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THEORETICAL FOUNDATIONS OF DIAGNOSTICS AND ASSESSMENT OF EXISTING REINFORCED CONCRETE BRIDGES

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ABSTRACT

The paper presents the theoretical basis for diagnostics and technical condition assessment of reinforced concrete bridges in service. The main groups of defects and damage are classified and their influence on load-carrying capacity is discussed. The review covers non-destructive testing methods, including ultrasonic, vibration-based and radiographic techniques, as well as static and dynamic load testing. Mathematical models for residual life prediction and reliability assessment are summarized, and an algorithmic workflow for bridge diagnostics is proposed. An example of practical application to a 24 m span bridge demonstrates the use of measured concrete strength, crack width, reinforcement loss and deflection data for assigning a condition category and repair decision. The study substantiates the need for an integrated, system-based approach to the evaluation of reinforced concrete bridge structures.

KEYWORDS

Reinforced concrete bridge, diagnostics, technical condition, non-destructive testing, load-carrying capacity, residual life, defects, cracking, reinforcement corrosion.

Introduction

Reinforced concrete bridges constitute the core of the bridge stock on the highway network of Uzbekistan. A substantial proportion of these structures was erected in the 1960s–1980s and is currently approaching or exceeding the normative service life of 50–70 years. As traffic intensity increases and axle loads rise, objective assessment of the actual technical condition becomes essential for making justified decisions on repair, strengthening or reconstruction.

Bridge diagnostics has become particularly important because long-term operation leads to accumulation of fatigue effects, concrete deterioration, reinforcement corrosion and changes in structural stiffness. At the same time, budget constraints often make full replacement impossible; therefore, engineering practice requires reliable methods capable of identifying dangerous damage, quantifying residual strength and forecasting the remaining service life.

The purpose of this paper is to systematize the theoretical foundations of diagnostics and assessment of existing reinforced concrete bridges, summarize the main inspection and testing methods, and present a rational framework for evaluating structural capacity and residual life.

2. Main Defects and Damage

During service, reinforced concrete bridges are exposed to variable traffic loads, climatic actions, aggressive media, water ingress and vibration. These factors cause a characteristic set of defects and damage that affect durability and the load-carrying capacity of structural members.

Table 1. Classification of defects in reinforced concrete bridges.

Defect group	Typical defects	Main causes
Concrete damage	Cracks (shrinkage, flexural, temperature); leaching; spalling; delamination of cover	Shrinkage, overloads, thermal effects, freeze–thaw cycles, poor concrete quality
Reinforcement damage	Corrosion of bars; reduction of steel area; loss of bond	Carbonation, chloride attack, electrochemical corrosion, repeated loading
Bearings and joints	Wear, skewing, seizure; joint failure and clogging	Uneven settlements, lack of maintenance, aging of materials, debris ingress
Waterproofing and drainage	Loss of integrity, blocked drains, leakage	Aging, mechanical damage, poor water management

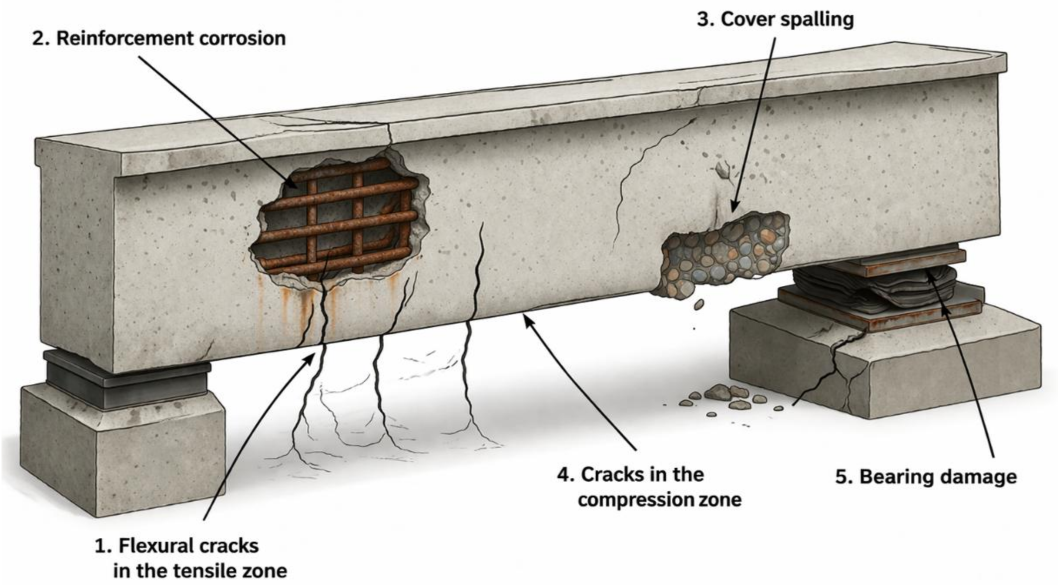

Figure 1. Typical defect locations in a reinforced concrete beam of a bridge superstructure: 1 – flexural cracks in the tensile zone; 2 – corrosion of main reinforcement; 3 – spalling of concrete cover; 4 – cracks in the compression zone; 5 – bearing damage.

The most dangerous defects are flexural cracks in the tensile zone of beams and slabs, corrosion-induced loss of reinforcement area, and damage to bearings that changes the structural scheme of the span.

3. Theoretical Basis of Bridge Diagnostics

3.1. Basic principles

- System approach: the bridge is considered as an interacting system of elements, joints, spans and supports.
- Objectivity: conclusions must rely on measured and calculated parameters rather than only on visual impressions.
- Continuity: the technical condition has to be monitored throughout the entire life cycle of the structure.
- Predictive orientation: diagnostics should support forecasting of condition change over time and planning of maintenance actions.

3.2. Generalized condition model

The technical condition of a reinforced concrete bridge can be represented by a vector of state parameters

$S = \{S_1, S_2, \ldots, S_n\} \quad (1)$

where S_i denotes a measured or calculated parameter characterizing an individual element, such as concrete strength, reinforcement cross-sectional area, crack width, carbonation depth, deflection or natural frequency.

A generalized condition index may be written as

$K\_gen = (\Sigma\, \gamma_i K_i) / (\Sigma\, \gamma_i) \quad (2)$

where K_i is the condition coefficient of the i-th element and γ_i is the weighting factor expressing the importance of this element in overall structural performance.

4. Diagnostic Methods

4.1. Visual and instrumental inspection

Visual inspection is the primary stage of bridge diagnostics and is aimed at identifying visible defects such as cracking, spalling, corrosion stains, excessive deflections and drainage malfunction. Instrumental inspection supplements the visual survey with measurements of geometry, settlements, crack width, cover thickness and alignment.

4.2. Non-destructive testing methods

The ultrasonic method is based on measuring the velocity of longitudinal waves in concrete. The concrete strength is estimated using a calibration relationship

$R = a \cdot v^b \quad (3)$

where R is the concrete compressive strength (MPa), v is the ultrasonic pulse velocity (m/s), and a and b are empirical calibration coefficients.

Table 2. Indicative evaluation of concrete condition based on ultrasonic pulse velocity.

Ultrasonic velocity, m/s	**Concrete strength, MPa**	**Condition rating**
> 4500	> 40	Excellent
4000–4500	30–40	Good
3500–4000	20–30	Satisfactory
3000–3500	10–20	Unsatisfactory
< 3000	< 10	Critical

Radiographic methods are used to estimate density and to detect internal defects such as voids and cavities. The concrete density may be expressed as

$\rho = (1 / \mu d) \cdot \ln(I_0 / I) \quad (4)$

where μ is the linear attenuation coefficient, d is the thickness of the tested zone, and I_0 and I are the incident and transmitted radiation intensities. Magnetic methods are commonly applied to determine the position and diameter of reinforcement and to estimate the extent of steel section loss due to corrosion.

4.3. Static load testing

Static testing remains one of the most reliable methods for evaluating the actual load-carrying capacity of a bridge span. The superstructure is loaded by a calibrated vehicle or a set of concentrated forces, and the measured response is compared with theoretical values.

For a simply supported beam subjected to a concentrated force P at midspan, the theoretical deflection is

$f = P \cdot l^3 / (48 \cdot E \cdot I) \quad (5)$

where P is the applied load, l is the span length, E is the modulus of elasticity of concrete, and I is the moment of inertia of the cross-section. From measured deflections, the effective modulus of elasticity may be back-calculated as

$E\_fact = P \cdot l^3 / (48 \cdot f\_meas \cdot I) \quad (6)$

4.4. Dynamic testing

Dynamic tests provide integral information on stiffness and damage accumulation by identifying the natural frequencies, modal shapes and damping characteristics of the structure. For a beam on two supports, the first natural frequency can be approximately written as

$f_0 = (\pi / 2l^2) \cdot \sqrt{(EI / m)} \quad (7)$

where m is the distributed mass per unit length. A reduction in natural frequency usually indicates a reduction in structural stiffness. The relative stiffness loss can be estimated from

$\Delta EI / EI_0 = 1 - (f\_dam / f_0)^2 \quad (8)$

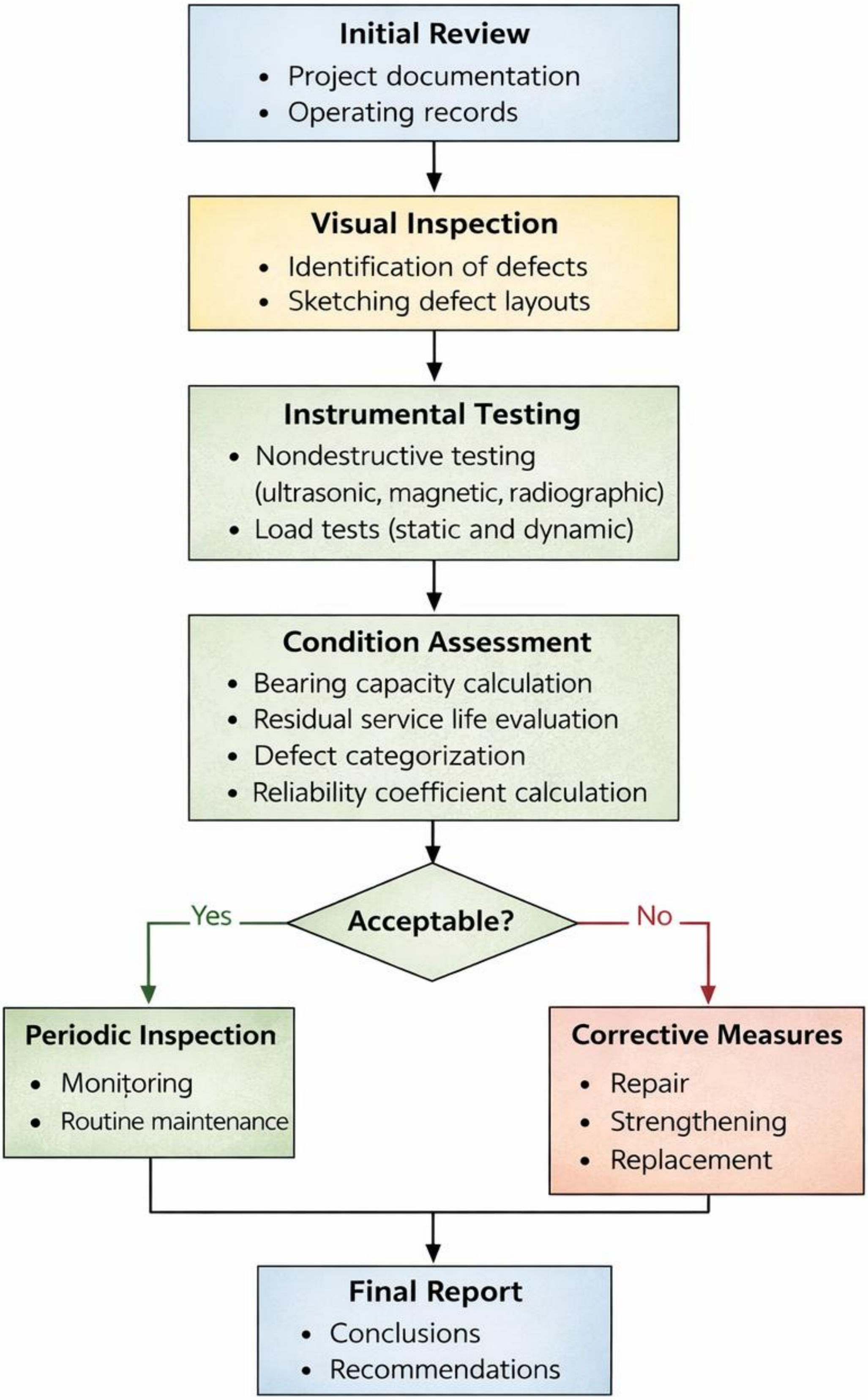

Figure 2. Algorithmic workflow of bridge diagnostic operations.

5. Load-Carrying Capacity and Residual Life Assessment

5.1. Determination of actual load-carrying capacity

The actual flexural resistance of a reinforced concrete member may be evaluated on the basis of measured material properties and the residual reinforcement area:

$$M_{fact} = R_b \cdot b \cdot x \cdot (h_0 - 0.5x) + R_{sc} \cdot A'_s \cdot (h_0 - a') \quad (9)$$

where R_b is the actual concrete compressive strength, b and h_0 are the width and effective depth of the section, x is the height of the compression zone, R_{sc} is the design resistance of the compression reinforcement, and A'_s is the area of compression steel.

The compression-zone height is obtained from equilibrium of internal forces:

$$x = (R_s \cdot A_s - R_{sc} \cdot A'_s) / (R_b \cdot b) \quad (10)$$

If corrosion damage is present, the actual area of tensile reinforcement may be estimated as

$$A_{s,act} = A_{s,des} \cdot (1 - \alpha \cdot t) \quad (11)$$

where α is the corrosion rate (%/year) and t is the duration of corrosion action (years).

5.2. Residual life prediction

Residual life can be estimated from the rate of change of a governing condition parameter. In general form,

$$T_{res} = (\delta_{lim} - \delta_{cur}) / V_\delta \quad (12)$$

where δ_{lim} is the limit value of the selected condition parameter, δ_{cur} is its current value, and V_δ is the rate of deterioration.

For strength-based degradation assessment, an exponential model is often used:

$$T_{res} = (1 / k) \cdot \ln[(R_0 - R_{min}) / (R_{fact} - R_{min})] \quad (13)$$

where R_0 is the initial strength, R_{fact} is the current strength, R_{min} is the minimum acceptable strength, and k is the degradation coefficient.

Table 3. Criteria for technical condition assessment of bridges.

Condition category	Description	Capacity reduction	Recommended action
I – Serviceable	No significant defects detected	0–5%	Routine maintenance
II – Operational	Minor defects and local deterioration	5–15%	Current repair
III – Limited serviceability	Substantial defects with reduced capacity	15–30%	Major repair or strengthening
IV – Unserviceable	Severe defects, emergency condition	> 30%	Reconstruction or replacement

6. Example of Practical Application

As an illustrative case, the paper considers the diagnostic assessment of a reinforced concrete girder bridge across the Syrdarya River, built in 1975 with a 24 m span. Measured parameters were compared with the design values in order to assign a condition category and formulate a strengthening strategy.

Table 4. Results of diagnostics for the bridge case study. *Considering corrosion damage identified by the magnetic method

Parameter	**Design value**	**Measured value**	**Deviation**
Concrete strength, MPa	30 (C25/30)	22.5	−25%
Ultrasonic velocity, m/s	4300	3700	−14%
Deflection under reference load, mm	8.2	12.6	+54%
Crack width, mm	< 0.20	0.35	+75%
Area of bottom reinforcement, cm²	28.3	24.1*	−15%

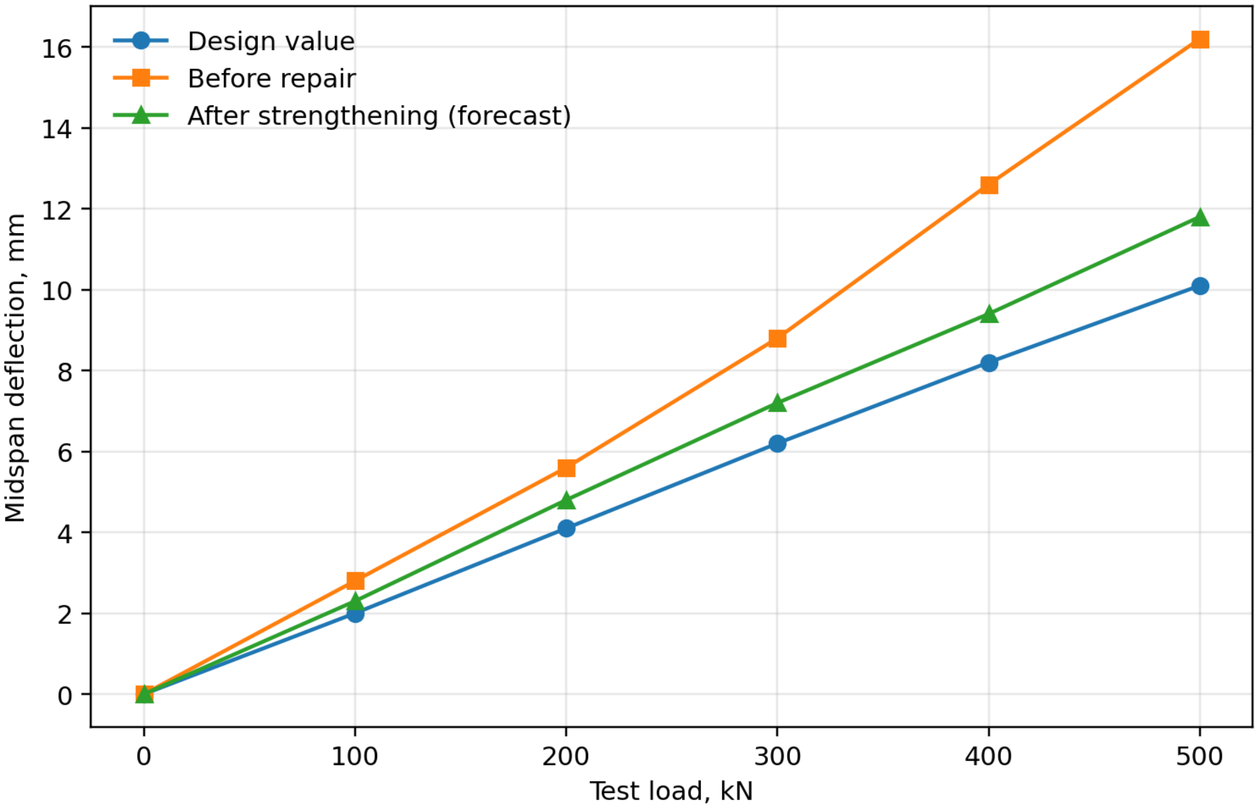

Figure 3. Midspan deflection versus test load: 1 – design value; 2 – measured before repair; 3 – forecast after strengthening

On the basis of the measured values, the bridge was assigned to Category III (limited serviceability). The recommended intervention included strengthening of the main girders by installing supplementary reinforcement and restoring the concrete cover in damaged zones.

7. Practical Recommendations

- Planned detailed inspections should be performed once every six years, while extraordinary inspections are required after floods, earthquakes, vehicle impacts or other extreme events.
- The diagnostic procedure should include the analysis of design and maintenance documentation, visual inspection, instrumental survey, non-destructive testing, and verification calculations; static and dynamic testing should be added when necessary.
- Strengthening should be considered when the reduction in load-carrying capacity exceeds 20%, crack width is greater than 0.30 mm, reinforcement area loss exceeds 10%, or measured deflections exceed code limits by 1.5 times or more.
- Special attention should be paid to bearings, joints, waterproofing and drainage because these elements strongly influence the deterioration rate of the load-bearing members.

8. Conclusions

- Diagnostics of reinforced concrete bridges is a complex scientific and engineering task that requires a system-based approach and the use of modern non-destructive testing methods.
- The governing technical condition parameters include concrete strength, reinforcement cross-sectional area, crack width, measured deflections and natural frequencies.
- Ultrasonic, magnetic and radiographic methods allow reliable assessment of material condition without damaging the structure.
- Mathematical models linking state parameters with residual life make it possible to forecast deterioration and justify maintenance or strengthening schedules.
- The proposed diagnostic algorithm improves the consistency of field surveys and increases the reliability of technical condition assessments.
- Future research should focus on automated bridge health monitoring and on probabilistic residual-life models calibrated to actual operating conditions.

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