements. This approach enables a more informed and targeted strategy to address any identified issues, thereby ensuring the overall resilience and stability of the structures.

b) Precision Assessment of Concrete Surface Strength: Rebound Hammer Testing Approach This objective involves utilizing rebound hammer testing to precisely assess the hardness of concrete surfaces. The focus is on obtaining accurate measurements to enable a detailed evaluation of material strength. By facilitating the identification of specific areas requiring attention or further investigation, this approach ensures comprehensive assessment and enhances structural integrity.

c) Accurate Measurement of Carbonation Depth and Corrosion Risk This objective entails conducting carbonation tests to accurately measure and map carbonation depth in concrete structures. By gaining insights into the risk of corrosion, the goal is to facilitate targeted identification of areas needing immediate attention or repair. This approach ensures proactive management of potential concerns, thereby preserving structural integrity.

d) Investigating the Relationship Between Ultrasonic and Rebound Hammer Test Results This objective aims to determine the correlation between ultrasonic pulse velocity results and rebound hammer test results. Utilizing Pearson's correlation coefficient, the objective is to ascertain whether a positive or negative linear relationship exists between these two NDT methods. This analysis provides valuable insights into their complementary roles in assessing structural integrity and aiding in informed decision-making processes.

2. Methodology

A. Methods

1) Ultrasonic Pulse Velocity Test

It is observed that the Ultrasonic Beat speed comes about with coordinate and circuitous strategies. The Coordinate Strategy employments an unhampered channel between transducers to straightforwardly transmit ultrasonic beats through homogenous materials. When coordinate transmission is troublesome or when assessing the surface layer, the Roundabout Strategy is valuable for measuring beat speed through a fluid or lean surface layer. A crossover procedure called the Semi-Direct Strategy employments halfway transmission through the fabric and coupling medium. It is suitable in circumstances when coordinate transmission is hindered or when a combination of coordinate and backhanded information is required. The usefulness of this instrument is unexpected upon the Energetic Young's Modulus, thickness, and Poisson's proportion of the fabric in utilize. To degree the time taken for travel, the transducers are situated on a smooth concrete surface. A coupling medium, such as petroleum jam or oil, is connected over the surface to guarantee viable acoustical coupling. The speed is at that point computed utilizing the equation v=L/T, where 'L' speaks to the remove between two tests, and 'T' is the time taken for the flag to travel this remove between the transducers as appeared in Fig. 3 and Fig. 4.

Fig. 3. Ultrasonic pulse velocity instrument

Fig. 4. Checking connectivity of UPV

As per IS 13311:1992 (PART I)

Table 1
UPV quality parameter

Average Pulse Velocity	Quality of Concrete
>4.5 km/sec	Excellent
3.5-4.44 km/sec	Good
3.3-3.55 km/sec	Medium
<3.05 km/sec	Poor

2) Rebound hammer test

The Rebound Hammer method operates on the principle that the rebound of a spring-loaded mass is affected by the hardness of the surface it strikes. To conduct the test, the hammer's plunger is firmly pressed against the concrete surface, perpendicular to it, until the mass is released from its locked position. Before starting the test, it's crucial to ensure the reliability of the rebound hammer by checking it against a designated anvil. This anvil should be made of steel with a Brinell hardness number of around 5000 N/mm². The test can be performed horizontally on a vertical surface or vertically in an upward or downward direction on horizontal surfaces. After the hammer strikes the surface, the rebound number is measured as a percentage of the distance traveled by the mass. This rebound velocity is then compared with a calibration graph to determine the compressive strength of the concrete.

Fig. 5. Rebound hammer

Fig. 6. Working of rebound hammer

As per, IS 13311:1992 (PART II)

Table 2
Rebound hammer quality parameter

Average Rebound Hamner values	Quality of Concrete
>40	Very Good
30-40	Good
20-30	Fair
20	Poor
0	Delaminated

3) Carbonation test

The purpose of the carbonation test is to evaluate whether the concrete cover provides adequate protection to the steel reinforcement against corrosion in the presence of both oxygen and moisture. Following the procedure outlined in ASTM C876-15: Corrosion potential of uncoated reinforcing steel in concrete, phenolphthalein indicator is applied to the surface of cylindrical cores immediately after extraction. This application allows for the measurement of the depth of carbonation within the concrete.

Fig. 7. Carbonation test

3. Case Study

A. Site Selection 1:

Structural Audit Report for old staff quarter residential building of class - iv, old residential Building No. 06, at MSEDCL, Jalgaon.

The structure is a G+2 double-storied RCC framed building, approximately 41 years old, constructed in 1978. Each floor comprises four residential blocks, each consisting of 1BHK units. The RCC framed structure features outer columns measuring 230 x 380 mm and internal columns measuring 230 x 450 mm on every floor. All floors are constructed with brick masonry, with an RCC slab roof. External walls are 230 mm thick at ground level and 230 mm thick on upper floors, while internal walls are 150 mm thick brick masonry. Access to each floor and the terrace is provided by one RCC dog-legged staircase within the structure. Waterproofing and plinth protection are absent on-site. RCC balconies adorn the front face of the structure on each floor. Recently, the main entrance canopy collapsed. Hajj is provided for each floor window.

External Faces of the Building Observations:

1) RCC columns are in very bad condition, it was provided with adequate sizes.
2) Some external beams having adequate sections rested on badly damaged columns.
3) Some external columns are highly damaged throughout the building and major cracks were observed throughout the columns.
4) A high amount of corrosion is observed in external columns and chajjas at all stages. Huge cracks were observed in RCC columns.
5) At many places column reinforcement was visible and highly corroded, we observed that the columns were too weak to withstand all the dead loads.
6) Some column's main longitudinal bars and stirrups are highly corroded and separated from the concrete.
7) The canopy was found in very bad condition and total reinforcement was also clearly visible.
8) High damage signs of steel exposures and corrosion were observed in columns.
9) In some places external plaster was found in bad condition and heavy cracks were observed in the walls.
10) The vegetation was observed in high amounts in columns and walls.
11) The RCC canopy of the entrance is collapsed, and the present reinforcement is highly corroded damaged, and visible.
12) Some major deflections were observed in the cantilever slab of balconies.
13) Major Cracks and steel exposure are observed in the balconies' cantilever slabs.
14) External brick masonry is in very bad condition.
15) External plaster is in highly bad condition and leakages from walls and found a high amount of dampness.
16) At some columns and wall joining places the walls are separated from columns.
17) Chajja's and other Projections of the building were found in very bad conditions. Projections adjoining the staircase cap were in unworkable condition.
18) The drop pardi from the balcony's cantilever slab was found in bad condition and highly damaged.
19) All Plumbing and Drainage works are done with PVC pipes.
20) In some places the leakages were present, it may be because of the faults in plumbing and drainage works.

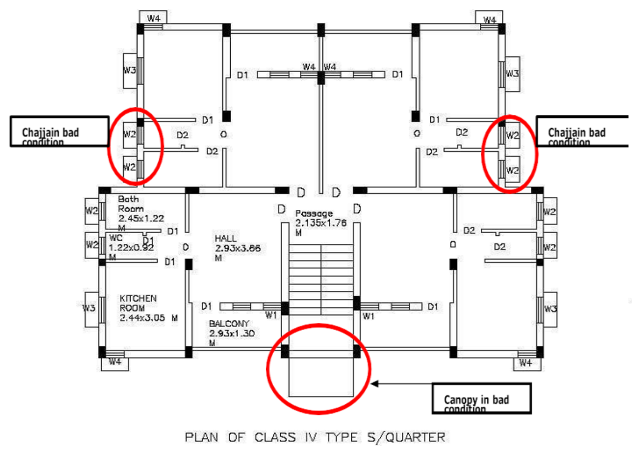

Fig. 8. Ground floor plan

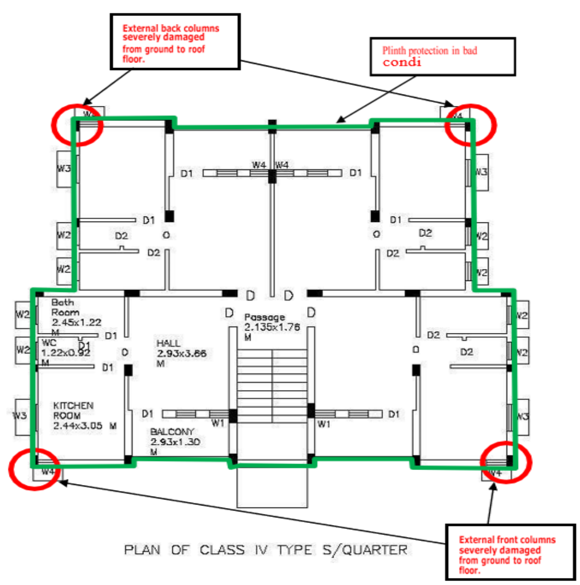

Fig. 9. First floor plan

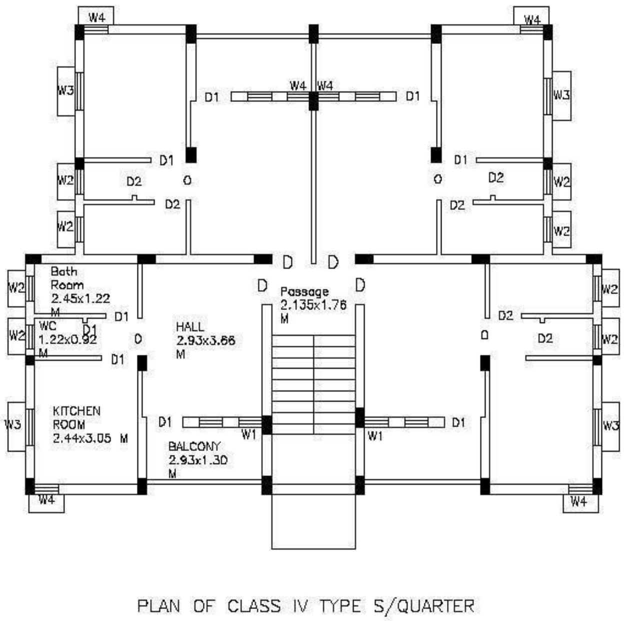

Fig. 10. Ground floor roof plan

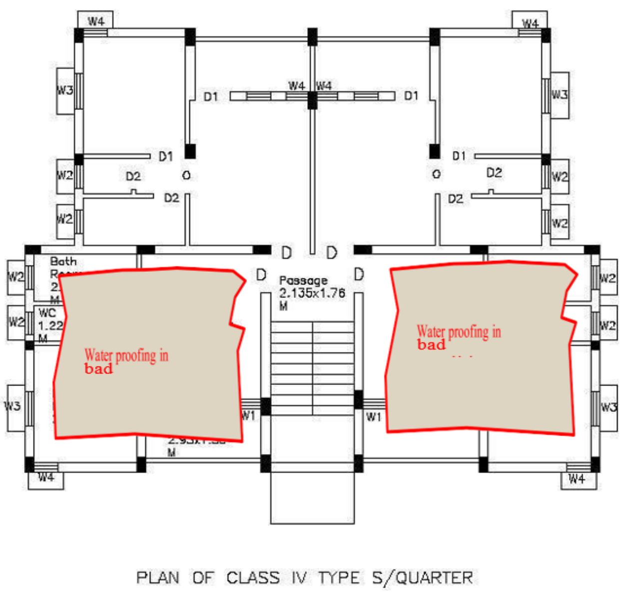

Fig. 11. First floor roof plan

B. Site Selection 2

Structural audit & present condition of Shahu Maharaj Civil Hospital, Near Mahanagar Palika/Nutan Maratha Mahavidyalaya, Jalgaon, Maharashtra, India.

Non-Structural Description and Conditions:

In the entire structure, at various locations like consulting room, autoclave room, medical officer room, X-ray room, Storeroom, pathology lab, passage areas, labor room, nurse room, female ward, general ward, nurse station, as well as the emergency room non-structural defects such as leakage marks observed on the ceiling and masonry wall, separation crack was observed in between beam and wall, and peeling of paint was observed. Fig. 13. Shows a 3D plan of the structure. To carry out various NDT methods over the structure 40 percent of structural members were been tested.

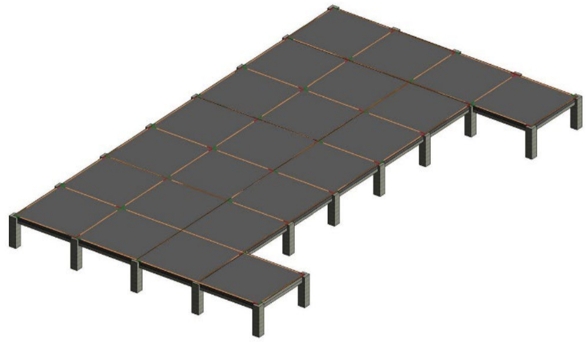

Fig. 12. 3D plan of hospital

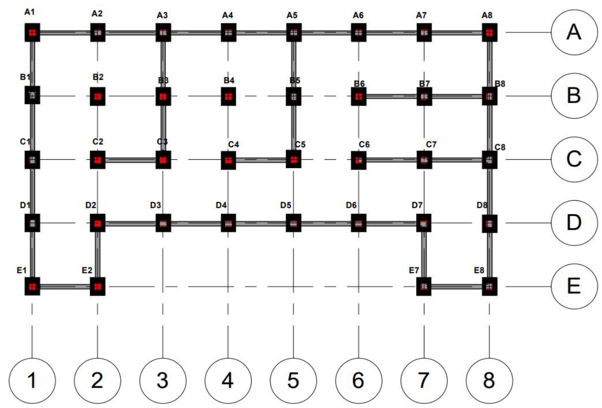

Fig. 13. Plan showing column details

Table 3
UPV AND Rebound Hammer calculations for columns

SR. NO.	RCC MEMBER STRUCTURE COLUMN	ULTRASONIC PULSE VELOCITY TEST				REBOUND HAMMER TEST		
		POINT	AVERAGE VELOCITY (km/Sec)	METHOD OF TESTING	Quality Remark	AVERAGE READING	COMP. STRENGTH (MPa)	Quality Remark
COLUMNS								
1	A-3	TOP	3.2	ID	Medium	30	23.8	Fair
		BOTTOM	3.0	ID	Medium	30	23.8	Fair
2	A-4	TOP	2.9	ID	Poor	31	25.0	Fair
		BOTTOM	3.0	ID	Medium	31	25.0	Fair
3	A-6	TOP	3.0	ID	Medium	32	26.4	Fair
		BOTTOM	3.1	ID	Medium	31	25.0	Fair
4	B-2	TOP	3.2	ID	Medium	30	23.8	Fair
		BOTTOM	3.0	ID	Medium	30	23.8	Fair
5	B-5	TOP	3.0	ID	Medium	31	25.0	Fair
		BOTTOM	3.3	ID	Medium	30	23.8	Fair
6	C-3	TOP	3.1	ID	Medium	30	23.8	Fair
		BOTTOM	3.0	ID	Medium	31	25.0	Fair
7	C-4	TOP	2.9	ID	Poor	30	23.8	Fair
		BOTTOM	3.1	ID	Medium	29	22.0	Fair
8	C-9	TOP	3.1	ID	Medium	32	26.4	Fair
		BOTTOM	3.0	ID	Medium	30	23.8	Fair
9	D-1	TOP	3.0	ID	Medium	30	23.8	Fair
		BOTTOM	3.1	ID	Medium	30	23.8	Fair
10	D-5	TOP	3.2	ID	Medium	32	26.4	Fair
		BOTTOM	3.0	ID	Medium	31	25.0	Fair
11	E-1	TOP	3.3	ID	Medium	30	23.8	Fair
		BOTTOM	3.1	ID	Medium	30	23.8	Fair
12	E-2	TOP	3.3	ID	Medium	31	25.0	Fair
		BOTTOM	3.4	ID	Medium	33	28.2	Fair
13	E-3	TOP	2.9	ID	Poor	30	23.8	Fair
		BOTTOM	3.2	ID	Medium	30	23.8	Fair
14	E-4	TOP	2.9	ID	Poor	32	26.4	Fair
		BOTTOM	3.0	ID	Medium	31	25.0	Fair

Fig. 13. Shows column position. Also, as per Table 1 and Table 2, quality remarks are marked.

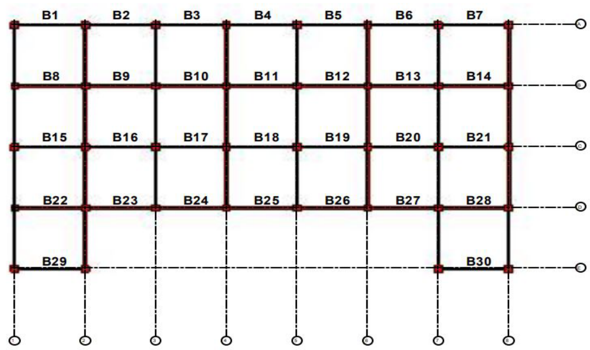

Fig. 14. Plan showing beam details

Table 4
UPV and rebound hammer test calculation for beams

SR. NO.	RCC MEMBER STRUCTURE BEAM	ULTRASONIC PULSE VELOCITY TEST				REBOUND HAMMER TEST		
		POINT	AVERAGE VELOCITY (km/Sec)	METHOD Of TESTING	Quality Remark	AVERAGE READING	COMP. STRENGTH (MPa)	Quality Remark
BEAMS								
1	B-4	TOP	3.1	ID	Medium	30	23.8	Fair
		BOTTOM	3.0	ID	Medium	31	25.0	Fair
2	B-6	TOP	3.0	ID	Medium	30	23.8	Fair
		BOTTOM	3.0	ID	Poor	30	23.8	Fair
3	B-9	TOP	3.1	ID	Medium	32	26.4	Fair
		BOTTOM	2.7	ID	Poor	31	25.0	Fair
4	B-10	TOP	3.1	ID	Poor	32	26.4	Fair
		BOTTOM	2.8	ID	Poor	30	23.8	Fair
5	B-13	TOP	3.0	ID	Medium	31	25.0	Fair
		BOTTOM	3.0	ID	Medium	31	25.0	Fair
6	B-18	TOP	3.0	ID	Medium	32	26.4	Fair
		BOTTOM	3.1	ID	Medium	30	23.8	Fair
7	B-20	TOP	3.0	ID	Medium	31	25.0	Fair
		BOTTOM	3.1	ID	Medium	31	25.0	Fair
8	B-22	TOP	3.1	ID	Medium	30	23.8	Fair
		BOTTOM	2.9	ID	Poor	31	25.0	Fair
9	B-24	TOP	3.0	ID	Medium	32	26.4	Fair
		BOTTOM	3.1	ID	Medium	32	26.4	Fair
10	B-26	TOP	3.1	ID	Medium	32	26.4	Fair
		BOTTOM	2.9	ID	Poor	32	26.4	Fair
11	B-28	TOP	3.0	ID	Medium	31	25.0	Fair
		BOTTOM	3.0	ID	Medium	32	26.4	Far
12	B-30	TOP	3.1	ID	Medium	32	26.4	Fair
		BOTTOM	2.9	ID	Poor	32	26.4	Fair

Fig. 14. Shows beam position. Also, as per Table 1 and Table 2, quality remarks are marked.

Fig. 15. Plan showing slab details

Table 5
UPV and rebound hammer test calculation for slab

SR. No.	RCC MEMBER STRUCTURE SLAB	ULTRASONIC PULSE VELOCITY TEST			REBOUND HAMMER TEST		
		AVERAGE VELOCITY (km/Sec)	METHOD OF TESTING	Quality Remark	AVERAGE READING	COMP. STRENGTH (MPa)	Quality Remark
SLABS							
1	S-1	2.9	ID	Poor	30	28.2	Fair
2	S-3	3.0	ID	Medium	30	28.2	Fair
3	S-6	2.9	ID	Poor	31	30.0	Good
4	S-8	2.7	ID	Poor	31	30.3	Good
5	S-11	3.1	ID	Medium	30	28.2	Fair
6	S-15	2.7	ID	Poor	31	30.0	Good
7	S-17	2.7	ID	Poor	31	30.0	Good
8	S-19	2.8	ID	Poor	31	30.0	Good
9	S-21	2.9	ID	Poor	30	28.2	Fair
10	S-23	2.7	ID	Poor	30	28.2	Fair

Fig. 15. shows slab position. Also, as per Table 1 and Table 2, quality remarks are marked.

Table 6
Observation for Carbonation test

SR. NO.	RCC MEMBER COLUMN	COLOUR INDICATION	CARBONATION DEPTH IN "MM"	REMARK
1.	C-1	NO COLOUR	Surface	Carbonation present
2.	C-2	COLOUR	Surface	Carbonation absent
3.	B-1	NO COLOUR	5 mm	Carbonation present
4.	C-3	NO COLOUR	Surface	Carbonation present
5.	C-4	COLOUR	5 mm	Carbonation absent
6.	B-2	NO COLOUR	Surface	Carbonation present
7.	S-1	NO COLOUR	10 mm	Carbonation present
8.	S-2	NO COLOUR	Surface	Carbonation present
9.	B-4	COLOUR	5 mm	Carbonation absent
10.	B-6	COLOUR	Surface	Carbonation absent

4. Discussions of Test Results

A. Site 1

After conducting a thorough visual inspection and detailed structural health monitoring of the building, the auditor concluded that the structure was unfit for use. The assessment revealed significant deterioration and structural deficiencies, indicating a critical condition of the building. Therefore, it is recommended that the building be demolished and reconstructed promptly due to its extremely poor health. Immediate action is necessary to mitigate safety risks and ensure the well-being of occupants and surrounding properties. Delaying reconstruction could lead to further deterioration and potential hazards, emphasizing the urgency of addressing the structural concerns without delay.

B. Site 2

Analysis of NDT results - (on average)

Table 7
Average UPV and rebound hammer test results

RCC Members		UPV result in AVG in km/sec(Integrity of concrete)	Hammer results in AVG in MPa (Surface Hardness of concrete)
RURAL HOSPITAL -PETH	COLUMN	3.08 km/sec	24.61 MPa
	BEAM	3.0 km/sec	25.28 MPa
	SLAB	2.84 km/sec	29.13 MPa

Based on Tables 3, 4, and 5.

Based on a comprehensive Structural Audit, which encompassed Visual Surveys and Non-Destructive Tests on selected RCC members, several key conclusions have been drawn as shown in Table 7. The Rebound Hammer test indicates that the concrete grade ranges from 24.0 to 30 MPa, corresponding to a grade between M15 to M20 as shown in Tables 3, 4, 5. The Ultrasonic Pulse Velocity Test reveals UPV values ranging from 2.7 to 3.1 km/Sec, suggesting doubtful to medium-grade concrete as per I.S.: 13311 (Part 1) as shown in Tables 3, 4, 5. However, due to micro-cracking and de-bonding in slab areas, UPV readings are on the lower side. The Carbonation test highlights that carbonation has initiated at a depth of 5 to 10 mm. Internal observations reveal leakages and dampness on the ceiling inside rooms and on walls at various locations, along with dampness and peeling of paint on the internal face of external walls inside rooms as shown in Table 6. Separation cracks are observed between beam & and masonry wall junctions, as well as column & and masonry wall junctions in internal rooms. Additionally, cracks are evident on brick masonry walls inside rooms. External observations include cracks and de-bonding on external plaster, algae & and vegetation growth on external walls, and Sintex water tanks directly resting on the terrace slab. Furthermore, cracks and de-bonding are observed on existing terrace waterproofing. The carbonation test signals the initiation of the carbonation process, with a recorded depth of approximately 7 mm within the buildings.

5. Recommendations

To ensure the structural integrity of the building, a series of recommended repair measures are advised. Firstly, any loose concrete or plaster should be promptly removed to prevent potential hazards. For RCC structural members, particularly in identified locations, it is recommended to treat these members with PMM (Polymer Modified Mortar) along with appropriate anti-corrosion measures. Temporary supports should be installed near damaged beams during the repair work. Micro-concrete with M35 grade is suggested for repairs to RCC members, especially where the thickness of PMM treatment exceeds 30mm. Additional steel reinforcement is advised for beams with severely corroded existing steel reinforcement. A protective coat of corrosion inhibitor should be applied to all exposed surfaces to halt corrosion activities. Corroded structural steel sections need to be cleaned with a wire brush and treated with anti-corrosive paint. Wall care putty should be applied to masonry walls exhibiting dampness, and external plaster with de-bonded sections should undergo patchwork with waterproofing coating. Acid treatment is suggested to remove vegetation growth.

6. Conclusion

In conclusion, for Site 1, the visual inspection and comprehensive structural health monitoring unequivocally demonstrated the precarious condition of the building, rendering it unsuitable for occupancy. The recommendation for immediate demolition and reconstruction underscores the urgent need to address the severe structural deficiencies identified, ensuring the safety and welfare of occupants and safeguarding against potential hazards in the surrounding environment. Site 2 exhibits doubts regarding concrete quality, with concerns about micro-cracking, de-bonding, and the initiation of carbonation. Observations of leakages, dampness, cracks, and external issues further emphasize the structural vulnerabilities. The recommended repair measures include the removal of loose concrete or plaster, the application of polymer-modified mortar, temporary supports near damaged beams, and the use of micro-concrete for repairs. Additional precautions involve corrosion inhibition, low viscous grouting, crack filling, and addressing external issues like cracks and de-bonding. In summary, the findings from the structural audits of all three sites necessitate immediate attention and a series of recommended repair measures to ensure the long-term integrity and safety of the structures. The recommended actions, including material-specific treatments, additional reinforcements, and corrosion prevention, aim to address the identified issues comprehensively and enhance the overall structural stability of the buildings.

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