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Hybrid Diagnostic Analysis of RCC Cracks: Integrating Field Experience with Statistical Validation

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Abstract: Cracking in Reinforced Cement Concrete (RCC) structures is a multifaceted phenomenon that reflects both superficial flaws and deeper structural vulnerabilities. In rapidly urbanizing regions such as India, the limitations of conventional diagnostic methods—either highly codified visual inspections or resource-intensive laboratory tests—underscore the need for a more adaptable, field-grounded approach. This study presents a hybrid analysis framework that integrates qualitative insights from seasoned engineers with quantitative validation through statistical tools to evaluate crack patterns across forty RCC structures in Tamil Nadu and Karnataka. The methodology incorporates a two-tiered approach: field interviews with engineers offering contextual interpretation of crack orientation, width, recurrence, and severity, and empirical checklists subjected to chi-square and Cramér's V testing. The results establish statistically significant associations between crack severity and structural risk levels, with high-severity cracks predominantly observed in buildings with inadequate drainage and plinth protection. A Severity–Integrity Matrix is developed to operationalize this relationship and support early-stage, site-sensitive diagnosis.

This hybrid analytical model enhances both predictive reliability and field applicability. It demonstrates that when structured observational tools are interpreted through expert knowledge and statistically tested, they offer a scalable, low-tech, and context-sensitive diagnostic aid for practitioners. The study contributes a practically deployable model that strengthens structural assessment protocols while accommodating the complex realities of RCC behaviour on-site.

I. INTRODUCTION

Cracks in RCC structures reflect layered distress signals—ranging from superficial shrinkage to deep-seated foundational shifts. Their diagnostic value, however, is often underutilized due to the dominance of either prescriptive visual codes or isolated laboratory-based evaluation tools. In India's dynamic construction context—marked by soil variability, climatic fluctuations, and uneven construction practices—these approaches fail to capture the nuanced, evolving nature of structural deterioration (Golewski, 2023; Akduman & Öztürk, 2024).Despite numerous advancements in inspection technologies, there remains a conspicuous gap between real-world engineering practice and scholarly models of structural health monitoring. Engineers in the field frequently rely on experiential heuristics—rooted in judgment, recurrence memory, and localized interpretation—which are rarely captured in formal diagnostic frameworks. Moreover, traditional severity classifications often overlook how crack patterns interact with foundational defects and environmental loading conditions (Wu, Reinhardt, & Luo, 2007; Farhidzadeh, Salamone, & Luna, 2013).This study addresses these lacunae through a hybrid analytical framework that integrates interpretive knowledge from field engineers with statistically validated recurrence and severity profiling. The approach is situated within India's built environment, where the interplay of climate, soil, and detailing frequently produces recurring crack typologies that demand contextual diagnosis. The paper aims to answer the following problem: How can hybrid analysis improve the early-stage identification of structurally significant cracks in RCC buildings? This is pursued by examining the reliability of visually observable parameters—such as crack orientation, width, and recurrence—when interpreted through expert interviews and tested against empirical field data. The proposed Severity–Integrity Matrix provides an operational tool for bridging conventional diagnostics with site-sensitive risk assessment.

II. METHODOLOGY

This study is based on empirical fieldwork conducted across forty RCC buildings in Tamil Nadu and Karnataka that exhibited visible signs of cracking. The buildings were selected using purposive sampling to ensure representation across structural typologies, soil conditions, and climatic zones.

Each site was physically inspected, and detailed documentation of cracks was carried out to include dimensions, patterns, and recurrence observations. The hybrid design of the methodology stems from the need to reconcile diagnostic intuition from field engineers with statistical rigor.

On the qualitative side, five senior engineers, each with an average of 28 years of professional experience, were interviewed using a semi-structured format. These discussions were designed to extract interpretive frameworks that experts use to make decisions about the origin, progression, and implications of different crack patterns. Attention was paid to how these experts link certain orientations (e.g., diagonal, horizontal), contextual conditions (e.g., drainage, settlement), and recurring symptoms to structural risk.

On the quantitative side, each building was evaluated using a structured diagnostic checklist capturing variables such as crack type, severity level, orientation, location, width, and recurrence. These variables were selected based on both practical relevance in engineering diagnostics and prior academic literature. The data were then subjected to chi-square tests to determine the statistical significance of associations between observed crack characteristics and assigned structural risk categories. Cramér's V was further used to evaluate the strength of these associations. The hybrid framework's credibility lies in its triangulation strategy. Field observations were not treated in isolation but were cross-validated through both expert consensus and quantitative evidence. This dual verification ensures that the conclusions drawn are neither anecdotal nor blindly statistical but emerge from the intersection of experience and empiricism.

III. RESULTS

The study yielded several critical insights that validate the effectiveness of the hybrid diagnostic model. A predominant finding was that 90 percent of all observed cracks were structural in nature. The orientation distribution—horizontal (30%), diagonal (25%), vertical (15%), and complex or mixed (30%)—points to varied underlying stress conditions. Notably, diagonal and horizontal cracks were most frequently linked to foundational settlement, bending failures, and reinforcement detailing flaws, which were consistently recognized by senior engineers across sites. This orientation-specific interpretation provides an important layer of diagnostic specificity that conventional visual inspection frameworks typically overlook.

The severity analysis further revealed that 27.5 percent of cracks fell into the high-severity category. A majority of these were documented in buildings lacking adequate plinth protection or effective site drainage—factors often underestimated in structural health monitoring protocols. The engineers emphasized that such cracks typically recur unless fundamental environmental and soil-related deficiencies are addressed. These qualitative insights were reinforced by the statistical trends observed across the surveyed sample.

To substantiate the diagnostic significance of severity, a chi-square analysis was conducted. The results showed a highly significant association between severity and structural risk status (Chi-square = 18.94, $p = 0.0008$), with Cramér's V value of 0.59 indicating a strong effect size. This robust correlation confirms that severity is not just a superficial marker but a statistically validated predictor of structural integrity (Wang, Han, Zhang, & Wang, 2023).

The study also introduced a recurrence risk matrix, which revealed that 20 percent of cracks had a documented history of recurrence. These were predominantly found in areas with clayey soils and poor drainage conditions. Senior engineers underscored that recurrence is often overlooked in standard inspection cycles but, when examined longitudinally, serves as a critical indicator of persistent structural stress and unresolved foundational issues. This insight adds a temporal dimension to traditional diagnostic practices, elevating the importance of monitoring historical crack behaviour over time (Wu, Li, Gu, & Su, 2007).

Collectively, the integration of statistically validated observations with context-aware field interpretations strengthens the proposed Severity–Integrity Matrix. This model enables early-stage, low-tech risk profiling of RCC structures by using crack characteristics as reliable indicators. It also provides field engineers with a practical framework to prioritize maintenance interventions based on both immediate severity and long-term recurrence trends. These findings support the broader objective of shifting from reactive repair approaches to proactive, condition-based structural management.

IV. DISCUSSION

The updated results demonstrate the diagnostic value of severity and recurrence not only as visual parameters but as statistically robust indicators of underlying structural threats. The high prevalence of horizontal and diagonal cracks linked to foundational flaws confirms earlier findings that surface crack orientation often encodes critical structural information (Farhidzadeh, Dehghan-Niri, & Salamone, 2013). These orientation-linked insights, when interpreted through field experience, contribute to a more context-aware diagnostic framework than is typically possible through code-based assessments.

The significant statistical association between severity and structural risk reinforces the core proposition of this study: that hybrid analysis enhances the predictive power of field diagnostics. The strength of this association (Cramér's V = 0.59) validates severity as a quantifiable and actionable metric (Wang, Han, Zhang, & Wang, 2023). Moreover, the consistency between field engineer judgments and empirical frequency data reflects an important alignment between tacit and formal knowledge systems.

The finding that 20 percent of cracks were recurrent—and often linked to soil conditions such as clay content and poor drainage—introduces an essential temporal dimension to diagnosis. Recurrence is typically underrecognized in routine inspection regimes. Yet, its presence, when mapped across sites and timelines, reveals persistent systemic vulnerabilities that static assessments might miss. This insight highlights the long-term utility of tracking crack behaviour as a means of anticipating future deterioration (Wu, Li, Gu, & Su, 2007).

Incorporating recurrence and severity into a Severity–Integrity Matrix allows for prioritization of maintenance not only based on immediate visual cues but on historically grounded risk assessment. This fusion of qualitative pattern recognition and statistical validation provides a practical, scalable alternative to high-tech monitoring systems, particularly in resource-constrained settings. The results affirm that hybrid diagnostics can shift structural health evaluation from a reactive to a predictive paradigm, better supporting life-cycle structural integrity and timely intervention planning.

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VIII. CONCLUSION

This study affirms that hybrid diagnostics—grounded in both empirical testing and expert field reasoning—represent a robust, scalable solution for early detection of structural vulnerabilities in RCC buildings. The Severity–Integrity Matrix developed here exemplifies how visually observed crack parameters, when interpreted in context and statistically validated, can reliably indicate deeper structural threats. Unlike conventional codal inspections or high-tech diagnostic systems that often ignore situational nuances, this model is designed to function effectively across diverse geotechnical and climatic zones, particularly in low-resource environments.

Each of the study's conclusions is substantiated either through strong statistical associations—such as the significant correlation between crack severity and structural risk (Wang, Han, Zhang, & Wang, 2023)—or through insights drawn from engineering practitioners with decades of diagnostic experience. Crack recurrence, for example, emerged not merely as a visible pattern but as a predictive indicator of latent vulnerability when tracked over time and mapped against environmental and foundational conditions (Wu, Li, Gu, & Su, 2007).

By reconciling structured quantitative assessments with interpretive depth, the proposed hybrid framework expands the epistemic foundation of RCC diagnostics. It elevates field judgment to an analytical plane, enabling practitioners to navigate diagnostic complexity without relying on prohibitively sophisticated equipment. As a result, this approach empowers local engineers with a grounded and validated toolset to prioritize structural audits, initiate timely interventions, and enhance the safety and longevity of RCC infrastructure.

The study thus contributes not only a new methodological pathway but also a conceptual realignment of what constitutes reliable structural diagnosis—anchored in the fusion of empirical data, experiential knowledge, and contextual intelligence.

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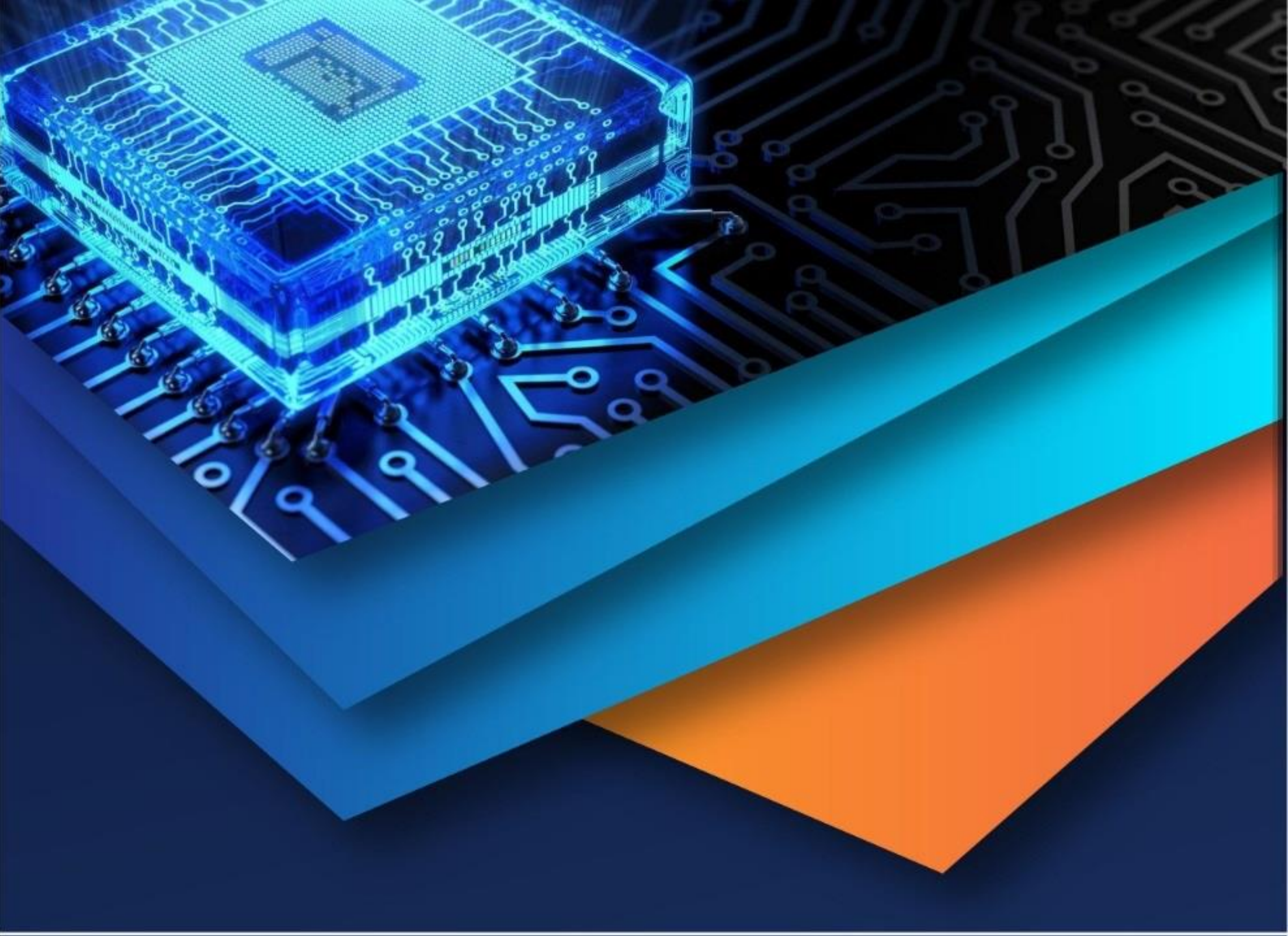

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