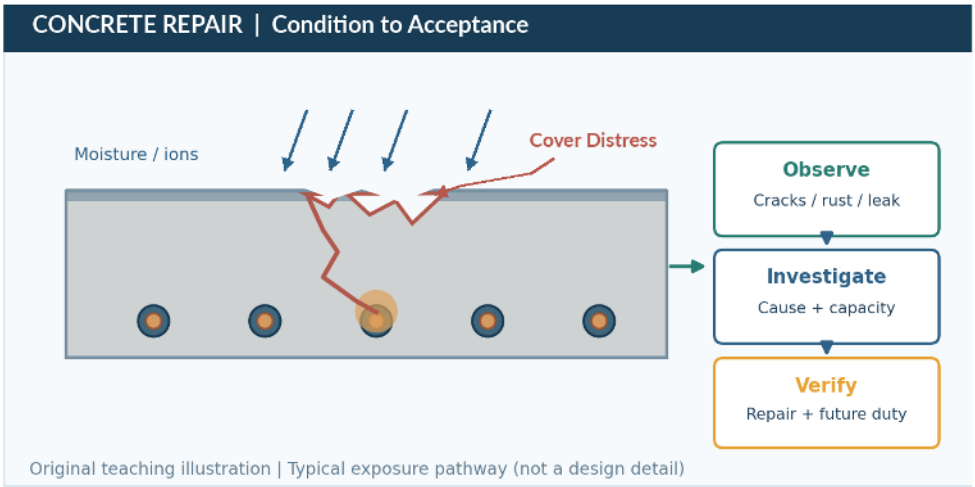
BUILDERCE | STRUCTURAL CONCRETE | 4 PDH

Concrete Structures: Deterioration, Repair Methods & Construction Quality

From observed distress to defensible repair and verified field performance



4 Professional Development Hours | 240-minute learning plan | Self-paced correspondence study

Assess evidence before choosing a repair. This course follows reinforced-concrete deterioration from observed distress through investigation, compatible intervention, field control and verifiable closeout. The drawings and quantitative examples are instructional and do not authorize an actual structural assessment or repair design.

Four applied modules	20 original instructional figures
Four case-based decision workshops	Separate post-test administered outside the learner manual

How to Study This Course

Coursework consists of an engineering reading and diagram sequence, four applied workshops and a decision record for each module. Work the cases before reading the accompanying interpretation, and verify each conclusion against the relevant technical sources and actual project constraints. The learning schedule totals 240 planned minutes; no seat-time or inactivity timer is imposed.

Learning block	Focus	Planned activity
Module 1	Assessment and evidence	35 min reading + 15 min case + 10 min decision record
Module 2	Deterioration mechanisms	35 min reading + 15 min case + 10 min interpretation
Module 3	Repair selection and value	30 min reading + 20 min case + 10 min comparison
Module 4	Field quality and closeout	35 min reading + 15 min case + 10 min record

Learning Objectives

- Classify concrete distress without assigning a cause from appearance alone.
- Select condition-investigation methods that answer defined engineering questions and recognize their limits.
- Differentiate mechanisms involving reinforcement corrosion, cracking, moisture, chemical attack and physical damage.
- Identify repair scope, substrate preparation, material compatibility and temporary-stability requirements.
- Prepare project-specific inspection, testing, acceptance and documentation controls.
- Compare repair strategies using service-life, interruption and recurrence risk rather than initial material cost alone.

PE

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CONCRETE / STRUCTURES / REPAIR / QUALITY

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Contents

How to study this course 2

Contents 3

MODULE 1 | Assessment first: safety, records and a defensible evidence base 4

MODULE 2 | Mechanisms: corrosion, cracking and durability 10

MODULE 3 | Repair selection, construction sequence and long-term value 16

MODULE 4 | Execution quality, acceptance, records and monitoring 22

Applied engineering record templates 28

Engineering glossary 30

Sources and edition control 31

MODULE 1 | Assessment First: Safety, Records and a Defensible Evidence Base

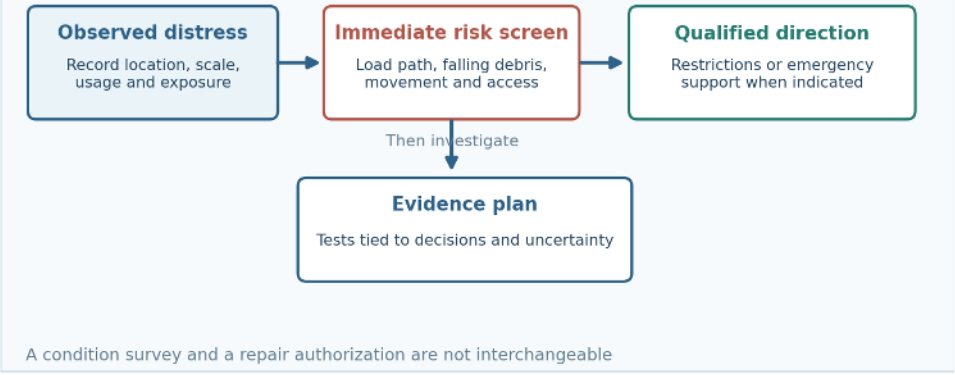
Learning allocation: 60 minutes: 35 guided reading / diagrams + 15 applied assessment + 10 decision recording

1.1 Establish the Governing Question Before Touching the Structure

A reinforced-concrete member can exhibit widespread visible damage and still retain substantial capacity, or it can appear nearly intact while hidden deterioration compromises its intended load path. The first engineering question is not, “Which repair material is fastest?” It is, “What performance and safety question must this assessment answer?” That answer determines whether the work is a preliminary visual screening, an immediate structural-safety evaluation, a durability investigation, a formal code-based assessment or a repair-design assignment. Define the asset, the affected members, current occupancy, exposure conditions, known modifications and the authority for making engineering decisions. An owner may ask for a patch estimate; an engineer may need to recommend a capacity review and temporary restrictions before anyone can safely establish a patch limit.

ACI CODE-562-25 provides a modern framework for existing structural-concrete assessment and rehabilitation; it does not automatically replace the edition adopted by a jurisdiction or the applicable existing-building code. An engineer establishes the legally governing design basis, the owner's required performance, and the documents controlling new work. ACI 318-25 addresses concrete design requirements but should not be assumed to govern an older building merely because it is the newest publication. Establish an edition-control record noting the adopted regulation, evaluated existing condition, selected repair provisions, and any decisions reserved for the licensed design professional. [S1, S2, S11]

FIGURE 1 | Assessment starts with a decision boundary



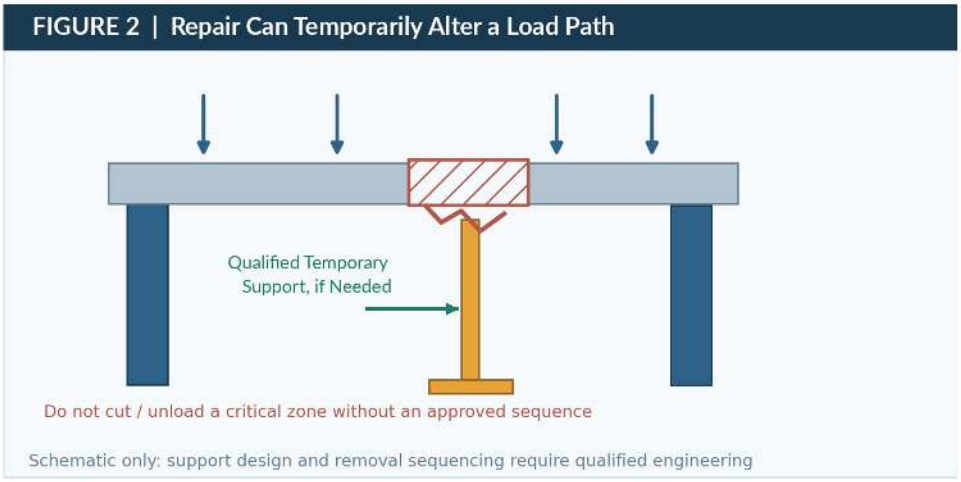
Triage. *Assessment question → decision boundary, then evidence planning.*

1.2 Read the Load Path and Manage the Immediate Boundary

Distress located at a column-to-slab interface, a transfer beam, a corbel or a heavily loaded support can have very different implications from similar-looking distress on a nonstructural curb. Trace the known gravity and lateral load paths through the damaged region. Identify prestressing or post-tensioning, anchorage zones, shear-critical locations, continuity, and any load redistribution that the structure might rely upon. Do not assume a slab or beam is safe merely because it has carried service loads for years. The assessment should identify whether occupancy limitations, cordoning, monitoring or a qualified temporary-support design is necessary pending investigation.

Removal work itself can change capacity. Breaking out concrete around a reinforcing cage, sawcutting near a tendon, or disturbing an anchorage can eliminate restraint or transfer forces unexpectedly. Temporary works belong in the engineering scope when the repair sequence affects stability. A sound plan documents who designs shoring, what support conditions are allowed, the permitted sequence, and how the structure will be checked before loading is restored. ACI CODE-562-25 addresses temporary shoring and bracing; it is a reason to plan that work, not a generic permission for any unreviewed shoring arrangement. [S1]

FIGURE 2 | Repair Can Temporarily Alter a Load Path



Load Path. Conceptual beam with temporary support. No generic shoring design is implied.

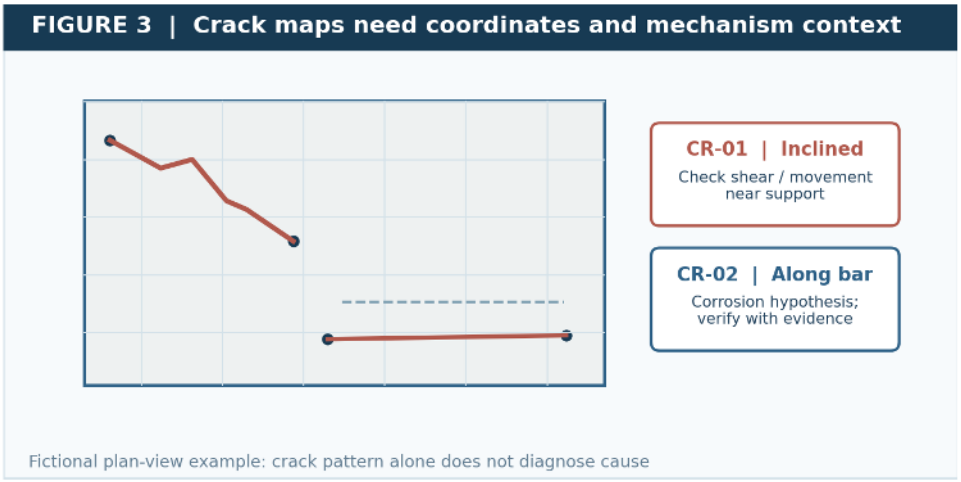
1.3 Describe Cracks Before Assigning Mechanisms

Record crack position, orientation, length, width and relationship to reinforcement, joints, supports and moisture. A flexural crack near a tension face, an inclined crack near a support, a crack parallel to a reinforcing bar, and a restrained-shrinkage crack may all appear as lines in a photograph but require different questions. The line pattern is evidence, not a diagnosis. A longitudinal crack following reinforcement with rust staining raises a corrosion hypothesis; a diagonal crack with changing width and visible distortion may raise a structural-response question. Neither appearance alone measures strength or identifies the causal chain.

Use dated photographs with a scale and location reference rather than undocumented “typical damage” images. Draw a plan, elevation or grid that identifies each observation. If there is a credible movement mechanism,

define the measurement direction and repeat interval before installing crack gauges. Movement measurements made without a baseline or temperature history can lead to false claims of stability or progression. Crack mapping becomes valuable when it is linked to a decision: whether to investigate, restrict use, inject, seal, monitor or redesign. [S3, S7]

FIGURE 3 | Crack maps need coordinates and mechanism context



Crackmap. *Fictional crack map with different competing interpretations.*

1.4 Build an Investigation Record That Other Engineers Can Reproduce

Start with original drawings, approved changes, prior repair records, maintenance events, leaks, coating history, exposure and any relevant load changes. A prior repair may hide the original extent of damage and introduce different material properties; a stain can have migrated from an upper surface; efflorescence can appear remote from the source of water. A dated record helps distinguish cause from coincidence. For each observation, preserve the grid reference, element description, date, method, reliability of access, photographs and immediate safety action. Use neutral terminology such as “hollow response at the marked grid,” rather than “failed concrete,” unless that conclusion is substantiated.

A useful condition map separates three layers: observation, interpretation and action. The observation layer contains measured cracking, sounding response, exposed steel, leakage and deflection. The interpretation layer contains ranked hypotheses with confidence qualifiers. The action layer states the next targeted test, the person authorized to decide, and the stop-work boundary. The separation prevents a contractor from interpreting a preliminary investigation sketch as an approved removal boundary or repair design. An engineer should be able to identify which records were observed in place and which facts were supplied secondhand. [S1, S3]

1.5 Choose Nondestructive Tests for the Question They Can Answer

Hammer sounding or chain drag can screen for subsurface discontinuities but is affected by member thickness, surface treatment and access. A cover meter can help locate reinforcing steel, while ground-penetrating radar can assist with cover, embedded features and anomalies under favorable conditions. Infrared thermography may reveal temperature contrasts associated with hidden defects when environmental conditions allow. Ultrasonic pulse velocity assesses wave-transit characteristics, not compressive strength without project-specific calibration. Half-cell potentials characterize electrochemical conditions that may be associated with corrosion activity; they are not direct measurements of steel loss or structural capacity. [S7, S12]

Each method has limitations that should appear in the report beside the finding. Was the concrete saturated? Was the surface coated? Was the test geometry appropriate? Did metal interference distort the instrument? Can an apparently continuous radar reflection distinguish a duct from closely spaced reinforcement? Specify why the selected method matters, establish a reference region, and pair screening methods with selective opening or laboratory tests where needed. A dense array of instrument readings is not automatically a stronger assessment than a smaller set that tests the right hypothesis. [S7]

FIGURE 4 | Choose tests by question, not by convenience

METHOD	QUESTIONS ANSWERED	KEY LIMIT
Sounding	Map possible delamination	Affected by access / section
Cover meter / GPR	Locate embedded features	Interpretation / calibration
Half-cell	Corrosion-likelihood patterns	Not direct steel loss
Core / petrography	Sample concrete condition	Local and invasive

Screening evidence is not a direct strength or capacity measurement

Methods. *Limits for selected condition-assessment methods.*

1.6 Direct Destructive Testing Rather Than Collecting Samples Indiscriminately

Core sampling can support questions about compressive properties, depth of deterioration, aggregate condition and petrographic features, but the location must be screened for reinforcement, tendons, structural effects and access constraints. Core strength interpretation requires the appropriate standard, condition, geometry and project-specific judgment; one small core does not establish the strength of an entire floor. Chloride sampling may use a depth profile because near-surface concentration and the concentration near steel are different questions. A measured chloride value is evidence of exposure, not proof that every bar has corroded. Carbonation-depth testing can identify a changed alkalinity front on newly fractured concrete, but local moisture, coatings and sampling technique affect interpretation.

Document the question, sample number, location, depth, storage and laboratory method before drilling. Record what the sample did not represent, such as a cracked hot spot versus an apparently sound reference zone. Where analysis hinges on material strength, selective investigation should be planned by a qualified engineer and interpreted using the governing code and defensible statistics. Avoid the misleading step of entering one laboratory number into a repair specification as if it described every member. ASTM standards such as C42/C42M provide established sampling approaches when their applicable editions and conditions are observed. [S1, S7, S12]

1.7 A Field Example: Exposed Concrete on a Parking-deck Beam

A three-level coastal parking deck has longitudinal rust staining, several hollow-sounding regions and a 1.8-meter crack along the soffit of a loaded edge beam. The owner requests a cosmetic patch before a holiday weekend. The engineer observes moisture discharge at an expansion joint above and cannot verify the as-built reinforcement. That combination creates at least three separate workstreams: examine the load path and immediate occupancy boundary, investigate corrosion and related defects, and only then develop a repair and drainage plan. A surface patch would obscure the critical evidence while leaving the joint leakage active.

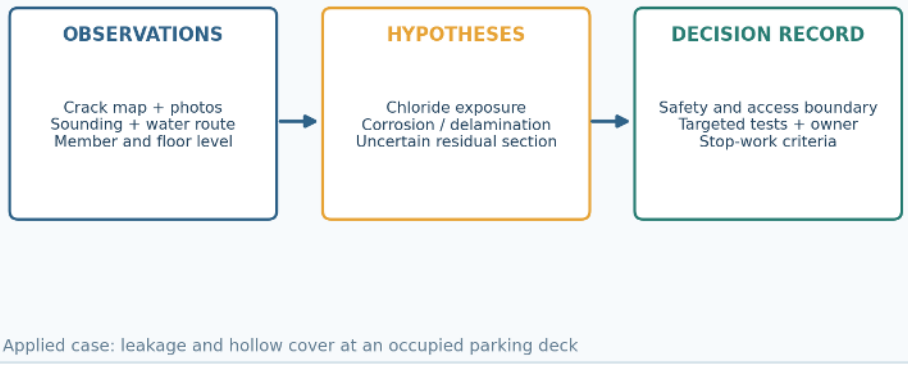
Document a hold point before concrete removal. Request the structural documents, locate and identify reinforcement or prestressing, evaluate load paths and decide on restrictions or temporary works. Mark the observed crack and sounding regions but label them preliminary. After adequate access and authorization, use selected openings, documentation, possible chloride profiling and corrosion evaluation to test the hypothesis. The repair scope should not be set from a single sounding map because hidden interfaces can change once loose material is removed. [S1, S3, S9]

1.8 Applied Workshop: Inspection Triage

Scenario. A 12 m by 4 m garage-bay soffit contains three marked distress zones: Zone A has 0.3 mm hairline transverse cracks without staining, Zone B has a 2.1 m longitudinal crack above a wet stain, and Zone C has an exposed reinforcement area at a supporting beam-column joint. The structure remains occupied. Create a condition log with location, observation, competing hypotheses, immediate actions, and information needed. Then rank the zones for further engineering attention. A justified ranking considers structural consequence and uncertainty, not just visual area. A response that automatically assigns all three to epoxy injection has skipped the assessment.

Suggested reasoning. Zone C deserves prompt structural attention because exposure at a heavily loaded connection may affect anchorage, cover and durability; physical access restrictions or shoring need engineering evaluation. Zone B suggests a leakage/corrosion pathway but requires measurement and evidence before being classified. Zone A may be lower urgency if there is no movement or load-path concern, but the location and history matter. The credible output is a controlled list of decisions and next tests, not an unsupported declaration that the deck is safe. [S1, S7]

FIGURE 5 | Observe, interpret, decide



Applied case: leakage and hollow cover at an occupied parking deck

Evidence. *Applied triage: separate observed conditions from hypotheses and actions.*

Module 1 | Example Decision Record

Classification	Illustrative record	Required next action
Observed	Spalls and hollow cover below leaking joint; column vicinity; condition map pending.	Record locations with scale; establish access boundary.
Uncertain	Load effect, embedded steel loss, cause and active moisture route unverified.	Assign engineer-owned assessment and targeted sampling.
Not authorized	Cosmetic patch quantity is not an approved repair limit or structural release.	Retain restrictions until documented engineering direction.

MODULE 2 | Mechanisms: Corrosion, Cracking and Durability

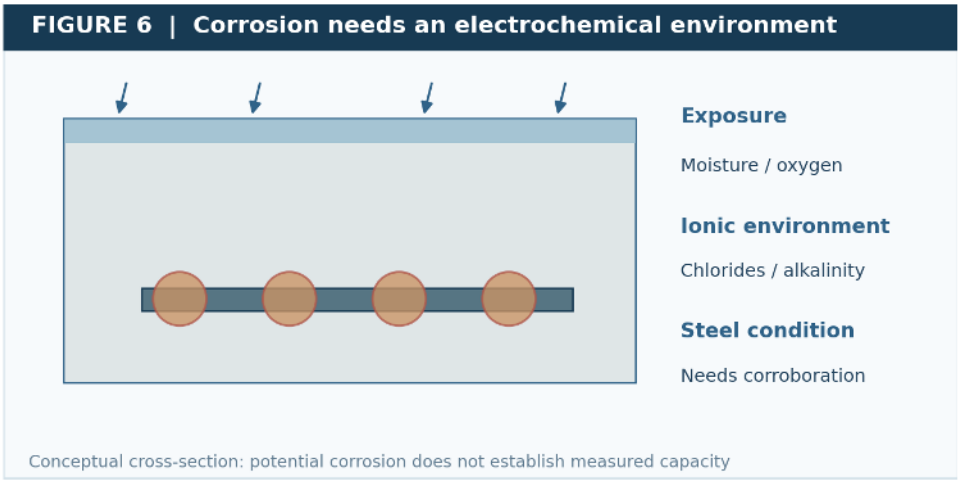
Learning allocation: 60 minutes: 35 guided reading / diagrams + 15 mechanism case + 10 interpretation

2.1 Reinforcement Corrosion Is an Electrochemical Process, Not a Color

Steel normally benefits from the highly alkaline environment of sound concrete. When chloride ingress or carbonation destroys or destabilizes the protective passive environment, steel corrosion can occur if moisture and oxygen conditions permit. Corrosion involves anodic and cathodic regions on the metal, an ionic pathway through pore solution, and electrochemical reaction products. Different portions of a bar can behave differently, so corrosion can be localized rather than uniform. Rust staining without visible spalling may precede significant cover loss; some severe internal corrosion can remain concealed. The engineer must evaluate the environment and the consequence, not simply categorize orange discoloration.

The products of corrosion can occupy greater volume than the original metallic iron, which can exert tensile stress on cover concrete. Longitudinal cracking, delamination and spalling may develop, but the sequence and severity depend on cover thickness, bond, restraint, moisture cycling and reinforcement arrangement. A crack is also an ingress path that can accelerate local exposure. This feedback loop explains why covering exposed steel without addressing active pathways can be short-lived. Corrosion control may require water management, chloride mitigation, better protection, appropriate repair geometry or a designed electrochemical system in addition to replacement material. [S3, S9]

FIGURE 6 | Corrosion needs an electrochemical environment



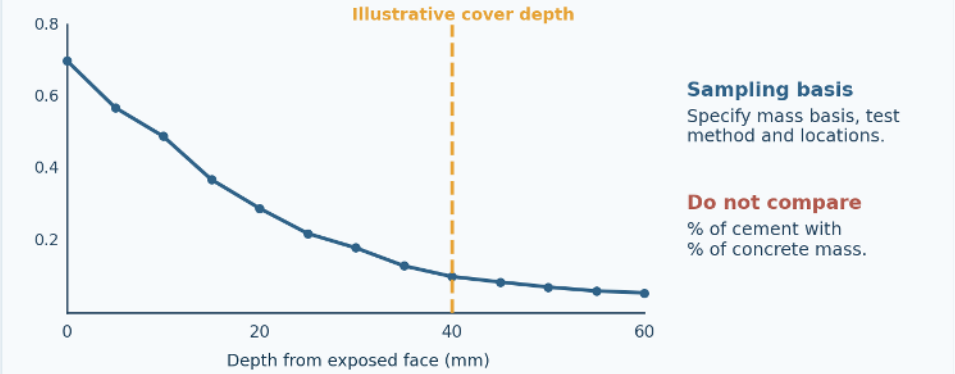
Corrosion. *Schematic interaction of exposure, steel and concrete.*

2.2 Chlorides: Source, Depth and Transport Environment

Marine spray, deicing salts, contaminated water and some historic material constituents can introduce chlorides. A chloride profile measured across depth is more informative than one bulk concentration, because the reinforcement may be near a steep concentration gradient. Over time, water movement and wetting/drying cycles alter transport; cracking and joints provide faster local pathways than the uncracked cover. Cover thickness matters, but two members with equal cover can experience different exposure because of geometry, ponding, drainage or coatings. An engineer should seek the source and determine whether exposure will continue after the repair.

There is no single field chloride number that independently declares all concrete unsafe or all bars actively corroding. Mixture chemistry, binding, pH, electrical resistivity, moisture, testing basis and reinforcement state affect interpretation. Use an appropriate standardized sampling and test approach, distinguish acid-soluble from water-soluble chloride measures, identify units and depth, and avoid mixing percentages of cement and concrete mass. The report should state what a result means at the observed depth and what further evidence supports a repair choice. [S3, S9, S12]

FIGURE 7 | A chloride profile has units, depth and uncertainty



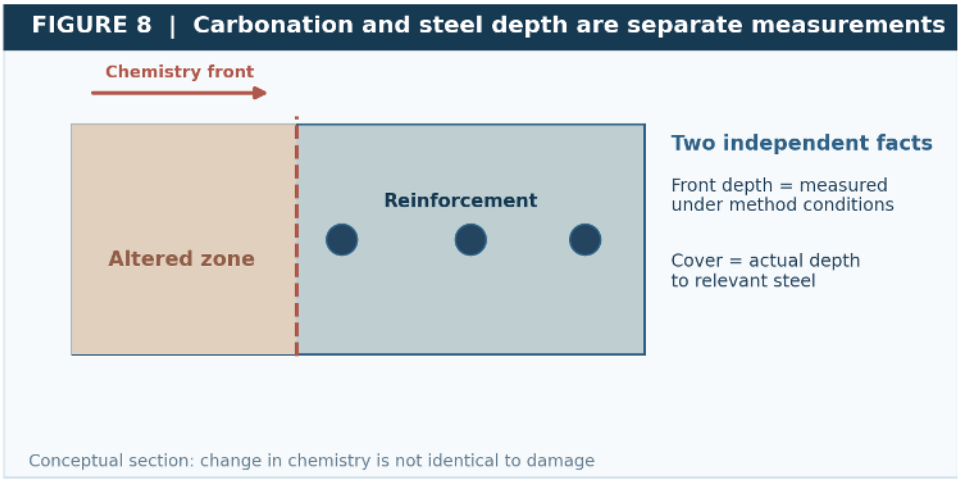
Chlorides. *Illustrative chloride-depth curve; no threshold or project value is asserted.*

2.3 Carbonation: Loss of Alkalinity May Be Important Without Surface Damage

Carbon dioxide reacts with alkaline phases in cement paste. The advance of the carbonation front can lower pore-solution alkalinity near reinforcement, potentially allowing depassivation when moisture and oxygen are present. The rate depends on permeability, exposure, moisture and cover. A white or dry surface is not a reliable indicator that reinforcement remains protected. Carbonation can progress in relatively dry environments while corrosion rates remain influenced by later changes in moisture. If the front approaches steel, a change in exposure can alter risk even without visible rust at the time of inspection.

Phenolphthalein indicator testing on a fresh fracture is a useful screening method, but it indicates a pH-related response rather than a universal quantitative measure of residual steel life. Surface treatments or repair

materials may produce complex patterns. Record where and how the depth was measured; compare it with actual cover, and use complementary information on moisture, chloride and steel condition. The result is one part of the mechanism assessment, not a stand-alone decision to replace all concrete or apply a coating. [S3]

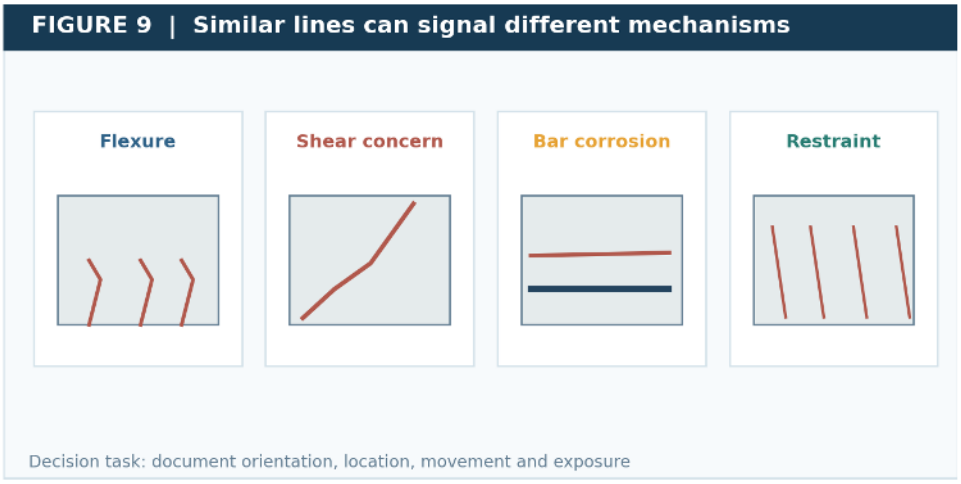


Carbonation. *Carbonation front and measured cover are distinct observations.*

2.4 Distinguish Structural Cracking from Restraint, Volume Change and Reaction

Cracking can arise from applied loading, restraint to drying shrinkage, thermal gradients, differential movement, reinforcement corrosion, alkali-silica reaction (ASR), sulfate attack, settlement or fabrication/curing conditions. Some mechanisms coexist. A patterned network of map cracking may prompt consideration of expansive reaction, but it can also appear in other circumstances. Directional or load-related cracks require a structural model, while moisture-related patterns require an exposure history. Repeated repairs that open again may indicate unaddressed movement or incompatible material stiffness rather than workmanship alone.

A useful comparison asks whether the crack is active or apparently dormant, whether it carries a load or water path, whether reinforcement is affected, and whether the cause can be removed. Structural injection intended to restore transfer across a suitable dormant crack is different from sealing a movement joint. Rigid material placed in an active joint can fail and transfer demand elsewhere. A load-path concern requires a licensed engineering assessment before any injection or stitching decision. The repair must follow mechanism and function rather than visual width alone. [S1, S3]



Cracktypes. *Four crack-pattern classes requiring different investigation.*

2.5 Physical Deterioration and the Exposure Boundary

Freeze-thaw cycling, abrasion, impact, fire exposure, fluid erosion and chemical attack can damage concrete through different pathways. Freeze-thaw risk is linked to saturation, pore structure and air-void system; wetting alone is not sufficient to diagnose it. Abrasion can remove protective cover even where embedded steel has not yet corroded. A fire-damaged member may have altered material properties, thermal cracking or unknown anchorage effects beyond the visibly affected layer. A cracked parking-slab overlay may reflect restraint and thermal movement rather than a deficiency of every underlying structural element.

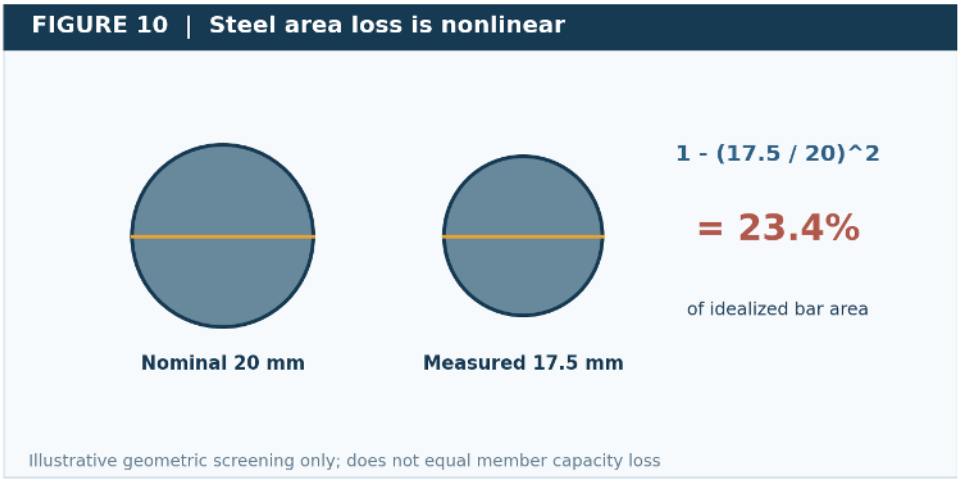
Select tests that distinguish the leading mechanisms. Petrography can provide evidence for reaction products and internal distress, while laboratory or field methods may support thermal or chemical damage evaluation. Work with an experienced laboratory on sample selection, because a specimen taken from the most dramatic surface may not represent adjacent sound material. When hidden structural systems or post-tensioning are possible, altered repair methods can be more dangerous than the original distress. Document the testing limits and reserve structural acceptance to the responsible professional. [S1, S3, S7]

2.6 Reinforcement Loss: an Instructive Calculation with a Strict Boundary

Suppose a nominal 20 mm bar is found to have an approximately circular residual diameter of 17.5 mm at one exposed location. As a simplified screening geometry, original cross-sectional area is pi times (20 mm)^2 divided by four, approximately 314.2 square millimeters. Measured residual area under the same circular assumption is pi times (17.5 mm)^2 divided by four, approximately 240.5 square millimeters. The geometric difference is about 73.6 square millimeters or 23.4 percent. The fraction is determined by the square of the diameter ratio, not a linear 12.5 percent reduction in diameter.

This calculation is deliberately not a capacity rating. Corrosion can produce pits and uneven loss, change bond and development, expose ties, affect anchorage, reduce confinement or shift force into other bars. The nominal bar size and field caliper measurement may not represent the critical section. The design engineer evaluates

residual strength, ductility, the affected load path, sampling uncertainty and possible strengthening under the governing code. Never conclude “23.4 percent capacity loss” solely from this area computation. [S1, S2]



Rebars. *Bar diameter comparison and geometric cross-sectional area change.*

2.7 Corrosion and Repair Can Move the Problem to an Edge

A localized patch that replaces chloride-contaminated concrete around one group of bars can create a different electrochemical environment at the adjacent unrepaired concrete. Under some conditions, increased corrosion at patch boundaries—often described as the incipient-anode or ring-anode effect—can follow. This is one reason long-term repair design sometimes includes a wider assessment area, barrier or drainage improvements, galvanic anodes or other engineered corrosion-control strategies. The phenomenon is not guaranteed to occur at every patch, and anodes are not a substitute for a sound material and exposure design.

Compare the local chloride evidence, ongoing wetting, electrical continuity, remaining cover, and required service life before selecting a strategy. A high-value repair may combine limited removal with an appropriately designed surface system and monitoring rather than repeated enlargement of the patch. In other cases more extensive removal and protection may be required. Methods selected for reinforced concrete cannot be copied uncritically to post-tensioned systems, dissimilar metals or electrically isolated components. [S3, S9]

2.8 Applied Workshop: Rank the Causal Hypotheses

Scenario. A concrete parking structure shows repetitive spalls below a coastal expansion joint. Near-surface chloride content is elevated in a laboratory profile, a separate location has a carbonation front approaching cover depth, and half-cell readings show spatial variation. Sounding identifies additional concealed delamination. Maintenance records document recurring ponding and a failed joint seal. Construct a causal map with source, transport route, affected material, observed symptoms and uncertain links. Mark which measurements locate damage, which suggest likelihood of corrosion, and which do not prove current capacity.

Suggested interpretation. The joint and ponding suggest an ongoing water exposure pathway; chloride near steel and mapped delamination support a corrosion concern but do not independently quantify steel loss. Carbonation is a separate plausible depassivation process at the selected location. Half-cell patterns require proper test conditions and correlation; they do not replace concrete removal, steel measurement and structural evaluation when indicated. Prioritize safety review at critical members, moisture control and selective confirmation rather than specifying epoxy injections for every visible crack. [S3, S7, S9]

Module 2 | Mechanism Evidence Register

Fictional parking-deck case. Each data stream has a different inference limit; none is a shortcut to a capacity determination.

Evidence	Supports	Still requires
Leakage below joint	Identifies repeated wetting and a transport route.	Record active source, duration and repair of the exposure pathway.
Chloride-depth profile	Supports a corrosion-exposure hypothesis with stated units and sampling depth.	Document specimen location, measurement basis and steel depth.
Half-cell spatial map	Assists comparison of corrosion likelihood under suitable test conditions.	Correlate with steel exposure and physical evidence before decisions.
Delamination sounding	Helps define where discontinuities may exist.	Verify selected locations and adjust approved removal limits.

MODULE 3 | Repair Selection, Construction Sequence and Long-term Value

Learning allocation: 60 minutes: 30 guided reading / diagrams + 20 design-choice case + 10 comparison

3.1 A Repair Is a Performance Intervention, Not a Matching Color

Repair alternatives should be evaluated against documented objectives: restore structural performance, prevent falling debris, control water, extend service life, manage chloride exposure, restore fire resistance or provide a protective finish. One project may need several outcomes. Distinguish urgent stabilization from permanent rehabilitation. A temporary protective measure might make occupancy safer without solving chloride contamination; a visually seamless patch may not restore structural capacity. The repair objective should describe the required function and acceptance method, not simply list a proprietary product.

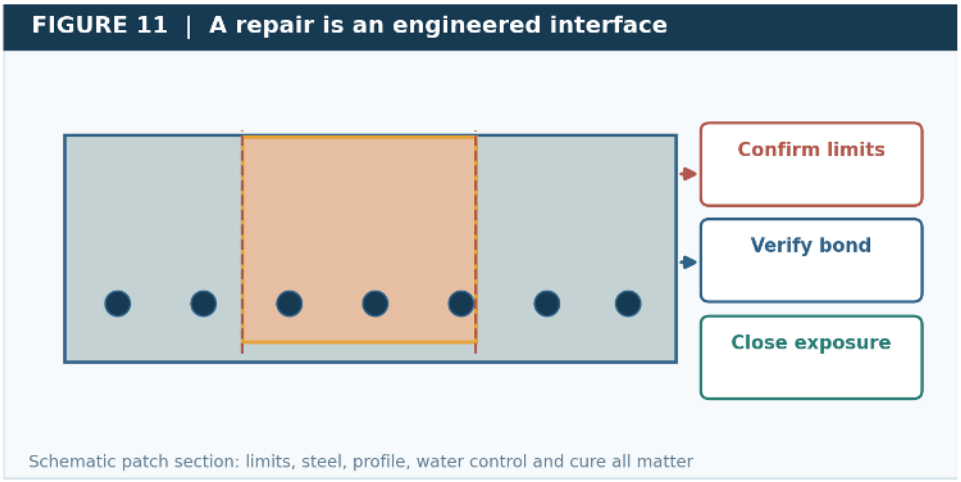
The design team should consider the remaining life of the asset, access and closure cost, geometry, exposure, appearance, future inspection and likelihood of recurrence. ACI CODE-562-25 establishes assessment and repair-design requirements; ACI PRC-546-23 provides selection and process guidance, while project specifications and the adopted code define binding requirements. The newest ACI publication is a technical reference unless legally incorporated or contractually adopted. [S1, S3, S5]

3.2 Removal Limits and Substrate Preparation Determine Whether a Patch Bonds

A typical repair sequence starts with controlled mapping and safe access, then removal of unsound or contaminated concrete to limits established or revised by the engineer. The contractor must protect remaining reinforcement and any tendons. Sound concrete near the removal perimeter can be damaged by excessive impact; the method may need adjustment if the residual substrate is bruised or microcracked. Sawcuts, where specified, must avoid embedded steel, avoid creating harmful stress concentrations and prevent feather-edge repairs where unsuitable. Cleaning and rebar preparation requirements vary with coating, bond, corrosion state and the selected repair system.

Surface roughness is not a universal number to maximize. ICRI Guideline 310.2R identifies concrete surface profiles, but the specified target depends on the repair method and material. A coating may need a different profile from a bonded structural patch. Soundness, cleanliness, moisture condition and substrate temperature can matter as much as visible texture. The contractor's prepared surface should be examined at a hold point before concealment. The project documents should state who accepts the substrate and how a mismatch is recorded. [S3, S5, S6, S10]

FIGURE 11 | A repair is an engineered interface

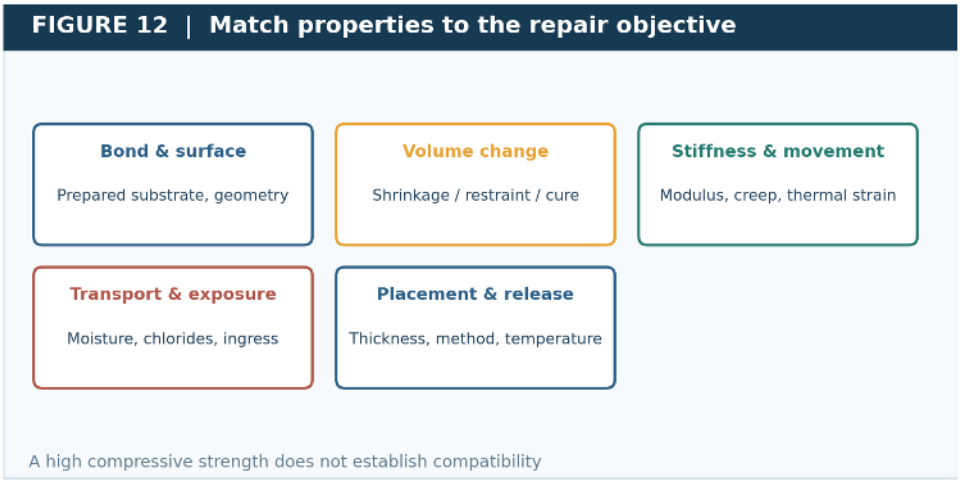


Repairsection. *Engineer-approved boundary and repair-material interface.*

3.3 Do Not Design Only for Compressive Strength

A repair material with exceptionally high nominal compressive strength can still be the wrong material. Evaluate the repair function, bond requirements, elastic modulus, shrinkage, creep, coefficient of thermal expansion, permeability, placement thickness, curing method, geometry and exposure. A stiff repair beside a more deformable existing substrate can concentrate stress or crack at interfaces. An overly impermeable surface system may trap moisture in a wall with a different drying path. An early-set mix may solve traffic-closure pressure while creating thermal or shrinkage concerns. Manufacturer data, qualification testing and engineer specifications must be read together.

For overhead or vertical work, application method and sag resistance can be decisive; for large volumes, heat development and crack control may dominate; for exposure to repeated wetting, permeability and corrosion control may be central. Evaluate whether repair mortar, cast-in-place replacement, shotcrete, overlays, protective treatments or strengthening systems meet the actual engineering objective. ACI PRC-546.3-23 focuses on materials selection, and ACI PRC-546-23 connects method to repair function. The contractor should demonstrate that proposed materials fit the specified conditions rather than relying on a generic “equivalent” claim. [S3, S4]

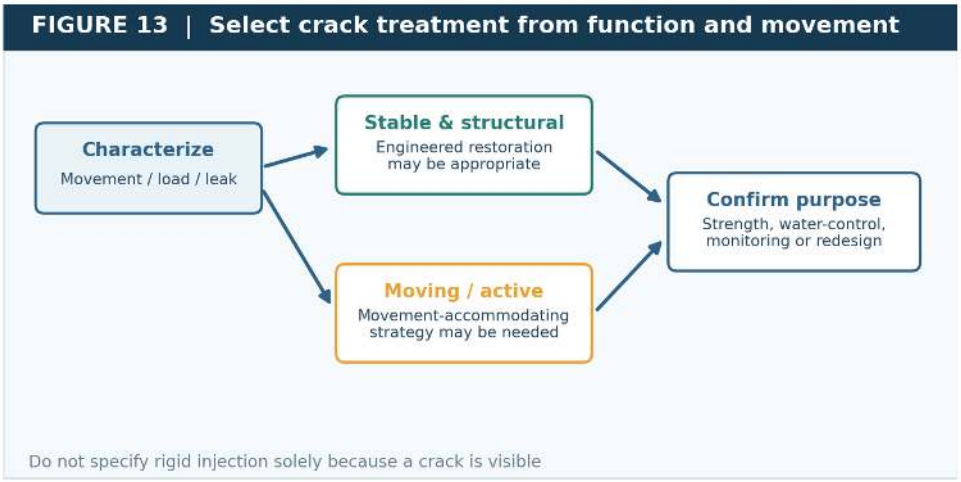


Materials. *Repair material selection factors beyond compressive strength.*

3.4 Crack Treatment Must Match Movement and Function

Epoxy injection may restore continuity across certain properly prepared, stable structural cracks when design conditions and penetration requirements are satisfied. It is not a universal solution to wet, actively moving or contaminated cracks. Routing and sealing or flexible joint treatment may be appropriate for a movement-driven water pathway where restoring structural continuity is not the objective. Other repairs may require removal, member strengthening or correction of differential settlement. The engineer must decide whether injected material would change structural action or create a new load path; this cannot be delegated inadvertently through a general note on a repair drawing.

Document crack width, accessibility, active moisture, cause, movement, required force transfer, temperature and acceptance evidence. In-service leak control is not evidence that a structural crack's full depth was bonded. Injection-port pressure or resin consumption alone cannot prove adequate penetration. ICRI 210.1R offers a framework for verifying epoxy crack injection. Acceptance may require observations, soundings or destructive checks selected for the work. [S1, S3]



Crackrepair. *Crack treatment begins with function and movement.*

3.5 When Patching Is Not Enough: Strengthening and Corrosion Management

If a member has insufficient residual capacity or an altered load demand, the solution may require member enlargement, supplemental reinforcement, prestressing, FRP strengthening, replacement or a change in operating loads. These are structural design projects, not enhanced patch recipes. They demand analysis of the original and modified load paths, interface behavior, anchorage, fire and environmental performance, construction sequence, quality assurance and inspection access. FRP systems are sensitive to substrate soundness, adhesive properties, anchorage, temperature and exposure and require design under the applicable technical and regulatory framework.

Where deterioration is primarily electrochemical and widespread, localized patching alone can give a poor life-cycle outcome. Surface sealers, waterproofing, joint replacement, drainage work, corrosion-resistant reinforcement, impressed-current or galvanic cathodic protection may be considered in a system-level plan. Each has limits and maintenance requirements. For bridges and parking decks, FHWA corrosion guidance lists patching, protection, membrane systems and engineered electrochemical measures among mitigation strategies. The selected approach must address the source and future inspection, not simply conceal the previous symptoms. [S1, S3, S9]

3.6 Sequence Stability, Access and Quality Without a Dangerous Shortcut

A plausible rehabilitation sequence may require access restrictions, temporary support, verification of embedded systems, localized concrete removal, reinforcement evaluation, corrosion-control work, substrate preparation, placement, curing, testing, loading restrictions and monitoring. The order matters. An engineer may approve removal only after defined stabilization; a testing agency may need an unobstructed prepared surface; the acceptance of reinforcing steel may precede application of a corrosion system. If a contractor proposes breaking several support zones at once, the engineer must evaluate any resultant load-path change rather than infer that a faster schedule is acceptable.

Contract drawings should identify the authority for structural changes, the boundaries of delegated design, the required submittals and field hold points. An RFI records a question, not an independent authorization to change member geometry or bar continuity. Where hidden damage is worse than expected, a clear stop-work and reassessment path prevents the crew from continuing on an invalid basis. For post-tensioned structures, detecting and avoiding tendons during investigation and repair is an essential project-specific safety requirement. [S1, S5]

3.7 Compare Alternatives Using Life-cycle Implications

Consider a fictional owner comparing Strategy A: a $42,000 localized patch now with an anticipated $19,000 follow-up in year 4, versus Strategy B: an $58,000 integrated patch, joint and drainage program with an anticipated $8,000 inspection/protective-system maintenance activity in year 6. Using a five-percent annual discount rate only for illustration, the present value of Strategy A is 42,000 + 19,000/(1.05)^4, approximately $57,631. Strategy B is 58,000 + 8,000/(1.05)^6, approximately $63,970. If those are the only costs, A has lower modeled present cost by about $6,338. The model does not establish the preferred engineering choice.

A rational owner comparison must also account for service interruption, falling-concrete risk, probabilities and consequences of further deterioration, future inspection, uncertain deterioration extent, structural functionality, access and residual value. If Strategy A entails a large unmodeled closure or recurrence risk, B may be preferable despite its larger deterministic present cost. Record the assumed event timing and sensitivity rather than implying a precision that the deteriorating asset cannot support. An economic model supports documented judgment; it cannot substitute for safety, code or engineering acceptance. [S3, S9]

FIGURE 14 | Compare discounted cost, but keep safety separate



Lifecycle. *Present-value example; costs and years are fictional.*

3.8 Applied Workshop: Specify the Right Intervention

Scenario. A parking-deck slab has approximately 7.2 square meters of marked distress in an area of recurrent standing water. Selective opening shows some corroded bars and variable cover, while joint leakage remains active. The contractor offers a rapid-setting patch material with high published compressive strength. Write a performance-based scope that includes investigation boundaries, structural review, water-source control, removal and preparation, reinforcement disposition, material compatibility, curing, quality controls and return-to-service. Calculate a preliminary area allowance of 15 percent only as a planning quantity: 7.2 x 1.15 = 8.28 square meters. State why this does not fix the final removal boundary.

Suggested approach. First define the load and access constraints and confirm whether temporary support is needed. Investigate and document the limits beyond visible damage, then address the joint and ponding pathway. Specify substrate acceptance and reinforcement engineering decisions before placement. Review the candidate material's modulus, shrinkage, moisture conditioning, thickness and cure in addition to nominal strength. The estimated 8.28 square meters is a budgeting allowance, not a field instruction to remove a prescribed area. Revise the scope if concealed damage or residual capacity requires different work. [S1, S3, S5, S6]

FIGURE 15 | Repair alternative evaluation card

OPTION	WHEN CONSIDERED	UNCERTAINTY	CONTROL
Local patch	Small discrete loss	Residual chloride field	Water control essential
Patch + protection	Broader exposure	Ongoing maintenance	Test and inspect plan
Structural rehab	Deficient performance	Design & temporary works	Explicit acceptance basis

Score the purpose and uncertainty; do not turn this into a generic product ranking

Repairchoices. *Structural repair alternatives and explicit uncertainty controls.*

MODULE 4 | Execution Quality, Acceptance, Records and Monitoring

Learning allocation: 60 minutes: 35 guided reading / diagrams + 15 integrated closeout case + 10 documentation

4.1 Make the Repair Specification Checkable Before Bidding

A construction-quality plan begins with controls that can be observed, recorded and verified. The documents should identify approved material properties or performance criteria, substrate preparation, environmental constraints, sequencing, temporary support responsibilities, inspection/hold points, test methods, acceptance criteria and repair of nonconformities. A note requiring “high-quality concrete repair” does not allow a field inspector to decide whether work passes. If a substrate bond requirement is important, specify the approved test, sample plan, equipment, acceptance basis and disposition for results that do not conform. Avoid adding arbitrary values from a product brochure without verifying the design and method.

ACI SPEC-563-25 provides contemporary specification context for repairing concrete buildings; adapt it to the project and governing code rather than copying a clause blindly. ACI 562-25 addresses design and quality assurance obligations. The engineer and testing agency should agree on what evidence triggers release of each hold point and what records show a later reviewer why the work was accepted. The contract must distinguish contractor QC, owner or engineer QA and the licensed design professional's reserved decisions. [S1, S5]

4.2 Before Placement: Verify the Substrate, Steel and Actual Limits

The moment before concealment is a critical decision point. Inspect the actual excavation geometry, soundness of exposed concrete, reinforcement continuity and condition, embedment, thickness, access to connection zones, water penetration and unexpected construction features. Compare the exposure with the latest marked condition map and approved repair documents. A contractor may discover severe corrosion or a tendon after the initial removal begins; the required response is to protect the area and obtain direction, not to improvise a rebar splice or reduce cover to fit a material. Photograph accepted areas with dimension references.

Verify material identification and batch controls, substrate cleanliness, prescribed surface profile, moisture conditioning and the appropriate interface treatment. Inspect preparation method for residual damage, particularly where heavy impact may have microcracked the substrate. The hold-point record should contain the date, location, acceptance basis, test results and authorization to proceed. A passing profile comparison does not establish soundness or bond by itself; no single test replaces the full acceptance decision. [S5, S6, S8]

FIGURE 16 | Controlled field release gates



Holdpoints. *Five typical stages requiring documented verification.*

4.3 Placement: Controllable Variables and Representative Observation

Quality during mixing and placing depends on controlled water, mixing sequence, pot life, temperature, batch identification, lift thickness and environmental exposure. A product that meets laboratory data may fail in a field repair if excessive water is added to regain workability or if an installation extends beyond material working time. For an overhead patch, support and application technique may be essential; for a large section replacement, consolidation and thermal response may control. Record the start of placement, material identification and measured field conditions against the specifications. Do not infer acceptability from a smooth troweled finish.

A mockup or trial installation can reveal practical incompatibilities between substrate, geometry, crew technique and selected material. It is especially valuable when access or placement geometry differs from a manufacturer demonstration. When the field condition changes, revise the method through authorized channels. The engineer should specify whether and when curing, finishing or load restrictions can be changed, including cold-weather, hot-weather or moisture concerns. Traceable placement records support later investigations without presuming that every defect has the same cause. [S3, S4, S5]

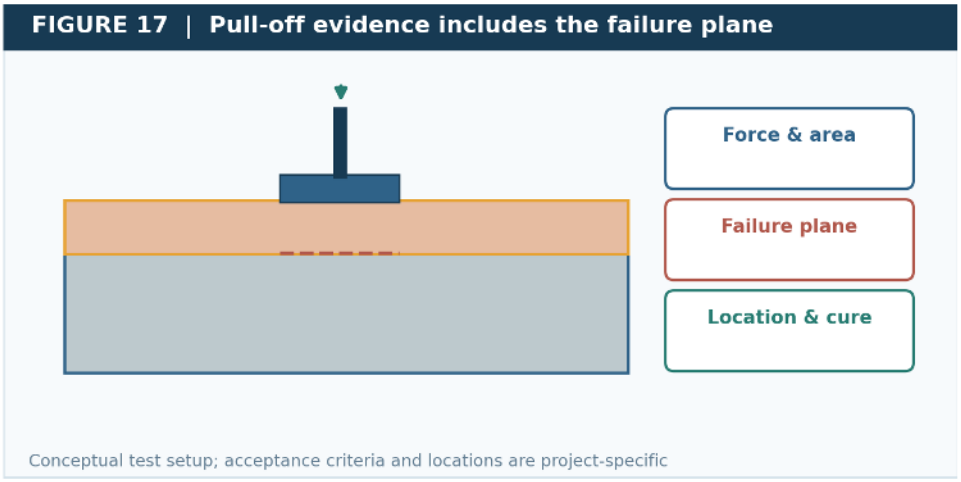
4.4 Bond, Strength and Acceptance: Tests Need a Stated Purpose

In-situ tensile pull-off testing can assess a repair system or substrate under a prescribed procedure, but a number alone is incomplete. Record the location, core or test geometry, surface preparation, adhesive, failure plane, age, curing and method. An apparently high pull-off number can be misleading if the test is performed only on convenient pristine areas; a low result may reflect a particular substrate failure or preparation problem. Select a statistically and practically meaningful sampling plan and apply acceptance limits from the project design and material system. ICRI 210.3R-2022 provides relevant pull-off guidance. [S8, S12]

Compressive-strength testing may support material qualification or acceptance where specified, but it cannot establish every structural repair outcome. A patch can meet compressive strength yet fail bond, shrinkage

compatibility or long-term moisture control. Likewise, successful coating adhesion does not prove that corrosion beneath untreated concrete has stopped. An inspection plan should identify separate checks for geometry, steel, substrate, placement, curing, bond and environmental performance. The required test frequency and criteria follow the approved design and specifications, not a generic number repeated across different projects. [S1, S5]

FIGURE 17 | Pull-off evidence includes the failure plane

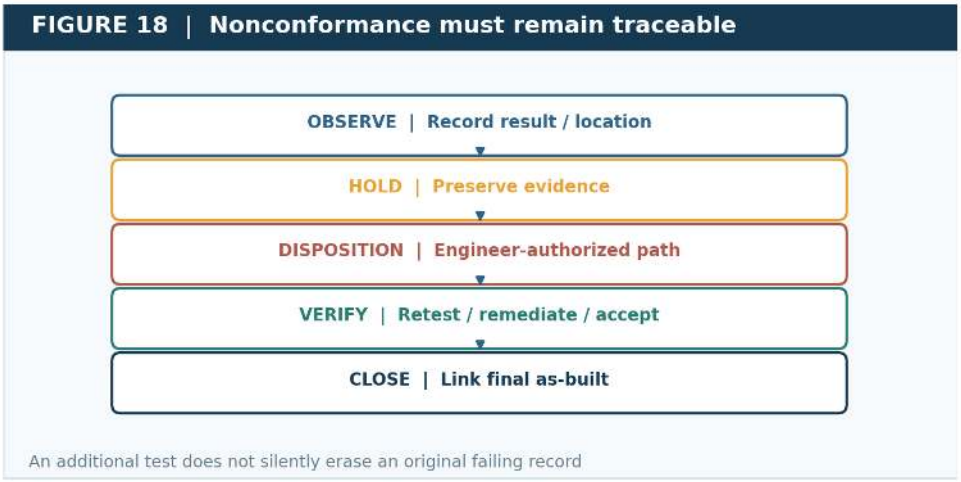


Pulloff. *In-situ tensile pull-off test interpretation elements.*

4.5 Deal with Nonconformance Without Obscuring the Record

A nonconformance is any observed deviation from an identified requirement: a contaminated surface, unexpected reinforcing condition, out-of-range placement temperature, missing test record, failed bond test or unapproved material substitution. Record the exact requirement, observed evidence, location and immediate containment action. Then distinguish correction (bringing work into compliance), repair (altering nonconforming work under engineered approval), acceptance as-is (only when properly justified and authorized), and replacement. The individual who detects a deviation may not have authority to approve a structural alternative.

Where a repair fails a test, determine whether it is a localized defect, a sampling problem or evidence of a systematic failure. Preserve failed specimens and the test conditions when possible. Write an approved disposition and verify effectiveness rather than merely adding a new photo to a file. A repeat test without stated criteria or a changed specimen geometry can create a false pass. Engineering quality records should let a future owner identify what failed, what decision was made, who authorized the decision, and how the final result was checked. [S1, S5]



Nonconf. *Nonconformance workflow from evidence preservation to closure.*

4.6 Turnover Is a Technical Record, Not a Folder of Unlabeled Photos

A useful closeout package includes the approved design basis, as-built repair maps, removal limits, reinforcing disposition records, batches and material certifications, inspection and test reports, nonconformance dispositions, approved changes, cure/return-to-service evidence and maintenance guidance. Link each piece to the repaired location. A photograph without a grid reference does not establish which beam or bay was accepted. If the structural design differs from the initial repair plan, the record should contain the approved change rather than forcing future reviewers to infer it from installation drawings.

Where a protective system requires periodic inspection or electrical testing, define what the owner must maintain, when to inspect, what constitutes an action trigger and who receives results. A twenty-year service-life aspiration without a program for failed joints or coatings is not a verified prediction. Include residual known defects or deferred repair zones without implying that the whole structure was returned to a zero-risk condition. Clear records support the professional duty to communicate limitations and future requirements. [S1, S3]

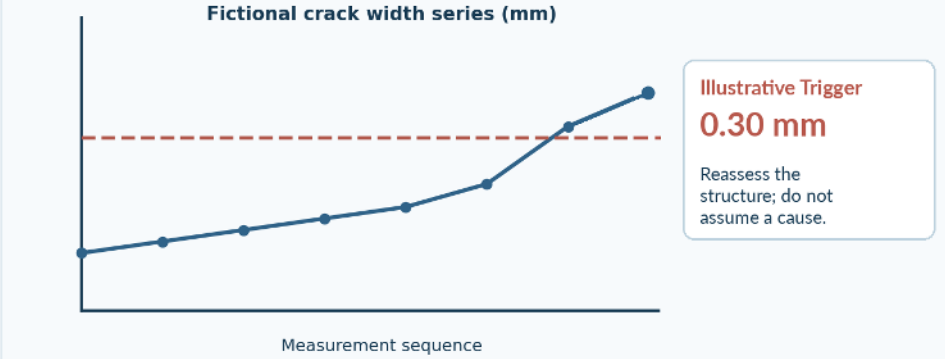
4.7 Monitoring: Compare Like with Like and Set Action Thresholds

Condition monitoring after repair may track water leakage, crack width, deflection, corrosion indicators, sounding response, coating continuity or environmental exposure. Choose a repeatable method tied to a specific decision. Readings at unlike temperatures, wetting states or equipment configurations can suggest changes that are not real. Establish location references, baseline, interval, data quality and who evaluates the trend. A monitoring plot without pre-defined action criteria can delay intervention until a new visible failure occurs.

Monitoring does not replace immediate action where a credible structural safety issue exists. An engineer should specify thresholds for reinspection or restrictions based on the actual structure, not general numerical

rules copied from another project. Where uncertainty remains, explain what the monitoring can resolve and what it cannot. For example, a stable crack width does not by itself prove uncorroded reinforcement. [S1, S7]

FIGURE 19 | A Monitoring Series Needs an Action Decision



Monitoring. *Fictional time series with a project-specific illustrative action trigger.*

4.8 Integrated Case: Close Out a Repaired Edge Beam

A three-level parking garage edge beam was stabilized and repaired after chloride exposure and joint leakage. The original damage map was 7.2 square meters but field removal reached 9.0 square meters. The contractor used two material batches and one day's placement was interrupted by rain. The testing agency reported one marginal bond result at an area near the interruption, while the remaining tests met the specified criteria. Prepare a structured closeout review: which materials and locations were affected; whether field removal changes were approved; the location and failure mode of the marginal result; whether the rain interval met environmental and curing requirements; how to disposition nonconformance; and which water-control repairs were actually completed.

Model reasoning. First reconcile removal maps against the engineer-authorized limits; an allowance alone does not approve increased removal. Tie each batch, test and incident to location. The marginal bond result requires the prescribed method and failure-plane context; repair or retest only under an approved disposition. Confirm joint correction and water-flow changes because the exposure source drove the original mechanism. Closeout should not claim restoration merely because the new surface looks complete. Include the approved action, retest or acceptance evidence, photographs, work restrictions, future inspection plan and remaining owner obligations. [S1, S5, S8]

FIGURE 20 | Tie repair evidence to its physical location

TRACE	EVIDENCE	RELEASE QUESTION
Zone G-2	9.0 m2 actual vs 7.2 m2 map	Verify approved expanded removal
Batch B2	Placement during rain interruption	Check environmental and cure log
Bond test T7	Marginal, failure plane noted	Authorized disposition before closeout
Joint J4	Water ingress source	Confirm completed leak correction

Fictional garage edge-beam closeout: accepted record is not a photo folder

Closeout. *Closeout example: relate batch, test, area and leak-control records.*

4.9 Professional Decisions and the Boundary of Continuing Education

The engineer's professional obligation is to communicate material limitations, avoid unsupported certainty and identify where additional licensed evaluation is necessary. Contractor means and methods, material manufacturer recommendations, owner operations and engineering-of-record decisions overlap but are not interchangeable. A repair submittal is evidence of proposed work; it is not necessarily a structural design approval. A test is evidence of a measured property, not a guarantee of structure-wide performance. A completion certificate for this education documents course participation under the provider's rules, not authority to inspect or approve any specific asset.

For a real project, confirm the jurisdiction's adopted codes, permits, required inspections, delegated design limits, qualified personnel and record-retention duties. Avoid reusing a generic repair detail where load paths, exposure or material properties differ. The overarching workflow is consistent: preserve safety; identify the relevant mechanism; establish an engineering objective; choose a compatible intervention; document execution and acceptance; and monitor the remaining risk. [S1, S3, S5]

Applied Engineering Record Templates

These blank tables support the four applied module workshops. They are educational decision-record examples, not an inspection form or a certificate of engineering approval.

Record a | Condition and Immediate Response

Asset / location	_____
Observed distress with dated evidence	_____
Structural consequence and current use	_____
Immediate safety restrictions / decision owner	_____
Targeted verification method and limitation	_____

Record B | Mechanism Hypothesis

Exposure source and transport route	_____
Mapped symptoms, depth and specimens	_____
Primary mechanism hypothesis	_____
Competing mechanism / unverified assumption	_____
Test that would change the decision	_____

Record C | Repair Alternative

Performance objective / service life	_____
Substrate and reinforcement conditions	_____
Selected repair system and compatibility	_____
Temporary support, sequencing and access	_____
Lifecycle tradeoffs and documented exception	_____

Record D | Quality and Closeout

Authorized removal limit / actual extent	_____
Substrate / steel / materials hold points	_____
Testing and nonconformance disposition	_____
Exposure source correction and maintenance	_____
Accepted as-built and future monitoring	_____

Engineering Glossary

Term	Application in this course
Carbonation front	Depth within which the chemistry has been altered by reaction with carbon dioxide; field indication depends on test method and conditions.
Concrete surface profile (CSP)	Visual/textural classification used to specify and verify selected concrete preparation, not a universal strength test.
Delamination	Subsurface separation or discontinuity in concrete detected or confirmed through appropriate investigation.
Depassivation	Loss of conditions that ordinarily protect reinforcing steel from corrosion.
Engineer of record	Licensed professional with defined responsibility for the engineering documents and decisions within the contracted scope.
Half-cell potential	Electrochemical potential measurement used under appropriate conditions to investigate corrosion likelihood, not a direct capacity or section-loss measure.
Hold point	Defined stage where work cannot proceed until specified inspection or authorization is complete.
Incipient-anode effect	Potential corrosion concentration in adjacent untreated concrete following localized repair under certain electrochemical conditions.
NDE	Nondestructive evaluation; screening or diagnostic methods selected for the engineering question and operating conditions.
Nonconformance	Measured or observed failure to meet a stated requirement, requiring documented disposition.
Repair system	Coordinated approach including surface, reinforcement, material, water control, application, QA and maintenance.
Residual capacity	Structural strength/serviceability available after damage; must be evaluated by appropriate engineering methods, not inferred from visual repair area.

Sources and Edition Control

References identify the publications consulted for technical scope and terminology. Standards may be revised or superseded; actual projects must use the legally adopted edition, contract documents, owner requirements and authoritative test methods in force for that work. Hyperlinks open publisher or agency pages. Source references are not reproduced in this manual.

S1. American Concrete Institute (ACI). ACI CODE-562-25, Assessment, Repair, and Rehabilitation of Existing Concrete Structures — Code Requirements and Commentary (2025).
Publisher / primary source

S2. American Concrete Institute. ACI CODE-318-25, Building Code for Structural Concrete — Code Requirements and Commentary (2025).
Publisher / primary source

S3. American Concrete Institute. ACI PRC-546-23, Concrete Repair — Guide (2023).
Publisher / primary source

S4. American Concrete Institute. ACI PRC-546.3-23, Materials Selection for Concrete Repair — Guide (published 2024; standard designation 2023).
Publisher / primary source

S5. American Concrete Institute. ACI SPEC-563-25, Repair of Concrete in Buildings — Specification (2025).
Publisher / primary source

S6. International Concrete Repair Institute. Guideline 310.2R-2013, Selecting and Specifying Concrete Surface Preparation (2013).
Publisher / primary source

S7. International Concrete Repair Institute. Guideline 210.4R-2021, Nondestructive Evaluation Methods for Condition Assessment, Repair and Monitoring (2021).
Publisher / primary source

S8. International Concrete Repair Institute. Guideline 210.3R-2022, In-Situ Tensile Pull-Off Tests to Evaluate Bond (2022).
Publisher / primary source

S9. Federal Highway Administration. FHWA-HRT-24-127, Best Practices for Corrosion Control and Mitigation (2024).
Publisher / primary source

S10. U.S. Bureau of Reclamation. Guide to Concrete Repair (2015).
Publisher / primary source

S11. International Existing Building Code and applicable adopted state/local building regulations. Confirm the adopted edition and jurisdictional applicability on each project.
Publisher / primary source

S12. ASTM International. ASTM C42/C42M-20 (drilled cores), C876-22b (corrosion potentials) and C1583/C1583M-25 (surface/bond pull-off testing), as required by the adopted test method edition and project specifications.
ASTM C42/C42M | ASTM C876 listing | ASTM C1583/C1583M-25