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Structural Evaluation of Constructed Highway Bridges via Field Testing and Finite-Element Analysis: A Review

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Annotation

This review covers assessment, stability management and structural evaluation of strengthened concrete bridge structures, with a focal point on both contemporary practice and future instructions within the discipline. It starts with an overview of purposeful, cloth and structural classes used to contextualize overall performance requirements for highways, railways, pedestrian and utility bridges. The evaluation highlights the use of visual inspection blended with focused non-unfavorable testing methods, such as infrared thermography, ground-penetrating radar, shock echo and ultrasonic pulse pace. It also discusses electrochemical techniques for assessing reinforcement corrosion, such as half-cell potential, electrical resistivity, linear polarization resistance, and electrochemical impedance spectroscopy. Emphasis is placed on how transport-related indicators – such as absorption, voids, resistivity and chloride migration – relate to corrosion risk. In addition, the review provides a summary of current applications of computer vision analytics and UAV (unmanned aerial vehicle) or close-range photogrammetry pipelines. The aim is to extend coverage, increase safety and enable quantitative fault mapping. However, practical limitations such as navigational challenges, light and wind conditions and uniformity in data collection are also taken into account. To reconcile observed responses with analytical assumptions, static and dynamic load testing has been integrated with calibrated finite-element modeling (eg CSIBridge). This approach supports usability verification and boundary condition updating. Finally, a life-cycle framework is proposed to integrate various maintenance, repair and strengthening options – for example, ultra-high performance concrete (UHPC).

Keywords: Bridge Assessment, Visual Inspection, Non-Destructive Testing, Load Testing, Finite Element Model.

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INTRODUCTION

A bridge is an engineered structure that provides safe passage over an obstacle while maintaining continuity of movement below; It does this by transferring the load from the transport surface or carrier through the primary elements in a reliable load path to the supports and foundation. From humanity's earliest crossings- fallen logs, ladders, and brush mats—targeted wooden beams emerged as bridging tools and social organization, while rope and fiber technology enabled early suspension footbridges in mountainous areas, which were reused as ancient materials. With the rise of complex societies, masonry and concrete expanded both in scope and durability: Roman engineers perfected stone arches and hydraulic (pozzolan) concrete, built aqueducts and highway bridges whose thrust geometry transformed gravity into compression supported by voussoirs and abutments, many of which are still in use. In East Asia, structural ingenuity spawned distinct lineages, exemplified by the Zhaozhou (Anji) Bridge (c. AD 605–616), an open-span segmental stone arch whose slender profile anticipated modern efficiency. In the twentieth century, concrete again transformed bridge design: reinforced concrete brought mass, freedom of form and economy to short- and medium-span slabs and girders, and pioneers such as Robert Maillart demonstrated the expressive strength of thin concrete in the Salginatobel Bridge (1930), where three-hinged deck arches with hollow sections. Married efficiency and beauty. Post-tensioning – prestressed and post-tensioned tendons with sound anchoring and grouting – enables record stresses with controlled cracking and deflection, slender box girders, segmental construction and reliable serviceability. By the end of the twentieth and beginning of the twenty-first century, advances in cable technology [1][2][3][4].

As the years pass on the evolution of bridge
Fig (1) Anji Bridge [5].

Bridges are essential elements of transport infrastructure that provide a continuous route across obstacles – such as waterways, valleys, highways or railways – while maintaining passage underneath. Their configuration and scale are governed by site conditions (including hydraulics and alignment), construction constraints and anticipated traffic needs. Structurally, a bridge consists of a superstructure (bearings, girders or beams, deck, joints, cover layers, barriers, drainage) and a substructure (foundations, piers and pier caps). Modern practice uses reinforced and prestressed concrete and steel to achieve strength, serviceability and durability under dead, live and environmental actions - often with post-tensioning; Where geometric constraints are required, horizontally curved layouts and overhangs are adopted, with torsional and dynamic effects addressed through finite element analysis and load modelling. [6][7].

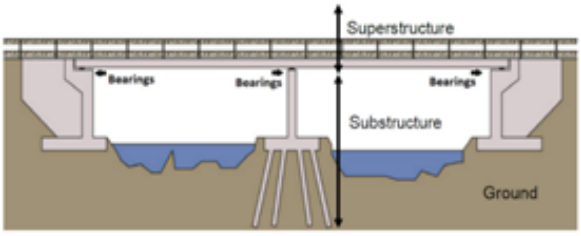


Fig (2) The main bridge components [8].

Bridges are integrated structural systems whose performance depends on the proper interaction of individual elements that establish and protect the global load path. The tire provides immediate contact with the road surface and traffic; It distributes the wheel load transversely and longitudinally to the primary sections, while protecting the reinforcement and facilitating drainage through slopes, spits and joints. Beams or girders (steel, reinforced or prestressed concrete; often function in conjunction with the deck) are the main flexible elements, carrying deck-induced bending and shear at the support; Stringers/floor joists (where present) divide the span and help share the load between the longitudinal members. Diaphragms/cross-frames stabilize the superstructure laterally, control distortion and improve distribution under eccentric and dynamic loading. Bearings transfer vertical and horizontal reactions from the superstructure to the supports while allowing necessary rotation and, where designed, controlling translation due to temperature, creep/shrinkage, braking, wind or seismic actions; Correct function prevents unexpected locking forces and misalignment. Movement clearance and ride quality are preserved while trying to limit water and debris infiltration into the expansion joints. Piers (columns or walls) and their pier caps/crossheads form the main vertical supports in spaces: the caps spread superstructure reactions to one or more columns and set the bearing geometry, while the columns provide axial and lateral demands to the foundation system. Anchorages tie the ends of the superstructure, retain the approach embankment (with rear walls and wing walls), and accommodate movements at the interface with the road, often along the approaches. [9][10][11][12][13].

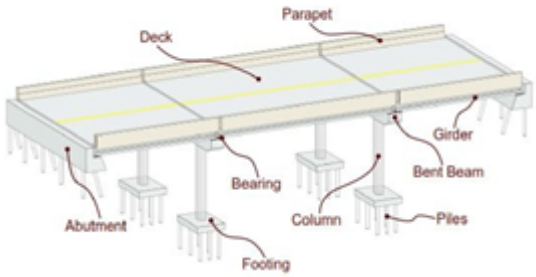


Fig (3) Main bridge elements [14][15].

TYPES OF BRIDGES

Bridges classified by function are defined by the service they provide and the performance requirements imposed by the service. A motorway bridge conveys mixed road traffic – cars, buses and heavy goods vehicles – and is therefore shaped by the road geometry (lane widths, shoulders, sight distances and clearances) and codified vehicle load models; Its primary function is to efficiently distribute constant, often heavy wheel loads through the tire beam system, while accommodating thermal and time-dependent movements through joints and bearings, all with details that preserve ride quality, drainage and longevity. A railway bridge carries trains and is controlled by concentrated axle loads, closely spaced wheelsets and very high cumulative fatigue demands; Its function is to provide a track support track with high longitudinal and torsional stiffness and strict limits of serviceability (deflection, torsion, acceleration) that protect track geometry and vehicle stability, while handling traction/braking forces and rail structure interactions for ballast systems or direct fixing systems. A pedestrian bridge serves pedestrian (and often bicycle) traffic and is generally light and thin; Its function emphasizes user comfort and safety, which is achieved by keeping natural frequencies away from footfall stimulation, providing adequate built-in or supplemental damping, ensuring aerodynamic stability, and meeting accessibility and safety regulations (barriers, lighting, anti-slip) for public use. A pipeline (utility bridge) supports pipelines and cables over obstacles as a free-standing crossing or as an attachment to another bridge; Its function is to carry the dead weight of loaded lines and operational actions – internal pressure, thermal expansion/contraction, vibration/water hammer. [16][17][18].

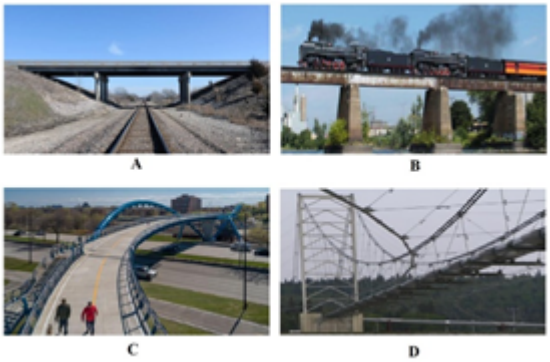


Fig (4) Types of bridged according to function : (A). Highway (B). Railway (C). Pedestrians (D).Pipeway [19].

Bridges can also be classified by construction material: wooden bridges – glued laminated (glulam) and, in some contexts, increasing use of engineered products such as cross-laminated timber – valued for low dead weight, speed of construction and stability; With proper conservation treatment, drainage and ventilation details and replaceable worn surfaces, they perform well in the short to medium term for rural highways and pedestrian crossings, although designers must deal with moisture, decay, fire resistance and long-term stiffness/creep. Reinforced concrete bridges (cast-in-place or precast) use the compressive strength of concrete and steel reinforcement for tension, when decking, waterproofing and crack control are appropriate, and provide strong decks and girders with good mass for vibration control and durability; They are suitable for short and medium term use and can withstand complex geometries, but require attention to cracks, chloride ingress and joint/waterproofing details during their life cycle. Prestressed concrete bridges (including prestressed and post-stressed, segmental and box girders) deliberately introduce compressive stresses to control tensile cracking and deflection, enabling thinner sections and longer spans with efficient material use; Their performance depends on tendon layout, anchorage and channel integrity, joint quality and handling of time-dependent effects (creep, shrinkage, relaxation, prestress loss), making QA/QC central to durability. Steel bridges (rolled or built-up plate girders, trusses, orthotropic decks) offer high strength-to-weight ratios, rapid shop construction and field construction, and excellent flexibility—advantages for long span, staged construction, and rapid bridge construction—while demanding [10][12][20][21].

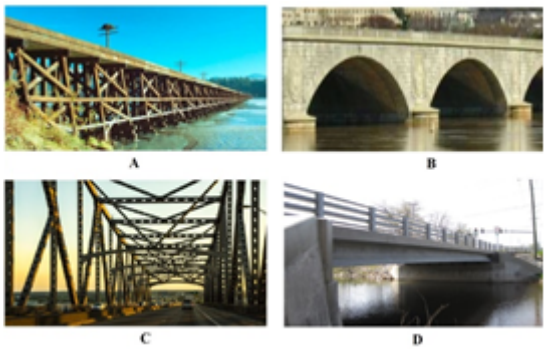


Fig (5) Types of bridged according to material of construction: (A). Timber (B). Masonry (C). Steel (D).Concrete [19].

Bridges can be classified based on their structural system, i.e. how the primary load path carries traffic movements from the deck to the abutments. Plate bridges rest on a plate-like deck—usually reinforced or prestressed concrete—which distributes the wheel load on one or both sides directly to the girders or supports; They are shallow, economical in the short to medium term, and controlled by serviceability (crack control, deflection, waterproofing). Arch bridges carry loads primarily in compression with curved ribs; The resulting horizontal thrust is resisted by a strong stop or tie (tied arch). Arches are suitable for sites with competent foundations, offer excellent

stiffness and durability when dry, and require careful control of thrust line and secondary bending effects. Truss bridges primarily use a triangular structure of slender members acting in axial tension or compression; Floor joists and stringers collect deck loads in trusses, providing material-efficient medium to long spans with modular, shop-friendly construction, but require careful fatigue-resistant details and corrosion protection at the connections. Stay bridges support the deck directly with stay cables attached to the pylons (fan/harp layout); The deck-pylon-strut ensemble forms a rigid continuous system suitable for long-span and staged (balanced-cantilever) construction, with design attention to fatigue/corrosion, anchorage details, aerodynamic behavior and axial bending interactions in the deck and pylons. Suspension bridges wrap the main cables over the towers and anchor them at the ends; Hangers support a braced deck (truss or orthotropic box), which enables the longest span by keeping most of the material in effective tension. Their design depends on cable size and anchorage, tower and saddle details [12] [16] [22].

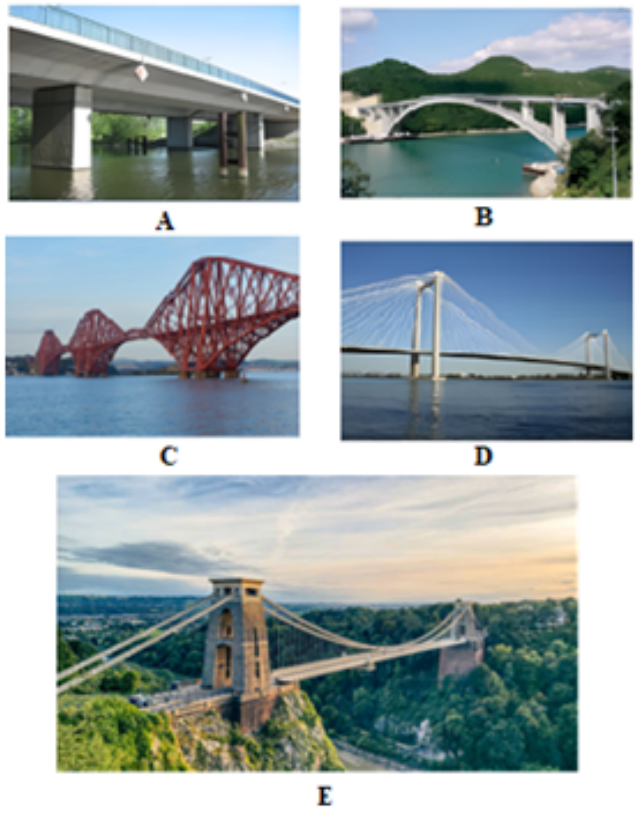


Fig (6) Types of bridged according to their structural system: (A). slab bridge, (B). arch bridge, (C). truss bridge, (D). cable-stayed bridge, (E). suspension bridge [23].

Finally, bridge superstructures are often classified based on how they are supported and sustained at the abutments, as this controls bending moment patterns, deflections, details and maintenance. In simply supported spans, the deck/beams rest on bearings at each end and behave as an isostatic beam; Under a uniform load w, the ideal elastic maximum mid-span moment with zero end moments ($wL^2/8$) – is easier to analyze and set up, but the deflection and steel/concrete requirements are greater than for continuous systems, and expansion joints are required at each support. A series of single-supported spans recreates the isostatic behavior of multi-span viaducts: the construction is simple and tolerant of differential settlements, but the high number of joints and bearings drives long-term maintenance (leaks, chloride ingress, deck deterioration). A continuous multi-span superstructure eliminates joints between pillars and transfers continuity to the supports; Positive mid-span moments are reduced and negative moments are developed at the pillars (requires top reinforcement/compression flanges), which leads to better material efficiency, less deflection and better ride quality, but analysis, detailing and construction layout are more involved and the system is sensitive to time-dependent effects (creep/shrinkage in concrete),

temperature gradients and pier settlements. A Gerber system (cantilever) uses internal hinges at calculated points of zero moment, so that each main span behaves as a cantilever from the piers with a single supported drop-in between the cantilever tips; This preserves some continuity benefits by keeping the structure statically fixed – reducing sensitivity to support settlement and simplifying analysis – at the expense of hinge details, inspection [10][24].

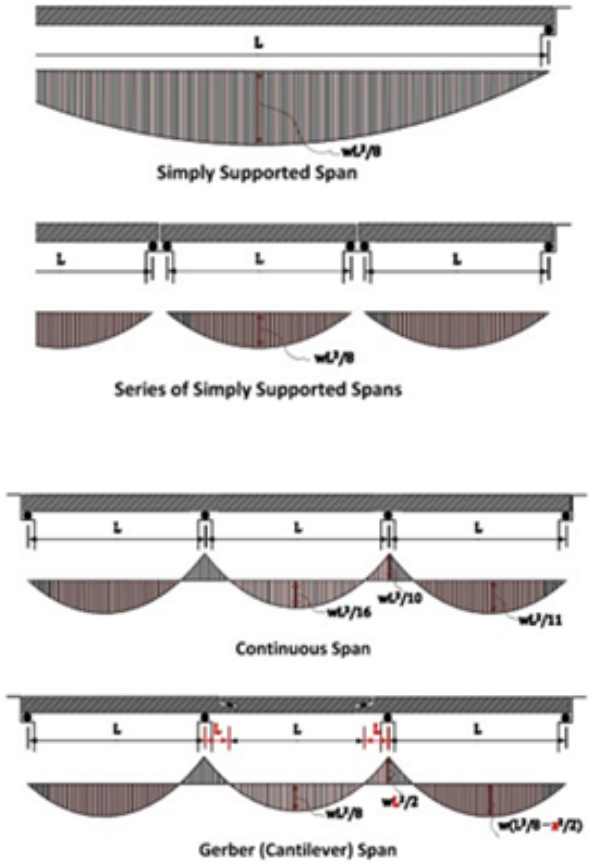


Fig (7) Types of bridged according to type of support.

BRIDGES DAMAGE INSPECTION

Bridge damage inspection is essential for identifying and tracking defects that affect the safety and functionality of bridges, especially bridges made of reinforced concrete. Various non-destructive testing methods, such as rebound hammer (Schmidt), ultrasonic pulse velocity, infrared thermography, ground-penetrating radar, impact echo testing, half-cell potential and electrical resistivity, are used in conjunction with routine visual inspection. In addition, unmanned aerial vehicles (UAV) and computer vision technology are used for advanced assessment. By integrating these findings into bridge management systems, it is possible to continuously evaluate, target maintenance and make informed decisions throughout the life cycle of a bridge.

Damage inspection and static load testing of Jiamusi PC Bridge was conducted by Nasir and Wang (2011). The overall condition of the bridge was found to be satisfactory; However, severely damaged expansion joints as well as diagonal and longitudinal web cracks were observed in Blocks 8 and 9. There was no evidence of carbonation or corrosion of the rebar. Load test results showed that deflections, stresses and strains were below theoretical values. Furthermore, no cracks occurred under the test load, which indicates that the bridge is in stable operating condition and has sufficient capacity [25].

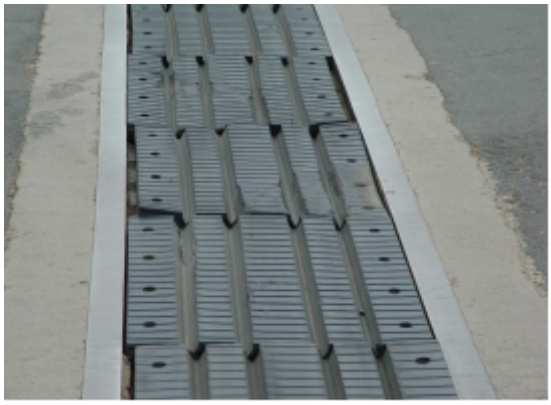


Figure (7) Damage of expansion joints [25].

VISUAL INSPECTION PRACTICE FOR REINFORCED-CONCRETE (RC) BRIDGES

Visual inspection (VI) remains the primary method for evaluating the condition of reinforced concrete (RC) bridges. However, it faces several challenges, including subjectivity, inconsistent rating systems, and accessibility limitations. Since 2006, the literature has gradually addressed these issues by introducing explicit error classification, quantitative decision-making frameworks, and technological developments such as unmanned aerial vehicles (UAVs), computer vision, and robotics. The following reviews will focus on these developments and explore how VI integrates with complementary non-destructive testing (NDT) and structural health monitoring (SHM) technologies as well as bridge management systems (BMS).

According to Omar and Moselhi (2022), the most effective way to deal with common reinforced concrete (RC) deck problems, such as cracking, delamination, spalling and corrosion, is to combine vibration inspection (VI) with targeted non-destructive testing (NDT). These techniques include ground-penetrating radar (GPR), infrared thermography (IRT), half-cell potential, resistivity testing, shock echo and surface waves. To effectively prioritize maintenance actions based on inspection findings, they recommend using risk-based monitoring in conjunction with data products that use mapping techniques [26].

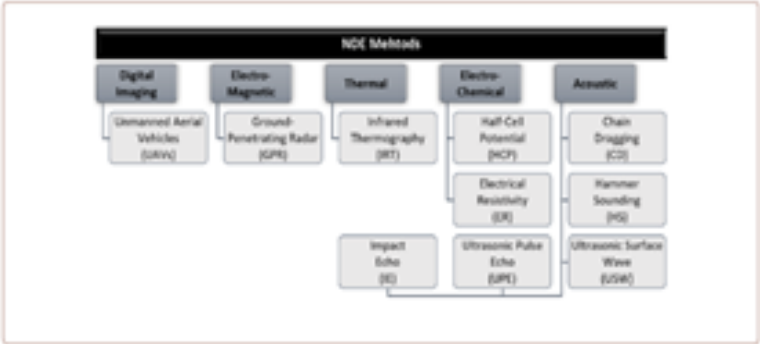


Figure (9) Common NDT Methods [26].

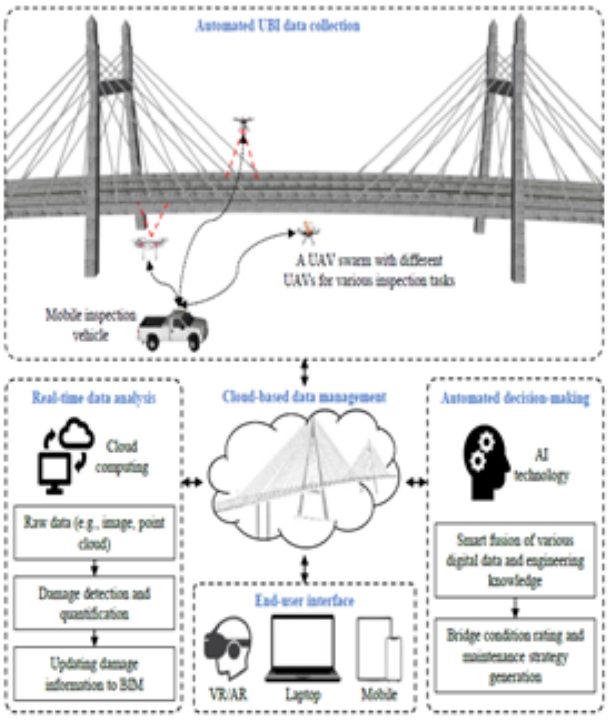
UAV/DRONE & CLOSE-RANGE PHOTOGRAMMETRY FOR RC BRIDGE INSPECTION

For the assessment of reinforced concrete (RC) bridges, unmanned aerial vehicles (UAVs), commonly known as drones, together with close-range photogrammetry (CRP) techniques – often using structure-from-motion – have become increasingly valuable tools. These technologies not only provide high-resolution images and three-dimensional reconstructions, but also facilitate data pipelines for computer vision and AI-assisted damage detection. In addition, they increase safety and coverage during inspections.

They compile case studies, flight planning guidance, payload options and regulatory considerations to operationalize drone inspections within the Department of Transportation (DOT) workflow. Gillins et al. (2018) report that agencies can integrate small unmanned aerial systems (UAS) into routine bridge inspections to increase safety, access hard-to-reach areas, and reduce traffic disruptions. In addition, their paper includes a list of restrictions, such as location without GPS service, lighting conditions, and wind limitations, as well as practical mitigations based on field deployment [27].

Figure (10) Components of an Unmanned Aircraft System [27].

According to Zhang et al. (2022), end-to-end automation for unmanned aerial vehicle-based inspection (UBI) remains limited. The authors evaluate different "automation levels" across a range of processes, including data capture, localization, 3D reconstruction, defect detection and decision support, based on 115 publications from 2007 to 2021. In their assessment, they not only identify barriers – such as challenges with GPS-denied navigation and the need to track objective fault analysis that is fully targeted – programs [28].



Figure(11) A vision for fully automated UBI [28]

COMPUTER VISION & DEEP LEARNING FOR SURFACE DAMAGE ON RC BRIDGES

To identify and measure surface defects, such as cracks, breaks, swellings and corrosion spots, on reinforced concrete bridges, we use computer vision (CV) and deep learning (DL) technologies. These tools enhance human visual inspection by converting images captured by unmanned aerial vehicles (UAVs) or close-range photogrammetry into coherent and quantitative position data..

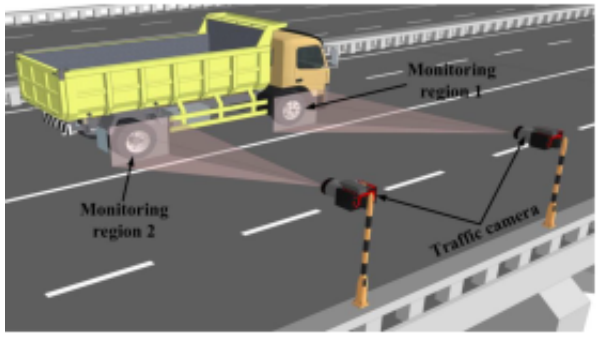


Figure (12) Vehicle weight identification using CV techniques [29].

NON-DESTRUCTIVE TESTING FOR CONCRETE BRIDGE DECKS

Non-destructive testing (NDT) allows inspectors to examine reinforced concrete bridge decks without physical contact. Typically, officials screen large areas using infrared thermography (IRT) and ground-penetrating radar (GPR). They then verify any suspicious areas using techniques such as impact echo (IE), limited core sampling or chain pulling.

The report is titled "Ground Penetrating Radar: Technology, Applications and Future Prospects" by Barrett et al. (2025), not only focuses on bridge applications such as rebar and pavement mapping, as well as moisture and degradation pattern analysis, but also provides a comprehensive overview of the basic principles of Ground Penetrating Radar (GPR). It discusses treatment procedures as well as different options for antennas and frequencies. The authors emphasize the importance of calibration and consistent deliverables to ensure that Bridge Deck assessments can be trusted [30].

Figure(12)The Robotics-Assisted Bridge Inspection Tool collects GPR rebar data [31].

ULTRASONIC & ACOUSTIC METHODS FOR RC BRIDGE ELEMENTS

Ultrasonic and acoustic non-destructive testing (NDT) techniques used on reinforced concrete (RC) bridges include ultrasonic pulse velocity (UPV), surface wave methods (SASW/MASW/USW), ultrasound/velocity tomography and acoustic emission (AE). In addition, the widely used Schmidt rebound hammer is also used.

Figure (13) Schmidt Rebound Hammer [32]

According to the research of Ndagi et al., when factors such as web geometry, humidity, temperature and reinforcement effects are controlled, ultrasonic pulse velocity (UPV) is effective in investigating deterioration and estimating the indirect strength of concrete. (2019). They outline sources of error and methods of correction for field applications involving concrete structures. Overall, UPV is a valuable tool for identifying degradation [33].

Figure (14) UPV Testing Instruments [33].

ELECTROCHEMICAL ASSESSMENT OF REBAR CORROSION IN RC BRIDGES

Commonly used and validated electrochemical methods for assessing steel corrosion in reinforced concrete bridges include half-cell potential (HCP), electrical resistivity (ER), linear polarization resistance (LPR) and electrochemical impedance spectroscopy (EIS)..

Corrosion of steel reinforcement in concrete is basically an electrochemical process controlled by the pore solution chemistry and the transport properties of the concrete: newly embedded steel is passivated by the highly alkaline pore solution (pH ≈ 12–13), but when chlorides penetrate deeper, the passivated protective film breaks down and localized anodic steel sites are corroded. and then cracking and spalling of the surrounding concrete due to extensive corrosion products. Because natural corrosion times can be long, laboratory evaluation often uses impressed current testing in chloride solution to accelerate steel corrosion, applying controlled direct current through the concrete electrolyte to reproduce initiation and propagation within days, enabling measurement of mass loss, corrosion rate, and cracking response. In parallel, durability indicators that control ionic transport – water absorption, permeable voids, electrical resistivity and chloride migration/diffusion coefficient – act as practical proxies for corrosion risk: low absorption and a refined pore structure reduce associated pathways for chloride ingress, increase bulk resistance, and maintain the corrosion resistivity, and the chemical interference. Consistent tests confirm that mixtures with refined pore networks exhibit reduced steel mass loss, lower corrosion rates and smaller corrosion-induced crack widths under applied current and 5% NaCl exposure, directly linking transport properties and microstructure to reinforcement safety performance [34][35].

Pagdala et al. (2022) provide a review comparing linear polarization resistance (LPR), electrochemical impedance spectroscopy (EIS), galvanostatic pulse technique and half-cell potential (HCP) under different corrosion conditions. They also discuss "rate influencers" such as humidity, temperature, cladding material and alloy composition, which can introduce biases in measurements of reinforced concrete (RC) structures [36].

CARBONATION AND SERVICE-LIFE OF RC BRIDGES

Carbonation is the process by which carbon dioxide (CO_2) from the surrounding atmosphere slowly enters the pores of concrete. Within these pores, CO_2 interacts with hydrated phases of the cement, causing a decrease in the pH of the pore solution. In reinforced concrete (RC) bridges, this reduction in alkalinity can cause passivation of the embedded steel, which can initiate corrosion. This risk is particularly high for components subject to varying humidity, insufficient capping, insufficient curing or microcracks..

According to Medvedev and Pustovgar (2023), despite the existing presence of carbonation mechanisms in radiation-affected infrastructure, uncertainties in the kinetics and modeling continue to arise. They explore testing and lifetime models in irradiated environments and recommend specific acceleration techniques for nuclear power plants [37].

Chavan and Mishra (2025) imply that even as CO_2 treatment can improve matrix density, excessive carbonation at an early age can adversely have an effect on lengthy-term strength. They emphasize the significance of balanced curing and good enough masking to reduce corrosion in strengthened concrete [38].

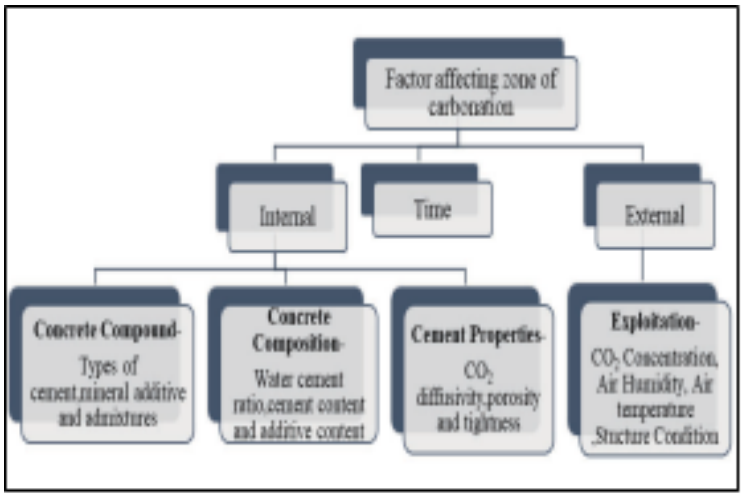


Figure (14) Classification of factors influencing carbonation [39]

STATIC LOAD TESTING

Static load checking out assesses the deflection and stresses of a reinforced concrete bridge the usage of predetermined vehicle placement. Effective techniques define unique load times, load periods and protection or stop thresholds. High-pleasant gadgets, which include both touch and non-touch types, report deflection, pressure and crack reactions. Clear acceptance criteria examine measured outcomes with theoretical answers such as hardness and stress limits, making sure information reliability.

Naser and Wang (2013) demonstrated that a skewed PSC box-girder bridge exhibited significant shear cracks near Pier 2 during a field inspection. Static and dynamic load tests as well as finite element modeling confirmed elevated tensile stresses near the mid-span (approx. 39 m). The primary concern was attributed to the initial tendon design, highlighting the need for reinforcement [40].

Khudair (2025) evaluates a precast prestressed concrete I-girder bridge using field damage inspection and finite element methods including modal, static and time history assessments. The structure is in fair to good condition, with no significant visible cracks and only minor corrosion at the expansion joints, which does not compromise the integrity. The most negative bending moment on Span 2 is approx. -3822 kN•m without deflection and a most upward deflection of approx. Five.31 mm. Under the automobile's stay load, the maximum deflection is approximately -3.Four mm, nicely beneath the running limit of 30 mm. Model analysis suggests an average herbal frequency of approximately 4.98 Hz. In comparison, site visitors-induced vibrations average approximately 3.75 Hz, indicating that the bridge has enough stiffness and minimum threat of resonance. In addition, dynamic acceleration and velocity remain underneath the consolation limits set by using ISO 2631 [41].

DYNAMIC LOAD TESTING

Dynamic load testing evaluates how the bridge reacts to traffic and wind forces. We determine the natural frequencies, mode shapes and damping characteristics through operational modal analysis (OMA). In addition, we estimate the dynamic amplification factor (impact factor) by observing controlled vehicle passes or unrestricted traffic. The results are then compared to models to refine assumptions about stiffness and boundary conditions, which help determine the bridge's serviceability and grades..

They propose a realistic workflow consisting of sensor arrangement, preprocessing, detection and validation to obtain reliable modal parameters from ambient traffic. Zahid et al. (2020) report that the major operational model analysis (OMA) techniques, both in time domain and frequency domain, have different advantages and disadvantages for bridges. [42]

Neser (2021) indicated that increasing superelevation had minimal impact on static properties, as bending moments and deflections showed only minor changes. Specifically, the upward deflection from preload decreased from approximately 12 mm to 11 mm, and the natural frequency remained approximately unchanged at 3.07 Hz. However, dynamic vibrations in the Z direction exceeded the natural frequency, indicating a reduction in stiffness at higher levels of superheight. [43].

MAINTENANCE, REPAIR, AND STRENGTHENING METHODS FOR RC BRIDGE STRUCTURES

Bridges don't fall apart all at once; instead, they slowly fall apart because of things like traffic, weather, and time passing. An all-encompassing engineering program sorts actions into three groups:

1. Maintenance: It is all about keeping the structure in good shape. The main things that need to be done are stopping water and chloride from getting in, making sure that joints and drains work properly, protecting steel parts, and keeping roads in good shape.

2. Repair: This means fixing something that has been broken so that it works again. Some ways to fix things are to seal or inject cracks, replace small areas of concrete, improve drainage systems, renew protective layers, and fix underlying issues like leaks or poor detailing.

3. Strengthening: The goal is to make the bridge stronger or stiffer when the demands on it go up or the resistance goes down. External post-tensioning, fiber-reinforced polymer (FRP) systems, bonded steel plates or substructures, and concrete linings or overlays are all ways to make things stronger. [44].

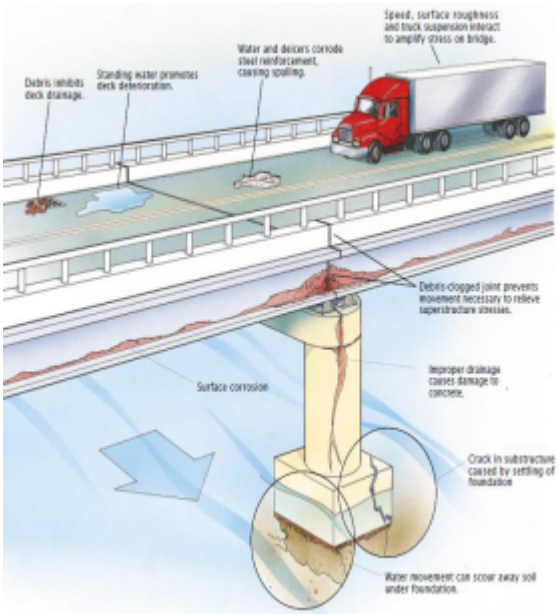


Figure (15): Common bridge deterioration [45]

Naser (2018) emphasized that the vertical arrangement of tendons substantially influences performance. Continuous tendons exhibited reduced service load deflection compared to single-supported configurations. Also, the deflections during the prestressing phase, both up and down, change in a systematic way depending on how the anchors are set up. Nasser came to the conclusion that continuous profiles are good for prestressed concrete bridges. [7].

According to the findings of Haber et al. (2018), ultra-high performance concrete (UHPC) overlays show a strong bond and low permeability, making them suitable for tire rehabilitation in cases where crack sealing alone is insufficient for protection. The performance at the interface is significantly affected by the quality of the surface treatment [45].

Neser and Wang (2010) evaluated the growth of the Jiamusi Bridge deck through external post-tensioning using ANSYS v3.1 and ANSYS v10. The T-cantilever and anchor beam met the vehicle 20/50 requirements; However, pier top box compression, which was approximately 1.91 MPa, indicated the need for deck reinforcement. The design followed the standards set by ASTM A416 for the strings and included specifications for the configuration of the anchor beam, damper and external tendons [46].

Ismail and Ahmed (2022) highlight that thin ultra-high-performance concrete (UHPC) overlays on reinforced concrete (RC) bridge decks can significantly improve both flexural capacity and durability, provided surface preparation and interface cutting are properly handled. Their review systematizes various parameters, including overlay thickness, texture depth, stud presence, and fiber content, while also discussing common failure modes such as interface debonding and flexural failure [47].

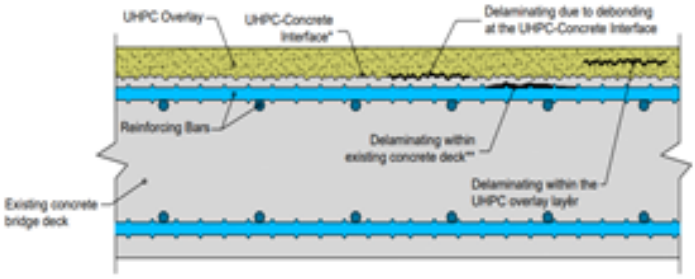


Figure (16): concrete bridge deck with a UHPC overlay [48]

NUMERICAL ANALYSIS USING *CSIBRIDGE*

CSiBridge is a specialized finite element platform designed for bridge modeling. It provides tools for handling load cases, stepwise construction, moving load effect surfaces and design verification. The software allows engineers to create parametric bridge components, including spans, bearings, diaphragms and tendons. In addition, it facilitates static, dynamic and seismic assessments using code-based load combinations.

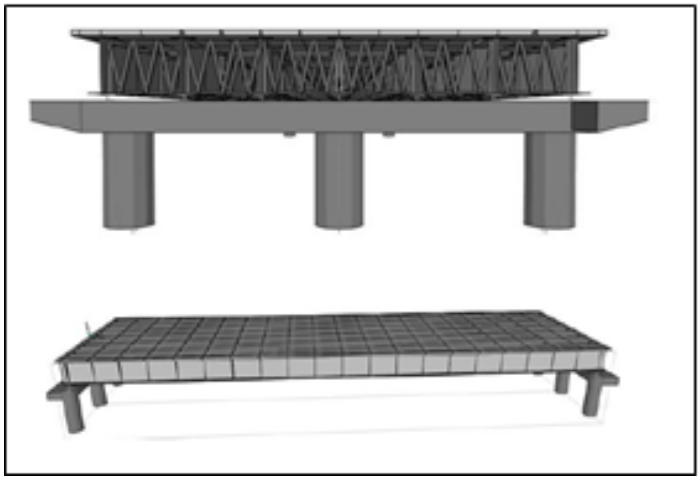


Figure (16): Example of bridge numerical analysis [49].

Mohammed et al. (2024) report on the assessment of a post-tensioned, horizontally curved prestressed concrete (PSC) box-girder bridge located in south Baghdad. The bridge consists of 13 spans, with end spans measuring 35 meters and interior spans measuring 44 meters, and has a deck width of 14 meters with a curve radius of 410 meters. The assessment involved a damage inspection and numerical analysis conducted using CSiBridge v25. The load cases modeled included dead loads, prestress (14 strands of 15.24 mm per tendon), moving HS20-44 trucks, temperature effects, wind, and service load combinations. The finite element model was employed to extract bending moments, tensile and compressive stresses, and deflections for both moving loads and combination cases. Static analysis results indicated that all stresses and deflections were below the limits set by the AASHTO LRFD (2017). For example, the peak fiber tensile stress turned into measured at 2.59 MPa, that is well below the maximum of three.53 MPa. The decrease compression was measured at 7.08 MPa, that's less than the maximum of 22.Five MPa. The stay load mid-span deflection become measured to be -zero.0079 m, which is drastically much less than the most of zero.0.5 m. Finally, the provider connection become measured to be -0.0161 m, that's less than the most of 0.036 m. These effects show that the bridge is difficult enough and might effectively manage cracks. However, the prestressing association near the supports need to be cautiously considered, as that is in which the best tensile stresses arise. Modal extraction revealed that the natural frequency became 2.34 Hz (mode three) and the common frequency of traffic-precipitated vibration turned into 4.70 Hz. This manner that the bridge's curvature and overhang purpose vibrations to continue even even as the weight is shifting. Dynamic displacements range from approximately -three.Eighty five mm (backside) to 1.86 mm (pinnacle) over the whole span, defining the serviceability response envelope of the CSIBridge. The look at determined that the CSiBridge v25 workflow, which covered analyzing the bridge's appearance, static and dynamic modeling and code checking, changed into capable of verify that the bridge turned into structurally sound, whilst also measuring frequency separation and vibration amplitude under practical moving hundreds [50].

Abdullah and Nassar (2025) evaluated a unmarried supported precast PSC I-girder bridge to assess its dynamic overall performance below transferring masses the usage of CSiBridge v24. The authors calculated natural frequencies and as compared them with components precipitated

through traffic congestion. They then mapped span displacements, velocities and accelerations to pick out areas experiencing high vibration demands. This have a look at serves as a clean counterpart to the composite I-girder instance, demonstrating how modeling and realistic shifting load scenarios can enhance serviceability tests. The results spotlight specific enhancements in stiffness and connections in which the loaded reaction approaches consolation limits [51].

Khudair et al. (2025) evaluated metal-girder/concrete composite spans the use of a combination of on-website online visible inspection and a calibrated finite detail version in CSIbridge model 25. The model covered both provider and manage load mixtures, modal sampling and time-records analysis for vehicles in motion. Field examination discovered no considerable defects or corrosion within the metallic, which requires renovation often on the enlargement joints. Static evaluation found out mid-span deflection of approx. 10.9 mm beneath stay load and 91 mm beneath controlling connections, each meet AASHTO LRFD serviceability criteria, indicating that the structure has sufficient stiffness under service situations. Furthermore, dynamic evaluation diagnosed a dominant site visitors-brought about frequency of approximately 6.42 Hz, at the same time as the assigned herbal frequency became approximately 2.Ninety five Hz. This distinction suggests that substantive vibrations can occur over the longest intervals. As a result, the authors advise including a diaphragm and/or an additional beamline to improve stiffness and reduce dynamic amplitude [49].

CONCLUSION

Bridges are interconnected structures, so they require a thorough assessment process to ensure they remain practical. There is evidence that a hybrid technique works quality, wherein systematic visible inspection is blended with correct non-damaging trying out (NDT) and electrochemical tracking to detect factors that purpose deterioration, mainly chloride intrusion and carbonation, which cause corrosion and disintegration of the metal. When used with established data standards and calibrated outputs, technologies such as UAVs, photogrammetry and computer vision can make inspections much easier and more environmentally friendly. Static and dynamic load testing should also be used to check and improve finite element models of how structures respond. This process makes it easy to find out how stiff something is, what the boundary conditions are, and what factors affect it. This makes it easier to rely on usability assessment and retrofit design. The choice of durability should be based on how well the material can transport (such as resistivity and chloride migration) and supported by corrosion indices (such as half-cell potential (HCP), linear polarization resistance (LPR) and electrochemical impedance spectroscopy (EIS)). Some interventions that may be required are drainage and joint rehabilitation, an ultra-high-performance concrete (UHPC) coating, cathodic protection and external post-tensioning. Quality assurance factors such as curing, waterproofing standards, tendon integrity and interface preparation are very important for consistent performance. Some of the key research needs are: (i) standardized, context-specific limits that link NDT/electrochemical results to real-world maintenance standards; (ii) Autonomous flight and observation protocols.

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