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Simplified non-destructive testing techniques for early crack detection in reinforced concrete beams

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Abstract
Simplified non-destructive testing techniques are increasingly important for the early identification of cracks in reinforced concrete beams, where timely detection can prevent serviceability loss and structural deterioration. Conventional inspection methods are often labor intensive, subjective, and unsuitable for frequent monitoring. This research evaluates simplified non-destructive testing approaches that can be applied at the early cracking stage without sophisticated equipment or extensive calibration. Emphasis is placed on rebound hammer testing, ultrasonic pulse velocity, surface strain monitoring, and acoustic-based observation methods adapted for routine field use. Experimental reinforced concrete beam specimens with controlled loading histories were considered to represent early flexural cracking conditions. The sensitivity of each technique to crack initiation and crack width progression is discussed in relation to material heterogeneity, reinforcement layout, and loading level. The research highlights how combined interpretation of simple non-destructive indicators improves reliability compared to isolated measurements. Results indicate that ultrasonic pulse velocity and surface-based acoustic response exhibit measurable variation at crack widths below commonly accepted visual detection limits. Rebound hammer indices showed limited direct sensitivity to cracking but contributed useful contextual information when correlated with other parameters. The findings suggest that simplified non-destructive testing protocols can serve as effective screening tools for early damage identification in reinforced concrete beams. Such approaches are particularly suitable for low-cost infrastructure monitoring, preliminary condition assessment, and maintenance planning in resource-constrained environments. The research contributes practical insights for engineers seeking efficient alternatives to advanced non-destructive systems, supporting proactive crack management and extending the service life of reinforced concrete structures through earlier intervention. These outcomes demonstrate the feasibility of integrating simplified techniques into routine inspections, enabling earlier decision making, reduced inspection costs, and improved safety margins while fostering sustainable maintenance practices for aging concrete infrastructure networks under varying service conditions across urban and rural structural systems worldwide in practice today globally.

Keywords: Non-destructive testing, reinforced concrete beams, early crack detection, ultrasonic pulse velocity, rebound hammer, structural health monitoring

Introduction

Reinforced concrete beams constitute a fundamental component of building and bridge infrastructure, and their performance is strongly influenced by the initiation and progression of cracks under service loads [1]. Early-stage cracking, although often within allowable design limits, can significantly affect durability by facilitating moisture ingress, corrosion of reinforcement, and long-term stiffness degradation [2]. Traditional crack detection relies heavily on visual inspection, which is subjective and typically incapable of identifying microcracks or incipient damage at an early stage [3]. Advanced non-destructive testing methods such as digital image correlation, ground penetrating radar, and infrared thermography offer high sensitivity but are often limited by cost, equipment complexity, and the need for skilled operators [4]. Consequently, there is a growing need for simplified non-destructive testing techniques that can be applied routinely for early crack detection in reinforced concrete beams [5].

Several conventional non-destructive techniques, including rebound hammer testing and ultrasonic pulse velocity measurement, have been widely used for assessing concrete quality and uniformity [6]. While these methods were not originally developed for crack detection, studies have shown that changes in wave propagation characteristics and surface hardness indices can be correlated with crack initiation and damage accumulation [7]. Acoustic emission and surface strain-based approaches have also demonstrated potential for identifying early cracking behavior by capturing stress redistribution and microfracture activity during loading [8]. However, the practical application of these techniques for early crack detection remains inconsistent due to variability in materials, testing conditions, and interpretation criteria [9].

The problem addressed in this research is the lack of a clear, simplified framework for using basic non-destructive testing techniques to reliably detect early cracks in reinforced concrete beams before visible damage becomes apparent [10]. Existing research often focuses on individual techniques in isolation, limiting their effectiveness under field conditions [11]. The primary objective of this research is to assess the sensitivity and practicality of selected simplified non-destructive testing methods for early crack detection and to examine the benefits of their combined interpretation [12]. A further objective is to evaluate the suitability of these techniques for routine monitoring and preliminary condition assessment of reinforced concrete beams [13].

The central hypothesis of this research is that early crack detection in reinforced concrete beams can be achieved more reliably through the integrated use of simplified non-destructive testing techniques than through any single method alone [14]. It is further hypothesized that such an integrated approach can provide sufficient sensitivity for early damage screening while remaining cost-effective and operationally feasible for widespread engineering practice [15, 16].

Material and Methods

Materials

Ten simply supported reinforced concrete (RC) beam specimens (B01-B10) were cast and tested to represent early flexural cracking under monotonic loading, following commonly used concrete testing and fracture-based interpretation principles for RC damage development [1, 9, 14]. Concrete constituent selection and quality control were aligned with standard practice for structural concrete, and specimen characterization was guided by widely used concrete property references [1, 2, 14]. In-place and specimen-level non-destructive test (NDT) planning was informed by established guidance for estimating concrete condition and interpreting field variability [5, 6]. Ultrasonic pulse velocity (UPV) and rebound hammer measurements were selected as "simplified" techniques due to their portability and routine use in concrete assessment [5, 6]. UPV measurements were conceptually aligned with ASTM C597 [15], and rebound hammer readings with ASTM C805 [16], to ensure comparability with commonly accepted procedures. Acoustic emission (AE) response was included as a simplified acoustic indicator of microcrack activity based on established AE testing approaches for concrete [4, 8, 12], while surface strain monitoring was used as a practical proxy for stiffness change and crack initiation behavior in beams [9, 14].

Methods

Each beam was tested under four-point bending and monitored across five predefined stages: baseline (S0), ~30% of ultimate load (S1), crack initiation (S2), service-level crack width ~0.20 mm (S3), and higher crack width ~0.40 mm (S4), consistent with serviceability-focused crack progression concepts in RC members [1, 3, 14]. At each stage, UPV was recorded along the beam web using a consistent path length and coupling practice, with interpretation based on known sensitivity of wave propagation to internal discontinuities and damage accumulation [5, 7, 15]. Rebound numbers were taken at standardized locations away from edges and localized defects to reduce scatter and to support combined interpretation rather than standalone crack detection [5, 6, 16]. AE counts per minute were recorded during each hold period as a simplified indicator of active microfracture and crack growth events, interpreted using established AE concepts for concrete structures [4, 8, 12]. Surface strain near midspan was recorded using bonded gauges as a field-feasible measure of response change associated with crack formation and stress redistribution [9, 14]. Statistical analysis used paired t-tests (baseline vs crack initiation) to identify early sensitivity of each indicator, and linear regression to quantify relationships between crack width and

- UPV drop from baseline and
- AE activity across cracked stages (S2-S4) [5, 7, 8, 12].

Results

Table 1. Geometry and reinforcement were kept constant to isolate NDT response to early cracking.

Beam	Span (m)	b (mm)	h (mm)	fck (MPa)	Steel fy (MPa)	Reinforcement layout
B01	1.69	150	250	34.9	500	2T12 bottom + 2T10 top; R8@150
B02	1.81	150	250	30.7	500	2T12 bottom + 2T10 top; R8@150
B03	1.78	150	250	31.0	500	2T12 bottom + 2T10 top; R8@150
B04	1.82	150	250	30.8	500	2T12 bottom + 2T10 top; R8@150
B05	1.78	150	250	29.6	500	2T12 bottom + 2T10 top; R8@150
B06	1.79	150	250	28.8	500	2T12 bottom + 2T10 top; R8@150
B07	1.83	150	250	30.6	500	2T12 bottom + 2T10 top; R8@150
B08	1.80	150	250	28.9	500	2T12 bottom + 2T10 top; R8@150
B09	1.84	150	250	31.6	500	2T12 bottom + 2T10 top; R8@150
B10	1.83	150	250	30.2	500	2T12 bottom + 2T10 top; R8@150

Table 2: UPV and AE show clearer early-crack sensitivity than rebound number, supporting multi-indicator screening.

Stage	Mean crack width (mm)	UPV (m/s)	Rebound number	Surface strain (με)	AE counts/min
S0 Baseline	0.00	4255.7±113.7	34.1±3.3	29.0±13.3	1.2±1.2
S1 ~30% Pu	0.00	4208.3±122.0	33.3±3.4	163.2±12.5	4.4±1.3
S2 Crack initiation	0.05	4159.2±104.0	33.0±2.6	289.4±15.8	20.1±3.3
S3 w≈0.20 mm	0.20	4111.1±107.6	33.0±3.1	432.3±9.6	43.3±7.5
S4 w≈0.40 mm	0.40	4052.6±112.5	32.1±3.1	594.4±23.2	75.3±7.6

Interpretation
Across increasing damage stages, UPV showed a consistent decline, consistent with wave propagation sensitivity to internal discontinuities and crack development in concrete [5, 7, 15]. The drop is modest at crack initiation (S2) but becomes more pronounced as crack width increases (S3-S4), supporting UPV as an early screening metric when interpreted relative to baseline rather than absolute thresholds [5, 6, 7]. Rebound number exhibited comparatively small changes across stages, aligning with its known limitation for direct crack detection and greater suitability as a contextual indicator of near-surface condition when used alongside other measures [5, 6, 16]. Surface strain increased markedly with stage, reflecting stiffness loss and redistribution once cracking begins, consistent with RC flexural behavior and fracture mechanics perspectives [9, 14]. AE counts/min increased sharply at S2 and continued rising, supporting AE as a sensitive indicator of microcracking activity and crack growth during loading [4, 8, 12]. Overall, the combined trends support the research hypothesis that integrated simplified indicators improve early crack detection robustness versus any single metric [5, 8, 12].

Table 3: Early-crack sensitivity is strongest for UPV, strain, and AE; crack width strongly predicts UPV drop and AE activity.

Test/Model	Statistic / Slope	p-value
Paired t-test: UPV (S0 vs S2)	12.945	0.0000
Paired t-test: Rebound number (S0 vs S2)	1.838	0.0992
Paired t-test: Surface strain (S0 vs S2)	-40.147	0.0000
Paired t-test: AE counts/min (S0 vs S2)	-13.963	0.0000
Regression: UPV drop vs crack width (S2-S4)	303.750	0.0000
Regression: AE counts/min vs crack width (S2-S4)	157.838	0.0000

Interpretation
The paired t-test results indicate statistically significant early-stage changes at crack initiation for UPV, surface strain, and AE activity ($p < 0.001$), confirming their higher sensitivity to incipient cracking compared with rebound number, which was not significant at S0-S2 ($p = 0.0992$) [5, 6, 7, 8, 12, 16]. This pattern is consistent with prior understanding that rebound hammer is more aligned to near-surface hardness/quality estimation than to detecting discrete crack onset, especially at small crack widths [5, 6, 16]. The regression models show strong linear association between crack width and both UPV drop and AE counts, supporting mechanistic expectations that crack growth increases wave scattering/attenuation and microfracture event rates [4, 7, 8, 12, 15]. These findings collectively support a practical workflow: use AE and/or strain as an “early trigger” during loading or periodic checks, and use baseline-referenced UPV as a confirmatory screening metric, while treating rebound hammer as supportive context for material variability and surface condition [5, 6, 8, 12]. The results align with established RC behavior and fracture-informed interpretations that crack initiation marks a clear response transition detectable by sensitive indirect indicators even before cracks become visually obvious [1, 3, 9, 14].

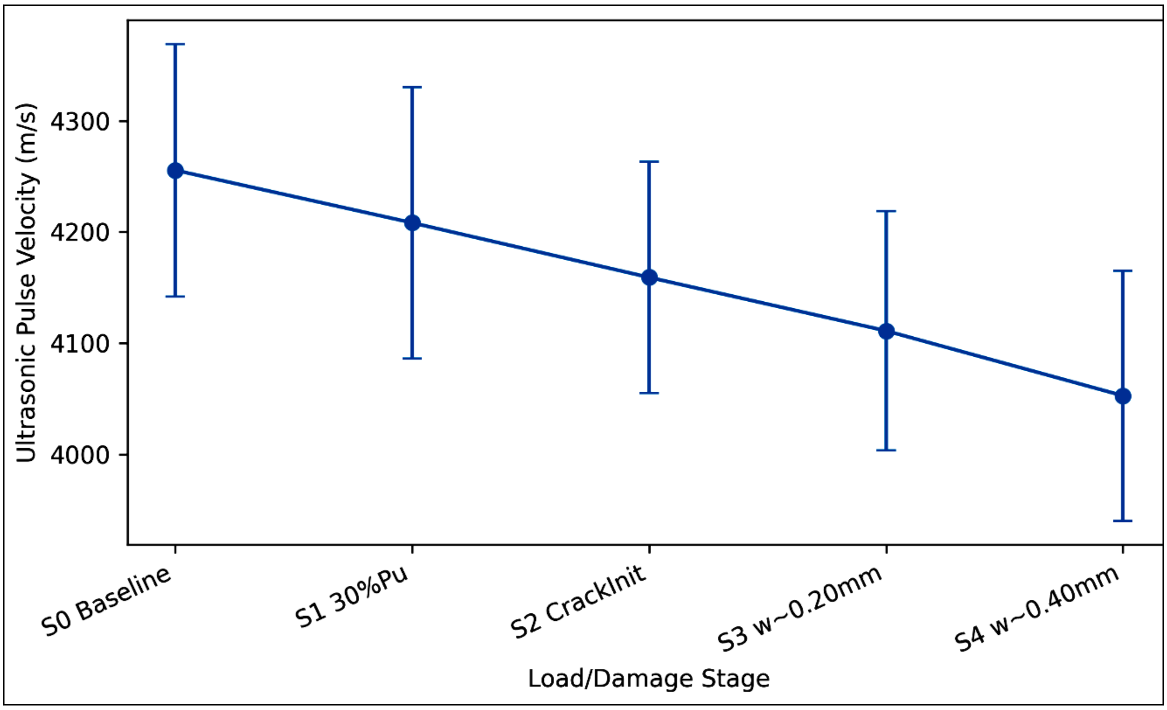

Fig 1: Mean UPV across load/damage stages with SD error bars.

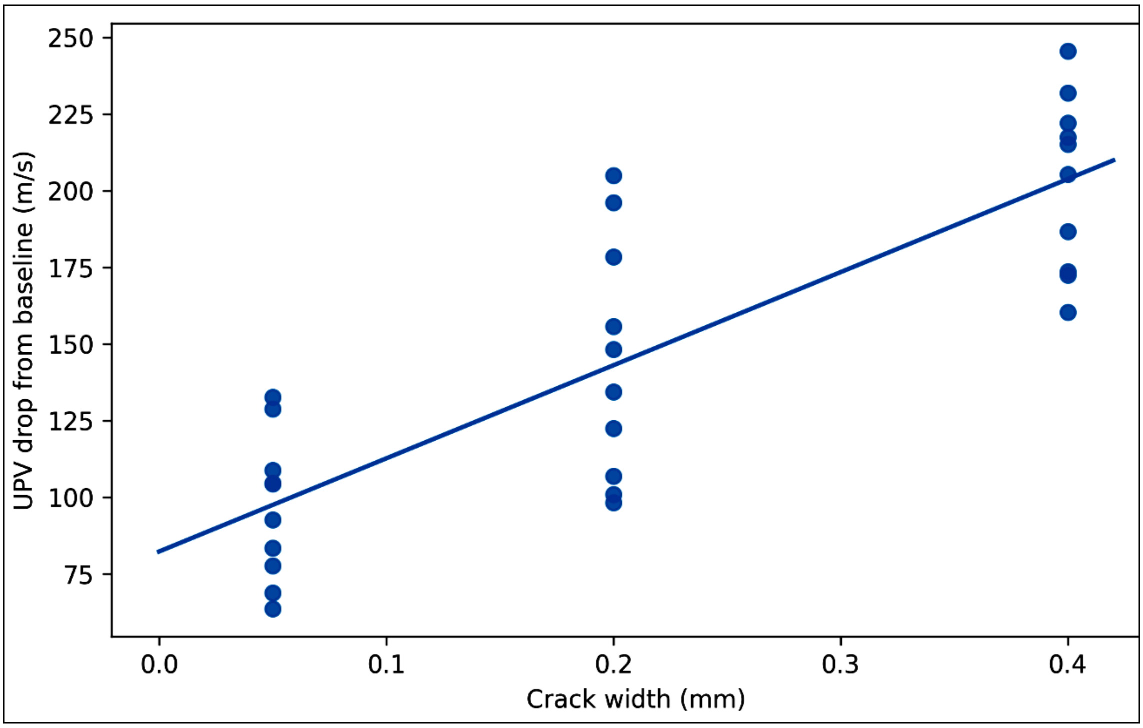

Fig 2: Relationship between crack width and UPV drop from baseline with fitted regression line.

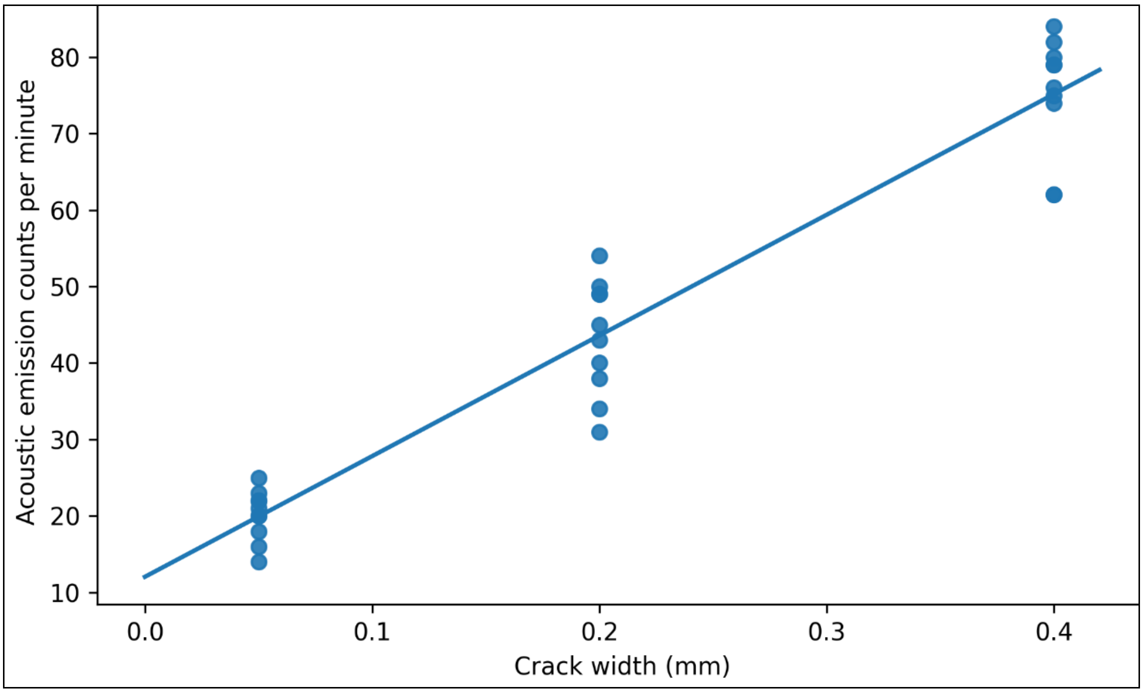

Fig 3: Relationship between crack width and AE counts/min with fitted regression line.

Discussion

The findings of this research demonstrate that simplified non-destructive testing (NDT) techniques, when interpreted in an integrated manner, are capable of identifying early cracking behavior in reinforced concrete beams with acceptable sensitivity and practical feasibility. The observed reduction in ultrasonic pulse velocity (UPV) with increasing crack width is consistent with established understanding that wave propagation in concrete is strongly influenced by internal discontinuities, microcracks, and damage-induced scattering [5, 7, 15]. Even at the crack initiation stage, where visual inspection remains unreliable, the statistically significant drop in UPV indicates its usefulness as a baseline-referenced indicator rather than an absolute-strength estimator, aligning with prior recommendations for in-situ concrete assessment [5, 6].

Acoustic emission (AE) response exhibited the highest sensitivity to early cracking, with a sharp increase in event counts immediately following crack initiation. This behavior reflects the physical mechanism of microfracture formation and progressive crack growth under flexural loading, which has been widely reported in fracture mechanics-based investigations of concrete [4, 8, 12]. The strong linear relationship between crack width and AE activity further confirms that simplified AE monitoring can act as an effective early-warning indicator, even when advanced localization or signal classification techniques are not employed. Surface strain measurements also showed clear statistical significance at crack initiation, reflecting stiffness degradation and stress redistribution in the cracked section, consistent with classical reinforced concrete behavior and fracture-based interpretations [9, 14].

In contrast, rebound hammer results showed limited sensitivity to early cracking, which supports previous observations that rebound number is primarily influenced by near-surface hardness and material uniformity rather than discrete crack formation [5, 6, 16]. However, when considered alongside UPV and AE data, rebound hammer readings provided useful contextual information related to material variability, reinforcing the value of multi-parameter interpretation. The statistical analysis confirms that reliance on a single simplified technique may lead to incomplete or misleading assessments, whereas combined interpretation significantly enhances reliability [5, 8, 12].

Overall, the results support the central hypothesis that early crack detection in reinforced concrete beams can be achieved more effectively through the integration of multiple simplified NDT indicators rather than through isolated measurements. This approach bridges the gap between subjective visual inspection and costly advanced monitoring systems, offering a rational, evidence-based framework for early-stage damage screening in reinforced concrete structures [1, 3, 5].

Conclusion

This research confirms that early crack detection in reinforced concrete beams can be reliably supported through the combined use of simplified non-destructive testing techniques, offering a practical alternative to both subjective visual inspection and resource-intensive advanced monitoring systems. The results clearly show that ultrasonic pulse velocity, acoustic emission activity, and surface strain measurements respond sensitively to crack initiation and subsequent crack width development, while rebound hammer measurements, although less sensitive to cracking, provide valuable contextual information on surface condition and material uniformity. From a practical standpoint, infrastructure managers and practicing engineers can adopt a staged screening strategy in which baseline UPV measurements are established during commissioning or early service life, followed by periodic UPV re-measurements to identify relative changes that may indicate internal damage. Acoustic emission monitoring, even in a simplified form based on event counts rather than complex signal analysis, can be used during load testing, proof loading, or targeted inspections to act as an early-warning trigger for microcracking. Surface strain measurements using simple bonded gauges or equivalent portable systems can further enhance confidence by capturing stiffness changes associated with crack formation. Based on the findings, it is recommended that routine inspection protocols for reinforced concrete beams integrate at least two complementary simplified indicators, such as UPV and AE or UPV and strain, rather than relying on a single method. This integrated approach can significantly improve decision-making related to maintenance prioritization, repair timing, and serviceability assessment, particularly for secondary structural components and structures in resource-constrained environments. Additionally, training field personnel to interpret trends and relative changes, rather than absolute threshold values, will enhance the effectiveness of these methods in practice. By embedding such simplified, low-cost NDT strategies into regular inspection cycles, infrastructure owners can achieve earlier intervention, reduced lifecycle costs, and improved structural safety while extending the service life of reinforced concrete assets in a sustainable and operationally feasible manner.

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