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Application of Non-Destructive Testing (NDT) Methods in the Detection of Early-Stage Damage in Reinforced Concrete Structures †

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Abstract

Reliable condition assessment is essential for the maintenance of existing reinforced concrete structures. Deterioration processes may develop before their extent is apparent from surface observations. In this study, "early-stage" refers to deterioration indicators that may precede clear or extensive visible manifestations, while individual non-destructive testing (NDT) methods provide indirect information on specific material properties. Their response may also be influenced by material, environmental and measurement conditions. Consequently, robust assessment requires the combined interpretation of complementary test results. This study examines anonymised field data from existing reinforced concrete structures, focusing on the diagnostic value of NDT and complementary methods, spatial variability of deterioration indicators, and the representativeness of locally obtained measurements.

Keywords: non-destructive testing; reinforced concrete; early-stage deterioration; condition assessment; ultrasonic testing; rebound hammer testing; half-cell potential; carbonation; diagnostic uncertainty

1. Introduction

Reinforced concrete structures are exposed throughout their service life to mechanical and environmental actions that may gradually alter the properties of concrete and reinforcement. Deterioration processes such as cracking, carbonation, chloride ingress, moisture penetration, and reinforcement corrosion may develop before their effects become clearly visible at the surface. Visual inspection is therefore essential for identifying and documenting existing damage, but it may not provide sufficient information for recognising deterioration processes at an early stage or for determining their extent.

Non-destructive testing (NDT) methods can provide additional information on concrete and reinforcement without causing significant damage, but each method responds to a specific physical, mechanical or electrochemical property rather than to overall structural condition [1,2]. Rebound hammer testing primarily reflects near-surface response and is affected by surface condition, moisture, carbonation and material heterogeneity [3]. Ultrasonic testing characterises wave propagation and can support crack investigation [4,5]. Half-cell potential measurements indicate corrosion-related electrochemical conditions but do not directly quantify corrosion rate or reinforcement loss [6–8]. These limitations must be considered in condition assessment.

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Assessment of existing reinforced concrete structures is further complicated by spatial variability. Concrete properties, reinforcement cover, carbonation depth, chloride content, moisture conditions, and the extent of deterioration may vary considerably between different locations within the same structure. Consequently, a result obtained at a single test location may accurately describe the investigated area without being representative of a larger structural element. This becomes particularly relevant when test locations are selected on the basis of previously observed damage. Targeted testing is appropriate for investigating a suspected deterioration mechanism, but conclusions drawn from such measurements should not automatically be extended to untested areas.

Reliable assessment therefore requires a clear distinction between the measured quantity, its interpretation as an indicator of deterioration, and the resulting conclusion regarding structural condition. The significance of a test result depends not only on the method used, but also on the location and conditions of measurement and on its relationship with other available information. Combining complementary observations and test results can therefore provide a stronger basis for interpretation than considering individual measurements separately.

This study examines anonymised field data obtained from existing reinforced concrete structures using non-destructive and complementary testing methods. The available data include rebound hammer and ultrasonic testing, half-cell potential and reinforcement cover measurements, carbonation depth and chloride content determination, as well as compressive strength testing of concrete cores. The results are examined with particular emphasis on spatial variability and on the agreement or disagreement between indicators describing different aspects of material condition and deterioration.

The objective of the study is to evaluate the diagnostic value and limitations of individual and combined test results in the assessment of deterioration of existing reinforced concrete structures. Particular attention is given to the distinction between local material properties and durability-related indicators, as well as to the representativeness of locally obtained measurements. The analysis is based on the premise that an individual test result should not be regarded as a diagnosis in itself; its diagnostic value depends on the context in which it was obtained and on its interpretation, together with complementary evidence.

2. Materials and Methods

2.1. Investigation Approach

The study is based on a retrospective analysis of field and laboratory data obtained during condition assessments of existing reinforced concrete structures. All information that could identify individual structures, locations, owners, or projects was removed, and the available data were organised into three anonymised case studies, referred to as Cases A, B, and C.

The original investigations followed a staged procedure comprising visual inspection, selection of test locations, in-situ testing, concrete sampling, and laboratory analysis. The scope of testing differed between the individual cases and was defined according to the observed condition and the objectives of each investigation. Test locations were predominantly selected following visual inspection, with measurements concentrated on areas considered relevant for further assessment. The resulting dataset therefore represents targeted diagnostic investigations rather than a statistically designed random sample of the structures.

The available data comprise rebound hammer testing, ultrasonic testing, half-cell potential measurements, determination of reinforcement position and concrete cover, carbonation depth, chloride content, compressive strength of concrete cores, and selected complementary tests. Since these methods address different properties of concrete and re-

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inforcement, their results were interpreted according to the physical, mechanical, chemical, or electrochemical information provided by each method.

2.2. Rebound Hammer Testing

Rebound hammer testing was used to assess the near-surface mechanical response of concrete and its variation between selected test areas. Testing followed the procedure of HRN EN 12504-2:2021 [3]. Several impacts were performed within each test area, and representative rebound values were determined from the recorded measurements. A Proceq Digi-Schmid rebound hammer, model NO-1 (Proceq SA, Schwerzenbach, Switzerland; serial no. 3511/083-01788) was used.

The rebound response was considered primarily as an indicator of near-surface concrete properties rather than as a direct measurement of compressive strength. Where estimated compressive strength values were available in the original test records, they were retained for comparative purposes. Their interpretation nevertheless accounted for the influence of surface condition, moisture, carbonation, aggregate characteristics, and local material heterogeneity.

The results were therefore examined primarily in terms of spatial variability and, where corresponding information was available, in relation to compressive strength obtained from concrete cores and other indicators of material condition. No direct correlation between rebound hammer results and core strength was assumed unless supported by corresponding test locations.

2.3. Ultrasonic Testing

Ultrasonic testing was used as a complementary method for cracks previously identified by visual inspection. Measurements were performed by ultrasonic pulse transmission in accordance with HRN EN 12504-4:2021 [4], using an indirect arrangement where required by geometry and accessibility. A Proceq PL-2 ultrasonic instrument (Proceq SA, Schwerzenbach, Switzerland; serial no. UP-01-001-0636) was used.

Within the available dataset, ultrasonic measurements were used to estimate the depth of selected cracks. The method was therefore not employed to establish a general classification of concrete quality based on ultrasonic pulse velocity. This distinction was maintained because ultrasonic wave propagation depends not only on the presence of discontinuities but also on concrete composition, density, elastic properties, moisture condition, reinforcement, aggregate characteristics, and measurement geometry.

The obtained results were consequently treated as local information on crack propagation into the concrete section and interpreted together with the corresponding visual observations. No conclusion regarding the overall condition of an element was derived from the ultrasonic measurements alone.

2.4. Half-Cell Potential Measurements

Half-cell potential measurements were used to investigate the electrochemical condition of embedded reinforcement in accordance with ASTM C876-22b [6]. Where the original test documentation was available, the reference electrode, measured potential range and applicable interpretation thresholds were retained. For Case B, measurements were performed with a $Cu/CuSO_4$ reference electrode using a Proceq Canin system (Proceq SA, Schwerzenbach, Switzerland; serial no. 17.728); the test report classified potentials greater than -200 mV as low corrosion likelihood, values from -200 to -350 mV as intermediate, and values below -350 mV as high corrosion likelihood.

Half-cell potentials were interpreted as categorical indicators of corrosion likelihood rather than as direct measurements of corrosion rate, reinforcement cross-section loss or

residual structural capacity [6–8]. Their diagnostic significance was evaluated together with reinforcement cover, carbonation depth, chloride content and visual observations.

Such combined interpretation is necessary because half-cell potential measurements are influenced by local conditions within the concrete, including moisture state, electrical properties of the concrete, temperature, and reinforcement cover. Accordingly, the analysis focused on whether the electrochemical response was consistent with other evidence relevant to the initiation or presence of reinforcement corrosion.

2.5. Reinforcement Cover and Carbonation Depth

Reinforcement position and concrete cover were determined by electromagnetic measurements at selected locations. Concrete cover was considered as a parameter governing the exposure and protection of reinforcement rather than as an indication of deterioration by itself. The documented reinforcement-cover instrument was a Proceq Profometer 5 (Proceq SA, Schwerzenbach, Switzerland; serial no. 52.3045).

Carbonation depth was determined on freshly exposed concrete surfaces using an indicator method. The results were evaluated in relation to the measured reinforcement cover, since the significance of carbonation for reinforcement corrosion depends on the position of the carbonation front relative to the embedded steel.

In addition to individual values, the spatial variation of carbonation depth was considered in the analysis. This was relevant because exposure conditions, concrete properties, moisture, cracking, and surface characteristics may vary between different areas of the same structure. Carbonation depth was therefore not interpreted independently as evidence of reinforcement corrosion.

2.6. Chloride Content

Chloride content was determined on concrete samples from selected locations as part of the durability investigation. For Case B, the original assessment reported acid-soluble chloride content on a concrete-mass basis and adopted a maximum criterion of 0.06% by mass of concrete, with conversion to cement mass based on an assumed cement content of 400 kg/m^3. The results were evaluated against the criterion documented in the source assessment rather than treated as a universal threshold.

The results were interpreted together with half-cell potential measurements, carbonation depth, reinforcement cover, and visual observations. Chloride content was treated as an indicator of exposure and conditions relevant to reinforcement depassivation rather than as direct evidence of the extent or rate of corrosion. This distinction allowed the chemical and electrochemical information to be considered separately before assessing their combined diagnostic significance.

2.7. Concrete Core Testing and Complementary Investigations

Concrete cores were extracted from selected locations to obtain direct information on the local mechanical properties of concrete and to complement the non-destructive measurements. Following specimen preparation, compressive strength was determined according to the procedures used in the original investigations. Concrete density and observations made during examination of the extracted cores were also considered where available.

Core compressive strength was treated as a local mechanical property and not as a direct measure of durability or overall structural condition. This distinction is relevant because concrete may retain relatively high compressive strength while deterioration processes are developing within the cover zone or while conditions favourable to reinforcement corrosion are present.

Additional results, including pull-off strength and capillary water absorption, were considered where available. These tests were used to provide supplementary informa-

tion for individual cases but were not treated as common primary indicators across the complete dataset.

2.8. Data Analysis and Interpretation

The analysis focused on three aspects: the spatial variability of measured properties, the agreement or disagreement between complementary indicators, and the extent to which locally obtained results could support conclusions regarding a larger structural area.

The results of different methods were not combined into a single numerical condition index. Each measurement was first considered according to the property it represents and the limitations associated with its interpretation. Complementary results were then compared to determine whether they provided converging, complementary, or potentially conflicting evidence regarding material condition and deterioration.

Particular attention was given to cases in which a favourable result for one material property coexisted with indicators of a different deterioration process. This included the comparison of local mechanical properties with carbonation, chloride-related and electrochemical indicators, as well as the relationship between visually identified cracking and its extent determined by ultrasonic testing.

The interpretation also accounted for the way in which the original test locations had been selected. Results obtained at locations chosen because of visible deterioration or other characteristic features were treated as targeted diagnostic evidence and were not assumed to be statistically representative of the entire structure. The distinction between the interpretation of a local measurement and the assessment of a broader structural area was therefore maintained throughout the analysis.

3. Results

The results obtained from the three case studies showed considerable variability between individual test locations and, more importantly, demonstrated that different testing methods described different aspects of material condition. Table 1 summarises the principal results used for the comparative analysis. The results are presented without information that could identify the investigated structures or individual projects.

Table 1. Summary of principal test results from the analysed case studies.

Case	Investigated Parameter	Principal Results
A	Reinforcement cover	Mean values: 43–51 mm; measured range: 34–67 mm
	Carbonation depth	Mean values: 0.8–16.8 mm; maximum depth: 19 mm
	Half-cell potential	Predominantly intermediate corrosion probability at two investigated areas
	Core compressive strength	Selected in-situ characteristic compressive strength: 40.9 MPa
B	Rebound hammer	Estimated compressive strength: 29.70–55.91 MPa
	Core compressive strength	Individual available results: 58.5–82.7 MPa
	Carbonation depth	Maximum mean depth: 23 mm
	Chloride content	Elevated values at two of four investigated locations [1]

Table 1. *Cont.*

Case	Investigated Parameter	Principal Results
B	Half-cell potential	Intermediate corrosion probability at the investigated area
	Ultrasonic testing	Estimated crack depths: 67, 74 and 166 mm
C	Core compressive strength	Mean values: 27.2 and 33.0 MPa
	Concrete density	Mean value: 2318 kg/m^3
	Capillary water absorption	Mean value: 1.763 kg/(m^2·h$^{1/2}$)

[1] Chloride content exceeded the criterion applied in the original condition assessment at two investigated locations.

3.1. Case A—Relationship Between Carbonation, Reinforcement Cover and Electrochemical Response

Case A illustrates the importance of considering carbonation depth in relation to reinforcement cover rather than interpreting either parameter independently. Mean reinforcement cover at the three investigated areas ranged from 43 to 51 mm, while individual measurements ranged from 34 to 67 mm. Carbonation measurements showed pronounced spatial variability, with mean depths ranging from 0.8 to 16.8 mm and a maximum measured depth of 19 mm.

At the investigated locations, the measured carbonation depths remained below the corresponding reinforcement cover. The available results therefore did not indicate that the carbonation front had reached the reinforcement at these locations. This finding, however, did not coincide with an entirely uniform electrochemical response. Half-cell potential measurements at two test areas were predominantly within the intermediate corrosion-probability range, while only a small proportion of measurements at one area indicated a high probability of corrosion.

This combination of results is relevant because the electrochemical response could not be explained solely by carbonation depth. The results demonstrate that a corrosion-related indicator should not be attributed to a single deterioration mechanism without supporting evidence from other measurements.

The concrete core results provided additional information on local mechanical properties. The selected in-situ characteristic compressive strength was 40.9 MPa. Although this result indicated satisfactory local mechanical properties of the investigated concrete, it did not resolve the interpretation of the electrochemical response. Mechanical properties, carbonation and corrosion-related measurements therefore provided complementary rather than interchangeable information.

3.2. Case B—Variability of Mechanical and Durability-Related Indicators

Case B contained the most extensive combination of testing methods and showed the clearest differences between indicators describing mechanical properties and those related to durability.

Rebound hammer testing was performed at ten test areas, with estimated compressive strength values ranging from 29.70 to 55.91 MPa. Concrete core testing produced higher individual compressive strength values at the available sampling locations, ranging from 58.5 to 82.7 MPa. Since the rebound hammer test areas and core sampling locations were not consistently paired, these values were not used to establish a direct correlation or correction relationship. The difference between the observed ranges was instead considered as evidence that surface-based estimates and direct core measurements should not be treated as equivalent measures of concrete condition.

Durability-related testing revealed additional information that could not be inferred from mechanical strength alone. The maximum mean carbonation depth was 23 mm. Chloride content was determined at four locations. The original assessment used a criterion of 0.06% chloride by mass of concrete; this criterion was exceeded at two locations, where the reported values were approximately four and five times higher. The chloride results therefore showed marked local differences within the investigated structure.

Half-cell potential measurements were available for one investigated area and both reinforcement directions. Measurements were performed with a $Cu/CuSO_4$ reference electrode. Potentials ranged from −232 to −311 mV for the horizontal reinforcement and from −273 to −320 mV for the vertical reinforcement. All measured values therefore fell within the intermediate range of −200 to −350 mV used in the source test report. At the same time, chloride testing identified two locations exceeding the criterion used in the original assessment. Chemical and electrochemical information are therefore considered together rather than as independent measures of corrosion extent.

Ultrasonic testing provided a further type of diagnostic information. Three visually identified cracks were investigated by an indirect ultrasonic method, and estimated crack depths of 67, 74 and 166 mm were obtained. These measurements added information on crack propagation into the concrete section that could not be established from surface observation alone. The results were treated as local crack-characterisation data rather than as a general measure of concrete quality.

Taken together, Case B demonstrates that relatively high local compressive strength does not exclude the presence of durability-related deterioration. Mechanical resistance, chloride exposure, carbonation, electrochemical response and crack development describe different aspects of the condition and need to be interpreted accordingly.

3.3. Case C—Mechanical Properties and Transport-Related Behaviour

Case C provided a more limited but useful dataset for examining the relationship between mechanical properties and transport-related behaviour of concrete.

The mean compressive strength determined on cores was 27.2 MPa for one group of structural elements and 33.0 MPa for another. The mean density of all tested specimens was 2318 kg/m^3. The mean capillary water absorption coefficient, determined on two specimens, was 1.763 $kg/(m^2 \cdot h^{1/2})$.

These results provide information on different material characteristics. Compressive strength describes the local mechanical response of the extracted concrete, whereas capillary absorption reflects its interaction with liquid water and is therefore relevant to transport through the pore system. The two quantities were not combined into a single condition parameter because the available number of measurements was insufficient to establish a quantitative relationship between them.

Case C consequently serves as an additional example of why mechanical properties alone cannot describe all aspects relevant to the durability assessment of existing concrete.

3.4. Comparison of the Case Studies

Comparison of the three cases revealed three recurring features. First, considerable spatial variability was present even within individual structures. This was particularly evident in reinforcement cover, carbonation depth, rebound-based strength estimates and chloride content.

Second, apparently favourable results obtained by one method did not necessarily imply favourable results for another aspect of material condition. The clearest example was the coexistence of relatively high local compressive strength with chemical or electrochemical indicators relevant to reinforcement corrosion.

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Third, the diagnostic significance of the results depended on the location and purpose of the measurements. Most test locations had been selected following visual inspection or because a particular feature required further investigation. The results therefore provide strong evidence for the local areas investigated, but their representativeness for untested parts of the structure remains limited.

The comparison consequently indicates that the main benefit of combining different testing methods is not simply the accumulation of a larger number of measurements. Its value lies in determining whether independent indicators provide consistent, complementary, or conflicting information regarding the deterioration process under consideration. This distinction forms the basis for the discussion presented in the following section.

4. Discussion

The comparison of the three case studies demonstrates that the main limitation in the assessment of existing reinforced concrete structures is not necessarily the availability of test methods, but the interpretation of the information obtained from them. Each investigated method describes a specific property or deterioration-related condition, and the significance of an individual result depends on its relationship with other available evidence.

4.1. Diagnostic Value of Individual Test Results

The results demonstrate the need to distinguish between material properties and deterioration indicators. Core compressive strength and rebound hammer testing provide information on mechanical and near-surface concrete properties, but do not directly describe carbonation, chloride ingress, or reinforcement corrosion. Therefore, favourable mechanical properties do not necessarily indicate favourable durability conditions.

This was evident in Case B, where relatively high core compressive strengths coexisted with elevated chloride contents and half-cell potentials entirely within the intermediate range defined in the source test report. In Case A, the maximum carbonation depth remained below the measured reinforcement cover, while half-cell potential measurements indicated an intermediate corrosion-likelihood category over substantial parts of the investigated areas. The electrochemical response could therefore not be attributed to carbonation alone.

These results demonstrate why half-cell potential measurements should be interpreted with complementary information such as carbonation depth, chloride content, reinforcement cover and visual observations, as recommended for corrosion-potential assessment [6–8]. They indicate electrochemical conditions associated with corrosion likelihood but do not directly quantify corrosion rate, reinforcement loss or residual structural capacity.

4.2. Complementarity of Different Investigation Methods

The value of combining different investigation methods lies in their ability to provide information on different aspects of deterioration. Visual inspection identifies surface manifestations, rebound hammer testing and concrete cores provide information on mechanical properties, carbonation depth and reinforcement cover describe conditions relevant to depassivation, chloride analysis provides chemical information, half-cell potential measurements provide an electrochemical indicator, and ultrasonic testing can provide information on crack propagation below the surface.

Considering these results together enables deterioration to be interpreted as a process rather than through isolated measurements. Agreement between complementary indicators increases confidence in the diagnosis, while disagreement may indicate spatial variability, different deterioration mechanisms, or limitations of individual measurements.

This is particularly important for incipient deterioration, where chemical or electrochemical changes may develop while mechanical properties remain relatively unaffected.

4.3. Spatial Variability and Representativeness of Measurements

The analysed cases showed considerable spatial variability in several measured parameters. Consequently, the diagnostic value of a local measurement does not necessarily imply that it is representative of a larger structural area.

In the original investigations, test locations were predominantly selected following visual inspection and were therefore targeted rather than randomly distributed. This approach is appropriate for investigating observed deterioration but limits the extent to which results can be extrapolated to untested areas. It may also overlook early deterioration at locations where visible symptoms have not yet developed.

For condition assessment, targeted measurements could therefore be supplemented by apparently unaffected reference locations. This would provide a basis for distinguishing deterioration-related changes from the background variability of the structure and reduce uncertainty associated with the selection of test locations.

4.4. Implications for Condition Assessment

The analysed results support a distinction between measurement, deterioration indicator, diagnosis, and overall condition assessment. This can be expressed as:

measurement → indicator → interpretation → deterioration mechanism → condition assessment → decision

Maintaining this distinction reduces the risk of assigning excessive significance to a single result. In particular, concrete strength should not be equated with durability, and corrosion potential should not be interpreted as direct evidence of reinforcement loss.

The objective of a multi-method investigation should therefore not be to maximise the number of tests, but to select complementary methods that address the relevant deterioration mechanisms and reduce diagnostic uncertainty. Reliable condition assessment depends both on the interpretation of complementary indicators and on the representativeness of the locations at which they are obtained. A limitation of the retrospective anonymised dataset is that the completeness of project-specific metadata varies between cases. Where original test documentation was available, such as for the Case B half-cell and chloride measurements, the documented electrode, potential ranges, interpretation thresholds and chloride criterion were retained; missing metadata in other cases were not reconstructed.

5. Conclusions

Within the limits of the targeted field dataset, early-stage detection refers to identifying deterioration-related indicators that may not be fully characterised by visual inspection alone. The analysis of the three anonymised case studies shows that reliable condition assessment of existing reinforced concrete structures cannot be based on individual test results alone. Each investigated method provides information on a specific material property or deterioration-related process, and its diagnostic value depends on interpretation together with complementary evidence.

The results demonstrate that favourable local mechanical properties do not necessarily exclude durability-related deterioration. In addition, spatial variability and the selection of test locations strongly influence the representativeness of the obtained results. Targeted measurements are valuable for local diagnosis but should not automatically be extrapolated to untested areas.

A multi-method approach can therefore improve the reliability of condition assessment when the selected methods provide complementary information. A clear distinction

between measurement, deterioration indicator, diagnosis, and condition assessment is essential for reducing uncertainty and supporting technically justified maintenance decisions.

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Abbreviations

The following abbreviations are used in this manuscript:

NDT	Non-destructive testing
UPV	Ultrasonic pulse velocity

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