

Detection and Assessment of Structural Weaknesses in Existing Offshore Structures

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Abstract

The structural integrity and serviceability of existing structures may deteriorate over time due to aging, environmental exposure, material degradation, overloading, inadequate maintenance, and repeated operational stresses. Early identification of structural deficiencies is essential for preventing progressive damage and ensuring safe and reliable performance throughout the service life of a structure. This study presents a systematic structural condition assessment of an existing structure using visual inspection and non-destructive testing (NDT) techniques. Ultrasonic pulse velocity (UPV) and rebound hammer tests were employed to evaluate the quality and relative strength of concrete without causing significant damage to structural components, following the provisions of IS 13311 (Part 1 and Part 2). Visual observations were also carried out to identify surface deterioration, including cracks, corrosion-related distress, spalling, and other visible defects. The collected NDT results were analyzed to identify variations in concrete quality and to determine structural elements requiring further investigation. The assessment indicated localized deterioration in several structural components, with Column 10 exhibiting comparatively lower strength and requiring particular attention. Based on the observed condition and test results, appropriate recommendations for repair, rehabilitation, strengthening, and continued monitoring were proposed. The study demonstrates the effectiveness of combining visual inspection with NDT techniques for detecting potential structural weaknesses at an early stage. The proposed assessment approach can support condition-based maintenance and improve structural reliability, durability, and service life. The findings are particularly relevant to offshore and marine-exposed structures, where environmental deterioration and limited accessibility can significantly influence long-term structural performance and safety.

Keywords: Structural audit, non-destructive testing (NDT), ultrasonic pulse velocity (UPV), rebound hammer test, concrete strength, visual inspection, building maintenance, IS:13311, structural integrity

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Received Date: July 30, 2026

Accepted Date: August 07, 2026

Published Date: August 11, 2026

Citation: Sanchita Hiwrale, Kunal Waghule, Om Jahagirdar, Tejas Tirukhe, Anuradha Kalamb, Hashmi S. Mujahid. Detection and Assessment of Structural Weaknesses in Existing Offshore Structures. Journal of Offshore Structure and Technology. 2026; 13(2): 52–69p.

INTRODUCTION

General

Existing structures are essential components of residential, commercial, industrial, transportation, marine, and offshore infrastructures. A structure is designed to safely resist various loads and environmental actions throughout its intended service life while maintaining adequate strength, stability, durability, and serviceability. In offshore engineering, structures include fixed offshore platforms, jacket structures, topside facilities, offshore processing units, marine terminals, offshore wind support structures, subsea structural components, and other facilities exposed to marine and operational environments. These structures are generally subjected to complex combinations of

gravity loads, wind loads, wave and current actions, cyclic loading, vibrations, temperature variations, accidental loads, and environmental degradation [1].

Unlike newly constructed structures, existing structures may experience gradual deterioration as a result of aging, repeated loading, corrosion, fatigue, accidental events, inadequate maintenance, modifications, and changes in operating conditions. Consequently, the original design assumptions may no longer accurately represent the actual conditions or capacity of the structure. Therefore, periodic inspection and structural condition assessment are necessary to determine whether an existing structure continues to satisfy the required safety and performance criteria [2].

Structural assessment involves systematic examination of structural components, materials, connections, foundations, and other critical elements to identify deterioration, damage, defects, or changes in structural behavior. For concrete structures, deterioration may occur in the form of cracking, spalling, loss of cover, reinforcement corrosion, leakage, and reduction in material quality. In steel offshore structures, common problems include corrosion, section loss, fatigue cracking, weld defects, buckling, and damage caused by impact or excessive loading [3].

The assessment of existing structures is particularly important in offshore environments because access for inspection and maintenance may be difficult, and marine exposure can significantly accelerate deterioration. Continuous exposure to seawater, salt-laden moisture, tidal variations, wave action, and atmospheric conditions can increase corrosion and material degradation rates. Therefore, an effective structural integrity management approach should combine visual inspection, non-destructive testing (NDT), engineering evaluation, repair, strengthening, and periodic monitoring [4].

General Service Life of Structures

The service life of a structure refers to the period during which it is expected to perform its intended function safely and satisfactorily under specified environmental and operational conditions. The structural service life is influenced by the quality of the design, construction practices, materials, loading conditions, environmental exposure, inspection frequency, maintenance procedures, and rehabilitation measures. A structure may remain functional for several decades if appropriate design, construction, inspection, and maintenance practices are followed. However, deterioration can substantially reduce its effective service life when defects are not detected and treated early [5].

For reinforced concrete structures, durability is strongly influenced by environmental exposure and protection of embedded reinforcement. The provisions of IS 456:2000 consider the durability requirements and exposure conditions in the design of concrete structures. However, the actual service performance of an existing structure depends not only on the original design but also on subsequent environmental and operational conditions. In offshore and marine structures, chloride penetration, carbonation, reinforcement corrosion, cracking, wetting and drying cycles, and other deterioration mechanisms can significantly influence long-term performance [6].

Similarly, steel offshore structures may experience progressive deterioration because of corrosion and fatigue resulting from repeated waves and operational loading. Localized corrosion can reduce the cross-sectional area of structural members, whereas fatigue may initiate and propagate cracks at welded joints and stress concentration regions. If such defects remain undetected, the structural capacity and reliability may progressively decrease [7].

Therefore, service life assessments should not be based solely on the chronological age of a structure. Instead, the actual condition, deterioration rate, loading history, environmental exposure, and remaining structural capacity should be considered. Structural audits and condition assessments provide important information for estimating the remaining service life and determining appropriate repair, strengthening, replacement, or continued monitoring requirements [8].

Factors Affecting Structural Service Life

Several factors influence the durability, safety, and service lives of existing structures. The major factors are discussed below:

1. *Construction quality*: Poor workmanship, inadequate compaction, improper curing, insufficient reinforcement cover, defective welding, poor-quality joints, and construction irregularities can introduce weaknesses that become more significant over time. Construction defects may also increase the susceptibility of structural members to corrosion, cracking, and fatigue [9].
2. *Materials used*: The quality and durability of concrete, reinforcement steel, structural steel, protective coatings, welding materials, and other construction materials directly affect the structural performance. Properly selected and adequately protected materials generally provide better resistance to environmental deterioration [10].
3. *Maintenance and inspection*: Regular inspection, cleaning, protective coating, corrosion control, waterproofing, repair of cracks, replacement of deteriorated components, and timely strengthening can significantly extend structural service life. In offshore facilities, planned inspection and maintenance are particularly important because deterioration may occur in locations that are difficult-to-access.
4. *Environmental exposure*: Environmental conditions have a major influence on deterioration. Offshore structures are exposed to seawater, salt spray, humidity, marine organisms, wave action, tidal fluctuations, and temperature variations. Chloride-induced corrosion is a particularly important deterioration mechanism for reinforced concrete and steel structures in marine environments.
5. *Soil and foundation conditions*: The condition of the foundations and supporting soil affects the overall stability of a structure. Settlement, scour, erosion, changes in seabed conditions, and deterioration of foundation components can influence the structural response and load transfer. Therefore, foundation assessment is an important component of the structural integrity evaluation of offshore structures.
6. *Loading and usage conditions*: Structures may experience loads different from those assumed during their original design. Increased operational loads, equipment modifications, accidental impacts, vibrations, wave loading, and repeated cyclic loads can affect structural performance. Therefore, changes in the use or configuration of an existing facility should be evaluated before implementation.
7. *Aging and deterioration*: Natural aging may result in the gradual degradation of materials and structural components. The deterioration rate depends on the exposure conditions, material properties, loading history, and maintenance practices. Identifying deterioration at an early stage allows for the implementation of corrective measures before significant structural capacity is lost.

Effect of Aging on Existing Structures

Aging is a major factor affecting the long-term performance of existing structures. As a structure remains in service, its components are repeatedly exposed to environmental conditions and operational loads. Over time, this exposure can cause physical, chemical, and mechanical deterioration. Typical deterioration mechanisms include cracking, corrosion, spalling, leakage, material degradation, fatigue damage, deformation, and loss of sections.

In reinforced concrete structures, aging may result in carbonation and chloride penetration, which can initiate the corrosion of embedded reinforcements. Corrosion products occupy a greater volume than the original steel and can generate internal pressure within the concrete, resulting in cracking, delamination, and spalling of the concrete. Continued corrosion may reduce the effective cross-sectional area of the reinforcement and consequently decrease the load-carrying capacity of structural members.

In offshore steel structures, aging is frequently associated with corrosion and fatigue. Corrosion may occur in splash zones, submerged members, joints, connections, and areas where protective coatings have deteriorated. Repeated waves and operational loading can produce cyclic stresses, which may eventually result in fatigue cracks, particularly around welded connections and geometric discontinuities.

The effects of aging may initially remain localized and difficult to identify through ordinary visual inspection. However, progressive deterioration can eventually affect the strength, stiffness, stability, and serviceability of structures. Consequently, systematic condition assessment using visual inspection and suitable NDT techniques is necessary to identify early stage deterioration and determine the need for further investigation.

Cracking

Cracking is a common visible indicator of distress in reinforced concrete structures. Cracks may be associated with shrinkage, thermal effects, settlement, reinforcement corrosion, excessive loading, structural movement, fatigue, or inadequate detailing. While some cracks may primarily affect appearance or durability, others may indicate significant structural distress.

The location, width, length, orientation, depth, and pattern of cracks provide useful information regarding their possible causes. For example, flexural cracks generally develop in regions subjected to bending, whereas diagonal cracks may be associated with shear stresses. Cracks parallel to the reinforcement may indicate corrosion-related expansion, whereas random surface cracking may be associated with shrinkage or environmental effects.

In offshore and marine environments, cracks are particularly important because they can provide pathways for water, chlorides, and other aggressive agents to reach the embedded reinforcement. Consequently, crack assessment should be an important part of structural condition surveys.

Settlement Cracks

Settlement cracks may develop when fresh concrete settles before sufficient hardening occurs. If the settlement occurs uniformly, significant cracking may not develop. However, reinforcement, embedded components, large aggregates, or changes in the section geometry may obstruct uniform settlement and create localized voids or cracks.

Settlement-related cracking can be particularly significant in deep beams, heavily reinforced sections, and structural members with geometric changes. If such cracks remain untreated, they may contribute to increased permeability and facilitate the penetration of aggressive environmental agents into the concrete. Therefore, identifying the cause and extent of settlement cracking is important during structural assessments.

Effect of Usage and Environmental Parameters

The performance of an existing structure is influenced not only by its age but also by its actual usage, loading history, environmental exposure, and maintenance conditions. Changes in operational requirements may increase the demand for structural members beyond the assumptions considered during the original design. In offshore facilities, the installation of additional equipment, modification of process systems, changes in platform functionality, and increased operational loads may alter the structural load distribution.

Repeated and cyclic loadings are other important considerations. Offshore structures are continuously subjected to waves, wind, currents, machinery, and operational loads. These repeated actions can contribute to fatigue damage, particularly at welded connections and stress concentration regions. Therefore, structural assessment should consider both static and cyclic loading effects, where applicable.

Environmental conditions can accelerate this deterioration. Marine structures are exposed to aggressive chloride-rich environments, wetting and drying cycles, wave impacts, marine growth, and atmospheric moisture. These factors may accelerate corrosion and reduce the effectiveness of the protective systems.

Leakage and Water Ingress

Water leakage and uncontrolled water ingress can adversely affect structural durability. Persistent moisture can cause dampness, deterioration of concrete, corrosion of reinforcements, degradation of protective coatings, and growth of microorganisms. In reinforced concrete structures, water penetration can facilitate chloride ingress and carbonation, thereby increasing the possibility of reinforcement corrosion in the structure.

In offshore facilities, water ingress may occur through damaged coatings, cracks, joints, penetrations, drainage systems, or deteriorated concrete. Early detection and repair of leaks are essential for preventing further deterioration and reducing long-term maintenance requirements.

Accidental and Impact Damage

Accidental events can cause significant damage to structural components. These events may include collisions, dropped objects, equipment failure, fire, explosion, excessive operational loading, or extreme environmental conditions. Offshore structures are particularly vulnerable to accidental loading because of marine traffic, lifting operations, heavy equipment use, and severe environmental events.

Accidental damage may result in local deformation, cracking, buckling, connection failure, coating damage, or the loss of a structural section. Even when a structure remains standing after an accident, hidden damage may reduce its residual capacity. Therefore, a detailed structural inspection and engineering assessment should be performed following significant accidental events.

Corrosion and Marine Exposure

Corrosion is a major deterioration mechanism in offshore structures. Steel components exposed to seawater and marine atmospheric conditions are susceptible to corrosion. The corrosion rate can vary depending on the location of the member, water chemistry, temperature, oxygen availability, coating condition, and exposure duration.

Particular attention is required for splash and tidal zones because repeated wetting and drying can create highly aggressive conditions. Localized corrosion and pitting can result in substantial section loss and stress concentrations. In reinforced concrete, chloride penetration can initiate reinforcement corrosion, which may cause cracking and spalling.

Therefore, effective corrosion management requires regular inspection, measurement of section loss where applicable, assessment of protective coatings, and timely repair or replacement of deteriorated components.

Structural Audits

A structural audit is a systematic technical assessment performed to determine the present condition, safety, durability, and serviceability of an existing structure. It involves the collection and evaluation of information related to the original design, construction, modifications, loading history, environmental exposure, visible defects, material properties, and structural behavior.

The primary objective of a structural audit is to identify structural deficiencies at an early stage and determine whether corrective measures are required to address them. A typical structural audit includes a preliminary document review, visual inspection, identification and mapping of defects, NDT, material assessment, structural analysis where necessary, evaluation of remaining capacity, and preparation of repair or strengthening recommendations.

For concrete structures, NDT methods such as the rebound hammer and ultrasonic pulse velocity (UPV) tests can provide useful information regarding surface hardness, concrete quality, uniformity, and internal discontinuities. These techniques enable engineers to investigate structural members without causing any significant damage. However, NDT results should be interpreted carefully and, where necessary, correlated with other investigations or laboratory tests.

In the context of offshore structures, structural audits become more complex because inspections may involve submerged, splash-zone, and difficult-to-access components. Remote inspection technologies, underwater inspection, corrosion monitoring, drone-based visual surveys, digital imaging, and advanced structural health monitoring systems can complement conventional inspection methods.

Structural audits should not be regarded as one-time activities. Periodic condition assessment allows changes in structural conditions to be tracked over time and supports condition-based maintenance. The findings can be used to classify structural components according to the severity of their deterioration and prioritize repair, strengthening, replacement, or continued monitoring.

Need for Structural Condition Assessment

The need for systematic structural condition assessments has increased because many existing structures are approaching or exceeding their original design service periods. Extending the operational life of an existing structure can often be more economical than complete replacement, provided that its structural integrity can be demonstrated and necessary rehabilitation measures are implemented.

Condition assessment helps engineers identify deteriorated members, evaluate their remaining capacity, determine the causes of damage, and establish appropriate intervention strategies to address these issues. It also provides information required for estimating the remaining service life and planning future inspection and maintenance activities.

Condition assessment is particularly important for offshore structures because structural failure can result in severe economic, environmental, and safety consequences. Failure of a critical offshore member may affect the stability of the entire facility and can interrupt production or pose significant risks to personnel and the surrounding marine environment. Therefore, the early detection of structural weaknesses is an essential component of offshore structural integrity management.

Role of Non-Destructive Testing in Structural Assessment

NDT provides an effective means of evaluating existing structural materials without causing substantial damage to the components investigated. NDT techniques are particularly valuable when the removal of material or destructive testing is impractical.

The rebound hammer test provides an indirect indication of surface hardness and can be used to assess the relative uniformity of concrete and estimate compressive strength when appropriate correlations are available. The Ultrasonic Pulse Velocity test measures the travel time of ultrasonic pulses through concrete and can provide information regarding concrete quality, uniformity, internal cracks, voids, and discontinuities.

The combined use of visual inspection, UPV, rebound hammer testing, and other appropriate investigation techniques can provide a more comprehensive understanding of structural condition than reliance on a single method. The interpretation of NDT results should consider the material characteristics, moisture condition, surface condition, member geometry, and applicable standards.

Objectives of the Study

The Main Objectives of The Present Study Area

- To assess the existing condition and structural integrity of selected structural components.
- To identify visible defects, such as cracks, leakage, corrosion, spalling, and surface deterioration.
- To evaluate concrete quality using UPV and rebound hammer tests.
- To identify structural elements exhibiting comparatively poor or deteriorated material conditions.
- To assess the significance of observed deterioration on structural safety and serviceability.
- To recommend suitable repair, rehabilitation, strengthening, and monitoring measures.
- To demonstrate the importance of periodic structural audits in extending the safe service life of existing structures.

- To develop an assessment approach that can support the structural integrity management of structures exposed to demanding environmental conditions, including offshore and marine environments.

Significance of Study

Assessing existing structures is essential for maintaining safety and reliability throughout their service lives. Visual inspection alone may not reveal hidden deterioration within structural members; therefore, the integration of visual assessment with appropriate NDT provides a more reliable basis for condition evaluation.

This study demonstrates how systematic structural inspection and NDT can be used to identify localized weaknesses and prioritize corrective measures. This approach is particularly relevant to structures exposed to aggressive environmental conditions, where deterioration can progress rapidly, and access for inspection may be challenging.

By identifying vulnerable structural components at an early stage, structural audits can help prevent progressive deterioration, reduce unexpected failures, optimize maintenance expenditure, and extend the operational life of existing infrastructure. The methodology and findings also provide a useful basis for developing condition-based inspection and maintenance strategies for offshore and marine structural systems in the future.

METHODOLOGY

The methodology adopted in this study consisted of a systematic structural condition assessment combining visual inspection and non-destructive testing (NDT). The investigation was designed to identify visible deterioration, assess the quality and uniformity of concrete, locate potentially distressed structural components, and provide a basis for repair, strengthening, and continued structural monitoring. The overall assessment procedure consisted of the following major stages.

1. Visual inspection
2. Non-destructive testing
 - UPV test
 - Rebound hammer test

The proposed methodology is applicable to the condition assessment of existing reinforced concrete structures and can also provide a basis for structural integrity assessment in marine and offshore environments, where deterioration due to moisture, corrosion, cyclic loading, and aggressive exposure may occur.

Visual Inspection

Visual inspection is the initial and fundamental stage of structural condition assessments. It provides direct information regarding the physical condition of structural and non-structural components and helps identify areas requiring detailed investigation. The inspection was carried out systematically by examining the accessible structural members and documenting visible defects, deterioration patterns, environmental exposure, and signs of distress.

Particular attention was paid to the columns, beams, slabs, walls, connections, and other load-bearing components. The location, extent, orientation, and severity of the observed defects were recorded. Photographs and inspection records can be used to establish baseline conditions against which future deterioration can be compared.

The Major Aspects Considered During the Visual Inspection Were as Follows:

General Condition Assessment

The overall condition of the structure was examined to identify signs of aging, deterioration, inadequate maintenance, or abnormal structural behavior. The inspection considered the conditions of

the concrete surfaces, structural members, joints, finishes, drainage arrangements, and other accessible components.

Cracks and Structural Damage

The cracks were examined with respect to their location, orientation, width, length, and pattern. Particular attention was given to cracks occurring in load-bearing members, areas surrounding the reinforcement, beam-column junctions, and regions subjected to high stress. Cracking may result from shrinkage, settlement, thermal effects, corrosion, overloading, fatigue, or structural movement.

The presence of extensive or progressive cracking was considered an indication for further investigation using NDT or other appropriate assessment techniques.

Corrosion and Rusting

Concrete surfaces were inspected for rust stains, exposed reinforcement, delamination, spalling, and other signs of reinforcement corrosion. Corrosion-related deterioration is particularly important in structures exposed to moisture, chloride-containing environments, and marine conditions. In offshore structures, corrosion may be accelerated in splash zones, tidal zones, and locations where protective systems have deteriorated.

Water Seepage and Dampness

Evidence of water seepage, dampness, leakage, staining, and moisture accumulation was also recorded. Persistent moisture can increase the risk of reinforcement corrosion, concrete deterioration, biological growth, and the degradation of protective systems. In marine and offshore structures, moisture-related deterioration can be associated with seawater exposure, tidal action, damaged waterproofing, drainage deficiency, and cracks.

Structural Deformation and Settlement

Structural members were visually examined for excessive deflection, deformation, tilting, settlement, displacement, and unusual geometric changes. Settlement-related distress may be associated with foundation movement, changes in soil conditions, inadequate bearing capacity, erosion, and differential settlement.

For offshore structures, changes in foundation or seabed conditions, scour, and movement of supporting systems may similarly influence the structural response and should be considered during a detailed integrity assessment.

Masonry and Plaster Condition

Where masonry walls and plastered surfaces were present, they were examined for cracks, debonding, dampness, surface deterioration, bulging, and separation from the structural elements. Although masonry and plaster are generally non-structural, their condition can provide useful information about building movement, moisture penetration, and localized distress.

Load-Bearing Components

Columns, beams, slabs, foundations, structural walls, and other primary load-bearing elements were considered. The assessment focused on visible cracking, spalling, deformation, corrosion, section loss, damaged concrete, and other conditions that could influence the load-carrying capacity.

Structural members exhibiting significant deterioration were identified for detailed NDT investigation.

Non-Structural Elements

Non-structural components, such as doors, windows, ceilings, partitions, service installations, drainage systems, and architectural finishes, were also examined. Damage to these components may

not directly indicate structural failure but can provide evidence of excessive movement, moisture penetration, settlement, or other underlying issues.

Non-Destructive Testing

Non-destructive testing was conducted to supplement the findings obtained from the visual inspection. NDT techniques allow the condition and relative quality of structural materials to be investigated without causing significant damage to structural members.

In the present study, two commonly used concrete NDT techniques were considered:

- UPV test.
- Rebound hammer test.
- The tests were carried out in accordance with the relevant provisions of IS 13311 (Part 1): 1992 for UPV testing and IS 13311 (Part 2): 1992 for rebound hammer testing.
- The results of these tests were interpreted together with visual observations to identify areas of comparatively poor concrete quality and structural deterioration.

Ultrasonic Pulse Velocity Test

The UPV test is a non-destructive technique used to assess the quality, uniformity, and internal condition of concrete. This method is based on measuring the time required for an ultrasonic pulse to travel through a known concrete path length. The pulse velocity was calculated as follows:

$$V = L/T$$

where:

- V = pulse velocity through concrete,
- L = path length travelled by the ultrasonic pulse, and
- T = transit time of the pulse.

A higher pulse velocity generally indicates a comparatively dense and homogeneous concrete, whereas a lower velocity may indicate cracks, voids, honeycombing, poor compaction, or other discontinuities. However, the pulse velocity should not be interpreted independently as a direct measure of compressive strength because several factors influence the measured value.

Factors Affecting UPV Measurements

The measured pulse velocity is influenced by the physical condition and composition of the concrete. The important factors include moisture condition, temperature, concrete age, aggregate type, path length, reinforcement, surface condition, and the presence of cracks or voids.

Moisture Condition

Moist concrete generally produces higher pulse velocities than dry concrete because water provides a better transmission path for ultrasonic energy. Therefore, the moisture condition of the test surface should be considered when comparing the results obtained from different locations.

Temperature

Temperature variations can influence the pulse velocity. Within moderate temperature ranges, the effect is generally limited; however, extreme temperatures can produce more significant variations. Consequently, the test conditions should be recorded wherever practical.

Reinforcement

The presence and orientation of the reinforcement can influence the UPV readings because ultrasonic waves travel at substantially higher velocities through steel than through concrete. Therefore, test locations should be selected carefully to minimize the influence of reinforcement, or reinforcement locations should be considered during interpretation.

Surface Condition

A rough, uneven, or damaged concrete surface can prevent proper coupling between the transducer and concrete. Therefore, the test surfaces should be adequately prepared to ensure effective contact between the transducers and concrete.

Path Length

The distance between transmitting and receiving transducers affects the measurement reliability. An adequate path length should be maintained in accordance with the testing standards and equipment requirements.

Cracks and Voids

Internal cracks, voids, honeycombing, and other discontinuities can increase the transit time, consequently reducing the measured pulse velocity. A significant reduction in velocity relative to comparable locations may indicate localized deterioration and require further investigation.

UPV Test Procedure

Before testing, the selected concrete surface was inspected and prepared to ensure adequate contact with the transducers. The transmitting and receiving transducers were positioned according to the selected test arrangements. A suitable coupling medium was used to ensure the effective transmission of the ultrasonic pulse.

The instrument was then used to measure the transit time of the pulse through concrete. Multiple readings were obtained from representative locations, and the corresponding pulse velocities were determined. Locations with comparatively low or significantly different readings were identified for further evaluation.

The results from different structural members were compared to assess the uniformity of the concrete quality. A localized reduction in pulse velocity compared with surrounding or representative areas may indicate the presence of internal discontinuities, poor-quality concrete, cracks, or other deterioration.

For a reliable structural assessment, the UPV results should preferably be correlated with visual observations and, where necessary, other material investigation techniques rather than being used as the sole basis for estimating concrete strength.

Rebound Hammer Test

The rebound hammer test is a commonly used non-destructive method for assessing the surface hardness and relative uniformity of concrete. The test is based on measuring the rebound of a spring-controlled mass after it impacts a concrete surface. The resulting rebound number provides an indication of the surface hardness and can be correlated with the compressive strength when appropriate calibration and correlation procedures are available.

The rebound number is affected by several factors, including surface condition, moisture content, carbonation, age of concrete, type of aggregate, direction of testing, and the condition of the testing instrument. Therefore, the rebound number should not be interpreted as the exact value of compressive strength without considering these influencing factors.

Rebound Hammer Test Procedure

The selected concrete surface was cleaned and prepared prior to testing. Loose particles, plaster, paint, or deteriorated material were removed as necessary from the test area. The rebound hammer was held perpendicular to the test surface, and readings were obtained from several points in the selected test region.

Individual readings were examined for significant variations, and representative values were considered to assess the relative surface hardness of the concrete. Areas with unusually low rebound numbers were identified as potentially weaker zones that required further investigation.

The test results were interpreted in accordance with IS 13311 (Part 2): 1992, the manufacturer's recommendations, and appropriate correlation charts, where applicable. It is important to note that rebound hammer results provide an indirect indication of concrete quality and surface hardness and should not be treated as a standalone measurement of structural capacity.

Interpretation of Rebound Hammer Results

Higher rebound numbers generally indicate harder and more uniform concrete surfaces, whereas comparatively low rebound numbers may indicate weak, deteriorated, porous, or otherwise abnormal surface conditions. However, the classification of concrete quality should be based on the applicable standard and project-specific calibration rather than a single arbitrary rebound number threshold.

In this study, areas exhibiting comparatively low rebound values were treated as locations requiring closer examination. These areas were correlated with the findings from visual inspection and UPV testing to improve the reliability of the structural condition assessment.

Integration of Visual Inspection and NDT Results

The final assessment was based on a combined interpretation of visual inspection, UPV results, and rebound hammer measurements. The use of multiple assessment techniques helps reduce the limitations associated with relying on a single test method.

Visual inspection provided information regarding surface deterioration and visible distress, whereas UPV testing provided information regarding the internal quality and uniformity of the concrete. The rebound hammer test provided an indication of the surface hardness and relative concrete quality. By comparing the results of all three approaches, structural members showing consistent evidence of deterioration can be identified more reliably.

Structural components showing significant defects or comparatively poor NDT results were classified as requiring further investigation, repair, strengthening, or periodic monitoring depending on the severity of deterioration.

Structural Assessment and Recommendations

Following the inspection and NDT program, the collected observations and test results were compiled for each investigated structural component of the bridge. Members showing significant deterioration or abnormal test values were identified as critical areas for the engineering evaluation.

The assessment considered the nature and extent of visible defects, NDT results, environmental exposure, probable deterioration mechanisms, and functional importance of each structural member. Based on these findings, appropriate recommendations were developed, including repair of deteriorated concrete, treatment of reinforcement corrosion, strengthening of deficient members, protection against further environmental deterioration, and periodic structural monitoring.

This integrated methodology provides a practical framework for evaluating the condition of existing structures and can be adapted for the structural integrity assessment of offshore and marine facilities, where environmental exposure, corrosion, fatigue, accessibility limitations, and long-term serviceability are major concerns.

RESULTS AND DISCUSSION

Test Results of Rebound Hammer Test

The rebound hammer test was conducted on twelve selected concrete columns to evaluate the surface hardness and obtain an indirect indication of the relative quality and uniformity of the concrete. Six

rebound readings were recorded at different points on each column to account for local variations in the concrete surface condition. The average rebound number for each column was calculated from the six individual readings, as shown in Table 1.

Table 1. Test results of visual inspection test

S.N.	Site name	Location	Condition	Picture	Method for repair (recommendations)
1	Anukul Nivas, Deolai Chowk, Chhatrapati Shivaji Nagar,	C1, C2, C3, C4, C5, C6, C10, C11	Minor cracks have been observed, and the rebound values are low.		Apply a coat of polymer-modified cement-based putty or crack sealant for durability and surface protection.
		Bedroom Slab	Bedroom Slab		Apply waterproofing treatments using elastomeric coatings or cementitious waterproofing to prevent moisture ingress.
		C4, C5, C6, C7	Major diagonal cracks are found near the column.		Use epoxy injection for non-structural cracks and structural strengthening.
		C8, C9, C12	Columns have medium rebound values.		Apply micro-concrete or polymer-modified mortar to restore column integrity and improve compressive strength.

		C10	Very low rebound values have been recorded.		Strengthen the column using concrete jacketing or steel encasement to restore load-bearing capacity.
2	MHADA housing society near VITS Hotel, Building No. 7	C1, C2, C3, C4	Concrete spalling, major diagonal cracks, and algae formation are present.		Concrete spalling is when the surface layer of concrete breaks or chips off, often exposing the steel reinforcement inside. To fix this, all loose and damaged concrete should be removed first. The exposed steel bars must then be cleaned and coated with an anti-corrosive material to prevent rust. After that, the area should be filled and repaired using micro-concrete or a polymer-modified mortar to restore the surface and strength.

The test results indicated variations in the rebound values among the investigated columns, reflecting differences in surface hardness and concrete quality. The overall average rebound number obtained from all 12 columns was 27.525. This value represents the general surface hardness of the tested concrete and provides a comparative basis for identifying columns with relatively higher or lower rebound response values.

Columns exhibiting rebound values considerably lower than the overall average were considered comparatively weaker zones and selected for closer evaluation. Such variations may be associated with differences in concrete quality, surface deterioration, moisture conditions, carbonation, workmanship, or other factors affecting the rebound response. Conversely, higher rebound values indicate harder surface conditions, although they do not independently confirm higher structural capacity.

The rebound hammer results were therefore interpreted in conjunction with the visual inspection findings and UPV test results. This combined approach provides a more reliable assessment of concrete conditions than relying on rebound values alone. Particular attention was given to structural members showing both visible signs of deterioration and comparatively low NDT values.

The results are useful for identifying potentially distressed structural components and prioritizing them for detailed investigation, repair, strengthening, or continued monitoring of the structure. In the context of offshore and marine structures, such assessments are particularly important because prolonged exposure to moisture, chlorides, marine environments, and cyclic loading can accelerate deterioration and affect long-term structural integrity, as shown in Figures 1 and 2 and Tables 2 and 3.

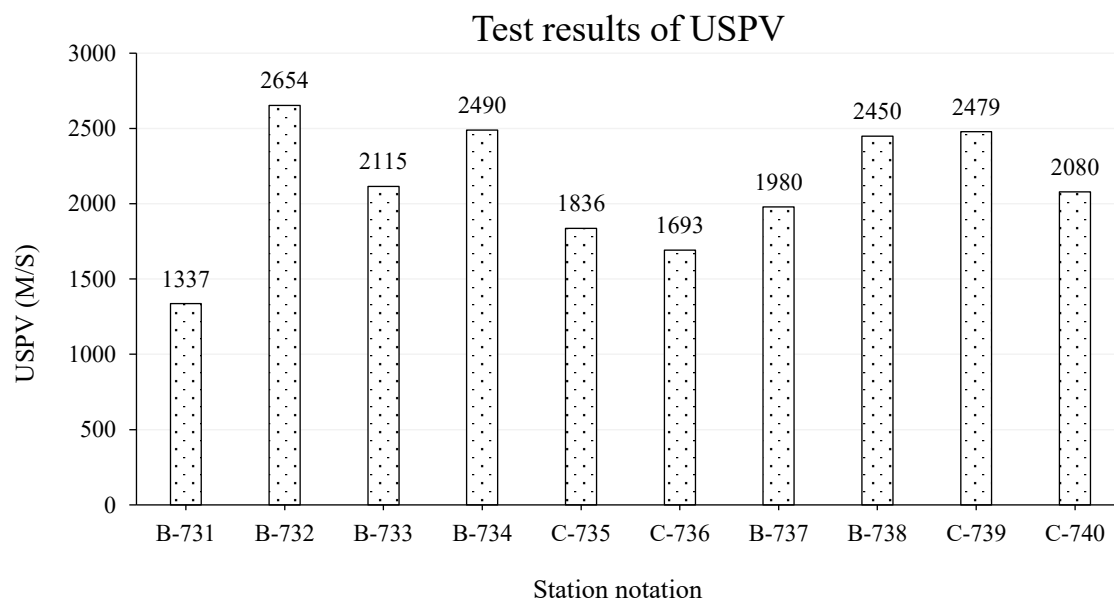
Table 2. The natural frequency of the transducer for different path lengths

S.N.	Average value of pulse velocity by cross-probing (km/s)	Concrete quality grading
(i)	Above 4.40	Excellent
(ii)	3.75 to 4.40	Good
(iii)	3.00 to 3.75	Doubtful ¹
(iv)	Below 3.00	Poor

¹In case of 'Doubtful' quality, it may be necessary to carry out further tests.

Table 3. Test results of ultrasonic pulse velocity test.

S.N.	Station notation	Structural element	USPV (M/S)	USPV (Km/S)	Remark
1	B-731	Beam @ M.L.L	1337	1.337	Poor
2	B- 732	Beam @ M.L.L	2654	2.654	Poor
3	B- 733	Beam @ 2nd slab Level.	2115	2.115	Poor
4	B- 734	Beam @ 2nd slab Level.	2490	2.49	Poor
5	C-735	Column @ 2nd floor.	1836	1.836	Poor
6	C- 736	Column on the 2nd floor.	1693	1.693	Poor
7	B- 737	Beam @ 3rd Slab Level.	1980	1.98	Poor
8	B- 738	Beam @ 3rd Slab Level.	2450	2.45	Poor
9	C- 739	Column @ 3rd Floor Level.	2479	2.479	Poor
10	C- 740	Column @ Terrace Level.	2080	2.08	Poor

**Figure 1.** Average rebound number of each column.

Test Results of Ultrasonic Pulse Velocity Test

The UPV test was carried out at different designated stations, ranging from B-731 to C-740, to evaluate the relative quality, uniformity, and internal condition of the concrete. The measured UPV-related values showed considerable variation among the investigated locations, indicating differences in the quality and condition of concrete within the assessed structural components.

The results ranged approximately from 1337 to 2654, with the highest recorded value of 2654 at station B-732 and the lowest value of 1337 at station B-731. The substantial variation between these locations indicates that the concrete conditions were not completely uniform throughout the area investigated.

Table 4. Quality of Concrete for different values of rebound number

S.N.	Average rebound number (RN)	Overall quality of concrete
1	RN=0	Delaminated
2	RN<20	Poor
3	RN=20 to 30	Fair
4	RN=30 to 40	Good
5	RN>40	Very Good

Station B-732 exhibited the highest measured value, suggesting comparatively better quality and more homogeneous concrete at this location. In contrast, B-731 recorded the lowest value and may represent a comparatively weaker or more heterogeneous zone that requires closer examination. Lower UPV values can be associated with internal cracking, voids, honeycombing, poor compaction, material deterioration, and other discontinuities within the concrete. However, UPV values should be interpreted in conjunction with visual inspection and other available test results rather than being considered direct measurements of compressive strength.

A general comparison of the station results indicated that several locations in the B-series recorded higher values than those observed in the C-series. This variation may be associated with differences in concrete quality, material composition, moisture conditions, age, reinforcement arrangement, or environmental exposure.

The results were used comparatively to identify locations that require further investigation. Areas exhibiting unusually low UPV values, particularly where low readings were accompanied by visible cracks, spalling, corrosion, or other signs of deterioration, were considered potentially vulnerable zones. The UPV findings were subsequently correlated with the rebound hammer results and visual inspection observations to obtain a more comprehensive assessment of the structural condition.

Overall, the UPV investigation demonstrates that non-destructive assessment can effectively identify variations in concrete quality and assist in prioritizing structural components for detailed evaluation, repair, strengthening, or periodic monitoring. Such an integrated approach is particularly relevant to offshore and marine structures, where environmental exposure and difficult inspection conditions can accelerate deterioration and complicate structural integrity assessment Table 4.

Test Results of Rebound Hammer Test

The rebound hammer test was conducted on 12 selected structural columns to evaluate the surface hardness and relative uniformity of the concrete. Each column was tested at six different points, designated as R1 to R6, and the average rebound number was calculated to obtain a representative value for each column. The test results provide a comparative indication of the surface condition and quality of the concrete in the investigated structural members.

The average rebound numbers obtained for the 12 columns varied from 19.3 to 31.3. The lowest average rebound number of 19.3 was recorded for Column 10, whereas the highest average value of 31.3 was recorded for Column 12. The overall average rebound number for all 12 columns was 27.525.

The relatively low rebound value obtained for Column 10 indicates a comparatively low surface hardness and suggests that this column may have poorer or more deteriorated concrete than the other investigated columns. Therefore, the condition of Column 10 requires particular attention and should be subjected to a detailed engineering evaluation before determining the appropriate repair or strengthening intervention. Visual inspection and UPV results should also be correlated with the rebound hammer findings to determine whether the low rebound response is associated with internal defects, deterioration, moisture conditions, surface carbonation, or other factors.

In contrast, Column 12 exhibited the highest average rebound value, indicating a comparatively greater surface hardness. Columns 7, 8, and 12 also show relatively higher rebound responses in the graphical comparison, suggesting comparatively better surface conditions among the tested members.

The graphical results demonstrated noticeable variations in the rebound numbers among the 12 columns. Such variations may arise from differences in concrete quality, surface conditions, moisture content, carbonation, aggregate characteristics, age, workmanship, and environmental exposure. Therefore, the rebound hammer test should be considered primarily as a comparative and supplementary assessment technique, rather than as a standalone determination of the structural load-carrying capacity.

The findings indicate that Column 10 should be prioritized for detailed investigation and appropriate remediation. Depending on the results of further structural assessments, repair, strengthening, corrosion treatment, or other rehabilitation measures may be required. For structures exposed to marine or offshore environments, timely intervention is particularly important because moisture and chloride exposure can accelerate deterioration and adversely affect long-term structural integrity, as shown in Figure 2 and Table 5.

Table 5. Test results of rebound hammer test.

Location	Rebound number						Average rebound number
	R1	R2	R3	R4	R5	R6	
Column 1	28	32	22	30	28	26	27.6
Column 2	26	30	30	30	30	28	29
Column 3	24	32	22	22	24	24	24.6
Column 4	22	22	26	20	28	22	23.3
Column 5	28	30	26	28	26	26	27.3
Column 6	32	26	32	30	30	28	29.6
Column 7	30	36	30	30	28	26	30
Column 8	32	34	28	28	28	30	30
Column 9	32	30	28	32	30	30	30.3
Column 10	20	20	20	18	18	20	19.3
Column 11	24	28	30	30	30	26	28
Column 12	36	32	30	32	32	26	31.3
Average							27.525

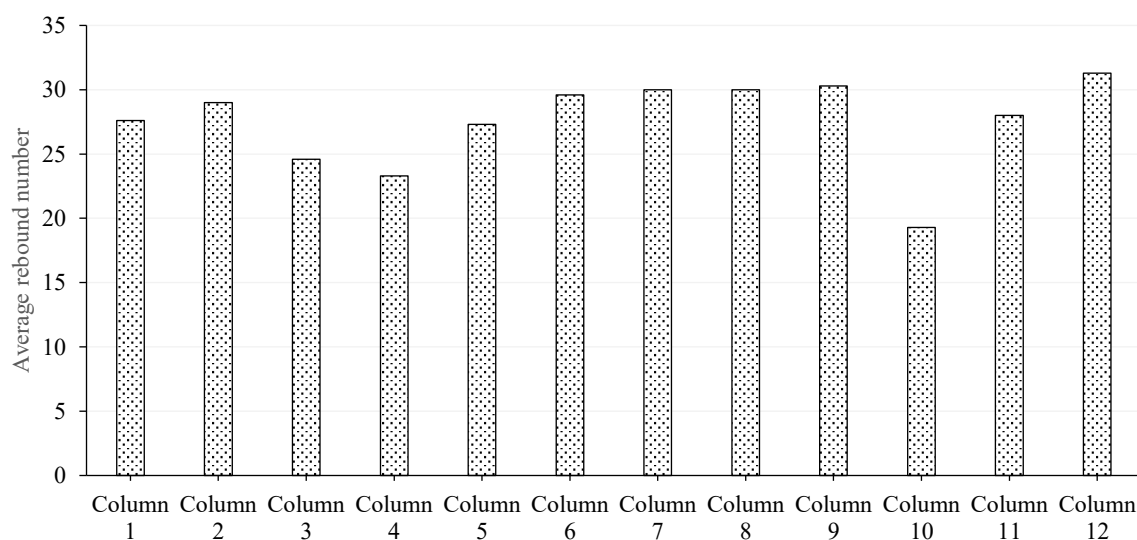


Figure 2. Average rebound number of each column.

CONCLUSION

This study presents a systematic structural audit and condition assessment of an existing reinforced concrete structure using visual inspection and NDT techniques. UPV and rebound hammer tests were employed to evaluate the relative quality, uniformity, and surface condition of concrete without causing significant damage to the investigated structural members. The integration of visual observations and NDT results provided useful information for identifying potentially vulnerable components and prioritizing further structural investigations.

The major conclusions drawn from the investigation are as follows:

1. *Variation in concrete condition:* The structural audit revealed noticeable variations in the condition and quality of the concrete among the investigated structural components. These variations demonstrate the importance of assessing individual members rather than assuming a uniform material quality throughout an existing structure.
2. *UPV assessment:* The UPV investigation indicated considerable variation in the measured values at various locations. Lower readings may be associated with internal discontinuities, cracks, voids, honeycombing, poor compaction, or deterioration. Therefore, the UPV results should be interpreted together with visual inspection and other test results.
3. *Rebound Hammer assessment:* The rebound hammer test showed variations in surface hardness among the 12 investigated columns. The average rebound values ranged from 19.3 to 31.3, with an overall average of 27.525. This variation indicates differences in the surface conditions and relative quality of the concrete.
4. *Condition of Column 10:* Column 10 recorded the lowest average rebound value of 19.3 and was therefore identified as a priority location for further investigations. A low rebound response indicates a comparatively low surface hardness; however, it should not be interpreted as proof of inadequate structural capacity. A detailed assessment using combined NDT findings, visual observations, and structural analysis is recommended before selecting the final strengthening method.
5. *Condition of Column 12:* Column 12 recorded the highest average rebound value of 31.3, indicating a comparatively higher surface hardness among the tested columns. Columns 7 and 8 also show relatively high rebound responses. Nevertheless, higher rebound numbers should be interpreted in relation to surface conditions, carbonation, moisture, and other influencing factors.
6. *Need for repair and rehabilitation:* Structural members exhibiting significant deterioration or consistently poor test results should be prioritized for appropriate remedial action. For Column 10, an immediate detailed engineering evaluation is recommended, followed by repair or strengthening if the investigation confirms inadequate structural performance or significant deterioration.
7. *Integrated assessment:* The findings demonstrate that no single NDT technique should be used independently to determine the safety of an existing structure. Combining visual inspection, UPV testing, rebound hammer testing, and, where necessary, additional material and structural investigations provides a more reliable basis for condition assessment.
8. *Importance of preventive maintenance:* Early detection and treatment of cracks, corrosion, leakage, spalling, and other deterioration mechanisms can reduce the rate of structural degradation and help maintain the required safety and serviceability levels.
9. *Relevance to offshore and marine structures:* The methodology is particularly relevant to offshore and marine structural systems, where exposure to seawater, chlorides, humidity, cyclic loading, corrosion, and difficult inspection conditions can accelerate deterioration. Regular structural integrity assessments can help identify vulnerable components before deterioration becomes critical.
10. *Periodic structural health monitoring:* Periodic structural audits and condition monitoring are recommended to track changes in structural performance over time. A planned inspection and maintenance program can support condition-based interventions, improve reliability, reduce unexpected repair requirements, and extend the useful service life of existing structures.

Overall, this study confirms the usefulness of combining visual inspection with NDT for the preliminary assessment of existing structural components. The identification of column 10 as a potentially vulnerable member emphasizes the importance of early detection and timely engineering interventions. Appropriate repair, strengthening, protection, and monitoring measures can contribute significantly to maintaining structural safety, durability, and long-term integrity.

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