

STRUCTURAL HEALTH ASSESSMENT OF RCC MEMBERS USING NON-DESTRUCTIVE AND PARTIAL DESTRUCTIVE TECHNIQUES AT ELEVATED FLOOR LEVEL OF A SPORTS STADIUM

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Abstract

This study presents a comprehensive evaluation of reinforced cement concrete (RCC) members situated at the +10.80 m level of an international cricket stadium in Gwalior, Madhya Pradesh, utilizing a series of nondestructive Tests (NDT) and Partial Destructive Tests (PDT). The investigation was undertaken to assess the in-situ material quality and structural integrity of slabs and beams using Ultrasonic Pulse Velocity (UPV), Rebound Hammer, and Core Compression and Chemical Analysis. The UPV results indicated a significant portion of the slab concrete quality falls within the “doubtful” category, while beams ranged from “medium” to “good” quality. Rebound hammer readings generally revealed surface hardness which, when correlated to compressive strength, suggested values potentially lower than the design grade (M30). Core compression tests revealed non-uniform in situ compressive strength (20.78–41.34 MPa); although most cores satisfied the M30 design grade, chloride concentrations exceeding IS 456:2000 limits establish a durability-governed corrosion initiation environment within slab and beam members. No carbonation effects were observed, and the sulfate content was within the acceptable bounds. This integrated approach highlights the need for localized rehabilitation and continuous monitoring to maintain structural reliability in large public infrastructure. The elevated chloride concentrations observed in the slab and beam cores establish a critical durability concern that directly influences corrosion-based maintenance planning of high-occupancy RCC structures. The study thus provides a practical durability-oriented decision framework for condition-based rehabilitation of stadium infrastructures.

Keywords: Core Compression Test; Non-Destructive Testing; Reinforced Concrete Assessment; Structural Integrity Evaluation; Ultrasonic Pulse Velocity

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Introduction

The structural performance of Reinforced Cement Concrete (RCC) members in high-occupancy structures such as stadiums plays a critical role in ensuring public safety. Over time, these structures are prone to deterioration owing to mechanical stress, environmental exposure, corrosion, and poor construction quality. Therefore, periodic condition assessments are indispensable for ensuring safety and serviceability (Kot *et al.* 2021).

Structural Health Monitoring (SHM) has evolved into a robust field that includes both traditional and advanced methods for identifying damages. The adoption of Non-Destructive Testing (NDT) techniques, such as Ultrasonic Pulse Velocity (UPV), Rebound Hammer, Half-Cell Potential, and Carbonation Depth Measurement, enables non-invasive in situ evaluation of RCC structures, offering valuable insights into their strength and durability characteristics (De Souza and Savoikar, 2023).

Beyond strength evaluation, corrosion detection is central to RCC health assessment. Methods such as Half-Cell Potential and Carbonation

Depth Testing help identify the loss of alkalinity and chloride ingress, which are key triggers of steel-reinforcement corrosion. Notably, a three-parameter correlation among Half-Cell Potential readings, pH levels, and UPV values has demonstrated high reliability in identifying corrosion-prone zones (Bosu Choudhury, 2019).

Visible deterioration indicators, such as spalling, cracking, and delamination, commonly observed in RCC slabs and beams, are often symptomatic of internal corrosion. When these visual cues are corroborated by electrochemical NDT findings, they enable the formulation of targeted rehabilitation strategies and assist in repair prioritization (Kumar *et al.* 2021).

As structures age, contemporary research increasingly advocates multiparameter SHM approaches. The integration of data fusion techniques and artificial intelligence models further enhances diagnostic accuracy and supports predictive maintenance frameworks, facilitating risk-based decision-making and long-term infrastructure sustainability (Mahmood, 2008).

Traditional visual inspections, when necessary, often fail to capture subsurface deterioration or accurately estimate residual structural capacity. This limitation is especially critical in complex and high-occupancy RCC structures such as stadiums, which are subjected to diverse loading conditions and environmental impacts (Kanwar *et al.* 2016).

In such cases, Partial Destructive Testing (PDT) methods, such as core extraction and pull-out tests, are used to validate the NDT outcomes and quantify actual material deterioration. These methods, which are applied selectively to minimize damage, provide essential insights into the residual strength parameters (BIS, 2021).

Among the widely used NDT methods, Rebound Hammer and Ultrasonic Pulse Velocity (UPV) are frequently employed to assess compressive strength and material uniformity. When combined through the SonReb method, these techniques yield improved predictions of in situ concrete strength (Yalamati *et al.* 2016; Bhirud and Makwana, 2024). PDT methods, such as core sampling, complement this approach by verifying and calibrating surface-based NDT data, particularly for load-critical components such as elevated slabs and beams on stadium floors (Tefera and Tarekegn, 2025).

Corrosion detection remains a critical concern for the aging of RCC structures. Tests such as Half-Cell Potential and Carbonation Depth Analysis are effective for identifying early-stage corrosion in embedded reinforcements, particularly in moist or open environments. The onset of such corrosion is often silent and accelerated by carbonation-induced pH loss or chloride penetration (Shahi and Narwade, 2018).

In recent years, vibration-based testing methods have been introduced into SHM frameworks. These rely on the detection of shifts in modal parameters, such as changes in the natural frequencies or damping ratios, which may indicate internal damage. When paired with artificial neural networks (ANNs), these approaches can localize and assess the severity of structural damage, even when they remain invisible to conventional inspection methods (Singh Kanwar *et al.* 2008).

Several field-based studies have demonstrated the practicality and effectiveness of integrating these methods. For example, a structural audit of an RCC health facility employed UPV and Rebound Hammer tests to locate deteriorated zones, which were later confirmed through core extraction (Venkatesh and Alapati, 2017). Likewise, a condition assessment of an industrial RCC frame using a cover meter and carbonation analysis revealed extensive reinforcement exposure, which was instrumental in formulating an appropriate repair plan (Kukade *et al.* 2019).

This multilayered approach is particularly pertinent in India, where climatic variability, inconsistent construction practices, and

maintenance gaps accelerate the degradation of concrete structures. Stadiums—due to their elevated RCC floors, susceptibility to crowd-induced vibrations, and exposure to thermal fluctuations—present unique challenges that demand comprehensive, integrated health monitoring strategies.

Despite the extensive application of non-destructive and partial destructive testing techniques for condition assessment of RCC structures, most existing studies predominantly focus on conventional buildings, bridges, and industrial frames, where deterioration is generally evaluated primarily on the basis of compressive strength adequacy. Systematic durability-governed investigations focusing on elevated RCC floor systems in high-occupancy stadium environments remain notably limited. Such structural components are subjected to unique exposure conditions including crowd-induced dynamic loading, open environmental exposure, thermal fluctuations, and moisture-chloride ingress, which significantly accelerate hidden durability deterioration mechanisms.

Moreover, the combined influence of internal microstructural heterogeneity, localized construction variability, and chloride-induced corrosion risk on the long-term serviceability of elevated RCC slabs and beams has not been sufficiently documented in current literature. In particular, the presence of hidden internal discontinuities detectable through ultrasonic methods but not reflected by surface hardness or compressive strength alone, presents a critical gap in durability-oriented structural health assessment frameworks.

The present study addresses this gap by conducting a layered NDT-PDT-based durability-governed structural health evaluation of elevated RCC slab-beam systems within an operational international cricket stadium. By integrating ultrasonic pulse velocity, rebound hammer testing, core compressive strength, and chemical durability indicators, the study establishes a comprehensive diagnostic framework that identifies hidden deterioration mechanisms governing long-term serviceability rather than relying solely on strength-based acceptance criteria.

Accordingly, this research provides a durability-oriented decision-support framework for preventive maintenance planning and rehabilitation prioritization of high-occupancy stadium infrastructure, thereby contributing a practically implementable structural health assessment methodology for large public RCC facilities.

The remainder of this paper is organized as follows. The methodology, including a site

overview and testing procedures, is described in Section 2. Section 3 presents and analyzes the results obtained from UPV, Rebound Hammer, core testing, and chemical assessments. Section 4 provides concluding remarks and summarizes the key findings, limitations, and recommendations for future work.

Materials and Methods

Site and Structural Overview

The structural health assessment was carried out at the +10.80 m level of an operational international cricket stadium located in Gwalior, Madhya Pradesh, as illustrated in Figure 1. The investigation focused on reinforced cement concrete (RCC) slab and beam components forming the elevated spectator floor system, which represents a structurally critical zone subjected to continuous service loading, crowd-induced vibrations, and open environmental exposure.

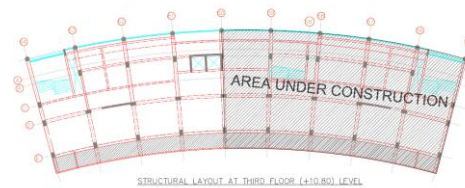


Figure 1. Structural layout of international cricket stadium located in Gwalior

The RCC slab under assessment was cast in April 2019 and evaluated in June 2019, corresponding to a concrete maturity age of 57 days at the time of testing. This age was deliberately selected to ensure that the concrete had achieved stable post-curing mechanical maturity beyond the standard 28-day strength development period, thereby minimizing the influence of early-age hydration variability on both non-destructive and partial destructive test results. At this maturity stage, ultrasonic pulse velocity and rebound hammer measurements provide reliable indicators of internal microstructural continuity, while moisture transport and chloride diffusion mechanisms become sufficiently active to enable early detection of durability-governed deterioration risks.

A detailed floor layout plan was developed to systematically identify test locations for slab and beam elements. The elevated floor was divided into a uniform grid to achieve representative spatial coverage of the slab panels and supporting beams. Zones exhibiting differential surface finishing, minor visible irregularities, service exposure to moisture, and high crowd-load intensity were

preferentially included to capture potentially vulnerable regions.

Core extraction locations were further refined using Ground Penetrating Radar (GPR) scanning to avoid reinforcement congestion and to ensure that the extracted cores represented structurally critical and exposure-relevant concrete regions. This integrated selection approach ensured that both globally representative and locally vulnerable zones were assessed, enabling a comprehensive evaluation of material integrity, structural performance, and durability-governed deterioration mechanisms of the elevated RCC floor system.

The scope of the investigation was limited to the +10.80 m level and excluded foundation, lower floor, and roof structural components. The testing program comprised four principal categories: Ultrasonic Pulse Velocity (UPV), Rebound Hammer testing, Core Compression testing, and Chemical Durability evaluation.

Non-Destructive Testing

Ultrasonic Pulse Velocity (UPV) Test

An Ultrasonic Pulse Velocity (UPV) test was conducted to evaluate the internal quality and homogeneity of concrete in both the slabs and beams. This test followed the guidelines of IS 13311 (Part 1): 1992 and employed the principle of measuring the time taken by an ultrasonic pulse to travel through concrete. The test setup involved placing a transmitter and receiver on either side of the concrete member (direct method) or on the same surface (semi-direct or indirect method) when the opposite faces were not accessible. The surface plaster was removed using a mechanical grinder to expose the parent concrete and to ensure good acoustic coupling. Digital readings of the UPV test

configuration in direct and indirect modes are shown in Figure 2. The velocity of ultrasonic waves was calculated using the formula as shown in equation 1:

$$V = \frac{\text{Path Length}}{\text{Transit Time}} \quad (1)$$

The UPV readings were classified in accordance with IS 13311 (Part 1):1992 (Bureau of Indian Standards [BIS], 1992a), wherein pulse velocities exceeding 4.5 km/s were considered “excellent,” values between 3.5–4.5 km/s as “good,” 3.0–3.5 km/s as “medium,” and readings below 3.0 km/s as “doubtful.” In this study, a total of 47 readings were obtained from slab locations and 51 readings from beam locations. These standardized classification limits were adopted as engineering control thresholds for evaluating in-situ concrete integrity and mapping spatial quality variation across the elevated floor system. Pulse velocity values above 4.5 km/s represent dense and homogeneous concrete with minimal internal discontinuities, whereas velocities in the 3.5–4.5 km/s range indicate structurally sound concrete with acceptable material continuity. Readings between 3.0–3.5 km/s reflect moderate heterogeneity associated with localized porosity and early-stage microcracking, while values below 3.0 km/s signify doubtful-quality concrete characterized by internal voids, honeycombing, and microstructural degradation. Accordingly, all slab and beam UPV readings were systematically classified using these standardized limits to identify deterioration-prone zones that are not externally visible, thereby forming the primary interpretative basis for slab–beam quality zoning and subsequent durability-based structural analysis.

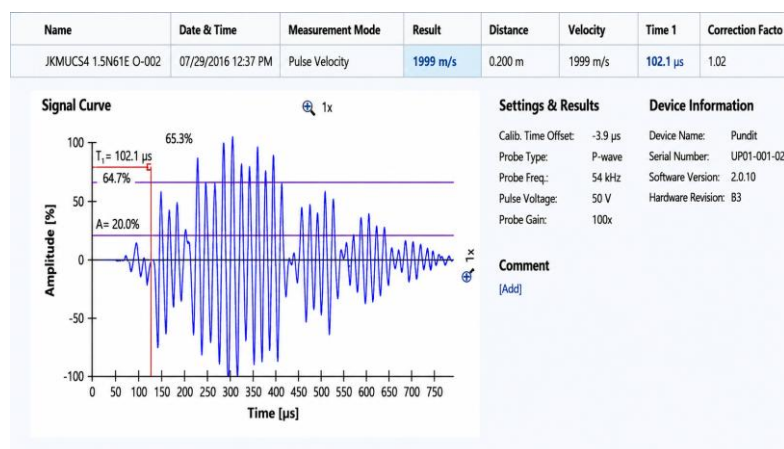


Figure 2. Ultrasonic Pulse Velocity (UPV) test reading

Rebound Hammer Test

The Rebound Hammer test was used to assess the surface hardness and estimate the compressive strength of concrete using surface rebound values. This test was conducted in accordance with IS 13311 (Part 2): 1992 (BIS, 1992b). A Schmidt Rebound Hammer calibrated to an impact energy of 2.25 Nm, was used for this purpose. Six rebound readings were taken at each designated test location on both the slabs and beams. The test was conducted by pressing a hammer plunger perpendicular to the concrete surface, and the rebound number was recorded for each impact. Prior to testing, the surface was cleaned and smoothed using a grinder to remove plaster and obtain direct access to the concrete. The operational orientation and contact procedure for the Rebound Hammer test are illustrated in Figure 3. The average rebound number at each location was used to estimate the compressive strength using the exponential formula in Equation 2.

$$f_{ck} = 2.77e^{0.048Q} \quad (2)$$

where Q is the average rebound number.

According to CPWD interpretations adapted for this work, values less than 20 were classified as "poor," 21-30 as "fair," 31-40 as "good," and 41-50 as "very good." Values exceeding 50 indicate carbonation. This test helped quickly evaluate surface-level conditions and confirm consistency with deeper assessments from UPV and core testing.

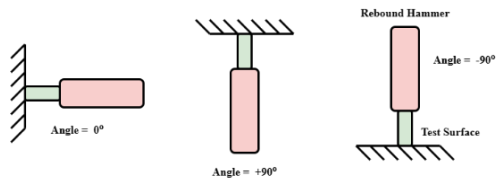


Figure 3. Schematic of Rebound Hammer operation on vertical and horizontal RCC surfaces

Partial Destructive Testing

Core Compression Test

Core compression tests were conducted to determine the in situ compressive strength of the concrete in accordance with IS 516:1959 (BIS, 1959). Six cylindrical core samples were extracted from the RCC members at the +10.80 m level, comprising five samples from the slab and one from the beam. Each core had a diameter of 67 mm and was drilled vertically using a rotary diamond coring machine. The locations were selected with the aid of a Ground Penetrating Radar (GPR) to ensure the

avoidance of reinforcement bars and capture structurally representative concrete zones (Figure 4). After extraction, the cores were carefully cleaned and their end surfaces were ground flat and perpendicular to the core axis. To ensure uniform stress distribution during testing, sulfur or gypsum capping was applied to both ends of the cores.



Figure 4. Workflow of core extraction, trimming, capping, and testing for compressive strength as per IS 516:1959

Compressive strength testing was performed using a 2000 kN capacity compression testing machine (CTM), as shown in Figure 5. The load at failure, denoted by W , was recorded for each sample. When reinforcement marks were observed within the core, a steel correction factor was applied to account for their influence on the failure load. The corrected load W_c was calculated using the formula shown in equation 3:

$$W_c = W \times \left(1 + 1.5 \times \frac{d \times h}{D \times L} \right) \quad (3)$$

where d denotes the diameter of the embedded steel, h denotes the cover depth, D denotes the core diameter, and L denotes core length.

Next, the compressive strength f of each core was calculated using equation 4:

$$f = \frac{W_c}{A} \quad (4)$$

where A is the cross-sectional area of the core,

$$A = \frac{\pi D^2}{4}$$

computed as



Figure 5. Compressive strength test setup showing cored specimen positioned in the CTM

The obtained compressive strength was then corrected for the L/D ratio using factors from IS 516:1959 (BIS, 1959), because the standard requires adjustment if the L/D ratio deviates from the ideal 2.0. The corrected compressive strength (f_c) was converted into equivalent cube compressive strength (f_{cube}) using a conversion factor of 1.25, considering that cylinder strength is approximately 0.8 times the corresponding cube strength (Neville, 2011).

$$f_{cube} = f_c \times \frac{5}{4}$$

The resulting equivalent cube strengths varied from 20.78 MPa to 41.34 MPa for the slab cores and 28.54 MPa for the beam core. Although the majority of the samples satisfied the M30 design requirement, one slab core fell below the threshold, indicating either localized deterioration or poor workmanship. Overall, the core test results confirmed and calibrated the nondestructive test interpretations, providing an empirical basis for structural evaluation.

The observed variation in core compressive strength (20.78–41.34 MPa) indicates non-uniform material compaction, local heterogeneity in cement paste distribution, and possible construction-stage inconsistencies across slab panels and beam members. While the majority of cores satisfied the M30 design-grade requirement, the presence of localized low-strength zones reflects internal microstructural discontinuities that may serve as preferential pathways for moisture and chloride ingress. This mechanical heterogeneity, when coupled with chloride concentrations exceeding the IS 456:2000 (BIS, 2000) permissible limit (0.6 kg/m³), establishes a high-probability corrosion initiation environment within the embedded reinforcement. Such a condition significantly accelerates depassivation of steel, leading to expansive corrosion products, cracking, and progressive loss of bond and cross-sectional steel area. Therefore, despite adequate global compressive strength, the

detected chloride levels govern the long-term durability performance and indicate an advanced stage of durability-governed deterioration within the elevated RCC floor system.

Chemical Testing of Core Samples

A chemical analysis of the extracted core samples was performed to evaluate the resistance of the concrete to environmental degradation and its potential to protect the embedded steel reinforcement. The tests focused on determining the chloride content, sulfate content, carbonation depth, and pH of the concrete matrix. The chloride content was quantified using a laboratory titration method in accordance with IS 14959 (Part 2): 2001 (BIS, 2001). The slab samples showed a chloride concentration of approximately 1.0 kg/m³, whereas the beam sample recorded 0.9 kg/m³. Both values exceeded the maximum allowable limit of 0.6 kg/m³ as stipulated in IS 456:2000 (BIS, 2000), indicating a high risk of reinforcement corrosion over time.

The carbonation depth was assessed using a phenolphthalein indicator sprayed onto freshly broken concrete surfaces. A pink coloration indicates a pH above 9.5, and hence no carbonation, whereas a colorless response indicates the presence of carbonation. In all six core samples, the phenolphthalein test showed no signs of carbonation, confirming the retention of alkaline protection (Figure 6). This was supported by pH testing

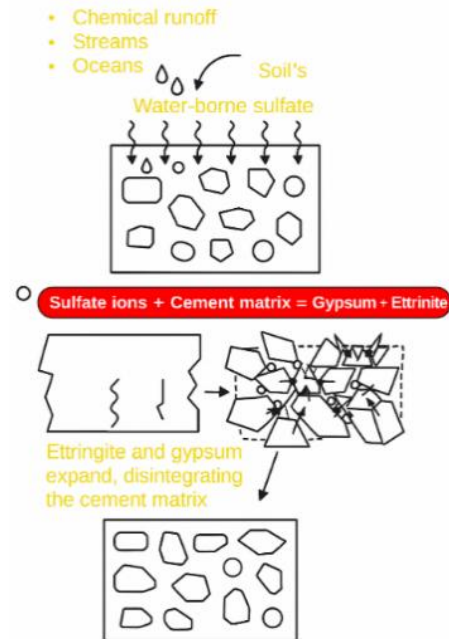


Figure 6. Laboratory process used for chloride and sulphate analysis from extracted concrete cores

conducted via water extraction methods, which consistently recorded values near 12, which is within the desirable range of 11-13.5 for durable concrete. The sulfate content was measured gravimetrically and expressed as a percentage by mass of cement, with results of 0.2% for the slab samples and 0.11% for the beam sample, well below the 4% permissible limit as per IS 456:2000 (BIS, 2000).

The chemical testing results suggest that although the concrete remains alkaline and uncarbonated, the elevated chloride content poses a serious long-term risk to the durability of the RCC members. Chloride-induced corrosion can initiate reinforcement degradation, leading to cracking and spalling, thereby reducing the service life of the structure. These tests complement mechanical strength assessments and collectively indicate the necessity for targeted rehabilitation and protective treatment for sustained structural performance.

Result and Discussion

A series of Non-Destructive and Partial Destructive Tests (NDT/PDT) were carried out on RCC members at the +10.80 m level of an international cricket stadium to assess the in-situ quality and integrity of concrete. The key observations and inferences are summarized below.

Ultrasonic Pulse Velocity (UPV) Test

UPV testing conducted at 47 slab and 51 beam locations revealed significant variability in the concrete quality. According to IS 13311 (Part 1):1992 (BIS, 1992a), concrete quality is classified based on the corrected pulse velocity:

- RCC Slabs: 58% of the readings indicated “doubtful” quality, 25% fell under

“medium,” and only 17% were in the “good” to “excellent” range, as shown in Figure 7.

- RCC Beams: Showed relatively better results with 39% rated “good,” 25% “medium,” and 36% “doubtful,” as shown in Figure 7.

Rebound Hammer Test

The rebound numbers used to indirectly estimate the compressive strength varied across tested members.

- RCC Slabs: Average rebound numbers ranged from 31 to 50+, with most readings falling under the “good” (31-40) and “very good” (41-50) quality ranges, as shown in Figure 8.

- RCC Beams: Showed similar trends, with 61% classified as “very good,” as shown in Figure 8.

The variability observed in Figure 8 across slab regions reflects spatial non-uniformity in surface densification and finishing quality of the elevated RCC floor. Higher rebound values in certain slab panels are attributable to localized surface densification resulting from differential curing, trowelling practices, and environmental exposure during construction. Conversely, comparatively lower rebound values in other slab zones indicate higher surface porosity and moisture retention, which reduce rebound response despite similar internal strength levels. This spatial variability highlights that rebound hammer results primarily characterize surface-layer conditions rather than true internal concrete integrity. Consequently, slab regions exhibiting “good” to “very good” surface hardness may still contain internal discontinuities detected by UPV testing, reinforcing the necessity of combined NDT-PDT

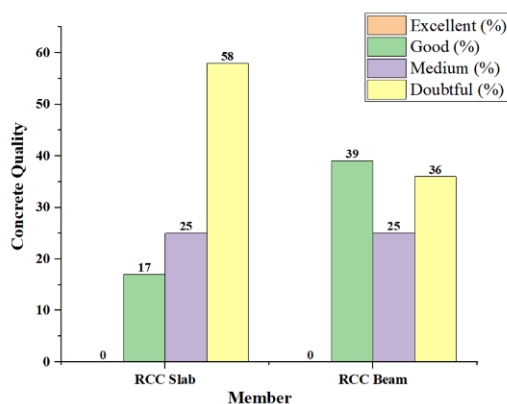


Figure 7. Distribution of Concrete Quality Based on UPV Results for RCC Slabs at +10.80 m Level

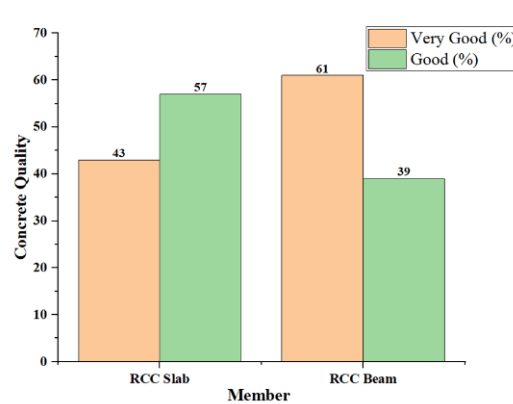


Figure 8. Surface Hardness Classification Based on Rebound Number for RCC Slabs

interpretation for reliable durability-based structural evaluation.

Core Compression Test

Six core samples (five from slabs and one from a beam) exhibited compressive strengths ranging from 20 to 41 MPa. After applying the correction factors.

- Three slabs exhibited equivalent cube strengths ≥ 35 MPa, as shown in Figure 9.
- Two samples, including the beam core, were between 20 and 30 MPa, as shown in Figure 9.

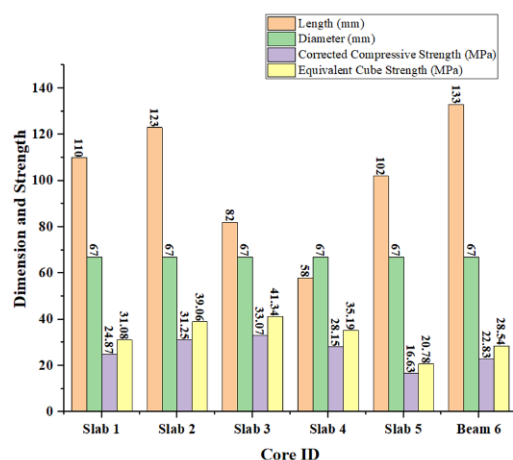


Figure 9. Corrected Compressive Strength vs. Equivalent Cube Strength for Core Samples

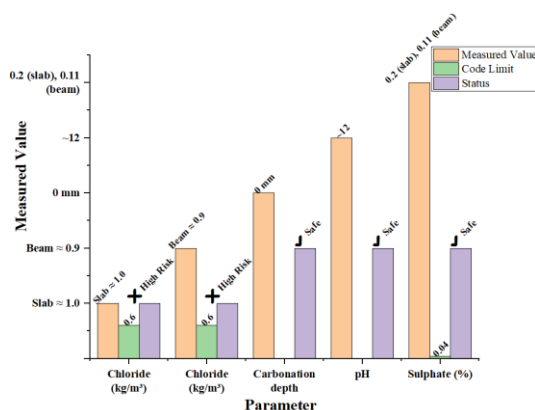


Figure 10. Durability compliance assessment of RCC slab and beam cores showing elevated chloride content beyond IS 456:2000 limits, while carbonation depth, pH, and sulphate content remain within acceptable bounds, indicating chloride-governed long-term durability risk

Chemical Test Results

- Chloride Content: Slabs (~ 1.0 kg/m³) and beams (~ 0.9 kg/m³) exceeded the

permissible limit (0.6 kg/m³ per IS 456) (BIS, 2000), indicating risk of reinforcement corrosion, as shown in Figure 10.

- Carbonation Depth: All cores were non-carbonated (pink with phenolphthalein), as shown in Figure 10.
- pH Test: All values were ~ 12 , indicating acceptable alkalinity, as shown in Figure 10.
- Sulphate Content: Within the permissible limit ($\leq 4\%$ by cement mass), as shown in Figure 10.

Technical Interpretation of UPV–RH Variations and Structural Implications

The UPV and rebound hammer results exhibit significant technical variation between slab and beam members, indicating non-uniform concrete integrity and construction quality at the elevated floor level.

The UPV measurements revealed that approximately 58% of slab locations exhibited pulse velocities below 3.0 km/s, classifying them as “doubtful quality” as per IS 13311 (Part 1):1992 (BIS, 1992a). Such low velocities are technically associated with internal microcracking, entrapped air voids, honeycombing, moisture-induced porosity, and poor compaction, which substantially reduce wave transmission efficiency and reflect loss of material continuity within slab panels.

In contrast, the beams demonstrated comparatively superior integrity, with 39% of readings falling within the “good” range (3.5–4.5 km/s), indicating better compaction and load-path continuity. This difference suggests construction-stage workmanship variability and differential exposure conditions between slab and beam elements.

Rebound hammer results further showed that although surface hardness generally fell within the “good” to “very good” categories, the estimated equivalent compressive strengths were predominantly lower than the specified design grade M30. This technical mismatch indicates that surface densification and finishing may mask internal deterioration, particularly in slab regions, leading to overestimation of actual structural capacity if rebound values are interpreted in isolation.

The combined UPV–RH interpretation therefore indicates that a substantial portion of slab concrete exhibits internal discontinuities despite acceptable surface hardness, representing a *hidden deterioration condition*. Such internal defects significantly increase vulnerability to chloride ingress, crack propagation, and corrosion-induced damage, even when core strength appears marginally adequate.

This technical variation confirms that structural adequacy based solely on compressive strength is insufficient, and that durability-governed deterioration is already active within slab elements at the elevated floor level.

The results highlight the localized deterioration in slab members, which is likely due to chloride-induced degradation and construction irregularities. While the rebound and UPV results indicate reduced surface quality, the core samples confirm that the internal concrete strength is generally within the acceptable bounds. Continuous monitoring and targeted repair are recommended to ensure durability.

Practical Durability Implications

Although the compressive strength of most core samples satisfies the design grade, the chloride content exceeding permissible limits indicates the potential initiation of corrosion in embedded reinforcement. This signifies that structural safety cannot be evaluated solely on strength parameters. The chloride-driven deterioration risk necessitates the adoption of protective measures such as surface sealers, corrosion inhibitors, and periodic electrochemical monitoring to prevent future spalling and loss of cross-sectional steel area.

Therefore, the findings of this study directly support durability-based maintenance decision-making for elevated RCC floors in stadiums and similar public infrastructure.

Comparative Interpretation of NDT and PDT Results

The UPV results classified a significant portion of slab concrete under the “doubtful” quality range, whereas core compression tests generally indicated that the in situ compressive strength satisfies the design requirements. This apparent variation can be attributed to the fundamental difference in sensitivity of the employed techniques. UPV is highly sensitive to internal discontinuities such as microcracks, voids, honeycombing, and moisture variation, which may significantly reduce pulse velocity without critically affecting the overall load-bearing capacity of the member.

In contrast, the core samples were extracted from structurally representative zones identified using Ground Penetrating Radar (GPR), intentionally avoiding major defects and reinforcement congestion. Consequently, the core compression results reflect the average intact concrete strength rather than localized deterioration zones detected by UPV.

Similarly, rebound hammer results primarily indicate surface hardness, which can be influenced by surface carbonation, moisture, and finishing

quality, and therefore may not always directly represent the internal concrete condition. The combined interpretation of UPV, rebound hammer, and core test results thus provides a more realistic and conservative assessment of the structural condition by capturing both localized deterioration and global strength adequacy. This layered interpretation framework supports informed maintenance prioritization and durability-based decision-making for elevated RCC floors in stadium structures.

Limitations and Discrepancies Between NDT and PDT Techniques

Non-destructive testing techniques such as UPV and Rebound Hammer provide rapid and wide-area assessment of concrete quality; however, their readings are inherently influenced by surface moisture, temperature, finishing quality, internal microcracking, and material heterogeneity. These factors can lead to conservative or scattered interpretations that may not always represent the true structural capacity of concrete members.

Partial destructive testing methods, particularly core compression tests, offer direct and reliable strength measurements but are localized in nature and dependent on selective sampling locations. Although GPR-assisted coring improves representativeness, core extraction may still miss critically deteriorated zones if deterioration is non-uniformly distributed.

Consequently, reliance on a single testing technique may result in incomplete or misleading structural diagnosis. The integrated interpretation of NDT and PDT results adopted in this study minimizes such discrepancies by combining global deterioration indicators with localized strength verification, thereby providing a more reliable and holistic evaluation of the in situ structural condition of elevated RCC floors.

Conclusions

Objective Achievement: - This study aimed to evaluate the structural health and in situ quality of RCC members at the +10.80 m level of an international cricket stadium using a comprehensive suite of Non-Destructive Testing (NDT) and Partial Destructive Testing (PDT) methods. This objective was successfully achieved through the systematic application of Ultrasonic Pulse Velocity (UPV), Rebound Hammer, Core Compression, and Chemical tests, which provided detailed insights into the material properties and potential durability issues of concrete used in slabs and beams.

Findings: - The Ultrasonic Pulse Velocity (UPV) test revealed that a significant proportion of the slab concrete at the +10.80 m level falls within the “doubtful” quality range, whereas the beam members exhibited comparatively better quality, predominantly ranging between “medium” and “good.” This indicates non-uniform material integrity and localized construction variability across the elevated floor system. Rebound hammer values showed surface hardness mostly in the “good” to “very good” range; however, combined UPV–RH interpretation revealed that a substantial portion of slab concrete contains internal discontinuities and microstructural defects despite acceptable surface hardness, indicating hidden durability deterioration and estimated compressive strengths lower than the target M30 grade. Core compression tests demonstrated that although most of the extracted cores satisfied or marginally exceeded the design compressive strength, localized low-strength zones were present, reflecting internal heterogeneity and potential workmanship deficiencies. Chemical durability evaluation identified chloride concentrations in both slab and beam cores exceeding the permissible limits specified in IS 456:2000 (BIS, 2000), thereby confirming the initiation of durability-governed deterioration mechanisms with a high potential for corrosion-induced reinforcement damage. Conversely, carbonation depth, sulfate content, and pH levels remained within acceptable ranges, indicating that chloride ingress presently constitutes the governing deterioration mechanism influencing the long-term serviceability of the assessed RCC members.

Uniqueness and Novelty: - This study uniquely integrates multiple in-situ testing methodologies to conduct a layered assessment of concrete quality in a high-profile public structure. Unlike studies that rely solely on a single type of test, this study demonstrates how a combined interpretation of UPV, RH, core strength, and chemical test results can provide a more reliable and comprehensive understanding of the structural conditions. The focus on a large-scale stadium structure adds novelty, highlighting how this method can be applied to critical high-occupancy civil infrastructure.

Implications for Civil Engineering: - The findings of this investigation carry significant implications for civil engineering practice, particularly in the domains of structural safety evaluation, durability assessment, and maintenance planning of high-occupancy RCC infrastructures. The integrated application of non-destructive and partial destructive testing methods demonstrated in

this study provides a reliable and practical framework for comprehensive in-situ structural health assessment. Although the majority of the tested RCC members satisfied the design compressive strength requirements, the elevated chloride content detected in the concrete cores represents a governing durability concern that may initiate reinforcement corrosion and progressive deterioration over time. This indicates that structural adequacy cannot be evaluated solely on the basis of mechanical strength parameters. Consequently, routine structural audits should incorporate chemical durability indicators alongside strength-based assessments to enable condition-based maintenance strategies and effective life-cycle management of critical public infrastructure such as stadium structures.

Early Diagnosis and Targeted Maintenance Contributions: - The integrated UPV–RH–core–chemical assessment framework enables early identification of hidden durability deterioration in RCC members before visible distress occurs. Slab regions exhibiting doubtful UPV quality (<3.0 km/s) despite acceptable surface hardness provide early warning of internal discontinuities and microcracking. Chloride concentrations exceeding IS 456:2000 limits establish chloride ingress as the governing deterioration mechanism, supporting targeted maintenance actions such as surface sealing, corrosion inhibitor application, and localized electrochemical protection in identified high-risk zones. The derived slab–beam quality zoning further facilitates maintenance prioritization and durability-oriented rehabilitation planning for high-occupancy RCC floor systems.

Research Limitations: - The scope of the study was limited to the +10.80 m level of the stadium, excluding lower levels, foundations, and roof structures. Core samples were extracted only from visually sound areas owing to accessibility constraints, potentially overlooking degraded sections. The rebound hammer and UPV results may have been influenced by the surface moisture or material heterogeneity, and the environmental conditions during testing were not fully controlled. Furthermore, the present investigation represents a single-time condition assessment and did not include long-term monitoring of carbonation depth progression (mm/year), chloride diffusion rates (kg/m³·year), surface moisture variations, or seasonal exposure effects. Consequently, the time-dependent kinetics of durability deterioration and corrosion initiation could not be quantified, and only the current durability status of the RCC members could be evaluated.

Recommendations for Future Research:

Future studies should expand the testing to all structural levels of the stadium and include dynamic load testing to assess performance under service conditions. Advanced diagnostic tools, such as Ground Penetrating Radar (GPR), Infrared Thermography, or Acoustic Emission Monitoring, should be explored to supplement NDT techniques. Longitudinal monitoring programs can help identify the trends in chloride penetration and concrete degradation. Data-driven approaches using artificial intelligence or machine-learning models can be developed to predict degradation and recommend maintenance interventions for similar RCC structures.

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Author Contributions

- **Vimal Kumar Gupta:** Conceptualization, Methodology, Investigation, Validation, Supervision, Writing – Review & Editing.
- **Saurabh Dubey:** Data Collection, Formal Analysis, Investigation, Writing – Original Draft, Visualization, Manuscript Preparation.

Ethics Approval and Consent to Participate

Ethics approval and informed consent were not required for this study.

Declaration of Generative AI

The authors declare that no Generative AI tools were used in the preparation of this manuscript.

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