

Risk-Based Retrofitting and Structural Refurbishment of Ageing Infrastructure in Saudi Arabia: An SBC-Compliant Framework for Long-Term Resilience.

Abstract

Ageing infrastructure in Saudi Arabia faces interacting threats from material deterioration, altered occupancy, extreme environmental exposure and uncertain construction records. Conventional refurbishment decisions often respond to observable defects or available budgets without explicitly connecting structural risk, code applicability and continued service. This critical review synthesises 30 DOI-traceable studies published between 2020 and 2025, together with the published scope of the Saudi Building Code, to develop a staged decision framework for existing buildings and associated civil assets. Its aim is to establish a defensible relationship between evidence quality, consequence-based prioritisation, retrofit mechanisms and verified in-service performance. The synthesis distinguishes condition from vulnerability, life safety from functional recovery, and repair from structural strengthening. A six-gate pathway is proposed covering asset classification, diagnosis, hazard-sensitive assessment, intervention selection, approval and longitudinal monitoring. Comparative appraisal shows that no retrofit technique can be chosen by nominal strength gain alone: deformation compatibility, foundations, constructability, environmental durability and nonstructural functionality control the outcome. The review identifies research needs concerning Saudi deterioration datasets, uncertainty calibration and auditable interfaces between assessment, design and maintenance. The resulting framework offers decision support rather than a substitute for project-specific engineering calculations or statutory approval.

Keywords: Saudi Building Code; SBC 901; existing buildings; structural refurbishment; risk-based retrofitting; asset resilience; life-cycle assessment; corrosion

1. Introduction

Saudi infrastructure owners increasingly face a choice between maintaining, strengthening, repurposing and replacing ageing assets. Reinforced-concrete buildings, bridges, transport facilities and public-service complexes can remain useful for decades, yet their original assumptions may no longer reflect contemporary demand. Extensions increase gravity loads; altered layouts interrupt

load paths; new equipment raises vibration demands; and an exposed member may lose capacity long before damage becomes conspicuous. A refurbishment decision is therefore not a simple comparison between repair expenditure and replacement cost. It concerns the residual capacity of an interconnected system and the consequences of inadequate intervention.

Recent research challenges the assumption that expenditure should follow visible deterioration alone. Portfolio risk frameworks emphasise occupancy, criticality and financial constraints [1–4], while functional-recovery studies show why meeting a narrow life-safety objective may not protect essential services after an extreme event [5,6]. These insights are particularly relevant when a hospital, transport interchange or utility facility must remain partly operational during structural works. The governing question becomes which intervention produces acceptable performance for an identified hazard, within an affordable and deliverable programme, with sufficient evidence to justify its claims.

Saudi Arabia presents diverse exposure conditions rather than a uniform national deterioration problem. Coastal structures confront chloride ingress and humid salt-laden conditions; arid inland locations experience intense thermal cycling and potentially aggressive soil chemistry; and seismic, wind and flood demands vary by site. Construction quality, maintenance history and undocumented alterations introduce additional heterogeneity. Global findings provide mechanisms and assessment techniques, but transferring numerical thresholds directly across climates, construction eras or structural typologies would conceal important uncertainty [13–18].

The research gap lies between three bodies of knowledge that are commonly treated separately: engineering diagnosis of existing assets, decision analysis for retrofit investment, and regulatory demonstration for alterations. The present review addresses that gap by joining them into an auditable risk-to-resilience process. Its contribution is a decision architecture with explicit evidence gates, rather than another catalogue that ranks strengthening methods independently of their setting.

1.1. Aim, objectives and questions

The study aims to formulate an evidence-led approach for selecting and governing structural refurbishment of ageing Saudi infrastructure under applicable Saudi Building Code requirements. Four objectives shape the synthesis: establish how material condition and hazard exposure should inform baseline risk; compare retrofit mechanisms against performance and constructability demands; translate the existing-building code pathway into verifiable project deliverables; and

develop monitoring criteria through which the intended resilience improvement can be checked over time.

Three questions guide the review. First, what information is necessary before an owner can credibly distinguish cosmetic repair from load-bearing intervention? Secondly, how should risk, functional dependence and life-cycle effects change the priority assigned to competing assets? Thirdly, what constitutes persuasive evidence that a designed retrofit has preserved both structural capacity and required operational continuity? The answers are necessarily conditional: asset-specific calculations and competent approval remain indispensable.

2. Review methodology

A structured critical narrative review was selected because the evidence spans experimental materials research, probabilistic deterioration modelling, seismic performance analysis, maintenance optimisation, asset management and digital inspection. These domains use incompatible outcomes; combining their numerical results into a single pooled effect would be scientifically misleading. Instead, the synthesis tests the reasoning that connects each method to a defensible engineering decision.

Literature identification concentrated on journal articles issued from 2020 through 2025. Thematic search concepts included existing structures, retrofit prioritisation, reinforced-concrete deterioration, seismic refurbishment, functional recovery, life-cycle resilience, structural assessment, corrosion, digital twins and maintenance optimisation. Thirty DOI-traceable publications were selected for direct conceptual relevance, complementary methods and inspectable publication metadata. Selection favoured sources establishing a measurable mechanism, a transferable analytical method or a material limitation. Studies of new buildings were considered only when their methods clearly informed decisions about existing assets. No unpublished survey, Saudi project dataset or new structural simulation is represented as having been conducted.

Evidence was classified into five linked domains: hazard and deterioration; consequence and interdependence; analytical reliability; intervention performance; and long-term verification. Experimental findings were separated from numerical case studies, review arguments and cross-sector transfer. This distinction prevents, for example, a laboratory increase in member ductility from being presented as an empirically established increase in whole-building recovery. The proposed framework emerged from comparing evidence across these domains and identifying points where a professional sign-off or new measurement changes the allowable decision. Its

adequacy is assessed conceptually against code scope, traceability and foreseeable failure mechanisms, not claimed as field validation.

The regulatory comparison uses the publicly described Saudi Building Code family, notably SBC 901 for existing buildings and SBC 201, SBC 301 and SBC 304 where relevant to occupancy, structural actions and concrete work. The exact enacted edition, local authority requirements, referenced standards and provisions applicable to a given alteration must be confirmed by the responsible licensed engineering team. National provisions are a regulatory input, not a DOI journal source; accordingly they are not counted among the 30 scholarly references.

3. Structural ageing as a multi-hazard process

Ageing is not itself a structural limit state. It is a time-dependent change in properties, boundary conditions and exposure that can alter the probability of violating one. For reinforced concrete, chloride transport, carbonation, cracking, moisture movement and reinforcing-steel corrosion form a coupled deterioration chain. Corrosion products can crack cover concrete and reduce bond, reinforcement area and local ductility. Coastal vulnerability studies also show the sensitivity of predicted deterioration to environmental correlations and diffusion assumptions [16–18,25]. A condition survey that records only surface cracking cannot reliably identify the remaining section or determine whether the governing mechanism is flexural, shear or anchorage failure.

Climatic change complicates extrapolation from past inspection intervals. Scenario studies of ageing concrete assets illustrate how different future temperatures and exposure histories may alter corrosion initiation, propagation and residual life [13,15,16]. Such models should be used to test scenarios rather than to create a spurious single expiry date. In Saudi coastal corridors, location-specific chloride exposure, windborne salt, wetting cycles, cover quality and repair history are more informative than geographical labels alone. Inland structures require different emphasis, including thermal movement, settlement, chemical exposure and the performance of joints.

Ageing also changes demands. Infill removal can create a soft storey; a new façade can increase attachment forces; added plant can exceed local slab capacity; and alterations to adjacent foundations can change support conditions. Seismic and extreme-wind assessment must therefore consider the complete current configuration, not merely the original design drawing. For existing bridges and public buildings, reliability can be undermined by modest losses in a critical connector even when most members remain sound. Deterioration models become useful only when linked to a credible load path and a particular consequence of failure.

A practical hazard register should distinguish slowly varying degradation from event loading and operational threats. The first group includes corrosion, fatigue, settlement and recurrent leakage. The second includes earthquake, wind, flood and accidental impact. The third includes construction-phase instability, fire, service interruption and inaccessible escape routes. Their interactions matter: a corroded joint may be tolerable under routine loading yet brittle under a rare event, while an otherwise efficient retrofit may create unacceptable disruption during installation.

3.1. Establishing an evidence-quality baseline

The initial assessment should reconcile documentary records with the as-built structure. Reliable inputs include occupancy history, drawings, previous strengthening designs, maintenance logs, foundation information and incident records. Surveyors should document the geometry of representative members, reinforcement arrangements, connection details, movement joints and locations of persistent moisture. Targeted testing may then encompass concrete strength, cover depth, chloride profiles, half-cell potential, ultrasonic response, carbonation depth or selective openings. These tools answer different questions; none should be treated as a universal proxy for capacity.

Digital capture can improve spatial traceability without eliminating uncertainty. Computer-vision reconstruction can locate visible defects within a three-dimensional asset representation [19], while linked geometric, monitoring and asset records can support future management decisions [20,21,24,27]. Nevertheless, photogrammetry cannot reveal an embedded anchorage detail behind a finished surface. Monitoring values need calibration, sensor provenance and interpretive thresholds. A BIM object labelled as a column does not prove that the assumed reinforcement and restraints exist. Decisions must retain an explicit list of observed, tested, inferred and unknown properties.

The review consequently recommends confidence classes for structural information: verified, corroborated, assumed and unresolved. These classes are not regulatory grades or statistically calibrated probabilities. Their purpose is to prevent an uncertain dimension or hidden connection from silently becoming a deterministic model input. Where a governing mechanism depends on unresolved evidence, the engineer should order proportionate investigation, adopt a defensible conservative assumption or restrict the asset until uncertainty is reduced.

4. Risk-based prioritisation across an asset portfolio

An effective asset priority list measures consequences as well as physical distress. Risk may be represented conceptually as the frequency or probability of an adverse state multiplied by its consequences, but useful prioritisation requires separate reporting of the drivers. Life-safety exposure, expected downtime, interdependent services, heritage value, cost and accessibility should not be collapsed into an unexplained score. Research on public facilities illustrates that owners may rationally choose strengthening, replacement, divestment or monitored retention, depending on policy and asset value [2,3]. Optimisation studies likewise show that the preferred project changes when the objective shifts between vulnerability, economic loss and resilience loss [4].

Critical infrastructure creates dependency effects beyond the individual building. A modestly damaged pump building can disable a wider network; a hospital access bridge can constrain emergency response; and a service corridor can determine the pace of restoring adjacent assets. Community-level design work therefore argues for recovery-based objectives that supplement traditional life-safety checks [5,6]. This does not imply that every existing building requires immediate occupancy after the maximum considered event. Performance targets should be negotiated around the actual service provided, the plausible hazards and the acceptable period of interrupted operation.

Budget allocation is another structural decision rather than merely an accounting exercise. Multi-facility maintenance research demonstrates the value of joint scheduling under deterioration and resource constraints [22]. Yet a low-cost intervention should not outrank an essential safety correction solely because its estimated benefit-cost ratio is high. A transparent programme first removes interventions that fail minimum safety and statutory gates; then compares feasible alternatives for residual risk, service disruption, affordability, embodied impacts and maintainability [1,23,26,28]. Sensitivity testing should expose whether a preferred option survives changes in hazard assumptions, unit costs or estimated remaining life.

Table 1 presents a qualitative prioritisation architecture intended for professional adaptation. It avoids invented numerical weights. Owners can establish thresholds for urgent restrictions, detailed analysis or routine monitoring; however, those thresholds must be justified against their own portfolio and competent regulatory requirements. An institutional risk committee can own portfolio priorities, but it cannot replace the structural engineer's responsibility for verifying specific load paths and compliance.

Dimension	Evidence	Decision application	Principal concern
Physical condition	Survey, targeted tests	Resolve hidden deterioration before modelling	Diagnostic uncertainty
Structural vulnerability	Updated geometry and loads	Assess governing limit states and continuity	Failure mechanism
Human consequence	Occupancy and evacuation	Prioritise potential casualties and exposure	Life safety
Service criticality	Dependence and outage maps	Set acceptable interruption and recovery	Functionality
Deliverability	Temporary works and access	Exclude unsafe or impracticable sequences	Construction risk
Whole-life effects	Cost, carbon, repair access	Compare feasible options under scenarios	Residual risk

182 *Table 1. Proposed qualitative risk-prioritisation matrix; no numerical weights are assumed.*

183 **5. Saudi code pathway: compliance as a verified process**

184 SBC 901 is the designated Saudi Existing Building Code and provides the appropriate starting point
185 for considering repairs, alterations, additions, changes of occupancy and related work on existing
186 buildings. Its existence is important because refurbishment should not be assessed as if every
187 intervention were a wholly new building. Equally, describing an intervention as repair does not
188 establish that more demanding requirements are irrelevant. The applicable classification must
189 follow the actual scope of work, change in demand, condition of the asset and instructions of the
190 competent authority.

191 The interface with SBC 201, SBC 301 and SBC 304 requires careful coordination. Project teams
192 should establish occupancy and risk classification, the relevant wind and seismic loading
193 parameters, the material design basis and the treatment of foundations and existing members. Where
194 provisions or referenced engineering standards invoke particular assessment procedures, those
195 requirements must be checked against the currently applicable authorised texts. This review does
196 not quote engineering acceptance thresholds or assert clause-by-clause conformity without access to

a project's design documentation. The term SBC-compliant in the title therefore describes a proposed governance pathway for achieving verified compliance, not certification of a hypothetical structure.

A defensible submission should map each regulatory question to a record: work classification, licensed survey, material test evidence, structural idealisation, load combinations, performance checks, detail drawings, temporary-works design, construction inspection and commissioning documents. Discrepancies must remain open actions rather than disappearing between consultants. If an addition shares foundations or lateral resistance with an older structure, interface forces should be investigated explicitly; if the addition is structurally separated, movement compatibility, pounding risk, utility continuity and separation detailing still require assessment [12]. Existing load-path uncertainty should be recorded before selection of strengthening technology.

The approval gate is fundamental. An internal claim of compliance is weaker than a completed design review, applicable permits, documented execution controls and records of installed materials. Even perfect design calculations cannot establish that concealed reinforcement, anchorage or connections were correctly constructed. The final compliance dossier should retain inspection results, change approvals and baseline measurements for future intervention. Figure 1 organises these evidence gates into a repeatable sequence.

A further distinction concerns mandatory safety obligations and voluntary resilience ambitions. A client may wish to retain a building through a future refurbishment cycle, but aspirational service-life claims must not displace the minimum acceptance criteria that apply to the particular work. Design teams should produce a compliance matrix assigning each relevant requirement to the responsible discipline, analytical evidence and construction witness point. Recorded departures require formal resolution before work progresses. This approach reduces the risk of treating an informal modelling assumption as an authorised design decision. It also gives inspectors a clear basis for checking whether concealed work remains consistent with the approved scheme.

SBC compliance pathway for existing assets

Each decision gate requires an auditable engineering deliverable



Figure 1. Proposed six-stage code-oriented evidence and approval sequence (original schematic).

6. Selecting structural intervention mechanisms

Retrofit technologies should be categorised by the deficiency they correct rather than by product identity. Member strengthening seeks additional capacity; system strengthening changes lateral or vertical load distribution; deformation enhancement delays brittle mechanisms; demand reduction uses isolation or dissipative devices; and repair restores damaged material. Several objectives may coexist, but their structural effects can conflict [7,8]. Enlarging a column, for example, may improve local axial resistance while increasing stiffness, attracting seismic actions and transferring higher demands to joints or foundations. Repairing cracked cover improves durability but does not necessarily resolve deficient shear reinforcement.

Evidence on reinforced-concrete retrofits illustrates these trade-offs. Experimental studies of steel bracing and yielding dampers describe substantial improvements in lateral capacity for the tested frames [10]; reviews of textile-reinforced mortar systems discuss confinement and strengthening potential alongside bond and application limitations [11]. Work on damper positioning addresses how relative movement between adjacent frames affects retrofit effectiveness [12]. Such findings are mechanism-specific. The review does not generalise their measured percentages to Saudi building stocks with different geometry, materials, boundary conditions or construction quality.

The dominant failure mode must be analysed at both component and structural-system scales. Shear walls can increase lateral stiffness but may transfer sizeable foundation actions and alter diaphragm demands. Braces offer targeted stiffness or energy dissipation yet require reliable connections to the existing frame. Fibre or textile systems can increase confinement with limited dimensional intrusion, but substrate preparation, anchorage, fire exposure and temperature-dependent material behaviour require close assessment. Post-tensioning, selective replacement or local foundation underpinning may be more appropriate when deformation compatibility or differential settlement governs. An occupied hospital may also favour a staged intervention with smaller work zones despite a higher nominal unit cost.

Performance-based procedures distinguish elastic checks from nonlinear redistribution and drift demands. Review literature supports explicit performance objectives for reinforced-concrete buildings [9], while recovery studies warn that structural strengthening alone can increase floor accelerations and expose sensitive nonstructural equipment [5]. Therefore, retrofit selection should consider partitions, suspended services, equipment anchorage and operational escape routes. A programme which retains the frame but renders an essential facility unusable has only partly achieved resilience.

6.1. Temporary works and refurbishment sequence

The construction state can be more vulnerable than either the original or completed condition. Removing masonry infill, cutting an opening, excavating beside foundations or installing temporary shoring changes the structural system before permanent strengthening is effective. Each transition needs a checked sequence, load transfer rationale and hold point. The temporary load combinations and stability assumptions should be independent of a diagram showing only the final retrofitted configuration.

Phasing also determines whether the intervention is feasible without unacceptable loss of service. For essential facilities, engineers and operators should define isolatable work zones, alternative access, emergency egress, vibration limits, dust containment, temporary utilities and agreed interruption windows. These are not merely contractor conveniences. They can affect whether a proposed strengthening solution is viable at all. Monitoring triggers for settlement, cracking or vibration should be established before intrusive works and tied to explicit actions when exceeded.

Interfaces between retained and replacement elements merit particular scrutiny. Anchor placement, reinforcement development, grout transfer, differential creep, long-term movement, diaphragm

continuity and differing stiffness must be checked. The issue is not only whether the new portion satisfies new-construction strength requirements, but whether the combined assembly develops the assumed forces through its full service life.

7. Integrating durability, sustainability and life-cycle cost

An intervention should be judged over its intended service extension rather than against initial cost alone. Risk-based bridge studies couple future deterioration with maintenance actions and lifecycle consequences [14–16]. Although their parameters are case-specific, the transferable insight is methodological: residual risk should evolve with corrosion, loading, inspection and repair. A single discount rate or nominal service life should not obscure uncertainties in access, asset criticality or future exposure.

Risk and environmental evaluation must also remain distinct. Life-cycle assessment can identify material and construction emissions, while life-cycle costing addresses cash flows; neither automatically measures catastrophic loss or social disruption. Integrating environmental data into design iterations is increasingly feasible using digital tools [26,29], yet retained-material benefits depend on the quantity and durability of added products, temporary works, transport and later maintenance. A low-carbon surface repair that demands repeated closures may perform worse across the asset's service life than a more invasive, durable intervention. Conversely, replacement can carry avoidable embodied impacts where targeted strengthening preserves usable capacity.

The review proposes a constrained comparison: reject options that fail mandatory performance or execution controls, then compare remaining options through expected downtime, future maintenance, embodied emissions, access requirements and discounted expenditure. Analytical sensitivity is essential. If the preferred strategy switches under modest changes in corrosion rate, programme duration or assumed component cost, the decision should be accompanied by a monitoring or reassessment trigger rather than presented as definitive.

The timing of investigation is economically significant. Early testing may prevent expensive strengthening where apparent distress has little structural consequence, but delayed diagnosis can allow corrosion or settlement to reach a stage requiring extensive closure. Decision analysis should therefore include the value of information: whether a targeted test could reasonably change the selection of intervention. Benefits are highest when uncertainty affects a safety-critical mechanism or separates two expensive alternatives. Conversely, collecting measurements without a decision

purpose wastes resources. Rehabilitation plans should identify what new information will trigger redesign, an altered inspection interval, or an emergency restriction, and who has authority to act.

8. Digital records and performance verification

Risk-based refurbishment benefits from a maintained digital evidence trail, but a digital twin is not itself evidence of structural adequacy. Research on digital inspection demonstrates that surface defects can be mapped and tracked [19], while facilities studies show the practical challenge of integrating sensors, models, data ownership and workforce capabilities [20,21]. A structural digital record must preserve dates, locations, inspection methods, model revisions, assumptions and the authority responsible for each decision. Without provenance, repeated visualisations can create confidence without improving accuracy.

For deteriorated bridges, integration of information models with numerical analysis provides a route to linking condition observations and engineering evaluation [24]. Monitoring should focus on mechanisms that might invalidate the design: drift under operational loading, settlement, joint movement, crack evolution, corrosion indicators, moisture ingress and critical connection response. The monitored quantity needs an expected range, a dependable acquisition method and an accountable decision owner. A sensor alarm without a response protocol does not constitute resilience management.

Validation should distinguish three stages. Design verification checks predicted performance under selected hazard and deterioration states. Construction verification checks installed materials, geometry, anchors and sequence against approved documents. Service verification compares measured behaviour with baseline predictions and operating requirements. Remote sensing can support prioritisation after major disruptions, but it does not eliminate the need for close inspection where safety depends on concealed damage [30]. Table 2 presents a proposed evidence register that links each intervention stage to a specific decision and retained record.

Decision gate	Accountable lead	Minimum retained evidence
1. Scope	Owner and licensed designer	Work classification, occupancy and regulatory matrix
2. Diagnose	Survey and testing team	As-built register, tests and evidence confidence

Decision gate	Accountable lead	Minimum retained evidence
3. Assess	Structural engineer	Hazard model, consequence assessment, performance target
4. Select	Designer and operator	Option appraisal, phasing and residual limitations
5. Deliver	Authority and contractor	Approval, inspection records and change control
6. Operate	Asset owner	Handover baseline, monitoring triggers and review dates

Table 2. Proposed compliance and resilience verification register for existing assets.

9. Discussion: a six-gate risk-to-resilience framework

The integrated evidence supports six decision gates. Gate one identifies asset function, legal work classification and credible hazards. Gate two confirms the information needed to model material condition and load paths. Gate three determines target performance and the consequences of failure, including downtime and network dependencies. Gate four compares feasible retrofit mechanisms against structural, construction and whole-life constraints. Gate five establishes approval, temporary-work safeguards and quality assurance. Gate six audits long-term performance and defines future inspection and intervention triggers. Figure 2 depicts this cycle as an accountable governance system, not a completed software model.

The sequence is deliberately iterative. A new chloride profile may require revision of remaining-life assumptions; an unexpected foundation condition can invalidate a bracing scheme; or an approval requirement can alter the construction sequence. Returning to an earlier gate is therefore correct engineering practice, not a process failure. Stronger documentation has a practical benefit: it allows future teams to distinguish an accepted residual risk from an undocumented oversight.

The literature exposes a persistent scale mismatch. Material tests quantify local strength or durability; structural models represent idealised systems; owners allocate money across portfolios; and regulators assess documentary compliance. No single dataset connects all four scales with equal confidence. The proposed framework limits that mismatch by requiring traceable transitions: member evidence informs structural assessment, structural assessment informs consequence

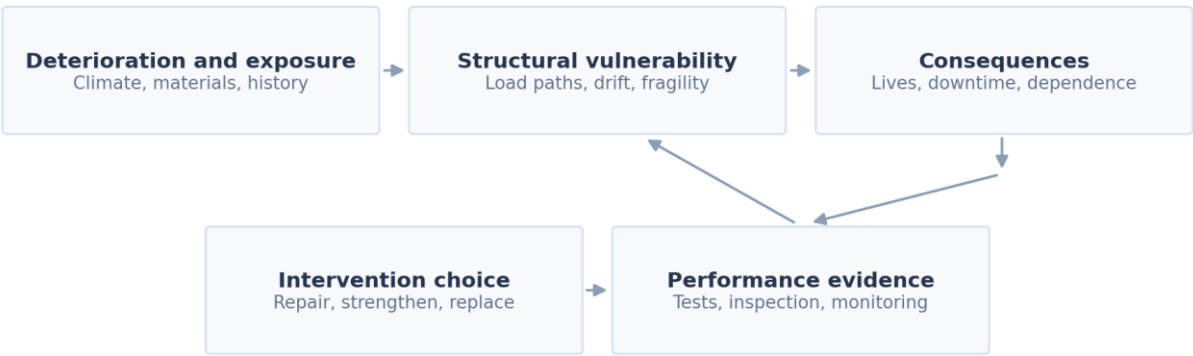
appraisal, and the selected option enters a verification plan. This is also why a universal numerical risk score is inappropriate without local calibration.

For Saudi asset portfolios, priority should be placed on comparable inspection vocabularies, exposure-specific deterioration models and post-intervention records that can be audited across organisations. Longitudinal monitoring is especially valuable where the effectiveness of intervention depends on workmanship, exposure or interface conditions. Nevertheless, monitoring should complement rather than postpone urgent safety action. When credible evidence indicates imminent failure, restriction, stabilisation or closure precedes portfolio optimisation.

Institutional delivery demands continuity between the owner, designer, contractor and operator. A risk register that ends at the design tender cannot represent the asset after material substitutions, intrusive discoveries or changed usage. Each gate should therefore name an accountable party and a communication route for deviations. Owners need a usable summary of residual limitations, including permitted loads, future inspections, known concealed uncertainties and restrictions on alterations. Facility staff require instructions written in operational language, rather than a stack of analytical printouts. This distinction improves the prospect that approved structural assumptions remain valid throughout occupation, particularly after successive minor works.

Risk-to-resilience feedback architecture

Structural safety, service continuity and residual risk are considered jointly



Iterate after new surveys, design changes, construction discoveries or monitored exceedances

Figure 2. Conceptual interaction between deterioration, vulnerability, consequences and verification (original schematic).

10. Limitations and research agenda

This is a critical evidence synthesis, not a statistically exhaustive review or validation exercise. The selected studies span varied countries, structural systems and measurement protocols; their reported benefits cannot be pooled into a Saudi design factor. The national code documents were examined for stated scope and document relationships, not reproduced as full licensed technical provisions. Local authority interpretation, site hazard parameters and contractual responsibility may change the practical implementation of the framework.

Four research tasks are particularly pressing. First, Saudi field studies should establish calibrated relationships between observed condition and residual structural resistance across coastal and inland exposures. Secondly, representative retrofit case studies should publish pre- and post-intervention model assumptions alongside measured response, including construction-stage effects. Thirdly, facility-level functional recovery should be evaluated together with damage to nonstructural components and service dependencies. Finally, multicriteria asset planning should report uncertainty and rejected alternatives, instead of presenting opaque priority rankings.

Prospective demonstration should use several real assets with contrasting exposures and functions, documenting decisions independently at every gate. Success metrics should include traceability of assumptions, inspection responsiveness, expected loss, outage duration, whole-life cost, carbon consequences and approved construction deviations. Such studies would test whether the framework improves decisions, rather than merely showing that a new diagram can describe familiar activities.

11. Conclusions

Resilient refurbishment requires more than repairing visible deterioration or increasing nominal member strength. The most defensible choice emerges when reliable condition evidence, current structural demand, consequences of failure, code applicability and construction feasibility are assessed together. The reviewed evidence shows that retrofit rankings change with the selected objective and that life-safety improvements do not automatically ensure continued operation. Coastal corrosion, changes in occupancy, concealed interfaces and nonstructural dependencies are therefore first-order issues rather than optional refinements.

The proposed six-gate framework links these concerns to Saudi existing-building regulation through a documented pathway from classification and investigation to approval and post-works

verification. It is intended to support competent engineers and infrastructure owners, not to certify code compliance in the absence of site-specific analyses. By retaining uncertainty, construction-stage controls and future monitoring within the decision, Saudi asset managers can prioritise interventions that extend useful life without obscuring residual risk. The next decisive contribution will be transparent field evidence connecting retrofit choices to verified long-term performance. Future validation should compare reviewed intervention choices against measured outcomes across Saudi climates, occupancies and construction eras.

References

1. Zhang, Y.; Fung, J.; Cook, D.; Johnson, K.; Sattar, S. (2024). Benefit–Cost Analysis for Earthquake-Resilient Building Design and Retrofit: State of the Art and Future Research Needs. *Natural Hazards Review*, 25(3). <https://doi.org/10.1061/NHREFO.NHENG-1910>
2. Brown, C.; Seville, E.; Horsfall, S.; Bugler, G.; Brunsdon, D.; Hare, J. (2022). Seismic repair and retrofit prioritization framework. *Earthquake Spectra*, 38(4), 2886–2900. <https://doi.org/10.1177/87552930221109292>
3. Zawacki, B.S.; Jafarzadeh, R.; Ingham, J.M.; Walsh, K.Q. (2020). Proposed Decision-Making Framework for the Risk Management of Publicly Owned Earthquake Prone Buildings. *Journal of Performance of Constructed Facilities*, 34(5). [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0001489](https://doi.org/10.1061/(ASCE)CF.1943-5509.0001489)
4. Liu, C.; Ouyang, M.; Mao, Z.; Xu, X. (2022). A multi-perspective framework for seismic retrofit optimization of urban infrastructure systems. *Earthquake Engineering & Structural Dynamics*, 51, 2771–2790. <https://doi.org/10.1002/eqe.3701>
5. Mohammadgholibeyki, N.; et al. (2023). Assessing the feasibility of achieving functional recovery goals through seismic retrofit of existing reinforced concrete buildings. *Earthquake Spectra*. <https://doi.org/10.1177/87552930231197669>
6. Sediek, O.A.; Roohi, M.; van de Lindt, J.W. (2024). A Decision Support Methodology for Seismic Design Requirements of Buildings to Achieve Community-Level Resilience Metrics. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, 10(3). <https://doi.org/10.1061/AJRUA6.RUENG-1213>
7. Almeida, R.; Rodrigues, H.; Gomes, M.G.; Furtado, A. (2024). Perspectives on integrated retrofitting of existing reinforced concrete buildings. *Procedia Structural Integrity*, 55, 135–142. <https://doi.org/10.1016/j.prostr.2024.02.018>

8. Caruso, M.; Couto, R.; Pinho, R.; Monteiro, R. (2023). Decision-making approaches for optimal seismic/energy integrated retrofitting of existing buildings. *Frontiers in Built Environment*, 9. <https://doi.org/10.3389/fbuil.2023.1176515>
9. Padalu, P.K.V.R.; Surana, M. (2024). An Overview of Performance-Based Seismic Design Framework for Reinforced Concrete Frame Buildings. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 48, 635–667. <https://doi.org/10.1007/s40996-023-01217-4>
10. Kothapalli, N.K.; Chidambaram, R.S.; Agarwal, P. (2023). Experimental Evaluation of Steel Bracings and Metallic Yield Damper as Retrofit Techniques for Severely Damaged RC Building Frames. *Journal of Earthquake Engineering*, 27(12), 3564–3587. <https://doi.org/10.1080/13632469.2022.2141373>
11. Kobbekaduwa, D.; Nanayakkara, O.; Di Sarno, L.; Krevaikas, T. (2024). Strengthening and repair of deficient reinforced concrete columns using textile-reinforced mortar: State-of-the-art review. *Structures*, 65, 106739. <https://doi.org/10.1016/j.istruc.2024.106739>
12. Asgarkhani, N.; Kazemi, F.; Jankowski, R. (2023). Optimal retrofit strategy using viscous dampers between adjacent RC and SMRFs prone to earthquake-induced pounding. *Archives of Civil and Mechanical Engineering*, 23, 7. <https://doi.org/10.1007/s43452-022-00542-1>
13. Nagaraju, A.S.V.; Kumar, R. (2024). Effect of climate change on structural safety of RC bridges in coastal region. *Structures*, 63, 106273. <https://doi.org/10.1016/j.istruc.2024.106273>
14. Al Hawarneh, A.; Alam, M.S. (2025). Maintenance Optimization Model for Existing Reinforced Concrete Bridge Piers Based on an Integrated Life-Cycle Cost and Performance-Based Design Approach. *Journal of Structural Engineering*, 151(10). <https://doi.org/10.1061/JSENDH.STENG-14270>
15. Lee, S.H.; An, L.-S.; Kim, H.-K. (2025). Risk-based bridge life cycle cost and environmental impact assessment considering climate change effects. *Scientific Reports*, 15, 725. <https://doi.org/10.1038/s41598-024-82568-4>
16. Koptika, N.; Robery, P.; Ninic, J.; Mitoulis, S.-A. (2025). Remaining Life of Ageing RC Infrastructure for Sustainable Development: Deterioration Under Climate Change. *Case Studies in Construction Materials*, 22, e04757. <https://doi.org/10.1016/j.cscm.2025.e04757>
17. Chi, X.; Xu, A.; Liu, Y.; Lun, P. (2023). Engineering vulnerability evaluation of building structures in coastal areas considering the effects of corrosion. *Frontiers in Materials*, 9, 1107378. <https://doi.org/10.3389/fmats.2022.1107378>

18. Zhao, T.; Zhang, Y.; Li, K.; Wang, J.; et al. (2023). A copula approach in the probabilistic evaluation of chloride ingress process for coastal concrete structures. *Structures*, 56, 104918. <https://doi.org/10.1016/j.istruc.2023.104918>
19. Wang, T.; Gan, V.J.L. (2023). Automated joint 3D reconstruction and visual inspection for buildings using computer vision and transfer learning. *Automation in Construction*, 149, 104810. <https://doi.org/10.1016/j.autcon.2023.104810>
20. Nguyen, T.D.H.N.; Ly, D.H.; Jang, H.; Dinh, H.N.N.; Ahn, Y. (2025). Digital twin framework to enhance facility management for relocatable modular buildings. *Automation in Construction*, 176, 106249. <https://doi.org/10.1016/j.autcon.2025.106249>
21. Signorini, M.; Pomè, A.P. (2025). Shaping the future of facility management: Market and literature insights on digital twin adoption. *Facilities*, 43(11–12), 818–834. <https://doi.org/10.1108/F-02-2025-0029>
22. Shi, Y.; Xiang, Y.; Xiao, H.; Xing, L. (2021). Joint optimization of budget allocation and maintenance planning of multi-facility transportation infrastructure systems. *European Journal of Operational Research*, 288, 382–393. <https://doi.org/10.1016/j.ejor.2020.05.050>
23. Wang, B.; Xia, X.; Cheng, Z.; Liu, L. (2020). Optimal maintenance planning in building retrofitting with interacting energy effects. *Optimal Control Applications and Methods*, 41, 2023–2036. <https://doi.org/10.1002/oca.2593>
24. Alsharif, M.A.; Thermou, G.; Ninic, J.; Tizani, W. (2025). Data integration framework for multi-level information modelling and numerical analysis of deteriorated RC bridges. *Advances in Engineering Software*, 202, 103860. <https://doi.org/10.1016/j.advengsoft.2024.103860>
25. Sun, D.; Cao, Z.; Huang, C.; Wu, K.; De Schutter, G.; Zhang, L. (2022). Degradation of concrete in marine environment under coupled chloride and sulfate attack: A numerical and experimental study. *Case Studies in Construction Materials*, 17, e01218. <https://doi.org/10.1016/j.cscm.2022.e01218>
26. Gay, I.C.; Hvam, L.; Haug, A.; Huang, G.Q.; Larsson, R. (2024). A digital tool for life cycle assessment in construction projects. *Developments in the Built Environment*, 20, 100535. <https://doi.org/10.1016/j.dibe.2024.100535>
27. Chen, X.Y.; Pan, Y.; Gan, V.J.L.; Yan, K. (2024). 3D reconstruction of semantic-rich digital twins for ACMV monitoring and anomaly detection via scan-to-BIM and time-series data integration. *Developments in the Built Environment*, 19, 100503. <https://doi.org/10.1016/j.dibe.2024.100503>

- 489 28. Mushtaha, A.W.; Alaloul, W.S.; Baarimah, A.O.; Musarat, M.A.; et al. (2025). A decision-
490 making framework for prioritizing reconstruction projects in post-disaster recovery. *Results in*
491 *Engineering*, 25, 103693. <https://doi.org/10.1016/j.rineng.2024.103693>
- 492 29. Scolaro, T.P.; Ghisi, E. (2025). Life cycle integrated multi-criteria decision model for roof
493 assessment. *Energy and Buildings*, 336, 115628. <https://doi.org/10.1016/j.enbuild.2025.115628>
- 494 30. Kopiika, N.; Karavias, A.; Krassakis, P.; Ye, Z.; et al. (2025). Rapid post-disaster infrastructure
495 damage characterisation using remote sensing and deep learning technologies: A tiered
496 approach. *Automation in Construction*, 170, 105955.
497 <https://doi.org/10.1016/j.autcon.2024.105955>