Global Academic Journal of Economics and Business

Available online at https://www.gajrc.com
DOI: https://doi.org/10.36348/gajeb.2026.v08i06.019

ISSN: 2706-9001 (P)
ISSN: 2707-2584 (O)

Review Article

Resilient Expansion of Operational Airport Infrastructure in Saudi Arabia: Structural Retrofitting, Construction Sequencing and Existing-to-New Structure Integration

Mohammed Abdul Rahman[1]*
[1]Independent Researcher

***Corresponding Author**
Mohammed Abdul Rahman
Independent Researcher

Article History
Received: 13.09.2026
Accepted: 06.11.2026
Published: 18.11.2026

Abstract: The expansion of an operational airport is a structural engineering problem embedded within a continuously functioning transport system. This review examines how existing airport assets can be retained and strengthened while new terminal, apron and airfield facilities are constructed alongside uninterrupted aviation operations. Its aim is to formulate an integrated engineering approach that links the diagnosis of existing structures, selection of retrofit interventions, construction sequencing and design of old-to-new interfaces. Thirty peer-reviewed publications issued between 2020 and 2025 were critically synthesised across airport performance, reinforced-concrete strengthening, interface mechanics, construction informatics and resilience assessment. The evidence distinguishes robust principles from techniques supported primarily by laboratory specimens or transferable non-airport projects. Three findings emerge: retrofit decisions require a credible as-built load-path model; sequencing must be checked as a succession of temporary structural states and operational constraints; and interface details must account simultaneously for shear transfer, differential movement, durability and accessibility. A staged assurance framework is proposed for Saudi Arabian programmes, with explicit decision gates and measurable performance indicators. The framework is conceptual rather than a validated airport case study. It offers a basis for future project-specific modelling, monitoring and comparative evaluation without claiming unmeasured reductions in risk, cost or interruption.

Keywords: Airport Infrastructure, Saudi Arabia, Structural Retrofitting, Construction Sequencing, Interface Shear, Operational Continuity, Resilience.

Copyright © 2026 The Author(s): This is an open-access article distributed under the terms of the Creative Commons Attribution **4.0 International License (CC BY-NC 4.0)** which permits unrestricted use, distribution, and reproduction in any medium for non-commercial use provided the original author and source are credited.

1. INTRODUCTION

Airport capacity expansion is often presented as a choice between building new infrastructure and extending an existing estate. At a functioning airport, however, the consequential decision is how the two estates can coexist while aircraft, passengers, staff and emergency services retain safe access. A new pier can alter pedestrian flows long before its structure is complete; a foundation excavation can affect an adjacent frame before any permanent connection exists. Consequently, structural adequacy cannot be separated from the sequence in which temporary and permanent works are installed. Research on runway investment identifies the need to select evaluation criteria according to the operational decision being

made, rather than assume that lowest initial cost represents best performance [1].

Saudi Arabia's aviation development ambitions give this problem particular practical significance. Expansion programmes may combine older terminal blocks, service buildings, buried networks and airfield pavements with larger facilities designed under newer load assumptions. The national setting also makes high-temperature exposure, dust, high cooling demand and the management of peak transport flows important design considerations. These are context-specific design concerns, not evidence that any particular Saudi airport possesses a structural defect. Redevelopment studies elsewhere show why preserving an established airport may still be justified by network demand even when new capacity is available [2].

Most relevant disciplines have evolved separately. Airport pavement research addresses serviceability, material selection and rehabilitation [3–6], terminal research examines assembly programmes and resilience under disruption [7–10]. Structural engineering studies concentrate on strengthening members, frames and connections [11–20], while informatics research seeks to improve constructability and information continuity [21–25]. Taken alone, each body offers a partial answer. Their practical integration requires attention to the moment when an incomplete building, temporary support system and active aviation environment interact.

The aim of this review is to establish a coherent engineering framework for resilient expansion of operational airport infrastructure in Saudi Arabia. Its objectives are to identify transferable retrofit strategies; examine how construction sequences govern temporary capacity and airport continuity; evaluate the mechanical and durability implications of existing-to-new interfaces; and propose auditable decision criteria for integrated delivery. Unlike an optimisation case study, this paper does not rank hypothetical projects using invented measurements. It critically synthesises published evidence, recognises boundary conditions and identifies the tests required before the framework can guide a real investment decision.

2. Review Design and Analytical Approach

An integrative critical review was selected because the research question crosses several evidence types: laboratory interface tests, numerical analyses, airport operations models, construction-planning methods and prior technical reviews. A meta-analysis would imply comparable interventions and outcomes that the literature does not provide. The review corpus comprises thirty identifiable, DOI-bearing journal publications dated from 2020 to 2025. Papers were selected purposively for explicit relevance to at least one component of airport continuity, structural adaptation, construction sequencing, new-to-old connection design or lifecycle resilience. The corpus is not represented as an exhaustive database search and no formal pooled effect estimate is attempted.

Each publication was read against four analytical questions. First, what physical system and construction or operational condition was studied? Second, which outcome was actually observed or simulated, and under what assumptions? Third, what limits transfer to a large operating airport in Saudi Arabia? Fourth, which project evidence would be required before using the finding? This approach prevents a successful coupon-scale bond test from being described as proof of airport-wide structural reliability, and prevents a scheduling algorithm demonstrated on isolated frames from being presented as an approved runway possession plan.

Synthesis proceeded through three interacting themes: existing-asset diagnosis and intervention, temporary-state constructability, and interface compatibility. Airport operational resilience and environmental performance were treated as cross-cutting acceptance conditions rather than separate decorative objectives. Conceptual relationships were checked for conflicting design consequences, particularly stiffness changes versus differential movement, accelerated installation versus inspection access, and uninterrupted service versus worker segregation. Table 1 records the evidence-to-decision matrix; Figure 1 presents the proposed integration. Neither table entries nor figures constitute original field measurements.

Table 1: Evidence-to-decision matrix for resilient expansion of operational airport assets

Evidence stream	Key question	Useful evidence	Transfer limit / gate
Operating airport	What service must remain available?	Delay and resilience models; closure mapping [8–10]	Approve passenger, airside and emergency access scenarios
Existing fabric	What can be retained safely?	Condition survey; load-path analysis; tests [4-11]	Release only after critical unknowns are resolved

Evidence stream	Key question	Useful evidence	Transfer limit / gate
Retrofitting	Which capacity or ductility deficit is corrected?	Member/frame intervention research [12–14]	Check new reactions, foundations and occupied works
Construction state	Is every intermediate arrangement safe?	Sequence search; precedence logic [21,22]	Independent temporary-works design and hold points
Structural interface	How will force and movement cross the joint?	Shear, roughness, anchorage tests [15–30]	Inspect substrate, bars, seals and deformation range
Lifecycle assurance	What happens after commissioning?	Maintenance and digital monitoring [6-25]	Handover baseline, limits and inspection ownership

3. Characterising the Operational Asset and Its Constraints

A credible expansion scheme begins with an asset boundary wider than the footprint of the new structure. Existing terminal frames, foundations, slabs, service trenches, apron interfaces, utilities and movement corridors may act as an interconnected system even when drawings show separate work packages. Investigation should therefore reconcile archive drawings with measured geometry, material testing, foundation records and the history of alteration. For airfield pavements, structural evaluation methods using falling-weight or heavy-weight deflectometers provide a useful parallel: capacity is inferred from measured response and design assumptions rather than appearance alone [4].

The structural assessment must establish present resistance and deformation demand without treating nominal design data as verified facts. Concrete strength may vary by location; reinforcement positions may differ from drawing schedules; inaccessible joints can conceal corrosion or movement. A tiered survey begins with records and visual mapping, continues through targeted non-destructive testing and selective opening, and ends with calibrated structural analysis where uncertainty affects the intervention. Digital-twin research demonstrates methods for updating numerical models with measurements to locate potential weaknesses, but those methods remain dependent on sensor coverage, model fidelity and identifiable loading [25].

Operational constraints should be written as engineering inputs. Examples include permissible closures, passenger-route capacity, rescue and firefighting access, runway safeguarding surfaces, dust migration pathways, vibration-sensitive installations and utility redundancy. Terminal simulation research finds that resilience metrics can differ substantially according to how disruption and recovery are defined [8]. Accordingly, an acceptable construction solution cannot be judged only by programme completion; it also needs a credible description of how service deteriorates, how quickly it recovers and which activities cannot be interrupted.

Environmental exposure affects both the old fabric and the planned joint. Temperature gradients across a long roof or apron can generate movement even when structural strength is adequate. Thermal cycles influence sealants and bearings, while chlorides and moisture may accelerate deterioration at vulnerable interfaces. Climate-resilience assessments emphasise preparedness and staged response [9, 10]. In Saudi airport applications, exposure design should use verified site weather records and measured movement ranges; generic regional assumptions should not replace a project-specific thermal model or exposure classification.

4. Structural Retrofitting Without Loss of Service

Retrofitting must answer two questions that are often conflated: what deficiency exists, and which intervention can be implemented safely under partial occupancy? The first concerns resistance, stiffness, ductility, durability or robustness; the second concerns access, noise, dust, temporary supports, curing time and emergency evacuation. A broad review of existing reinforced-concrete buildings distinguishes local member improvements from global systems that alter lateral resistance [11]. That classification is particularly useful at airports because strengthening one beam and adding an external stability frame impose very different access and interface demands.

Local strategies include section enlargement, bonded or mechanically secured composites, reinforced cementitious jackets and targeted connection upgrades. Experimental work on thin fibre-reinforced cementitious jackets reports improved column flexural behaviour and energy dissipation under tested conditions [14]. Such evidence supports material selection but not unqualified adoption. Surface preparation, original reinforcement, anchor installation, fire performance and achievable workmanship must be examined in context. The most attractive retrofit may be the one with fewer interventions inside occupied space,

rather than the option with the greatest isolated specimen strength gain.

Global strategies include external frames, braces or supplementary lateral systems attached to an existing building. The exoskeleton approach studied by Hsiao and colleagues was developed with continued building occupancy as an explicit consideration [12]. Other experiments have investigated prestressed external steel frames as a means of increasing lateral resistance [13]. For a terminal, however, the introduction of global stiffness may attract actions into foundations that were not designed for them. New load paths, transfer elements and the influence on neighbouring bays require three-dimensional analysis covering both service and extreme loading combinations.

Combined structural and environmental refurbishment offers a further possibility when terminal envelopes are being renewed. Prefabricated textile-reinforced panels have been examined for simultaneous strengthening and thermal improvement [28], while a broader review describes the opportunities and trade-offs of integrated seismic-energy interventions [29]. These findings are not airport-specific. They suggest an investigation route where façade replacement or plant upgrades are already scheduled, but the weight, attachment loads, airtightness and accessibility consequences must be checked before any combined package can be justified.

Retrofit verification should match the governing failure mechanism. An analysis model can demonstrate an intended load redistribution, whereas site evidence must show that anchors, substrate, reinforcement and joints actually permit it. Hold points may include substrate acceptance, reinforcement scans, installation records, material traceability, curing checks and proof testing where relevant. Monitoring should target predicted response variables, such as settlement, joint opening or member strain, rather than collecting sensor readings without a decision threshold. Airport authorities should require a documented return-to-service test that confirms both structural safety and restored operational access.

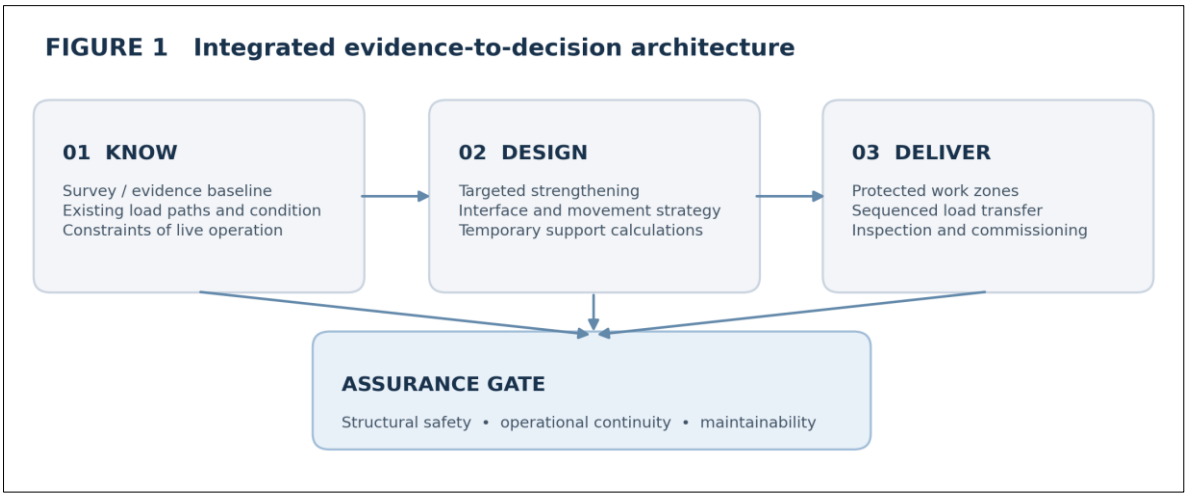


Figure 1: Original conceptual architecture connecting asset evidence, retrofit design and staged delivery through a shared assurance gate

5. Sequencing Construction alongside Aircraft and Passengers

Construction sequencing is not merely the ordering of activities in a scheduling application. Every removal, excavation, lift or connection changes the temporary equilibrium of an evolving structure. A sequence that is safe in its final configuration can be unsafe between removal of an existing restraint and activation of its replacement. Research on constructability-driven frame design formalises this problem by evaluating displacement and stress during candidate assembly sequences [21]. Its algorithms concern specified structural models; airport adoption additionally requires operational restrictions, uncertain discovery conditions and independently checked temporary works.

The first stage should protect the live system. Before intrusive work, the project team needs approved work-area segregation, utilities isolation plans, emergency arrangements and a verified schedule of possessions. Temporary support design must cover credible accidental events and foreseeable changes in load distribution. Subsequent activities can be grouped into enabling works, off-line construction, interface preparation, planned transfer and reopening. The transfer stage deserves special scrutiny because loads and services may move

between old and new systems while both remain partially complete.

An effective programme uses explicit precedence relations that include engineering release conditions. For example, drilling connection holes must follow reinforcement mapping; temporary propping cannot be removed until grout strength and inspection are accepted; access barriers should not move before passenger-route testing. Sequential pattern-mining research demonstrates how construction logic may be derived from historical project records [22]. Such patterns are useful as planning aids, but they cannot determine the safe order of operations where structural geometry, aviation rules and existing defects differ from those in the training record.

Four-dimensional information models can link work packages, space, resources and closure periods. A published airport-terminal study examined the time-cost optimisation of large-span steel construction using building information modelling [7]. For an extension project, the same coordination principle should extend to temporary escape routes, crane exclusion envelopes, façade openings, plant changeovers and commissioning zones. Model quality matters: inaccurate as-built geometry can create false confidence in clash detection. Ground-service digital-twin research suggests that construction models should be coordinated with the information used to manage live airport processes [24].

Operational resilience is an active constraint rather than a benefit added after scheduling. Terminal-level research shows that a disruption's effect depends on how delays propagate and how recovery is measured [8]. Work windows should therefore be assessed against passenger demand, aircraft movement, security processing and contingency capacity. Digital-twin studies of airport ground services illustrate how real-time process information can support delay diagnosis [24]. However, a construction planner must not infer the structural safety of a temporary support arrangement from operational simulation alone. The two models answer different questions and require coordinated, separately validated assumptions.

Figure 2 translates these principles into a sequence of stage gates. The most important rule is that programme acceleration cannot bypass the technical release criteria at a stage boundary. Shortening a curing interval, postponing an inspection or opening an unverified interface may create a hidden deficit that later manifests as settlement, cracking or loss of access. Conversely, prefabrication, off-line service diversions and controlled nighttime possessions can reduce exposure without relaxing performance criteria. The preferred sequence is the one with acceptable performance in every intermediate state, not simply the earliest completion date.

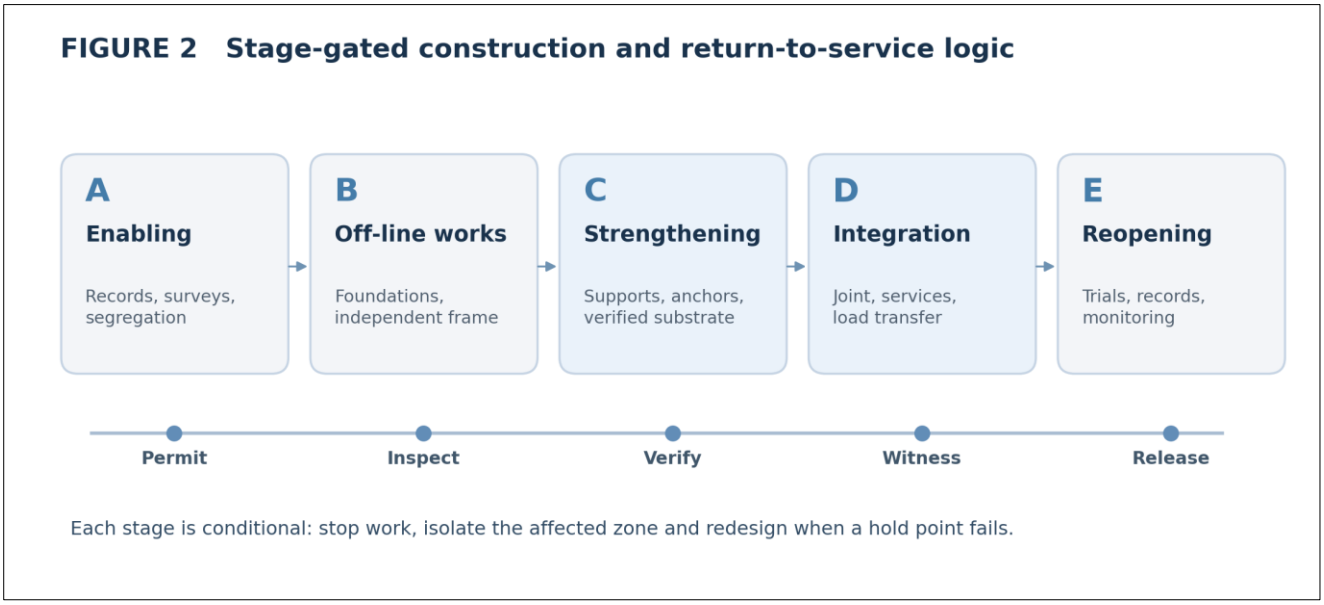


Figure 2: Proposed stage-gate sequence for construction adjacent to airport operations; stages denote decision logic, not a site-specific programme

6. Existing-To-New Structural Integration

The interface between retained and added infrastructure is the central engineering decision because it determines whether two parts behave independently or transfer actions together. A rigid structural tie can support continuity and

redistribution but also transmit differential settlement, temperature movement and dynamic effects. A movement joint permits relative displacement yet requires durable weatherproofing, fire separation, service flexibility and safe traversability. Neither option is universally superior. The governing decision is the compatibility of anticipated actions and movements with the existing load path and planned function.

For concrete-to-concrete connections, interface shear resistance depends on surface texture, confinement, reinforcement crossing the plane and the quality of execution. Direct shear experiments on old and new concrete show the influence of roughness treatment and dowel arrangement on shear-slip response [15]. Additional tests using varied preparation methods caution that nominally comparable roughness does not guarantee identical capacity [16]. Therefore, selecting a roughness category from a specification is not a substitute for verifying the substrate and the construction procedure that produced it.

Where reinforcement must be introduced into existing concrete, post-installed bars can provide a practical load-transfer route. Their reliability depends on properly qualified materials, anchorage geometry, installation controls and conditions of service [17]. Anchor drilling near congested reinforcement or slab edges creates hazards that design calculations alone do not remove. Research on low-invasive haunch retrofits confirms that connection behaviour and adjacent slab participation can influence frame response [20]. Testing and detailing must therefore include edge distances, crack conditions, group effects and accessibility for future inspection, rather than assume that all installed dowels mobilise simultaneously.

Bonding agents and advanced cementitious materials may improve particular failure modes but should not be treated as interchangeable. Experiments comparing an amended epoxy system with alternative surface treatments show that interface preparation remains consequential [18]. Tests of ultra-high-performance concrete distinguish monolithic from non-monolithic shear transfer and demonstrate the importance of fibre content and interface condition [19]. A new high-strength topping may still form a vulnerable composite member if its interface cannot reliably transmit required shear. Material optimisation must follow, not replace, verification of structural action.

Differential movement becomes critical where new foundations are deeper, loads increase substantially or old slabs have accumulated settlement. Analysis should consider long-term creep and shrinkage, thermal gradients, construction-stage loading and plausible foundation displacement. These effects have different timescales and cannot be represented by one maximum gap value without justification. If movement compatibility is uncertain, a deliberately articulated interface with independent gravity resistance may offer a more robust arrangement. If moment continuity is necessary, designers must demonstrate that rotations, shear transfer and deformation compatibility remain acceptable throughout service life.

Joint detailing also affects operational integrity. Changes in floor level can impede accessibility and luggage handling; cracks and water penetration may interrupt electrical services; poorly protected joints can form paths for smoke, dust or contaminants. Airport-specific acceptance criteria should therefore extend beyond nominal joint strength to include movement tolerance, fire and acoustic performance, maintainable seals, inspection access and resistance to local exposure. Table 2 provides an interface-focused decision register. It requires project teams to disclose which assumptions are measured, which are modelled and which remain unresolved before structural integration is authorised.

Table 2: Interface design register linking uncertainty, mechanical decisions and acceptance requirements

Interface issue	Preferred investigation	Design decision	Acceptance evidence
Shear transfer	Roughness profile, strength, reinforcement scan	Keyed, dowelled or separated detail	Test basis; checked design; inspection record
Differential settlement	Foundation records; movement baseline	Rigid tie or articulated transition	Predicted displacement within detailed capacity
Thermal movement	Site temperatures; restraint modelling	Joint width, bearings and flexible services	Movement and seal qualification
Installation uncertainty	Drilling trial; access and curing review	Anchor type, layout and work window	Qualified system; installed logs; hold point
Operational interfaces	Passenger route, airside access, fire strategy	Transitions, partitions and service flexibility	Route trial; protection and reopening approval

7. Integrated Decision Framework for Saudi Airport Programmes

An integrated framework should preserve traceability between technical diagnosis, programme decisions and operational permission. Figure 1 organises the process around three evidence streams: existing-condition knowledge, intervention and interface design, and temporary-state delivery. These streams converge at a stage gate where safety, service continuity and lifecycle outcomes are reviewed together. The concept adapts literature from separate disciplines; it is not an empirically validated scoring model and does not assign arbitrary weights to incompatible hazards.

Decision-making should begin with non-negotiable constraints. A proposal that cannot maintain emergency access, adequate temporary structural resistance or a viable passenger route must be revised before economic comparison. Among feasible alternatives, evaluation can consider direct expenditure, interruption exposure, embodied carbon, maintainability and future adaptability. Prior work on airport pavement material selection demonstrates the value of transparent multicriteria criteria definition [3], while lifecycle-informed building material research indicates why economic, environmental and social effects should not be reduced to procurement price [23]. The actual weights should be established by accountable airport stakeholders rather than borrowed uncritically from unrelated projects.

A practical performance register should distinguish leading and lagging measures. Leading measures include percentage of critical as-built elements verified, proportion of connections inspected before concealment, temporary-work design releases, model clashes resolved and contingency resources available. Lagging measures include unplanned closure hours, settlement exceedances, rework, interface leakage and defects recorded after handover. Measures need stated denominators, recording frequency, ownership and response thresholds. A dashboard without these definitions can create an appearance of control while obscuring the real engineering state.

For Saudi deployment, project governance should include the airport operator, structural designer, specialist retrofit contractor, airside safety representatives, facilities management and the authority responsible for relevant approvals. Responsibilities for temporary works, service isolation and reopening should be assigned individually, not inferred from a general construction contract. Thermal exposure, dust control, labour access and peak-travel periods should appear in the method statement and programme assumptions. The emphasis is on a transferable procedure that can be tailored to local regulatory conditions, not an assertion that a single detail or construction window is suitable across all airports.

8. Critical Discussion and Research Priorities

The strongest cross-disciplinary inference is that resilience arises from the compatibility of structural and operational states over time. Airport resilience studies describe performance during disruption and recovery [8, 9], while structural retrofit experiments demonstrate mechanisms that can improve selected components [12–14]. Neither evidence base independently proves the performance of a partially completed, occupied terminal extension. Treating their combination as a verified intervention would overstate the literature. The proposed framework instead identifies where coordinated modelling, monitoring and contractual release controls are required.

Evidence quality differs markedly across the themes. Some interface studies use controlled shear specimens [15-30], which support mechanistic interpretation but cannot directly establish long-term performance under aircraft-induced vibration, thermal cycling or aggressive exposure. Large-frame studies provide stronger evidence about structural redistribution, yet often assume a simplified boundary condition [12, 13]. Informatics papers show how sequences can be searched or represented [21, 22], but their outputs depend on the completeness of input constraints. This diversity explains why a numerical pooled effectiveness estimate would be misleading.

Future research should instrument a real extension zone before intrusive works, record ambient movements and document as-built uncertainties. A calibrated staged finite-element model could then predict movements during excavation, strengthening and load transfer. Parallel operational simulation could evaluate closure scenarios using transparent service-level indicators. Field measurements would permit falsification of both models, rather than merely confirm project expectations. Comparative studies should test rigid versus articulated interfaces, alternative possession strategies and the relative value of prefabricated retrofits under otherwise equivalent conditions.

Longer-term work should investigate deterioration at mixed-age joints, the inspectability of concealed anchorage, and how maintenance access influences total cost. Airport terminal energy research shows that building services can be a substantial lifecycle concern [26], while broader terminal optimisation considers both carbon and indoor conditions [27]. Integration with

refurbishment may therefore offer efficiencies, but such benefits should be quantified within a clearly bounded project study. Digital twins are promising for detecting change [25], they still require data governance, sensor calibration and unambiguous links to corrective action.

An additional issue is causal attribution. A project that records fewer delays after a retrofit may also have changed staffing levels, passenger volumes, contractor access arrangements or seasonal operating procedures. Without a baseline and a credible comparator, improvement cannot be assigned to the structural intervention. Similarly, a construction package completed ahead of its planned date may still impose greater disruption than an alternative arrangement because its work windows intersect demand peaks. Future evaluations should therefore record concurrent operational changes, define the counterfactual, and distinguish construction efficiency from transport-system resilience. Reporting confidence ranges for inferred structural performance would also prevent survey uncertainty from disappearing behind a single deterministic model result. The strongest studies will publish unsuccessful interventions and unanticipated interface movements, because these observations are especially valuable for defining safe transfer limits.

Several recurrent hazards warrant separate treatment in future applications. An excavation next to a retained foundation may cause displacement before any visible defect appears in the superstructure. In this circumstance, a monitoring trigger is only useful if it was determined from a credible soil-structure model and tied to a pre-agreed action. A crane lift above an occupied service corridor creates an operational exclusion requirement regardless of the capacity of the lifted member. Likewise, the installation of a high-strength connector can redistribute loads into the weaker existing substrate. These pathways illustrate why checklists should be specific to the mechanism and the stage rather than generic to a construction trade. Site managers should record the assumed causal chain, the observable warning sign, the response owner and the means of returning to a demonstrably safe condition.

An appropriate pilot study would establish a prospective monitoring protocol before selection of the final interface option. Baseline surveys would describe movement, crack patterns, concrete properties, foundation geometry and operational service levels. Design teams could then compare two technically compliant schemes under common loading and work-window assumptions, recording not only construction duration but also required access restrictions and residual maintenance obligations. The comparison should use the same method of estimating embodied impacts and whole-life expenditure for both alternatives. Following construction, documented interface performance and operational interruptions would be checked against predictions at defined intervals. Independent assessment of discrepancies, including outcomes that contradict preferred design expectations, would turn the present conceptual synthesis into a testable engineering methodology. Independent checking should include design assumptions, staged load combinations, monitoring triggers and explicit acceptance criteria for reopening the adjacent operational area. Where relevant, the evidence register should distinguish measurements taken before construction from observations obtained after temporary restraints have been installed. Further investigation is particularly important when archival drawings conflict with observed reinforcement details, foundation levels, movement joints or the known history of alterations. Engineering responsibilities should remain identifiable across design, temporary works, installation, inspection, commissioning and long-term facilities management. The proposed methodology should be evaluated using comparable pre-intervention and post-intervention evidence rather than retrospective claims of anticipated benefits. The final acceptance decision should incorporate an independently reviewed register of unresolved risks, documented evidence of structural compatibility, confirmed operational permissions and a named owner for each residual inspection obligation during service.

9. CONCLUSIONS

This review establishes a structural and operational rationale for expanding functioning airport infrastructure without treating continuity as an afterthought. The first conclusion is that retrofit choices are only defensible when existing geometry, material properties and load paths are sufficiently verified. The second is that temporary construction states deserve the same systematic safety scrutiny as the final structure. The third is that existing-to-new interfaces require an explicit choice between continuity and accommodation of movement, supported by testing, detailing and maintainability assessments.

For Saudi airport programmes, an integrated sequence of investigation, structural option appraisal, temporary-state verification, controlled interface installation and evidence-based reopening offers a practical, demonstrably robust route to resilient delivery. The framework does not replace regulatory approvals, specialist design or site investigation. Its contribution is to make assumptions, interactions and release conditions

visible at the point where engineering and operations decisions meet. Future airport demonstrations should measure structural response, service continuity and lifecycle consequences together to establish whether the proposed integration produces quantifiable improvements.

REFERENCES

1. Alabi, B. N. T., Saeed, T. U., Amekudzi-Kennedy, A., Keller, J., and Labi, S. (2021). Evaluation criteria to support cleaner construction and repair of airport runways: A review of the state of practice and recommendations for future practice. Journal of Cleaner Production, 312, 127776. https://doi.org/10.1016/j.jclepro.2021.127776
2. Dobruszkes, F., Grippa, T., Hanaoka, S., Loko, Y., Redondi, R., Vowles, T., and Wang, J. (2021). Multiple-airport systems: The (re)development of older airports in view of noise pollution issues. Transport Policy, 114, 298–311. https://doi.org/10.1016/j.tranpol.2021.10.013
3. AlKheder, S., AlKandari, D., and AlYatama, S. (2022). Sustainable assessment criteria for airport runway material selection: A fuzzy analytical hierarchy approach. Engineering, Construction and Architectural Management, 29, 3091–3113. https://doi.org/10.1108/ECAM-01-2021-0052
4. Sun, J., Chai, G., Oh, E., and Bell, P. (2023). A review of PCN determination of airport pavements using FWD/HWD test. International Journal of Pavement Research and Technology, 16, 908–926. https://doi.org/10.1007/s42947-022-00170-1
5. Li, M., Zhang, W., Wang, F., et al. (2024). A state-of-the-art assessment in developing advanced concrete materials for airport pavements with improved performance and durability. Case Studies in Construction Materials, 21, e03774. https://doi.org/10.1016/j.cscm.2024.e03774
6. Barua, L., and Zou, B. (2022). Planning maintenance and rehabilitation activities for airport pavements: A combined supervised machine learning and reinforcement learning approach. International Journal of Transportation Science and Technology, 11, 423–435. https://doi.org/10.1016/j.ijtst.2021.05.006
7. Yu, J., Wang, J., Hua, Z., and Wang, X. (2022). BIM-based time-cost optimization of a large-span spatial steel structure in an airport terminal building. Journal of Facilities Management, 20, 469–484. https://doi.org/10.1108/JFM-12-2020-0097
8. Zapola, G. S., Silva, E. J., Alves, C. J. P., and Müller, C. (2024). Towards a resilience assessment framework for the airport passenger terminal operations. Journal of Air Transport Management, 114, 102508. https://doi.org/10.1016/j.jairtraman.2023.102508
9. Hsu, C.-C., Chang, H.-C., Li, Y.-C., and Liou, J. J. H. (2024). Developing an airport resilience assessment model for climate change. Journal of Air Transport Management, 119, 102646. https://doi.org/10.1016/j.jairtraman.2024.102646
10. Burbidge, R., Paling, C., and Dunk, R. M. (2025). Adapting Latin American and Caribbean airports to a changing climate: Impacts, challenges and solutions. Climate Risk Management, 47, 100684. https://doi.org/10.1016/j.crm.2024.100684
11. Gkournelos, P. D., Triantafillou, T. C., and Bournas, D. A. (2021). Seismic upgrading of existing reinforced concrete buildings: A state-of-the-art review. Engineering Structures, 240, 112273. https://doi.org/10.1016/j.engstruct.2021.112273
12. Hsiao, F.-P., Weng, P.-W., Li, Y.-A., Kawamoto, T., Lin, Y.-C., and Haryanto, Y. (2023). Study on retrofitting of existing reinforced concrete buildings with the exoskeleton design-U-frame method. Composite Structures, 324, 117562. https://doi.org/10.1016/j.compstruct.2023.117562
13. Jung, J.-S., Lee, B.-G., and Lee, K.-S. (2023). Seismic capacity evaluation of existing reinforced concrete buildings strengthened with a novel prestressing steel frame system for increasing lateral strength. Journal of Building Engineering, 79, 107856. https://doi.org/10.1016/j.jobe.2023.107856
14. Del Zoppo, M., Di Ludovico, M., Balsamo, A., and Prota, A. (2023). Repair, flexural upgrading and seismic retrofit of RC columns with reinforced FRCC light jacket. Construction and Building Materials, 408, 133604. https://doi.org/10.1016/j.conbuildmat.2023.133604
15. Zhang, W., Yan, B., Ye, Y., and Yi, W. (2024). Direct shear test study on old and new concrete. Journal of Building Engineering, 82, 108391. https://doi.org/10.1016/j.jobe.2023.108391
16. Bai, M., Ding, T., Zhao, Y., and Zhao, Y. (2024). Shear performance of new-to-old concrete interface based on various surface preparation techniques and roughness. Case Studies in Construction Materials, 21, e03549. https://doi.org/10.1016/j.cscm.2024.e03549
17. Fuchs, W., and Hofmann, J. (2021). Post-installed reinforcing bars – Requirements for their reliable use. Developments in the Built Environment, 5, 100040. https://doi.org/10.1016/j.dibe.2020.100040
18. Kaur, M., Chawla, H., and Kwatra, N. (2023). Effect of GO-modified epoxy on the bond behavior of old-new concrete and comparison with different

surface preparation techniques. Construction and Building Materials, 396, 132369. https://doi.org/10.1016/j.conbuildmat.2023.132369

19. Muzenski, S., Haber, Z. B., and Graybeal, B. A. (2023). Monolithic and non-monolithic interface shear performance of ultra-high performance concrete. Engineering Structures, 281, 115667. https://doi.org/10.1016/j.engstruct.2023.115667
20. Marchisella, A., Muciaccia, G., Sharma, A., and Eligehausen, R. (2021). Experimental investigation of 3d RC exterior joint retrofitted with fully-fastened-haunch-retrofit-solution. Engineering Structures, 239, 112206. https://doi.org/10.1016/j.engstruct.2021.112206
21. Huang, Y., Garrett, C., and Mueller, C. (2024). Constructability-driven design of frame structures with state-space search methods. Automation in Construction, 167, 105711. https://doi.org/10.1016/j.autcon.2024.105711
22. Le, C., Shrestha, K. J., Jeong, H. D., and Damnjanovic, I. (2021). A sequential pattern mining driven framework for developing construction logic knowledge bases. Automation in Construction, 121, 103439. https://doi.org/10.1016/j.autcon.2020.103439
23. Figueiredo, K., Pierott, R., Hammad, A. W. A., and Haddad, A. (2021). Sustainable material choice for construction projects: A life cycle sustainability assessment framework based on BIM and fuzzy-AHP. Building and Environment, 196, 107805. https://doi.org/10.1016/j.buildenv.2021.107805
24. Liu, C., Zhang, Y., Chen, Y., Liu, S., Hu, S., Luo, Q., and Chen, L. (2024). Digital twin-enabled delay diagnosis traceability and propagation process for airport flight ground service. International Journal of Intelligent Systems, 2024, 7458758. https://doi.org/10.1155/int/7458758
25. Löhner, R., Airaudo, F., Antil, H., Wüchner, R., Meister, F., and Warnakulasuriya, S. (2024). High-fidelity digital twins: Detecting and localizing weaknesses in structures. International Journal for Numerical Methods in Engineering. https://doi.org/10.1002/nme.7568
26. Yildiz, O. F., Yilmaz, M., and Çelik, A. (2022). Reduction of energy consumption and CO2 emissions of HVAC system in airport terminal buildings. Building and Environment, 208, 108632. https://doi.org/10.1016/j.buildenv.2021.108632
27. Xiong, S.-H., Xiong, X., Li, G., et al. (2024). Green production of airport terminals considering carbon footprint and indoor air quality: A multi-objective optimization perspective. Building and Environment, 263, 111859. https://doi.org/10.1016/j.buildenv.2024.111859
28. Baek, E., Pohoryles, D. A., Kallioras, S., Bournas, D. A., Choi, H., and Kim, T. (2022). Innovative seismic and energy retrofitting of wall envelopes using prefabricated textile-reinforced concrete panels with an embedded capillary tube system. Engineering Structures, 265, 114453. https://doi.org/10.1016/j.engstruct.2022.114453
29. Pohoryles, D. A., Bournas, D. A., da Porto, F., Caprino, A., Santarsiero, G., and Triantafillou, T. (2022). Integrated seismic and energy retrofitting of existing buildings: A state-of-the-art review. Journal of Building Engineering, 61, 105274. https://doi.org/10.1016/j.jobe.2022.105274
30. Wu, E., Ayinde, O., and Zhou, G. (2023). Shear behaviour and constitutive model of old-to-new concrete interface with single roughness tooth: Experimental and numerical investigation. Structures, 53, 1196–1214. https://doi.org/10.1016/j.istruc.2023.05.008.