Comprehensive Risk-Based Evaluation of Existing Structures Using Rebound Hammer Testing and Multi-Criteria Decision-Making Approaches

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Abstract

This study presents an integrated framework for evaluating the structural condition of existing reinforced concrete buildings using a combination of rebound hammer testing, the Hybrid Risk Assessment Method (RAM), and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Four buildings of varying ages and usage types were selected to capture diverse structural conditions and exposure environments. Rebound hammer tests, conducted in accordance with IS 13311 (Part 2): 1992, provided in-situ compressive strength estimates, while RAM quantified the severity, probability, and detectability of potential failures to derive a Risk Priority Number (RPN) for each structure. These risk scores, along with building age and rebound values, were incorporated into the TOPSIS multi-criteria decision-making framework to rank the buildings by their proximity to an ideal condition. Results indicated that Building 3 exhibited the highest relative closeness to the ideal solution (RCi = 1.0), followed by Building 2, Building 1, and Building 4, the latter having the highest risk and lowest performance. The integrated RAM–TOPSIS approach demonstrated its effectiveness in combining qualitative expert judgment with quantitative field data, enabling a robust, data-driven prioritization of maintenance interventions. This methodology enhances the reliability of non-destructive testing outcomes and supports cost-effective, safety-focused asset management for existing structures.

Keywords- Building condition assessment, Non-destructive testing, Rebound hammer test, Risk Assessment Method (RAM), TOPSIS

1. Introduction

The study on the rebound hammer testing used to test the quality of concrete in existing structure has become a matter of great concern because of usage in evaluation of the strength of concrete in situ (non-destructively) to provide the necessary information that is involved in structural maintenance, retrofitting and safety analyses of the infrastructure (Brencich et al., 2020; Diaferio & Varona, 2022a)(E. Schmidt, 1950; Szil, 2022). Since its development in the middle of the 20-th century, the rebound hammer test has developed as a quick, cost-efficient technique, along with other non-destructive approaches to testing (ultrasonic pulse velocity (UPV))(Mohammadreza Hamidian, 2012)(Pereira & Romão, 2018). The growing attention to the structures that are already in use, especially in seismic areas, and in cities, has highlighted the practical value of concrete quality assessment approaches, which are reliable. (Bernardo, 2019; Nobile, 2014). Statistic scenarios indicate that there is a huge variation in rebound hammer outcomes in various structural components and types of buildings, thus necessitating the development of effective interpretative models (Atoyebi O. D.; Afolayan J. O.; Arum C.; et.all, 2023). In addition, combination of rebound hammer testing and other complementary techniques such as UPV has been proved to improve the accuracy of measurements, as various shortcomings of single-method technique testing are known (Gómez et al., 2024)(Monteiro & Gonçalves, 2009; Qasrawi, 2000).

Although popular, the rebound hammer test is affected by poor reproducibility of concrete properties, environmentally related effects, and uncertainties of calibration effects (Brencich et al., 2013, 2020; Breysse & Martínez-Fernández, 2014). There is a crucial information gap, regarding importantly, the universally acceptable conversion models, which perfectly relate the ratios of rebound indices and compressive strengths of concrete mixes in various mixes and conditions of structures (Breysse & Martínez-Fernández, 2014; Diaferio & Varona, 2022a; Kouddane et al., 2022). Controversial views continue to exist on the reliability of the test with some researchers stressing the applicability of the test in initial testing and homogeneity testing (Diaferio & Varona, 2022b; Szilágyi et al., 2014), whereas others warn against its application in a stand alone strength predictor because of huge dispersion in measurement (Atoyebi et al., 2019; Brencich et al., 2020). The results of such a gap are dramatic because in the case of incorrect strength assessment, faulty structural analysis and a lack of safety may be achieved (Brencich et al., 2013; Dauji & Karmakar, 2022). Moreover, other variables like surface preparation, moisture and overall stresses in a material also lead to uneven rebound readings, which makes it difficult to standardize the results (Brencich et al., 2020; Brozovsky et al., 2019)(Alwash et al., 2017).

This paper aims at determining the quality of in-situ concrete in the existing reinforced concrete structures by conducting rebound hammer test to improve decision tree in maintenance prioritization by combining Risk Assessment Method (RAM) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The study will be based on the idea of integrating non-destructive testing findings with a structured risk assessment and multi-criteria ranking methodology in order to create a comprehensive, data-driven framework that would not only evaluate the structural condition of buildings, but could also identify and prioritize buildings that must be treated urgently. The combined approach overcomes shortcomings of individual approaches to structural health assessment and leads to more sound and effective structural health management procedures.

2. Methodology

The research methodology included sampling four of the existing reinforced concrete structures of different age and conditions, rebound hammer tests according to the IS 13311 (Part 2): 1992 in order to estimate in-situ compressive strength, and structural risk assessment using the Risk Assessment Method (RAM) based on severity, probability, and detectability scores as well as TOPSIS multi-criteria decision-making method to rank the structures in terms of their approach to the ideal condition.

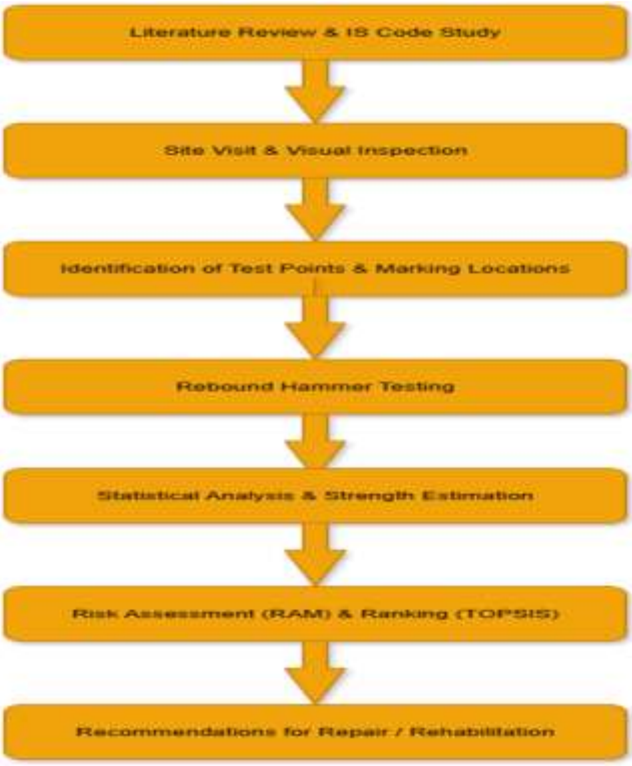

Fig. No 1 Methodology Flow Chart

3. Case Study Selection

The four existing reinforced concrete buildings that were the focus of the case study were chosen to cover the variety of structures in terms of their structural age, type of use, or exposure conditions that are typically experienced in urban structures. The selection was based on specific criteria to ensure a representative sample for analysis:

Age Variation: The age of the buildings varied between very new buildings (2-3 years) to older buildings of over 15 years in age and this allowed the effect of ageing on the quality of the concrete to be determined.

Functional Diversity: The sample incorporated residential, commercial, and institutional buildings in order to identify the effect of usage patterns on the structural performance.

Environmental Exposure: The sites were selected to show varying degrees of exposure, such as roadside vibration, direct weathering, and pollution which may all lead to faster material wear.

Accessibility for Testing: All the structures offered safe and workable inspection access and non-destructive examination with no interruption of usual operations.

The inclusion of buildings of disparate ages, conditions and working environment in the study also ensured that test results obtained using the rebound hammer and subsequent calculation using the RAM-TOPSIS model would be generalizable and have practical value to the decision maker to prioritize on structural maintenance efforts.

3.1 Case Study Analysis – Building Decision-Making Assessment

There were four buildings, situated in Vathar and Peth Vadgaon, measured through planned decision-making model integrated Risk Assessment Method and TOPSIS. The case studies also presented general building type, structural and safety assessment, cost-effectiveness, environmental and regulatory factors, and social/community implications. The data backbone of analysis was done by field inspections, rebound hammer test, and cost estimation.

Overview of Building Conditions

1. **Building 1 (Vathar, 2015, Private, In Use)**

Good and Stable ratings of Structural integrity, foundation stability and load bearing capacity.

Rebound numbers: 25-32; compressive strength: 16-24 MPa (Moderate).

Small fissures spotted; repair will cost ₹10900- ₹16400 (labour included).

Demolition has high environmental impact and recycling possibilities are low in favor of repair.

Social gains: Constructive economic, no heritage limitations.

2. **Building 2 (Vathar, 2023, Private, Under Construction)**

Structural evaluation: Fair shape with some cracks on some of the elements.

Rebound numbers 30.04, Beams 31.26; compressive strength, 25 26 MPa (Good).

Repair costs ranging between ₹7,400 - ₹11,900.

Regulations have been complied with; knocking down is not encouraged because it is environmentally intensive.

Like social profile Building 1 but many beneficial effects on the community.

3. **Building 3 (Vathar, 2023, Private, In Use)**

Structural analysis: Excellent integrity and poor fire safety compliance.

Rebound numbers: 31.04or 33.25; compressive strength: 28.5and 29.15 MPa (Moderate).

Repair cost: ₹8,150–₹12,850.

Environmental profile typical of past buildings-high impact of demolition and low recycling potential.

Positive economic and social consequences with regard to repair and further usage.

4. **Building 4 (Peth Vadgaon, 2010, Private, In Use)**

Good structural score and yet a wall had major cracks and the roof was leaking; fire safety did not comply.

Rebound numbers: 19.75- 24.57; compressive strength: 10-14.05 MPa (Moderate).

Repair cost: ₹12000 - ₹17900, the highest in case studies.

The same applies to environmental and social concerns in which repair is more desirable than demolition.

Common Observations Across Case Studies

- **Structural Performance:** The four buildings are structurally sound and the capacity of the loads and the foundation is in good shape. The rebound hammer test has a range of Moderate to Good whereby rehabilitative work as opposed to reconstruction is adequate.

- **Economic Feasibility:** It is seen that in all occasions repair costs are really small compared to the likely cases of demolition and reconstruction. Building-by-building costs range between ₹7,400 - ₹17,900.

- **Environmental & Regulatory Impact:** Demolition impact was high in all cases and, conversely, waste recycling potential was low. Every building complies with the current codes of building requirements.

- **Social & Community Considerations:** No heritage constrictions, or Community Support For Demolition available. Continuing use benefits the local economy.

3.2 Frequency and Normal Distribution Curve

The figure 2 to 7 shows how surface hardness of concrete in the four evaluated buildings which include Building 1, Building 2, building 3, and Building 4 is arrived at in terms of graphical measure using frequency histograms of rebound hammer test results and overlapping possible distributions, superimposed normal distribution curves.

Figures 2 and 3 present the values of the rebound of the Building 1. Frequency histogram (Fig. 2) shows that the numbers of un rebound are rather widely spread suggesting the oneness in the quality of concrete surfaces. Normal distribution graph (Fig. 3) indicates a rather symmetrical pattern and mellowed peak that would signify a normal distribution of test points being in the background of average strength range. However, minor pulls indicate to the presence of isolated soft spots or patches.

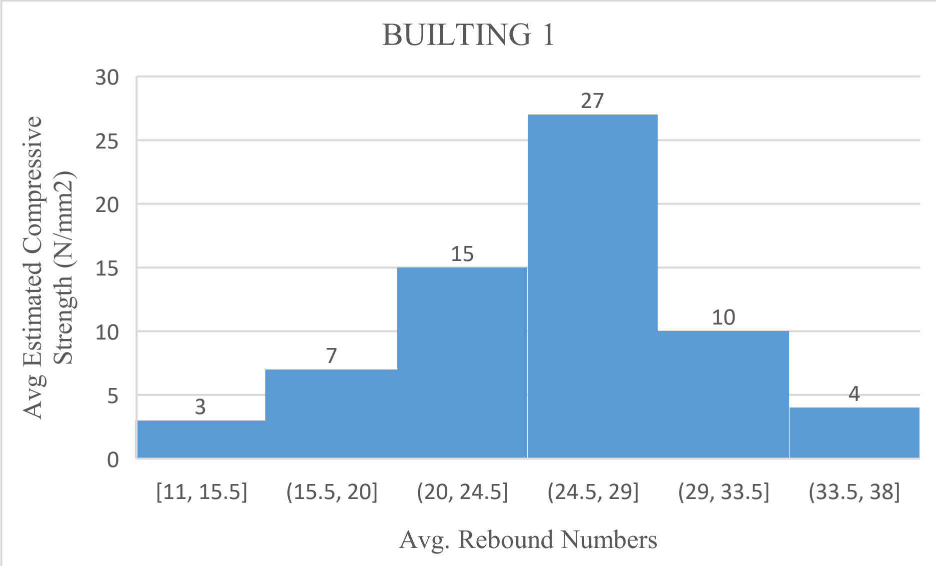

Fig No. 2 Building 1 Frequency Histogram

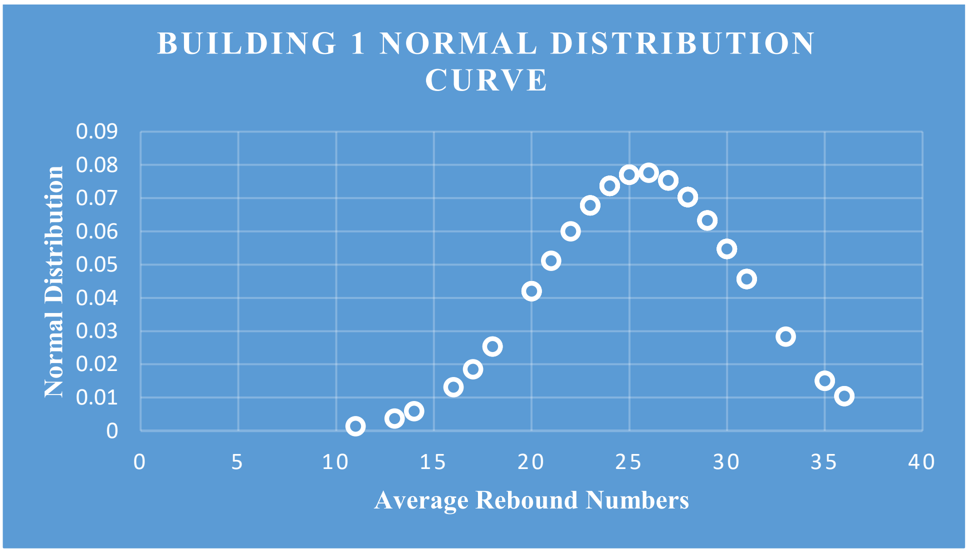

Fig No. 3 Building 1 Normal Distribution Curve

The Building 2 is presented in images 4 and 5. More equitable distribution is seen on the histogram (Fig. 4) and values are grouped closely and indicate stability of the surface quality. The steepness of the peak of the normal curve (Fig. 5) shows that there was minimal variation, and there was a higher level of homogeneity in concrete quality of sampled areas.

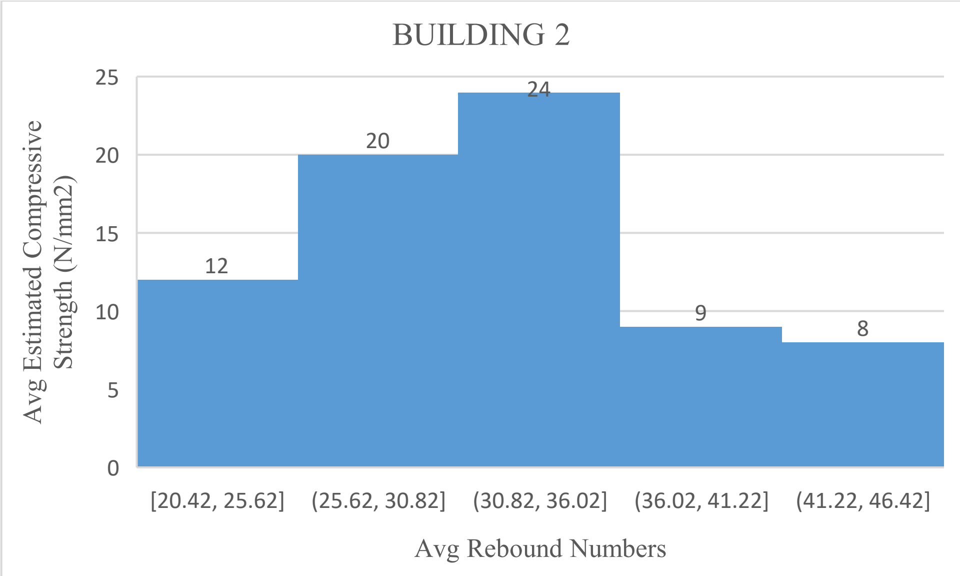

Fig No. 4 Building 2 Frequency Histogram

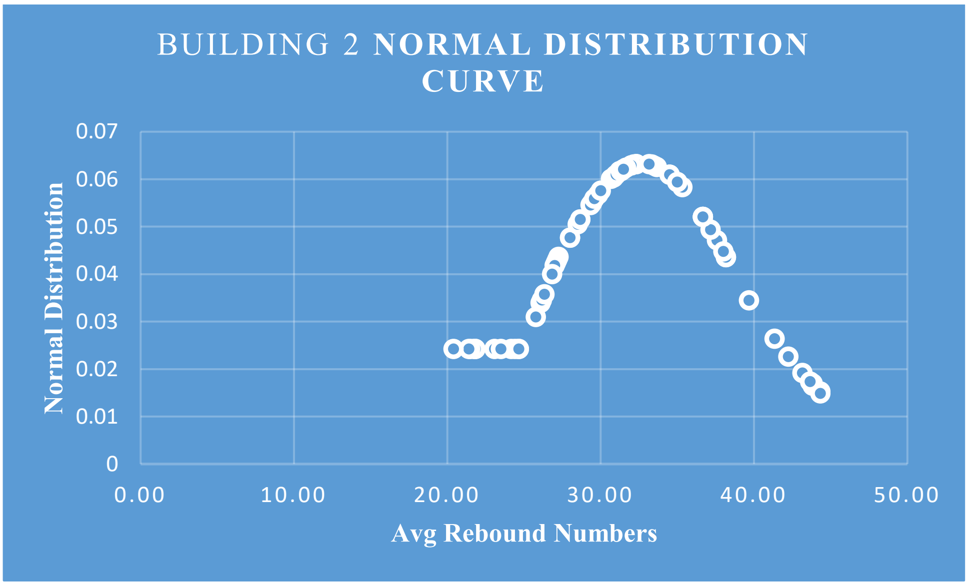

Fig No. 5 Building 2 Normal Distribution Curve

Figures, as presented in figures 6 and 7, show the results of the Building 3. The mode is left skewed, which can be observed in the histogram (Fig. 6) with maximum density on the left sides that indicates better surface hardness and good overall cases. The normal curve (Fig. 7) is slightly inflated on the head showing that there can be scattered area of density as far as increase of density concrete or over-strength areas.

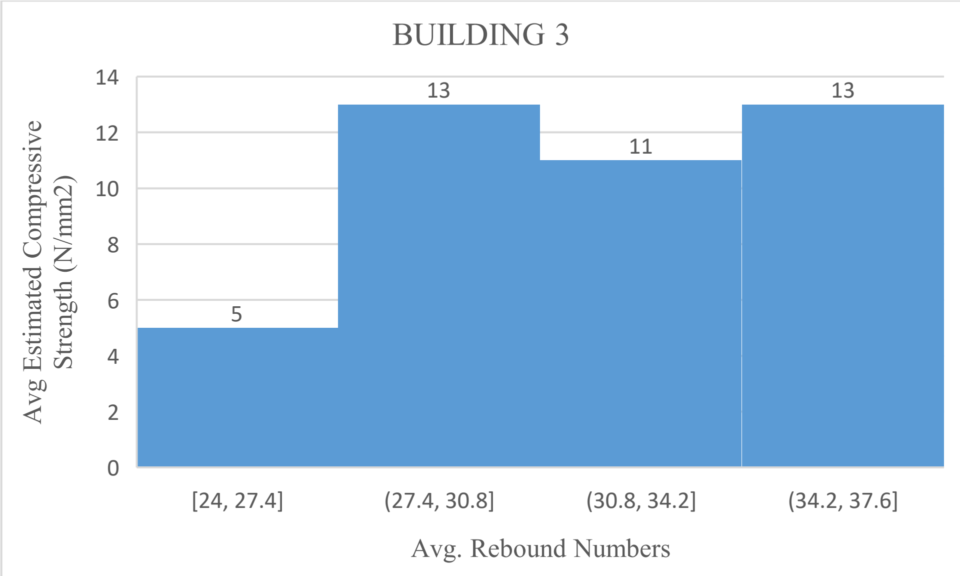

Fig No. 6 Building 3 Frequency Histogram

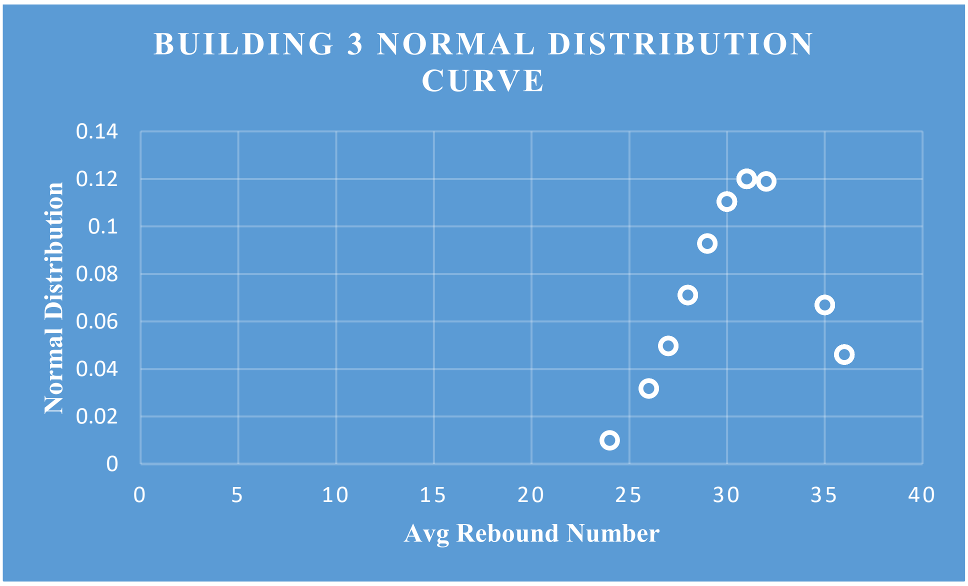

Fig No. 7 Building 3 Normal Distribution Curve

Figure 8 and 9 depict how the Building 4 looked like. As shown by the histogram (Fig. 8), the distribution is comparatively wide-spread, so there is no uniformity in the concrete quality. The shape of the graph of the normal distribution (Fig. 9) is flatter, and it is wider, which indicates the dispersity of the safety of the surface and reveals the presence/possibility of degradation/an uneven work at the time of its creation.

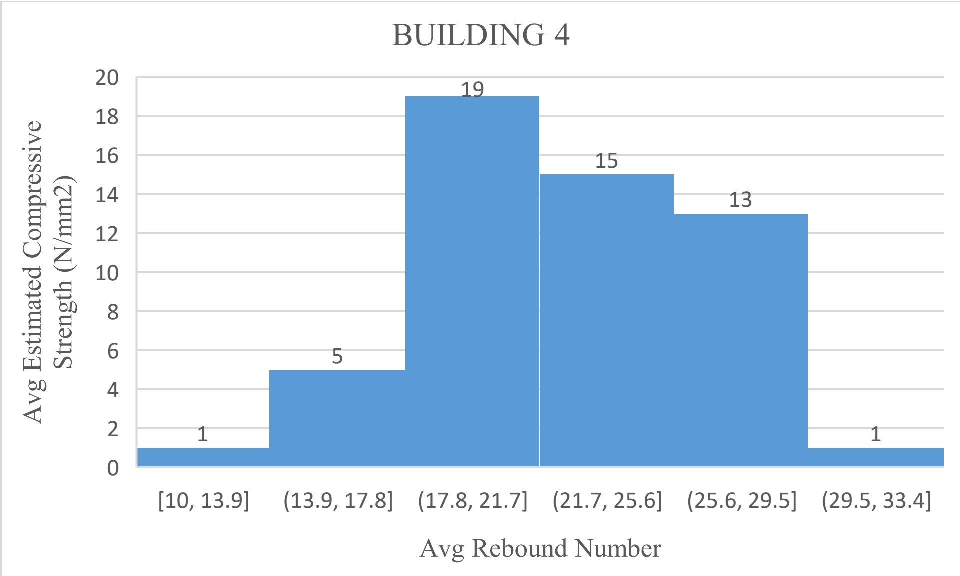

Fig No. 8 Building 4 Frequency Histogram

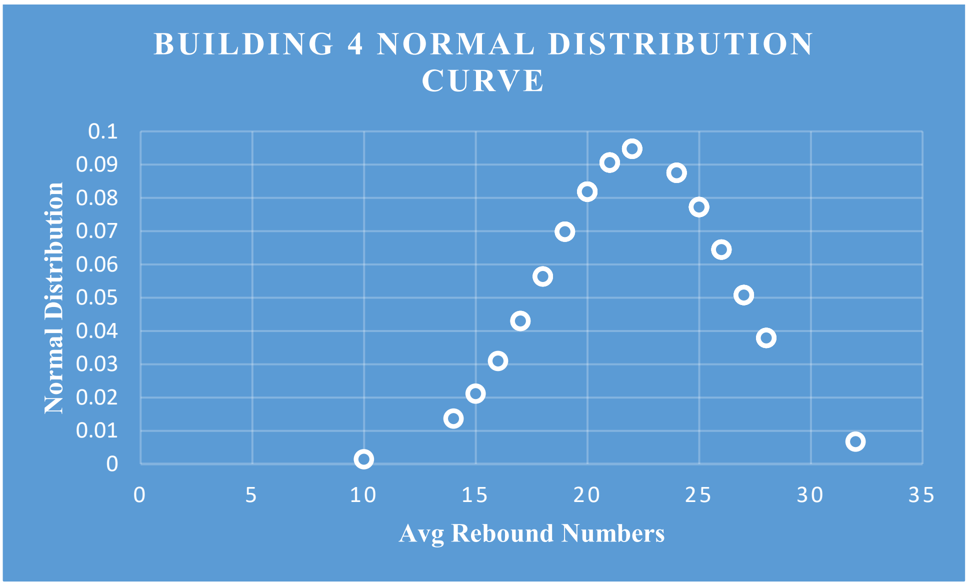

Fig No. 9 Building 4 Normal Distribution Curve

On the whole, the graphical representations allow picturing the level of homogeneity and quality of concrete within the structures. Such buildings as the Building 2 and Building 3 perform consistently and reliably and could be used as benchmark buildings, but Building 1 and Building 4 have broader distributions which should be looked at further or fixed in specific locations.

4. Risk Assessment Method (RAM) and TOPSIS Integration

The study of risks involved the involvement of a Risk Assessment Method coupled with an implementation of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to orderly assess and rank the maintenance requirements of the identified buildings. In this method, subjective knowledge (experience of experts) is used along with quantitative data in the field, so that the technical precision and practical decisions can be achieved.

Risk Assessment Method

Evaluates three core parameters for each structure:

- **Severity (S):** The likelihood of the possible failure of consequence which includes insignificant cosmetic damage (Rating 1), all the way up to complete collapse and potential loss of life (Rating 10).
- **Probability (P):** The probability of occurrence, i.e. the rare events (Rating 1) through to the existing failure already present (Rating 10).

- **Detectability (D):** The ease of finding out where a problem will develop before failure, with the schedule being very easy to impossible during the normal inspection (Rating 1 to 10).

The **Risk Priority Number (RPN)** for each building is calculated as: RPN=S×P×D

Table No. 1 Risk Assessment Method Score

Building	Severity (S)	Probability (P)	Detectability (D)	RPN = S × P × D
Building 1	4	2	5	40
Building 2	3	1	5	15
Building 3	3	1	5	15
Building 4	5	2	6	60

TOPSIS Method

While RAM quantifies the risk level, TOPSIS provides a multi-criterion ranking framework by incorporating both risk and structural condition parameters. In this study, three criteria were used:

1. **RPN** (cost criterion – lower is better) = Weight=0.5
2. **Age of Structure** (cost criterion – lower is better) = Weight=0.3
3. **Average Rebound Value** (benefit criterion – higher is better) = Weight=0.2

TOPSIS Steps Applied:

1. **Decision Matrix Formation:** Compile data for all criteria across the four case study buildings.

A summary of the TOPSIS decision matrix of options of four buildings concerning performance criteria of RPN, Age and Rebound Value can be seen in Table 2. It is on this basis that the matrix is used to rank and normalize during the decision-making process.

Table No. 2 Decision Matrix

Building	RPN	Age	Rebound Value
Building 1	40	11	27.75
Building 2	15	3	30.63
Building 3	15	2	31.91
Building 4	60	15	22.28

2. **Normalization:** Convert each criterion to a dimensionless scale using vector normalization to enable comparison.

In Table 3, the normalized decision matrix, both the values are scaled in opposition to the Euclidean of the criterion in question. The step has the purpose of making each unit and each magnitude comparable and to be able to conduct the multi-criteria analysis in TOPSIS objectively.

Table No. 3 Normalize the Matrix

Building	RPN	Age	Rebound Value
Building 1	0.532	0.581	0.489
Building 2	0.200	0.158	0.540
Building 3	0.200	0.106	0.562

Building 4	0.798	0.792	0.392

3. **Multiply by Weights:** Assign weights based on relative importance (RPN = 0.50, Age = 0.30, Rebound Value = 0.20).

A weighted normalized matrix (Table 4) is derived in which the weight assigned to each of the criteria enumerated is multiplied by itself. The vectors of the Ideal Best and Ideal Worst will be achieved then as a reference points in calculation of relative proximity of each of the alternatives in the TOPSIS method.

Table No. 4 Weights Factors Multiplying

Building	RPN (0.5)	Age (0.3)	Rebound (0.2)
Building 1	0.266	0.174	0.098
Building 2	0.100	0.048	0.108
Building 3	0.100	0.032	0.112
Building 4	0.40	0.24	0.08

Ideal Best = [0.1, 0.032, 0.112] ← Minimum for RPN & Age, Maximum for Rebound

Ideal Worst = [0.40, 0.24, 0.08] ← Maximum for RPN & Age, Minimum for Rebound

4. **Euclidean Distance Calculation:**

Table 5 indicates the Euclidian distance of each of the buildings to the Ideal Best (S +) and Ideal Worst (S -) solutions which are of critical relevance to the degree of closeness each alternative poses to the Ideal scenario. These distances form the final relative closeness scores in TOPSIS method.

Table No. 5 Euclidean Distances

	Building 1	
S+	0.048	0.2195
S-	0.0313	0.1768
	Building 2	
S+	0.00027	0.0165
S-	0.127	0.356
	Building 3	
S+	0.0000	0.0000
S-	0.133	0.365
	Building 4	
S+	0.1331	0.3649
S-	0.000	0

5. **Relative Closeness (RCi):** Calculate each alternative's closeness to the ideal solution:

The Relative Closeness (RCi) values would be depicted on Table 6 and it would measure the proximity of each building to the ideal solution it agrees with the TOPSIS. Building 3 has the highest with RCi= 1 that is, the building with the best performance and after which Building 4 has RCi= 0, the worst.

Table No. 6 Relative Closeness

Building	RCi
Building 1	0.446
Building 2	0.956
Building 3	1
Building 4	0

6. **Ranking:** Order the buildings from highest to lowest value to determine maintenance priority.

Table No. 7 Final Ranking

Building	Rci	Ranking
Building 3	1	1
Building 2	0.916	2
Building 1	0.447	3
Building 4	0	4

Final Remark- Building 3 is in the best condition (lowest risk), followed by Building 2, Building 1. Building 4 has the highest risk and should be prioritized for intervention.

The calculation of RPN using RAM and asking RAM to be used as a main input in a TOPSIS decision matrix together with structural age and rebound test outcomes allow the proposed method to guarantee that the risk severity along with the measured structural performance shapes the ultimate prioritization. The combination of this framework presents a reasonable, quantitative and vulnerable maintenance decision-making system.

5. Result and Discussion

The Risk Assessment Method (RAM) and the Technique order of preference by similarity to ideal solution (TOPSIS) were integrated in a two-tier analysis of the four buildings that included Building 1, Building 2, Building 3 and Building 4. These methodologies provided both qualitative and quantitative data on the structural condition, the extent and magnitude of risks as well as the order of priorities to repair or undertake maintenance works.

Risk Assessment Findings

The RAM framework procedure was employed and the severity (S), probability (P) and detectability (D) scores were measured in each building and the risk priority number (RPN) was calculated. The findings were:

- Building 4: Highest RPN of 60, indicating critical risk and priority for intervention.
- Building1: Moderate RPN of 40.
- Building 2and 3: Equal RPN of 15, indicating low risk.

These values indicate that Building 4 has the most threatening mix of structural issues, the probability of collapse as well as the toughness to find fault, whereas both Building 3 and Building 2 may be characterized as structurally safer.

Decision Matrix and TOPSIS Ranking

The decision would be subjected to further tuning in terms of the decision-making technique known as TOPSIS using RPN, age of the building and rebound hammer values (surrogate to surface concrete strength). Criteria were set with the following set of weights: The following set of weights was used on criteria:

- RPN: 50% (cost-based risk)
- Age: 30%

- Rebound Value: 20% (benefit)

After normalization and weighted scoring, the TOPSIS relative closeness (RCi) values were:

- Building3: RCi = 1.000 (Rank 1 – Ideal choice, structurally safe)
- Building 2: RCi = 0.956 (Rank 2 – Very good condition)
- Building 1: RCi = 0.446 (Rank 3 – Moderate condition)
- Building 4: RCi = 0.000 (Rank 4 – High-risk structure)

Interpretation and Implications

Building 3 and Building 2 are characterized by excessive resilience to the slight risks and hence they only require easy monitoring once maintained.

Although building 1 has a medium RPN, it requires special repairs and the majority of repairs were of cosmetic nature and not life saving repair work.

Building 4 was in the last position and therefore very fast action is required.

6. Conclusion

This study is an attempt at a critical approach of structural safety and integrity assessment of existing structures based on Non-Destructive Testing (NDT) techniques, Hybrid Risk Assessment Method (RAM) and Top Slicing Ideal Solution Process (TOPSIS) decision-making tool. Qualitative observations incorporated into the quantitative data set, which included rebound hammer test findings, building age, and risk prioritizing scores, made it possible to evaluate the structural conditions in a multi-dimensional way. Among the four buildings under consideration, building 2 and the Building 3 proved to have low risk and high structural reliability which should be only periodically maintained. On the other hand, the Building 1is structurally stable but had minor imperfections that should be corrected. The weakest structure which has the largest Risk Priority Number (RPN) and the minimum TOPSIS score is Building 4 and it direly requires structural intervention. RAM and TOPSIS proved rather efficient in sequencing building safety levels and making data-driven decisions on building maintenance. Statistical analysis of frequency histograms and normal distribution curves show that there are some peculiarities in the concretes surface hardness and uniformity. Overall, Buildings 2 and 3 show satisfactory results, although Building 1 needs to be moderately researched and Building 4 should be examined and provided with special maintenance to rule out all the potential issues associated with durability. This broad-scale model does not only make structural audits more reliable, but also guarantees effective prioritization of reparation tasks, advancing structural soundness, the safety of the occupants, and cost-efficient management of assets in the long-term.

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