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Comparative Structural Audit of Low-Rise and Mid-Rise RCC Buildings Using Non-Destructive Testing Techniques

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Abstract

The long-term safety and serviceability of Reinforced Cement Concrete (RCC) buildings depend on periodic structural health assessment, particularly as structures age and are exposed to progressively adverse environmental and loading conditions. Destructive testing methods, while accurate, damage structural members and are impractical for routine assessment of occupied buildings. This study presents a comparative structural audit of a low-rise (G+1) and a mid-rise (G+4) RCC residential building using Non-Destructive Testing (NDT), namely the Rebound Hammer Test, the Ultrasonic Pulse Velocity (UPV) Test, and a Rebar Locator survey, supported by systematic visual inspection. Field investigations were carried out on columns and beams at each floor level of both structures. Results show that the mid-rise building consistently exhibited higher rebound numbers, higher estimated compressive strength and higher UPV values than the low-rise building. The average estimated compressive strength of the mid-rise building ranged from 28.65 MPa to 32.78 MPa against 25.50 MPa to 28.77 MPa for the low-rise building, while UPV values ranged from 3515-4036 m/s (good quality) for the mid-rise building and 3294-3682 m/s (medium-to-good quality) for the low-rise building. A strong positive correlation was observed between rebound number and pulse velocity in both structures. The study demonstrates that combined use of Rebound Hammer and UPV testing provides a reliable, rapid and economical basis for structural audit, condition assessment and rehabilitation planning of existing RCC buildings, and that building height, age and exposure conditions measurably influence in-situ concrete quality.

Keywords: Non-Destructive Testing (NDT); Rebound Hammer Test; Ultrasonic Pulse Velocity (UPV); Rebar Locator; Structural Audit; RCC Buildings; Compressive Strength; Low-rise and Mid-rise Structures

1. Introduction

Reinforced Cement Concrete (RCC) is the predominant construction material for residential, commercial and institutional buildings owing to its strength, durability, economy and adaptability to varied structural forms. However, RCC structures deteriorate progressively with age due to moisture ingress, carbonation, reinforcement corrosion, poor workmanship, overloading, thermal effects and inadequate maintenance. Continuous urbanisation and the increasing stock of ageing buildings have made structural condition assessment an essential component of civil engineering practice, both for ensuring occupant safety and for planning cost-effective repair, retrofitting or rehabilitation.

Conventional destructive testing (e.g., core cutting) provides accurate strength data but damages the structural member, is costly, time-consuming and often impractical in occupied buildings. Non-Destructive Testing (NDT) methods overcome these limitations by allowing rapid, in-situ evaluation of concrete quality without impairing the structural member. Among the available NDT techniques, the Rebound Hammer Test and the Ultrasonic Pulse Velocity (UPV) Test are the most widely adopted in field practice because of their simplicity, portability, low cost and established correlation with concrete compressive strength (IS 13311 Parts 1 & 2). The Rebound Hammer Test evaluates surface hardness through the rebound of a spring-loaded mass, while the UPV Test evaluates the internal homogeneity and density of concrete by measuring the transit time of an ultrasonic pulse. A Rebar Locator (cover meter) further complements these tests by verifying reinforcement position, spacing and cover, all of which affect both structural performance and the reliability of NDT readings.

Building height is known to influence the loading regime, structural detailing, quality control during construction and exposure conditions of RCC members. Mid-rise buildings are typically subjected to higher axial loads on lower storeys, use richer concrete mixes to meet strength requirements, and may receive more rigorous quality control during construction and supervision compared to low-rise individual buildings. This provides a rational basis to expect measurable differences in in-situ concrete quality between low-rise and mid-rise construction, which the present study investigates empirically through field NDT.

2. Need and Significance of the Study

A review of published literature indicates that most existing studies on NDT-based structural assessment focus on a single building, a single testing method, or laboratory-controlled specimens, with limited emphasis on side-by-side, field-based comparison between buildings of different height categories. Consequently, the influence of building height, loading condition and site exposure on in-situ concrete quality remains inadequately documented under real field conditions. Furthermore, several earlier studies rely exclusively on either the Rebound Hammer Test or the UPV Test, which individually provide only partial information — surface hardness in the former and internal homogeneity in the latter — without a combined and cross-validated assessment.

The present study addresses this gap by carrying out a controlled, comparative field investigation on one low-rise (G+1) and one mid-rise (G+4) RCC building using both Rebound Hammer and UPV testing, supplemented by rebar location and systematic visual inspection. The need for such a study stems from:

- The large and ageing stock of existing RCC buildings requiring periodic, non-invasive structural audit for safety certification and insurance/legal compliance.
- The absence of destructive-testing feasibility in occupied residential structures.
- The requirement for reliable, cross-validated data (rather than a single NDT method) to reduce estimation error in compressive strength and concrete quality assessment.
- The practical value of quantifying how building height and floor level affect concrete quality, which is directly useful to structural auditors, maintenance engineers and municipal building-audit authorities.

The findings of this study are intended to assist practising structural auditors, facility managers, and municipal/regulatory bodies mandating periodic structural audits of ageing buildings, by providing field-validated evidence on the comparative reliability and sensitivity of NDT methods across building typologies.

3. Review of Literature

Several researchers have examined the application of NDT methods to RCC structures. Studies employing combined Rebound Hammer and UPV testing report improved reliability compared with either method used alone, since surface hardness and internal homogeneity provide complementary information on concrete condition. Investigations restricted to the Rebound Hammer Test alone have shown that rebound values are sensitive to surface moisture, carbonation depth, surface preparation and the age of concrete, underscoring the need for corroboration with an internal-quality method such as UPV. Independent UPV-based studies confirm that pulse velocity is an effective indicator of internal cracking, honeycombing and voids, with higher velocities corresponding to denser, better-compacted concrete. Investigations of ageing buildings under long-term environmental exposure report progressive strength and quality reduction associated with moisture ingress and carbonation, reinforcing the case for periodic structural audit. Field studies on multi-storey buildings further indicate that concrete quality can vary with floor level, loading history and local maintenance practice, motivating floor-wise data collection as adopted in the present investigation. Collectively, the literature supports the combined-NDT approach used here but leaves a gap — addressed in this paper — in direct, floor-wise, building-height comparison under field conditions.

4. Methodology

4.1 Selection of Structures

Two existing, in-service RCC framed residential buildings were selected for the study on the basis of accessibility and willingness of occupants to permit testing: a low-rise building of G+1 (Ground + 1 upper floor) configuration and a mid-rise building of G+4 (Ground + 4 upper floors) configuration. Both structures are conventional RCC beam-column framed construction with brick masonry infill.

4.2 Visual Inspection

A preliminary walkthrough visual inspection was carried out on both buildings prior to instrumented testing, to document surface cracks, dampness, honeycombing, spalling and leakage marks, and to guide the selection of representative NDT test locations. Observations were recorded systematically with photographic documentation.

4.3 Selection of Test Locations

Columns and beams were selected as the primary structural members for testing. Test points were located at the mid-height of columns and the soffit of beams, at positions that were structurally representative and physically accessible on every floor of each building. Test-point layouts for both buildings are shown in Fig. 1.

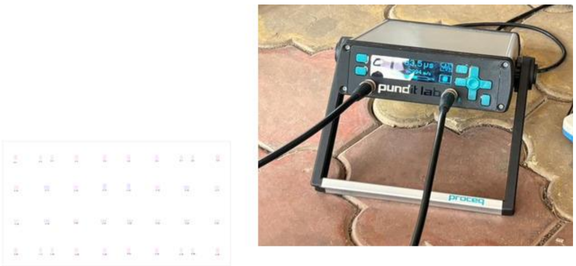

Fig. 1. Structural test-point layout: (a) Mid-rise building (G+4) column grid; (b) Low-rise building (G+1) column grid

4.4 Non-Destructive Test Methods

Three complementary NDT methods were used, as summarised below and illustrated in Fig. 2.

Fig. 2. Field instruments used: (a) Rebound Hammer; (b) Ultrasonic Pulse Velocity (UPV) tester; (c) Rebar Locator (cover meter)

(a) Rebound Hammer Test (IS 13311 Part 1 / ASTM C805):
A spring-controlled mass is impacted against the concrete surface through a plunger; the rebound distance, expressed as the Rebound Number, is correlated with surface hardness and hence approximate compressive strength. Higher rebound numbers indicate denser, stronger concrete. Surfaces were cleaned and smoothened prior to testing, the hammer was held perpendicular to the surface, and multiple readings were taken and averaged at each location per manufacturer and code guidance.

(b) Ultrasonic Pulse Velocity Test (IS 516 Part 5/Sec 1 / ASTM C597):
An ultrasonic pulse is transmitted through the concrete member between a transmitting and a receiving transducer coupled to the surface with gel; the transit time is used to compute pulse velocity, which depends on the density, elastic properties and internal homogeneity of the concrete. Higher velocities indicate dense, well-compacted concrete free of significant voids, while lower velocities suggest cracking, honeycombing or deterioration.

(c) Rebar Locator / Cover Meter Survey:
An electromagnetic cover-meter was used to verify the position, spacing, approximate diameter and concrete cover of embedded reinforcement at the tested locations, ensuring that Rebound Hammer and

UPV readings were not distorted by proximity to reinforcement, and providing supplementary information on detailing adequacy.

4.5 Test Procedure and Data Recording

At every test location, the sequence followed was: (i) surface cleaning and preparation; (ii) rebar-locator survey to confirm cover and avoid direct testing over embedded bars; (iii) Rebound Hammer testing with multiple (typically 6-8) impact readings averaged to a single rebound number; and (iv) UPV testing with the transducers coupled using gel, in either direct or indirect transmission mode depending on member accessibility. All readings were logged floor-wise and member-wise (column/beam) in standardised observation sheets for subsequent analysis.

5. Data Collection

Field data were collected from 20 columns and 15 beams in the mid-rise (G+4) building across all five floor levels (Ground, 1st, 2nd, 3rd and 4th), and from 6 columns and 6 beams in the low-rise (G+1) building across both floor levels (Ground and 1st). At each structural member, an averaged Rebound Number and an averaged UPV reading were recorded, together with the corresponding estimated compressive strength (from the manufacturer's rebound-strength correlation chart) and a qualitative concrete-quality grade derived from standard UPV quality classification (IS 13311 Part 1). A summary of the buildings investigated is given in Table 1.

Parameter	Low-Rise Building	Mid-Rise Building
Configuration	G + 1	G + 4
Structural system	RCC framed with masonry infill	RCC framed with masonry infill
Columns tested	6	20
Beams tested	6	15
Tests conducted	Visual inspection, Rebound Hammer, UPV, Rebar Locator	Visual inspection, Rebound Hammer, UPV, Rebar Locator

Table 1. Summary of the buildings investigated

Representative floor-wise averaged data extracted from the field observation sheets are presented in Tables 2-5. The complete member-wise raw data set (60 individual test locations) is available with the authors and forms part of the underlying project documentation.

6. Data Analysis and Results

6.1 Visual Inspection Findings

Visual inspection revealed hairline shrinkage/thermal cracks on beam surfaces and wall-plaster junctions, dampness and moisture patches near beam-column junctions and terrace slabs (attributable to inadequate drainage and rainwater exposure), minor surface weathering/discolouration, and localised honeycombing at beam corners consistent with minor compaction deficiencies during casting. No major structural cracking, excessive deflection or distress was observed in primary members (columns and beams) in either building; defects were predominantly serviceability-related rather than indicative of structural distress. Representative site conditions are shown in Fig. 3.

Fig. 3. Representative visual defects observed during inspection: (a) dampness/staining at a beam soffit; (b) hairline surface crack on a column face

Fig. 4. Field investigation in progress — Rebound Hammer and Rebar Locator testing on a column

6.2 Rebound Hammer Test Results

Table 2 presents floor-wise average estimated compressive strength derived from Rebound Hammer readings for the mid-rise building, and Table 3 for the low-rise building. Fig. 5 shows the member-wise rebound number trend for both buildings, and Fig. 6 shows the correlation between rebound number and estimated compressive strength.

Floor	**Avg. Compressive Strength – Column (MPa)**	**Avg. Compressive Strength – Beam (MPa)**
GF	28.65	28.53
1st	31.40	30.80
2nd	32.53	32.03
3rd	32.03	30.73
4th	32.78	30.80

Table 2. Floor-wise average estimated compressive strength — Mid-rise building

Floor	Avg. Compressive Strength – Column (MPa)	Avg. Compressive Strength – Beam (MPa)
GF	25.50	25.30
1st	28.77	28.40

Table 3. Floor-wise average estimated compressive strength — Low-rise building

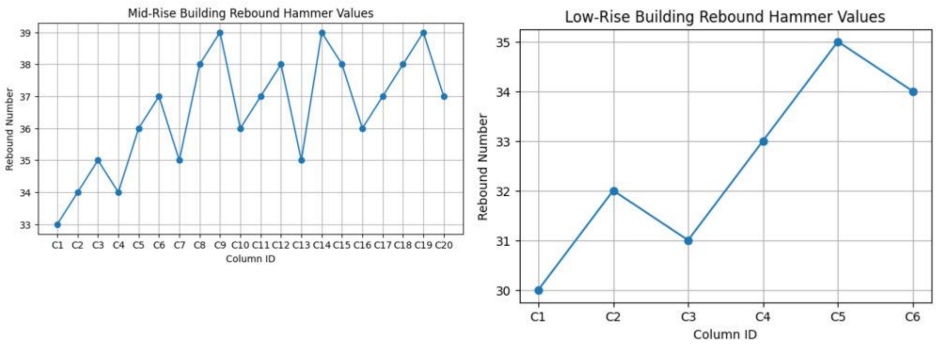

Fig. 5. Member-wise Rebound Number trend: (a) Mid-rise building columns (C1-C20); (b) Low-rise building columns (C1-C6)

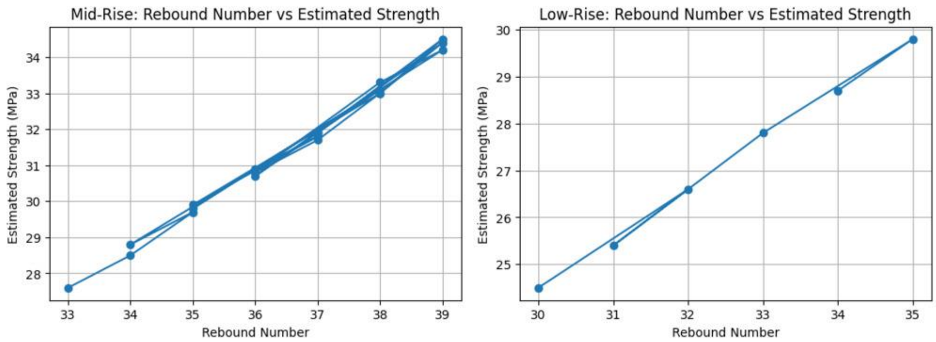

Fig. 6. Correlation between Rebound Number and estimated compressive strength: (a) Mid-rise building; (b) Low-rise building

The overall increase in average column compressive strength from ground floor to the topmost floor was 14.42% for the mid-rise building (Ground Floor to 4th Floor) and 12.82% for the low-rise building (Ground Floor to 1st Floor). A minor decrease was observed between the 2nd and 3rd floors of the mid-rise building (-1.54% for columns, -4.06% for beams), which may be attributed to localised variation in curing, cover, or surface carbonation rather than a systematic structural deficiency, since UPV data for the same floors did not indicate a corresponding reduction in internal quality.

6.3 Ultrasonic Pulse Velocity (UPV) Test Results

Table 4 and Table 5 present floor-wise average UPV values for the mid-rise and low-rise buildings respectively. Fig. 7 presents member-wise UPV values for beams in both buildings in bar-chart form.

Floor	Avg. UPV – Column (m/s)	Avg. UPV – Beam (m/s)
GF	3515.00	3625.00
1st	3981.50	3771.00

Floor	Avg. UPV – Column (m/s)	Avg. UPV – Beam (m/s)
2nd	3998.00	3842.00
3rd	4035.75	3754.33
4th	4023.25	3894.67

Table 4. Floor-wise average UPV — Mid-rise building

Floor	Avg. UPV – Column (m/s)	Avg. UPV – Beam (m/s)
GF	3413.67	3294.00
1st	3681.67	3623.67

Table 5. Floor-wise average UPV — Low-rise building

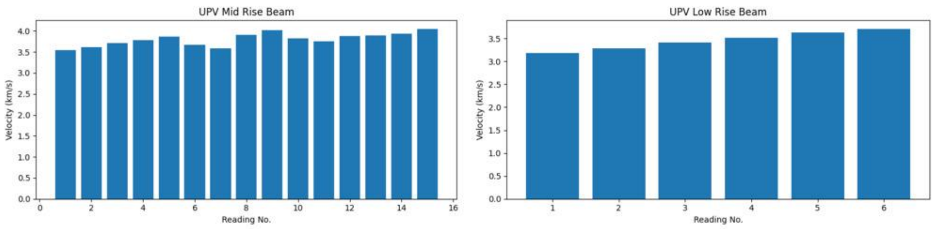

Fig. 7. UPV values recorded on beams: (a) Mid-rise building; (b) Low-rise building

UPV values for the mid-rise building ranged from 3515 m/s to 4036 m/s, classifying the concrete as "good" quality throughout the structure as per standard UPV quality classification. The low-rise building recorded UPV values between 3294 m/s and 3682 m/s, classifying as "medium to good" quality. The overall increase in column UPV from ground floor to top floor was 14.31% for the mid-rise building and 7.85% for the low-rise building; the corresponding increase in beam UPV was 7.37% for the mid-rise building and 10.01% for the low-rise building — the only parameter in which the low-rise building showed a marginally higher percentage improvement, which may reflect its simpler two-floor loading transition rather than superior absolute concrete quality, since its absolute UPV values remained below those of the mid-rise building at every corresponding floor.

6.4 Comparative and Correlation Analysis

A consistent positive correlation was observed between Rebound Number and UPV across both buildings and across all floors: floors recording a higher average rebound number also recorded a higher average UPV, and vice versa (Table 6). This cross-validation between an internal-quality method (UPV) and a surface-hardness method (Rebound Hammer) increases confidence that the observed strength gradation reflects genuine variation in concrete quality rather than measurement artefact, and confirms that no significant internal defects, honeycombing or voids were present in either structure at the time of testing.

Floor	Mid-Rise: Rebound Strength (MPa)	Mid-Rise: UPV (m/s)	Low-Rise: Rebound Strength (MPa)	Low-Rise: UPV (m/s)
GF	28.65	3515.00	25.50	3413.67
1st	31.40	3981.50	28.77	3681.67
2nd	32.53	3998.00	-	-

Floor	Mid-Rise: Rebound Strength (MPa)	Mid-Rise: UPV (m/s)	Low-Rise: Rebound Strength (MPa)	Low-Rise: UPV (m/s)
3rd	32.03	4035.75	-	-
4th	32.78	4023.25	-	-

Table 6. Combined Rebound Hammer – UPV comparison (column data), floor-wise

Table 7 summarises the overall comparative performance of the two buildings across all measured parameters.

Parameter	Low-Rise Building	Mid-Rise Building	Observation
Column strength increase (GF to top floor)	12.82%	14.42%	Mid-rise higher
Beam strength increase (GF to top floor)	12.25%	8.13%	Low-rise higher
Column UPV increase (GF to top floor)	7.85%	14.31%	Mid-rise higher
Beam UPV increase (GF to top floor)	10.01%	7.37%	Low-rise slightly higher
Concrete quality (UPV classification)	Medium to Good	Good	Mid-rise better
Overall structural condition	Satisfactory	Satisfactory to Better	Mid-rise better

Table 7. Overall comparative performance summary

7. Discussion

The results indicate that the mid-rise (G+4) building exhibited consistently higher rebound numbers, higher estimated compressive strength and higher UPV values than the low-rise (G+1) building, both in absolute terms and, for most parameters, in the rate of floor-wise increase. This is plausibly attributable to (i) the use of richer concrete mixes and more stringent quality control typically associated with taller structures designed to resist higher cumulative loads; (ii) proportionally lower moisture and weathering exposure per unit height in the more recently or more carefully constructed mid-rise structure; and (iii) differences in curing practice and supervision between the two projects. The isolated minor decrease in mid-rise beam/column strength between the 2nd and 3rd floors does not correspond to a simultaneous drop in UPV at the same floors, suggesting the effect is localised to surface conditions (e.g., carbonation or minor surface finish variation) rather than a genuine reduction in internal concrete quality.

The visual inspection findings — limited to serviceability-level defects such as hairline cracking, dampness and minor honeycombing, with no major structural distress — are consistent with the NDT results, which did not indicate the presence of significant internal voids or cracking in either structure.

This agreement between qualitative (visual) and quantitative (NDT) assessment strengthens the overall reliability of the structural audit conclusions.

From a practical standpoint, the study confirms that combined Rebound Hammer and UPV testing, cross-validated against each other and against visual inspection, provides a dependable, rapid and non-invasive basis for assessing in-situ concrete quality of existing buildings, and that building height/loading category is a measurable factor influencing that quality — information directly relevant to prioritising structural audit and maintenance resources across a building stock of mixed typology.

8. Conclusion

- The mid-rise (G+4) RCC building exhibited higher average estimated compressive strength (28.65-32.78 MPa) than the low-rise (G+1) building (25.50-28.77 MPa), based on Rebound Hammer testing.
- UPV values for the mid-rise building (3515-4036 m/s) classified the concrete as "good" quality throughout, while the low-rise building (3294-3682 m/s) classified as "medium to good" quality.
- A consistent positive correlation was observed between Rebound Number and UPV in both buildings, confirming the internal consistency and reliability of the two NDT methods when used together.
- Visual inspection revealed only minor, serviceability-related defects (hairline cracks, dampness, localised honeycombing) in both buildings, with no evidence of major structural distress, consistent with the NDT findings.
- Building height and associated construction/loading practice measurably influenced in-situ concrete quality, with the mid-rise building demonstrating superior overall performance in the majority of measured parameters.
- The combined use of Rebound Hammer and UPV testing, supported by rebar location and visual inspection, is confirmed as a reliable, economical and non-invasive methodology for structural audit, condition assessment and rehabilitation planning of existing RCC buildings.

9. Recommendations

- Cracked and damp-affected portions identified during visual inspection should be monitored periodically and repaired using appropriate crack-injection or patch-repair techniques.
- Waterproofing treatment should be provided at terrace and roof slab locations to prevent continued moisture penetration, particularly where water stagnation was observed near overhead tanks.
- Proper roof/terrace drainage slope and outlets should be maintained to avoid water stagnation, which was identified as a contributing factor to dampness and long-term durability reduction.
- Periodic (e.g., 3-5 year) structural audit using combined Rebound Hammer and UPV testing is recommended for both building categories, with more frequent monitoring for older or heavily loaded members.
- Where NDT results indicate borderline or lower-quality zones (e.g., ground-floor members subjected to higher moisture exposure), supplementary core testing should be considered before finalising repair/rehabilitation decisions, since NDT provides an estimate rather than a direct strength measurement.
- Future studies should extend the comparative dataset to a larger sample of buildings across multiple height categories, ages and geographic/climatic zones, and should incorporate additional NDT methods (e.g., carbonation depth testing, half-cell potential for corrosion assessment) to build a more comprehensive structural health database.

10. Limitations and Scope for Future Work

The study is based on one building from each height category, which, while providing valuable field-based comparative insight, limits statistical generalisation to all low-rise and mid-rise construction. Estimated compressive strength values are derived from empirical rebound-strength correlation charts rather than from core-extracted destructive testing, and therefore carry the inherent approximation associated with NDT-based strength estimation. Future work should extend the sample size across multiple buildings of each category, incorporate core testing on a limited sub-sample for calibration/validation of the NDT-based strength estimates, and examine additional influencing variables such as concrete age, mix design records, and micro-climatic exposure.

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