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Systematic Review

Earthquake-Resistant Structural Design and Retrofitting Technologies: A Systematic Review of Performance Materials and Resilience Outcomes

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Abstract

Many buildings erected before modern seismic provisions remain prone to brittle failure, excessive drift and residual deformation, with loss of use often continuing long after the shaking stops. We reviewed recent structural design and retrofit technologies for earthquake-resistant buildings using a PRISMA 2020-adapted protocol. Ten ranked searches covered publications from 2018 to 2026. The final sample comprised 64 open-access journal studies with verified digital object identifiers; 63 of them (98.4%) were published from 2021 onward. Each study was coded by intervention, method, reported outcome and reporting quality. Seven themes were identified: performance-based design, base isolation, damping and energy dissipation, bracing and self-centring systems, fibre-reinforced polymer and jacketing methods, masonry and heritage retrofit, and integrated life-cycle retrofit. No single intervention performed best in every setting. Isolation worked well when displacement capacity and near-fault demand were checked explicitly. Dampers and braces reduced drift and energy demand, although uncertainty in device properties affected fragility and risk estimates. FRP and jacket strengthening addressed local member deficiencies, but their use still required assessment of the building-level load path. Retrofit decisions also increasingly involved energy, cost and environmental consequences alongside seismic performance. Based on this synthesis, we developed a framework linking hazard, vulnerability and performance objectives to intervention families and resilience outcomes. The framework is a preliminary map for similar problems. It cannot replace a full, case-specific investigation of any one building. Further work is needed on full-scale validation, uncertainty propagation, nonstructural performance, functional recovery and comparable life-cycle metrics.

Keywords: earthquake-resistant buildings; seismic retrofit; base isolation; energy dissipation; self-centring systems; fibre-reinforced polymer; performance-based seismic design; structural resilience

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1. Introduction

Building loss during an earthquake does not follow from magnitude alone. Ground motion and local site conditions act through the building's configuration, construction

quality, condition and ability to deform without losing gravity-load resistance. Recent post-earthquake studies continue to associate severe damage with soft or weak storeys, short columns, inadequate reinforcement, poor workmanship, irregular load paths and vulnerable infills or partitions [1,2]. Whether damage remains repairable, progresses to collapse or prevents reoccupation depends on how the structural and nonstructural systems respond and transfer demand.

Modern seismic design permits controlled inelastic behaviour during rare events to protect life. That objective reduces collapse risk, yet it does not by itself control repair cost, residual drift or downtime after moderate shaking. Recent work has therefore extended performance targets to immediate occupancy, reparability, functional recovery and lifetime risk. Fragility and loss models, nonlinear response-history analysis, soil–structure interaction models and machine-learning surrogates are now used to relate engineering demand parameters to these decisions [3–6].

The range of retrofit options has expanded beyond concrete and steel jacketing. Designers now consider fibre-reinforced polymer (FRP), fabric-reinforced cementitious matrices, viscous or friction dampers, buckling-restrained braces (BRBs), self-centring devices, base isolation, timber or cross-laminated timber panels, and combined seismic-energy envelopes. These measures affect stiffness, strength, damping and residual deformation in different ways. They also impose different constraints on architectural use, construction and environmental burden [7–11]. Comparing only one response measure would therefore give an incomplete basis for selection.

1.1. Review Gap and Contribution

Most earlier reviews examine a single device family, material, building type or regional code. This focus is useful for technical depth, but it separates decisions that interact in practice. Added stiffness may reduce drift while increasing force demand. Isolation can reduce superstructure acceleration but requires a large displacement zone. Likewise, FRP confinement may repair a deficient joint without correcting a weak global load path. Reviews of sustainable retrofit add another layer: seismic safety, operational energy, embodied impacts and demolition avoidance need to be considered within the same decision [9,10,12,13]. The present review brings these strands together and reports quantitative claims only when they can be traced to a specific study and test condition. Compared with reviews that concentrate on a single device family, a single hazard mechanism or a single building typology, the present review differs by coding all seven intervention families under one PRISMA-adapted protocol and a shared evidence-appraisal rubric, so trade-offs between families can be compared on a consistent basis rather than read across separate papers; this cross-family, evidence-appraised synthesis is the specific novelty claimed here.

1.2. Objective and Research Questions

This review examines recent evidence on structural design and retrofit technologies for earthquake-resistant buildings. It focuses on how the interventions work, where their limitations arise and which conditions should guide their selection. For researchers, the intended benefit is a single, evidence-appraised reference point for comparing intervention families that are usually reviewed separately; for practitioners, it shows how each intervention family has performed in comparable settings before a case-specific assessment begins. The scope is deliberately preliminary. This review does not compete with a detailed investigation of a particular building; its aim is to give insight into similar problems, not to settle a design choice on the reader's behalf. The review is organised to build toward that objective in stages: Section 2 sets out how studies were found, screened and appraised; Section 3 profiles the included evidence base as a whole; Section 4 examines each of the

seven intervention families in turn; Section 5 synthesises across families into a comparative decision framework; and Sections 6 and 7 state the limitations and conclusions that bound how far the synthesis can be generalised. Four questions were used:

- RQ1. Which structural design principles and assessment methods most consistently support earthquake-resistant building performance?
- RQ2. How do isolation, damping, bracing, self-centring, FRP, jacketing, timber, and masonry-strengthening strategies influence seismic demand and damage?
- RQ3. What methodological patterns and evidence-quality limitations affect comparison across the literature?
- RQ4. How can seismic performance, functional recovery, cost, and environmental outcomes be integrated into retrofit decisions?

2. Methodology

2.1. Review Protocol

We used a PRISMA 2020-adapted protocol suited to engineering evidence (the completed PRISMA 2020 checklist is provided as Supplementary Materials. Records passed through identification, DOI-based deduplication, title and abstract screening, eligibility verification, data extraction and quality appraisal before descriptive and thematic analysis. The included literature combined experimental, numerical, analytical, case-study and review evidence, and the reported response measures were not directly comparable. Pooling these results in a statistical meta-analysis would have implied a common effect that the data did not support. We instead examined distributions, recurring findings, boundary conditions and quantitative results within their original study contexts. The included sample retained a small number of review-type records (6 of 64, 9.4%) alongside primary experimental, numerical, analytical and case-study evidence. Each record's method type is tagged explicitly in Table A1 (Appendix A), so review-derived statements can be distinguished from primary-study findings and are read as contextual synthesis rather than added weight of evidence; no primary finding is double-counted through an included review that cites it. This review was not registered, and a review protocol was not prepared in advance.

2.2. Search Strategy and Eligibility

OpenAlex served as the discovery index. We checked candidate records against Crossref, DOI resolver records, publisher pages and institutional repositories. The search targeted open-access journal articles in journals screened as Q1 or Q2 within relevant Scopus or Web of Science categories. Ten ranked search strings were run, and the first 100 records from each query were exported. The search window extended from 1 January 2018 to 9 September 2026, although no eligible 2026 article remained in the final sample as shown in Table 1 and Summarise for Inclusion and exclusion criteria in Table 2. Only English-language journal articles were retained. Restricting the search to open-access articles in Q1/Q2-ranked journals was adopted to support reproducibility: it facilitated that every included record could be independently retrieved and re-screened by other researchers without institutional subscription access, and it prioritised outlets with an established peer-review standard. We acknowledge that this choice can exclude relevant paywalled or lower-quartile evidence, which is why it is reported as an explicit eligibility filter in Table 1 rather than an implicit one, and its effect on coverage is revisited as a limitation in Section 6. Table 1 summarises the search logic, including the Boolean structure and applied filters: the terms listed for each search concept (population/system, hazard, intervention, outcomes) were combined with the Boolean operator AND across concepts and OR within each concept, together with the date, article-type and access filters also listed

in Table 1. Scopus and Web of Science were used specifically to verify the journal-quartile standing of every candidate record; OpenAlex and Crossref served as the operational search and deduplication layer because their DOI-linked, open-access metadata could be queried and independently re-run without institutional subscription access, which is the reproducibility rationale stated above. The review's temporal scope (2018–2026) was a deliberate design choice to capture the current generation of retrofit evidence rather than re-surveying earlier benchmark literature; where an included study itself validates its results against an established benchmark structure, test protocol or code-based performance limit, that comparison is preserved in the extracted finding reported in Table A1 rather than restated here as a separate citation.

Table 1. Search concepts and eligibility filters.

Search Element	Terms or Filter
Population and system	building OR reinforced concrete OR steel frame OR masonry
Hazard	earthquake OR seismic
Intervention	retrofit OR strengthen OR base isolation OR damper OR bracing OR self-centring OR FRP OR jacketing
Outcomes	drift OR fragility OR damage OR collapse OR resilience OR recovery OR life-cycle
Filters	2018–2026; journal article; open access; DOI present; target Q1/Q2 journal standing

Table 2. Inclusion and exclusion criteria.

Decision	Criteria
Include	Peer-reviewed journal article; building-focused structural design or retrofit; 2018–2026; English; open-access route; verifiable DOI; relevant Q1/Q2 journal.
Exclude	Bridges, tunnels, pipelines, offshore structures, dams, and other non-building infrastructure; conference abstracts; non-English reports; papers without DOI or accessible evidence; weak relevance to design or retrofit.
Decision rule	Retain studies that report a design, assessment, retrofit mechanism, performance result, or implementation framework applicable to earthquake-resistant buildings.

2.3. Study Selection

The ten searches produced 1000 ranked records. DOI deduplication and screening for building relevance, journal standing, open-access status, publication date and title or abstract content removed 936 records. The remaining 64 reports underwent eligibility assessment, followed by DOI and bibliographic verification. Because duplicate removals were not recorded as a separate intermediate count, Figure 1 presents one combined removal stage rather than an estimated split. Two authors independently screened the candidate records against the Table 2 eligibility criteria and cross-checked their decisions; disagreements were resolved by discussion and, where needed, by the corresponding author acting as the third, deciding reviewer.

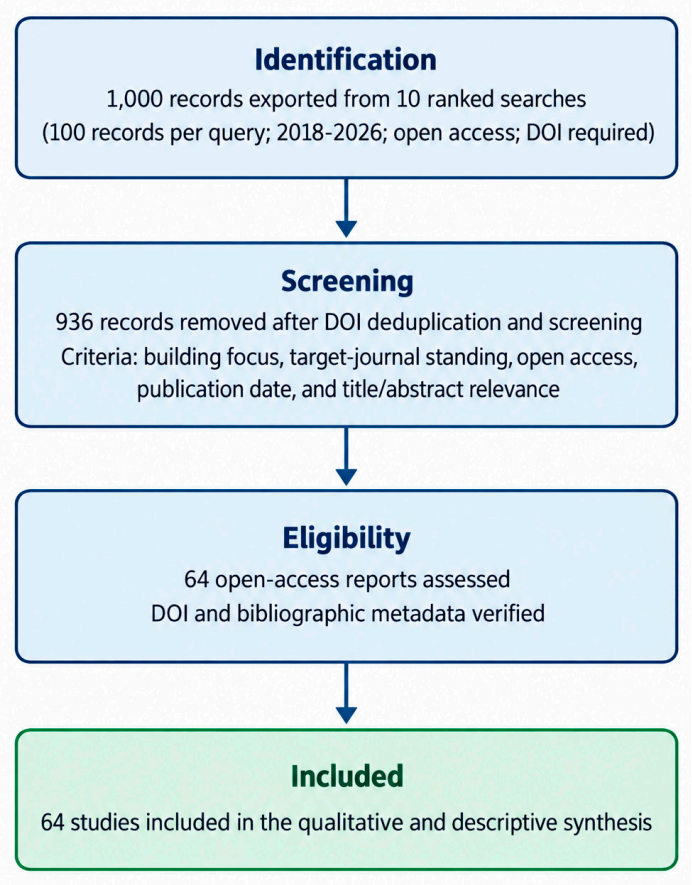


Figure 1. PRISMA 2020 adapted study-selection flow.

2.4. Data Extraction and Quality Appraisal

For every study, we recorded the authors, publication year, title, journal, DOI, open-access route, method, intervention theme and main outcome reported in the accessible abstract or article. Methods were grouped as experimental, numerical or analytical, analytical or design study, case study, or review. Theme coding took two passes. The first used intervention terms; the second checked whether the assigned theme matched the main engineering mechanism described in the title and outcome statement. Adapted engineering evidence appraisal question was implemented as Table 3. The five method categories were made mutually exclusive through a fixed classification order: a record was coded as a review only if its own stated design was a literature review or synthesis; otherwise, it was coded as a case study only if it reported a single instrumented building or event without a comparative experimental or numerical component; remaining records were coded as experimental where physical specimen or full-scale testing was reported, as numerical or analytical where simulation or statistical modelling was reported without new physical testing, and as analytical or design study where a framework, procedure or design method was proposed or evaluated using existing data. Each record received exactly one method code under this hierarchy. Physical testing took precedence. Any record that reported new tests on a specimen, sub-assembly or full-scale element was coded as experimental, even when its title presented the work as an assessment or design study. Both coding rules were then re-applied to all 64 records, and two entries in Table A1 were corrected. Entry 49 (Karabini et al. [14]) tested full-scale RC T-joints under quasi-static cyclic loading, so it was moved from analytical or design study to experimental. Entry 29 (Won et al. [15]) deals with machine-learning damage prediction that accounts for soil-structure interaction; its title and outcome point to assessment rather than life-cycle retrofit, so it was moved

to performance-based seismic design. Table 4 reports the thematic composition of the evidence base after these corrections.

Table 3. Adapted engineering evidence appraisal.

Criterion	Question	Score
Q1 Objective	Is the engineering objective or decision problem explicit?	0–2
Q2 Method	Is the analysis, experiment, design, or review method identifiable?	0–2
Q3 Evidence	Are the building, model, specimen, data, or intervention described?	0–2
Q4 Outcomes	Are performance outcomes or conclusions clearly reported?	0–2
Q5 Validity	Is comparison, validation, uncertainty, sensitivity, or limitation addressed?	0–2

Table 4. Thematic composition of the evidence base.

Theme	Studies	Illustrative Sources
Bracing and self-centring systems	12	[16–19]
FRP, jacketing and advanced materials	11	[20–23]
Base isolation	9	[24–27]
Performance-based seismic design	9	[3,5,6,15,28]
Life-cycle and multi-performance retrofit	8	[9,10,29]
Masonry and heritage retrofitting	8	[2,30–32]
Dampers and energy dissipation	7	[33–36]

Studies scoring 9–10 were assigned high reporting quality, scores of 7–8 were classed as moderate, and scores of 0–6 were classed as limited. These scores describe the completeness of the information available for this review. A low abstract-level score should not be read as a final judgement on the technical quality of the full paper. The five appraisal criteria in Table 3 (objective, method, evidence, outcomes, validity) follow the generic quality-appraisal dimensions common to evidence-synthesis methodology, adapted here to engineering studies; every score, coding decision and thematic assignment was made and cross-checked by the authors against the source article, and no score or extracted finding was adopted directly from automated or AI-generated output without author verification.

2.5. Synthesis Approach

We calculated counts by publication year, method, theme and quality category, then constructed theme-by-year and theme-by-method matrices from the approved source table. The thematic analysis compared the physical mechanism, reported benefits, limitations and selection conditions of each intervention family. Heterogeneity among studies was explored descriptively rather than statistically. Studies were grouped by intervention theme, research method and publication year. Numerical findings were retained only when they could be traced to an included study. Results from different structural systems, hazard levels or performance definitions were not pooled. No sensitivity analysis was conducted, because no pooled quantitative estimate was produced whose robustness could be tested. Instead, quantitative values are reported only within their original study context. Risk of bias due to missing results was not assessed with statistical methods because no meta analysis was performed and the outcomes were heterogeneous.

Certainty of the body of evidence was not graded with a formal framework such as GRADE, because that approach is designed for pooled effect estimates from comparable studies and no such estimates were produced. Confidence in the evidence was instead described through the adapted reporting-quality appraisal (Table 3), which reflects the completeness of the information available for each study rather than a judgement of its technical validity.

3. Overview of Included Studies

Of the 64 included studies, 63 (98.4%) were published from 2021 onward. The largest annual group appeared in 2021 (n = 23), while 2022 and 2023 each contributed 14 studies. The smaller counts for 2024 and 2025 reflect this review's ranked-search and eligibility procedure; they do not establish a decline in publication across the field. Figure 2 shows the distribution within the reviewed sample.

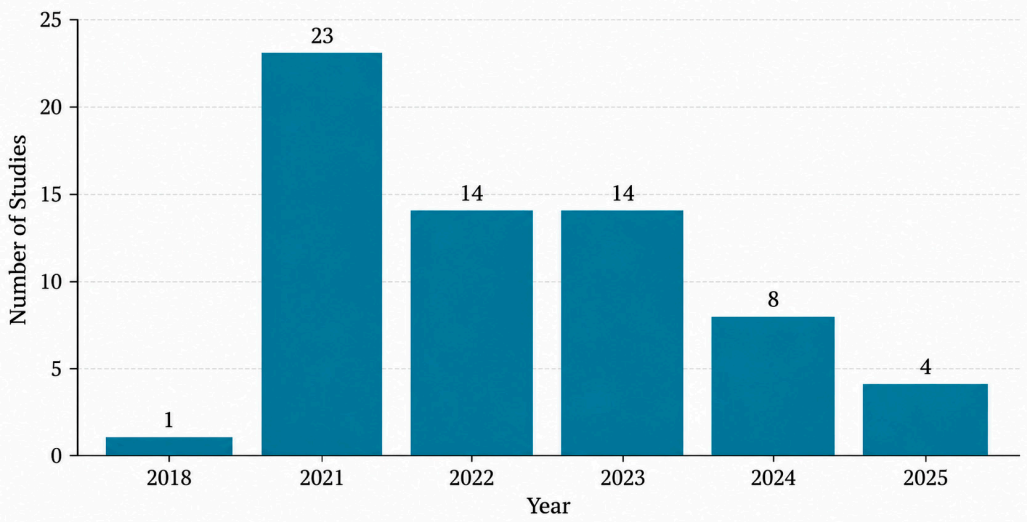


Figure 2. Publication trend of the 64 included studies.

Analytical and design studies made up the largest method group (n = 32, 50.0%). Numerical or analytical models were the next most common (n = 14, 21.9%), followed by experimental investigations (n = 9, 14.1%). The mix ranged from full-scale and component tests to fragility studies, optimisation, machine learning, post-earthquake assessment and conceptual reviews, as shown in Figure 3. Given this methodological spread, one pooled effect size would have concealed rather than clarified the evidence.

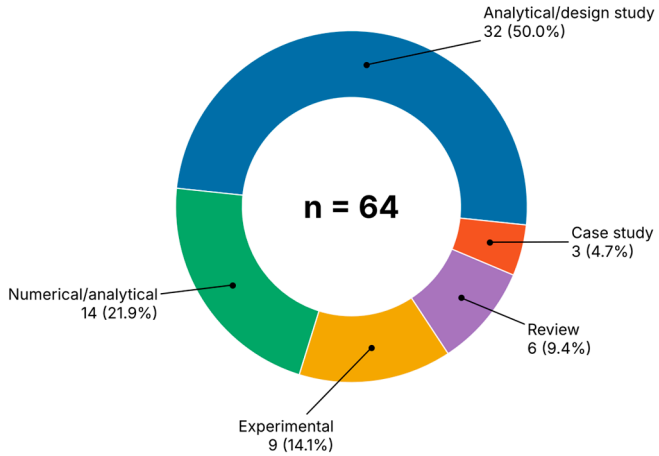


Figure 3. Distribution of research methods in the included corpus.

Figure 4 presents this thematic composition graphically, confirming that bracing and self-centring systems and FRP jacketing and advanced materials account for the largest shares of the evidence base. Fourteen studies received a high reporting-quality rating, forty-five were rated moderate and five were rated limited. Many abstracts stated the intervention and main outcome but gave little information on uncertainty, validation or study limitations. Figure 5 should therefore be read as a summary of reporting completeness, not as a ranking of retrofit technologies.

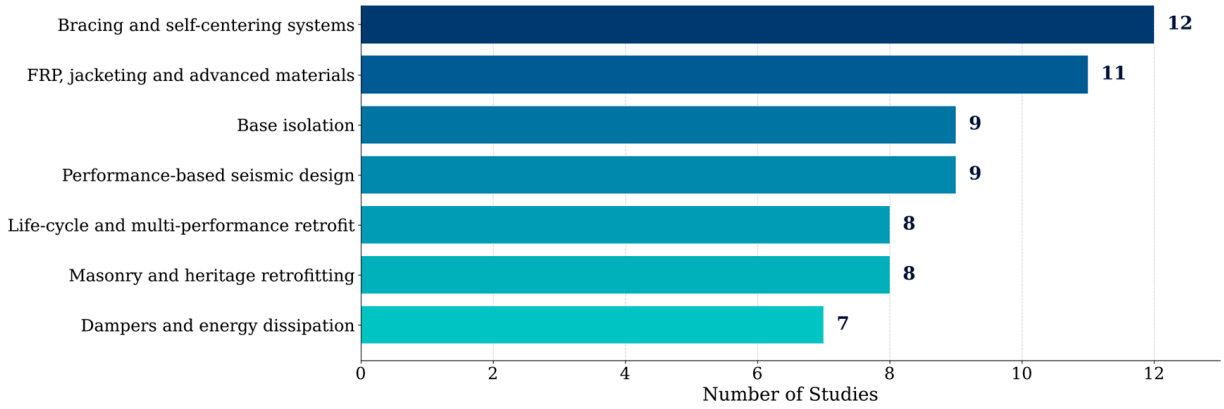


Figure 4. Thematic distribution of included studies.

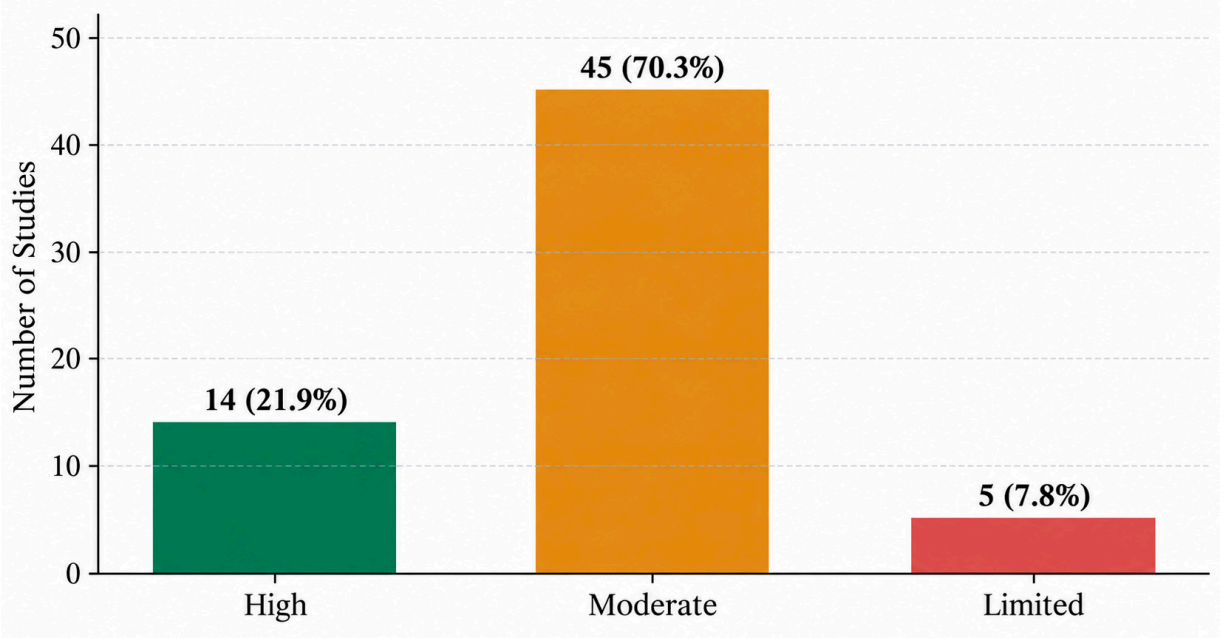


Figure 5. Distribution of adapted reporting-quality ratings.

Coverage became more varied after 2021. Earlier records centred mainly on observed masonry performance, whereas later studies gave more attention to self-centring systems, life-cycle decisions, advanced retrofit materials and data-driven assessment. Experimental evidence was concentrated on member and material retrofits and in selected recentring devices. Life-cycle and performance-based themes depended more heavily on analytical frameworks, as shown by the two matrices in Figures 6 and 7.

Study location was not reported consistently enough to support a country-level chart. We did not substitute author affiliation for research location because the two may refer to different countries.

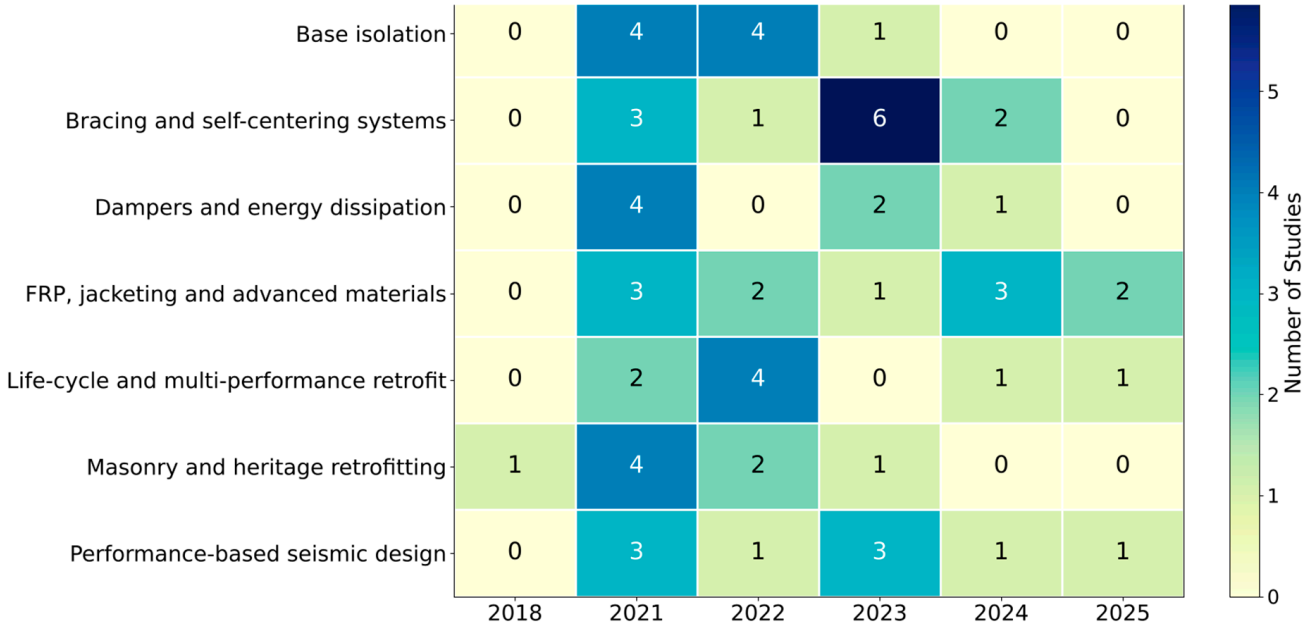


Figure 6. Theme-by-year distribution of included studies.



Figure 7. Theme-by-method distribution of included studies.

4. Thematic Findings

4.1. Performance-Based Seismic Design and Assessment

Performance-based seismic design links hazard and structural response to damage states and their consequences. In the reviewed literature, fragility curves, regional vulnerability models, nonlinear analysis, soil–structure interaction and machine learning were

used to estimate damage probability or severity [3–6]. Unlike a compliance check alone, these methods can distinguish life safety from repairability and recovery.

Machine-learning models reduced the computational burden of repeated fragility or damage calculations when trained on representative nonlinear simulations and tested against independent cases [4,5,15]. This advantage matters for regional portfolios and optimisation loops. Outside this review's own dataset, Ruggieri et al. [37] reached a similar regional-scale goal by a different route. Their method is not a machine-learning surrogate. It is an analytical–mechanical, multidimensional discrete sampling procedure that derives regional fragility and loss estimates for existing RC buildings. We cite it only as a non-data-driven counterpart: it shows that portfolio-scale savings in computation do not depend on machine learning alone. Transferability remains the main constraint. Accuracy may fall when building typology, ground-motion characteristics, soil conditions or damage definitions differ from the training data. Policy studies raise a related concern: risk estimates have practical value only when they are linked to targets, implementation, knowledge transfer and monitoring [28,38].

Soil–structure interaction cannot always be treated as a secondary modelling detail. Where foundation flexibility is appreciable, a fixed-base model may misrepresent period, damping, foundation demand and storey drift [3]. The answer to RQ1 is therefore a staged assessment: set the performance objective, represent site and structural uncertainty, choose nonlinear or surrogate analysis at the appropriate decision scale, and convert the resulting response into damage, loss or recovery measures.

4.2. Base Isolation

Base isolation lengthens the effective period and concentrates deformation at the isolation interface, thereby reducing force and acceleration demand in the superstructure. The reviewed studies covered sliding, rubber-bearing, friction-pendulum and geotechnical systems in new and existing reinforced-concrete buildings [24,25,27,39–43]. Damage above the isolation plane was generally reduced. Performance, however, depended on displacement capacity, restoring force, stability, moat clearance and compatibility between the isolation layer and the superstructure.

Far-field performance alone is a poor basis for selecting an isolator. A system that performs well under far-field records may respond differently to near-fault pulse-like motion [24]. Risk analyses also found that the governing failure mode could move from the superstructure to the isolation system, so reducing ordinary damage did not necessarily provide a large collapse margin [25,27]. Machine learning may help screen maximum isolator displacement, but mechanics-based checks are still needed for final design [26].

Geotechnical isolation applies the same demand-reduction principle through a deformable foundation layer. Eco-rubber gravel mixtures and rubberised-concrete rafts dissipated energy while reusing waste materials [40,42]. The approach appears suitable for low-rise buildings, but questions remain about settlement, drainage, ageing and site variability. Isolation is most defensible when the project can provide the required displacement and inspection space and when near-fault motion, vertical demand and soil effects are checked directly.

4.3. Dampers and Energy Dissipation

Supplemental dampers reduce deformation and energy demand without making primary members the sole source of dissipation. The sample included viscous and friction brace dampers, tuned mass damper–inerter systems, hysteretic devices and reviews of passive energy dissipation [11,33,35,36,44,45]. Friction brace dampers reduced maximum

storey drift in experimental work on retrofitted RC buildings [36]. Tuned mass systems were more sensitive to frequency, damping and assumptions about nonlinear response [35,44].

Damper properties should not be treated as exact design inputs. Manufacturing tolerance, ageing, temperature, installation and modelling uncertainty can move the real response away from what nominal coefficients predict. These sources belong in the assessment itself, not in a blanket safety factor.

No damper type ranked first under every criterion. The choice depended on the target response, architectural constraints, maintenance, temperature sensitivity, construction sequence and cost, as well as the required balance between acceleration and drift [11,33]. Dampers were most useful where the gravity system remained viable, but deformation demand affected several components across the building. Device-property uncertainty also arises for buckling-restrained braces (BRBs). A BRB is a bracing element rather than a stand-alone damper, so its quantified result is presented only once, in Section 4.4.

4.4. Bracing and Self-Centring Systems

Bracing creates a direct lateral-force path and can add stiffness, strength, dissipation or recentering capacity. The reviewed configurations included BRBs, tension-only dissipative braces, hybrid self-centring braces, piston-based braces and dual steel systems [16–19,46–51]. In one experimental programme, a shape-memory-alloy hybrid brace provided about 9% equivalent viscous damping and fully recentred at the tested amplitudes [19].

Low residual drift is a major benefit of recentering systems, although it depends on the recentring mechanism remaining intact. Ping et al. [48] examined tendon failure and found that the lifetime probability of exceeding 0.5% residual drift rose from 1.78–3.54% to 5.46–9.71% in the structures studied. A peak-drift check would not capture this vulnerability. Recentring components, anchors and replaceable fuses therefore require redundancy and access for inspection.

Hybrid braced systems reduced collapse loss and outperformed conventional alternatives in some life-cycle comparisons, but the result changed with assumed lifetime, hazard, repair model and device cost [17,46,49,51]. Bracing also limited deformation demand on infills and partitions in the study by Sorace et al. [50]. This makes it relevant to functional recovery as well as structural safety, provided that foundation demand, connection forces and architectural conflicts are resolved. Device-level uncertainty also matters for this theme: in one low-ductility RC frame retrofitted with BRBs, uncertainty in the brace properties increased fragility by up to 21% and changed the estimated seismic risk by up to 56% [52]. The result is case-specific, but it shows that BRB design values, like other bracing and self-centring devices, should not be treated as fixed nominal inputs without a sensitivity check.

4.5. FRP Jacketing and Advanced Materials

FRP and fabric-reinforced systems strengthen existing members with little added mass or change in member size. Their corrosion resistance and relatively rapid installation are practical advantages. The reviewed applications included CFRP ropes and sheets for damaged joints, FRP column jackets, fabric-reinforced cementitious matrices for masonry, corrosion-damaged concrete, composite ropes, natural-fibre textiles and corrosion-free hybrid walls [8,14,20,22,23,53–57].

Local strengthening has to be assessed within the complete building system. Slabs and transverse beams alter joint restraint and load transfer, which can make an isolated subassembly model misrepresent the benefit of an FRP retrofit [56]. Bond, anchorage, confinement geometry, corner preparation, fire, moisture and the condition of the existing

concrete remain decisive. Natural-fibre and cementitious systems may carry a lower environmental burden, but current evidence does not yet resolve their long-term durability and variability [23,55].

The reported gains varied with the retrofit and test arrangement. Composite rope strengthening maintained improved behaviour up to 4% drift in full-scale T-joints [14]. In a single-storey case, combined RC jacketing and FRP wrapping increased ultimate capacity and overstrength by factors of 2.04 and 1.82 in the two principal directions [57]. These values cannot be transferred directly to other buildings because geometry, reinforcement, prior damage, loading protocol and retrofit layout differ. FRP and jackets are suited to targeted member deficiencies; torsion, foundation demand, weak global capacity or a discontinuous load path require a building-level response. The 4% figure reported for the composite-rope retrofit refers to the imposed storey drift ratio (interstorey displacement divided by storey height) sustained under quasi-static cyclic loading of full-scale exterior beam-column T-joint subassemblies, not a whole-building drift or a monotonic pushover limit; readers comparing it with other studies in this review should match it against the same loading protocol and specimen scale rather than against whole-building drift limits.

4.6. Masonry Heritage and Infill Retrofitting

Masonry response is sensitive to material variability, wall connections, diaphragm action, openings and out-of-plane restraint. The behaviour of infills also changes the response of the surrounding frame. Evidence from Central Italy and later post-earthquake assessments linked damage in ordinary and heritage masonry to construction details and incomplete box action [2,58]. Nonlinear static models can assist the assessment, although benchmark results varied materially with the software and modelling assumptions used [30].

Recent retrofit studies examined timber interventions, insulated concrete-form systems, fabric-reinforced matrices and cross-laminated timber panels [21,23,32,59]. Full-scale and hybrid tests were particularly informative because they exposed connection failure, load redistribution and interaction with existing members. Timber-based systems add relatively little mass and may improve energy dissipation, but their performance is governed by connector behaviour and compatible force transfer [21,32].

Masonry infills are not structurally neutral partitions. They alter stiffness and torsion and may create short-column action or local concentrations of demand. Their damage can also dominate repair work and downtime. Mainshock–aftershock sequences add a second demand to infills and frames that are already damaged [31,50,60]. Retrofit objectives should account for out-of-plane stability, deformation compatibility and nonstructural damage limits alongside life safety.

4.7. Life-Cycle and Multi-Performance Retrofit

A seismic retrofit also changes embodied carbon, operational energy, construction waste, cost and disruption. Frameworks in the reviewed literature combined seismic vulnerability with energy performance, economic loss or environmental classification [9,10,12,13,15,61–63]. The common implication was practical: structural and energy measures should be compared as intervention packages rather than optimised in isolation.

Life-cycle assessment can change which retrofit appears efficient. A material-intensive solution may still be justified if it avoids demolition, repeated repair, long downtime or high expected loss. The opposite can also occur: a structurally effective intervention may carry a high environmental cost when it requires extensive demolition and new concrete. In the cases examined by Passoni et al. [13], life-cycle-based retrofit options had lower impacts than traditional seismic intervention and demolition-reconstruction.

Loss-based design connects structural analysis more directly to a project decision, but simplified estimates still require calibration. Rubini et al. [63] reported a maximum overestimate of 15.4% across four illustrative applications when the simplified method was compared with refined nonlinear analyses. Such tools can support early-stage design if their uncertainty is stated. RQ4 is answered through a multi-criteria process in which safety remains a constraint while lifetime loss, recovery, carbon, energy, heritage value, feasibility and disruption are compared.

5. Discussion and Synthesis

5.1. Cross-Theme Interpretation

The seven themes can be understood as three groups of interventions. Isolation modifies how earthquake demand enters the building. Dampers, braces and self-centring systems change how the structure stores, dissipates and recovers energy. FRP, jackets, timber and masonry measures act mainly on member capacity or system connectivity. Performance-based assessment and life-cycle evaluation provide the decision criteria across all three groups. Technologies that appear to compete may therefore solve different parts of the same problem and can be used together. Table 5 makes this comparison explicit by setting each strategy's mechanism, primary value, critical limitation and most suitable decision context side by side, so that apparently competing technologies can be screened critically against a shared set of criteria rather than judged in isolation; the unresolved gaps this comparison exposes are carried forward into the research agenda in Section 5.3.

Table 5. Comparative decision matrix for seismic design and retrofit strategies.

Strategy	Mechanism	Primary Value	Critical Limitation	Most Suitable Decision Context
Base isolation	Reduce transmitted acceleration and force; concentrate displacement	Low superstructure damage; operational continuity	Large isolator displacement; near-fault pulses; ageing and clearance	Buildings where isolation plane, inspection, and moat displacement are feasible
Viscous or friction damping	Dissipate input energy and reduce drift	Global demand reduction with limited member enlargement	Device uncertainty, maintenance, temperature and connection forces	Existing frames with viable gravity system and distributed drift deficiencies
BRB and conventional bracing	Add stiffness, strength, and stable hysteretic dissipation	Clear load path; replaceable yielding components	Foundation and connection demand; architectural conflict; residual drift	Frames requiring global lateral-strength and drift improvement
Self-centring systems	Combine dissipation with restoring force	Low residual drift and improved recovery	Tendon or recentering failure; complexity; cost	Essential or high-value buildings with recovery targets
FRP and jacketing	Increase local shear, confinement, flexural, or axial capacity	Lightweight and rapid local intervention	Bond, fire, anchorage, substrate condition; may not fix global weakness	Member-level deficiencies after building-level assessment
Masonry and timber systems	Improve wall connectivity, diaphragm action, stiffness, or dissipation	Low-mass options; heritage and envelope compatibility	Variable materials and connections; out-of-plane behaviour	Masonry, heritage, and infilled RC buildings
Integrated multi-performance retrofit	Optimize structural, energy, cost, carbon, and disruption outcomes	Avoids isolated decisions and may prevent demolition	Data intensity and non-comparable metrics	Portfolio and public-building programmes with long planning horizons

Accordingly, the intervention families should not be interpreted as directly interchangeable alternatives. Member-level measures such as FRP strengthening and jacketing primarily address local deficiencies in strength, confinement, shear capacity, or connection behaviour, whereas bracing, supplemental damping, self-centring systems, and base isolation primarily modify the global structural response. Selection should therefore begin with the governing failure mechanism and required performance objective before quantitative outcomes from different retrofit families are compared.

5.2. Integrated Decision Framework

Figure 8 sets out the decision framework derived from the review. Hazard and exposure, building vulnerability and performance objectives define the assessment stage. The results then guide the selection or combination of isolation, dissipation or member-level retrofit, followed by evaluation of the resilience outcome. The sequence matters. Intervention should follow identification of the controlling failure mode and the required post-earthquake function, rather than begin with a preferred product or material. The framework in Figure 8 is presented as a conceptual, qualitative synthesis map, not a weighted or validated decision-support tool: it combines evidence from studies with different hazards, structural systems and performance definitions, so it should guide the order and scope of questions asked during retrofit decision making rather than assign numerical scores or rankings to competing interventions. The PRISMA-based procedure used in this study governs the identification, screening, and synthesis of published evidence and is not proposed as an engineering design protocol for individual projects. Accordingly, Figure 8 is intended to support the organisation and interpretation of evidence alongside engineering judgement, rather than replace code-based analysis, project-specific modelling, experimental verification, or professional design experience. Quantitative validation of the framework, including explicit criteria weights, project-specific structural analysis, and independent case-study testing, remains an important direction for future work and is identified in Section 5.3. The same figure can also be read as a taxonomy of this review, mapping how the assessment tools, intervention families and resilience outcomes discussed throughout the paper relate to one another.

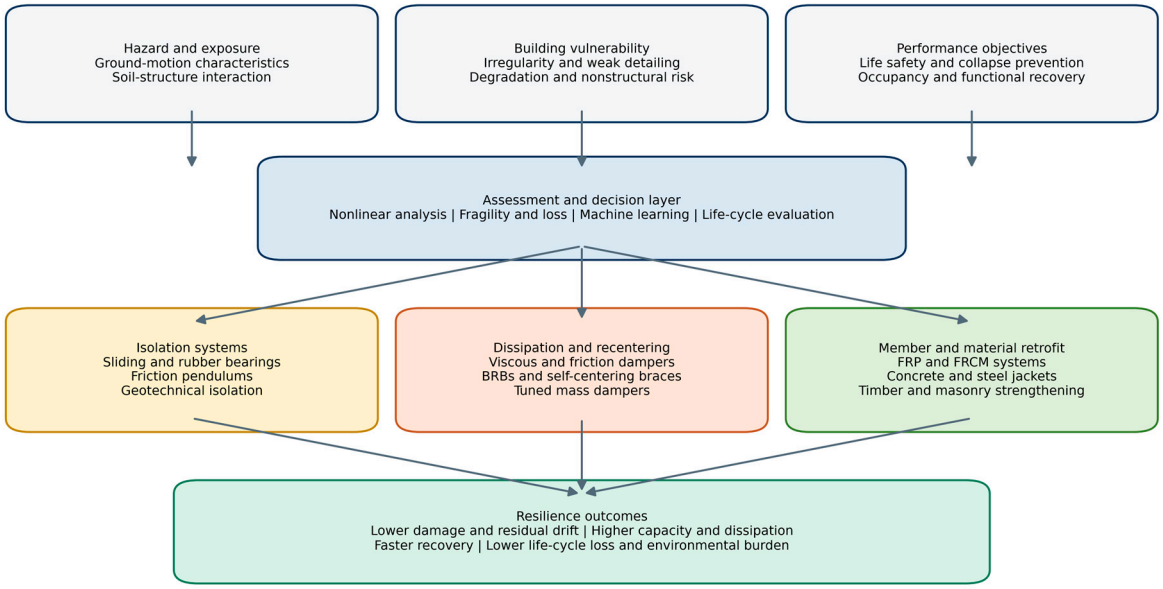


Figure 8. Integrated seismic design and retrofit decision framework developed from the synthesis.

Case-Based Illustration of the Decision Framework

To demonstrate how the proposed framework can be interpreted at the building level, a case-based illustration was developed using documented evidence already included in the reviewed literature. This illustration does not constitute an independent reanalysis or validation of the original case; rather, it demonstrates how the assessment–intervention–resilience sequence in Figure 8 can be applied to an established building-level retrofit context.

A representative example is the existing school-building application reported by Caruso et al. [29], in which structural retrofit, energy-refurbishment, and integrated retrofit alternatives were examined within the same building-level decision context. In the present review, this documented case is used to illustrate the sequence proposed in Figure 8. The first step is to identify the governing vulnerability and performance objective before selecting a retrofit technology. Where the assessment identifies local deficiencies in member strength, confinement, detailing, or connection behaviour, interventions such as FRP strengthening or jacketing become relevant candidate measures. Where the dominant problem is instead excessive global drift, inadequate lateral resistance, or distributed seismic demand, system-level interventions such as bracing, supplemental damping, self-centring systems, or base isolation become more relevant.

The framework therefore does not rank retrofit technologies independently of context. Instead, it narrows the feasible intervention set by matching the identified structural deficiency to the physical mechanism of each retrofit family. This distinction is important because member-level strengthening may improve local capacity without correcting a deficient global load path, whereas a global response-control system may reduce overall seismic demand without resolving a vulnerable local component. Where local and global deficiencies coexist, a combined retrofit strategy may therefore be more appropriate than a single intervention.

A second screening stage considers implementation constraints. Base isolation, for example, may provide substantial reduction in transmitted seismic demand, but its applicability depends on displacement capacity, available clearance, foundation and interface modifications, constructability, and the governing ground-motion characteristics. Bracing may improve lateral stiffness, strength, and load-path continuity, but may increase connection and foundation demands or conflict with architectural use. Supplemental damping may reduce drift and energy demand with less modification of primary structural members, while self-centring systems become particularly relevant where low residual deformation and rapid functional recovery are explicit objectives.

The final stage is project-specific verification of the selected intervention or combination of interventions. This includes nonlinear structural response, foundation demand, constructability, cost, downtime, nonstructural performance, and uncertainty in the governing seismic demand. The case-based illustration therefore demonstrates the practical interpretation and application of the proposed qualitative framework, while project-specific validation remains dependent on calibrated structural analysis, code-based verification, and, where available, experimental or field evidence.

5.3. Research Agenda

A dedicated gap check accompanies this agenda. Among the recurring methodological gaps in the reviewed literature, coupling soil–structure interaction (SSI) with machine-learning surrogate models in day-to-day practice remains largely unresolved: SSI studies in this review [3,64] established that foundation flexibility can materially change period, damping and drift, while the machine-learning studies [4,5,15] were trained and validated on fixed-base or single-site cases. No study in the reviewed sample reported a surrogate

model trained across a range of foundation and soil conditions and validated against SSI-inclusive nonlinear analysis, which is why it is listed as the top unresolved challenge in Table 6 below alongside the other priorities identified from this synthesis.

Table 6. Priority research agenda.

Priority	Recommended Evidence	Expected Contribution
Comparable performance metrics	Report peak drift, residual drift, acceleration, damage state, repair time, collapse probability, and uncertainty with consistent definitions.	Enables cross-technology comparison and future meta-analysis.
Full-scale system validation	Extend component tests to buildings that include slabs, foundations, infills, partitions, façades, and services.	Reveals load-path and nonstructural interactions.
Device and material uncertainty	Propagate manufacturing tolerance, ageing, corrosion, temperature, bond degradation, and installation variability.	Prevents nominal models from overstating reliability.
Functional recovery	Connect engineering response to occupancy, repair sequencing, utilities, and reinspection.	Moves practice beyond life safety and direct repair cost.
Integrated life-cycle evidence	Use transparent service life, hazard, carbon, energy, repair, discount, and demolition assumptions.	Makes sustainability claims comparable and auditable.
Data-driven models	Publish training domains, validation cases, uncertainty bounds, and interpretable predictors.	Improves transferability of machine-learning tools.
Coupled SSI-surrogate modelling	Train and validate machine-learning or surrogate fragility models across varied foundation stiffness and soil conditions, benchmarked against SSI-inclusive nonlinear analysis.	Closes the SSI-machine-learning gap identified in this review and extends data-driven tools to sites where a fixed-base assumption is not defensible.

Figure 9 summarises these same priorities graphically, so the relative urgency and expected practice impact of each item can be compared at a glance rather than read row by row. The positions are indicative only. They summarise the authors' reading of the reviewed evidence, are not a measured priority score, and are best used as a starting point for discussion rather than a ranking.

For quantitative validation of the proposed decision framework, future work should apply Figure 8 to a common benchmark building under a defined seismic-hazard scenario. Alternative retrofit strategies should be evaluated for the same structural model, ground-motion set, performance objectives, and uncertainty assumptions, allowing the framework-derived intervention choices to be compared with calibrated nonlinear analysis and, where available, experimental or field evidence. Such a controlled benchmark would test whether the qualitative decision sequence remains consistent when competing retrofit options are assessed under identical conditions.

5.4. Practical Implications

For new buildings, the literature supports regular configuration, continuous load paths, ductile hierarchy, capacity design and explicit checks of diaphragms and connections. Performance targets may also need to go beyond collapse prevention. Isolation and self-centring systems become more attractive when continued operation or low residual drift is

an explicit project requirement. For an existing building, assessment should first establish whether the weakness is local, global or both. FRP and jackets suit local member deficiencies. Dampers or braces address distributed drift and energy demand, while isolation requires space for a new interface and its displacement zone.

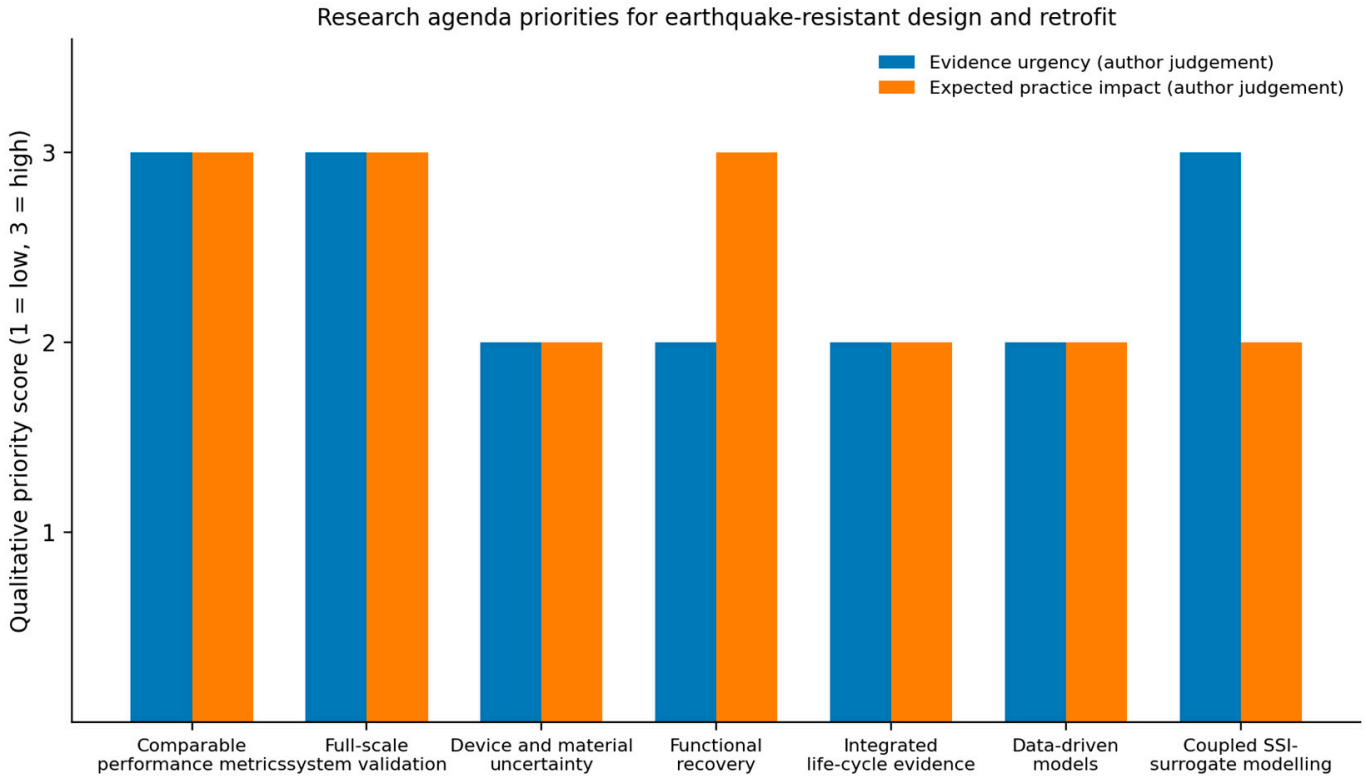


Figure 9. Qualitative research-agenda priorities by evidence urgency and expected practice impact (author judgement, not a formal survey or bibliometric score).

Retrofit verification should proceed in stages. Fragility or surrogate models can help screen a building portfolio, but final design needs calibrated nonlinear models and, where available, experimental or field evidence. Sensitivity checks should include near-fault pulses, foundation flexibility, aftershocks, variation in device properties and degradation. Nonstructural components and recovery targets also need early attention because they may control repair cost and downtime even when the main structure remains stable.

6. Limitations

Five limitations affect the interpretation of this review. The search used ranked OpenAlex results and open-access availability rather than direct exports from subscription databases, so some paywalled studies may have been missed. Journal quartiles vary by database, subject category and year; their status should be checked again at submission. Study location was not reported consistently and was not inferred from author affiliation. The quality score mainly reflects the information available to this review, which means it measures reporting completeness more directly than full methodological validity. Finally, the interventions and outcome definitions were too heterogeneous to support a defensible pooled effect size. All quantitative values are therefore reported within their original study context. The 64-study sample and the 2018–2026 search window were a deliberate scope for this review rather than an attempt at exhaustive coverage; a broader review spanning additional years, subscription-only sources and lower-tier journals would likely change the relative weight given to each theme and is a natural extension of this work. Because eligibility was restricted to Q1/Q2 journals, trends reported here reflect where this literature

concentrates within that band and should not be read as a claim about the full population of earthquake-engineering research; readers using this review to judge overall research trends, rather than the trends within Q1/Q2 open-access literature specifically, should treat the thematic proportions as indicative rather than definitive. This caution applies most strongly to the smaller groups in Table 4: dampers and energy dissipation (seven studies), life-cycle and multi-performance retrofit and masonry and heritage retrofitting (eight each), and base isolation and performance-based seismic design (nine each). With so few Q1/Q2 open-access records in each family, any cross-study trend reported for these families in Sections 4.1–4.3, Sections 4.6 and 4.7 is more exposed to selection and journal-scope effects than the larger bracing (12 studies) or FRP (11 studies) groups and should be read as a description of this sample rather than a settled claim about the field-wide performance of any of these technologies. The resulting sample size is consistent with comparable recent reviews in this field: a 2025 critical review of integrated seismic and energy retrofit drew on 54 studies from a 2010–2025 window [64] and a 2026 systematic review of deep-learning-based post-earthquake damage assessment retained 46 studies from a 2015–2025 window [65]; the 64-study, 2018–2026 sample used here falls within the same order of magnitude as these comparable, recency-focused syntheses rather than being an outlier for this type of review.

The small size of several subsets is the main weakness of this review, and we state it plainly. Once 64 records are split across seven themes and five method types, many cells in Figures 6 and 7 hold zero, one or two studies. Subsets this small cannot form stable clusters, so the review cannot tell whether a pattern inside one theme is a real tendency or simply a result of which papers were retrieved. For the same reason, we did not attempt a cluster or network analysis of retrofit strategies by building type, hazard level or performance objective. The present work should therefore be read as a preliminary step. It shows where the evidence sits and which questions keep returning; it does not answer them. Meaningful clusters for seismic retrofitting will only emerge from a much larger sample, drawing on subscription databases, a longer time window and reconnaissance or other grey literature, and building that sample is the most useful next step for this line of work.

Limitations of Quantitative Syntheses Among Retrofit Methods

Direct quantitative comparison among retrofit methods is constrained by the heterogeneity of the underlying studies. Reported performance measures were obtained from different structural systems, building geometries, material properties, ground-motion characteristics, hazard levels, modelling assumptions, specimen scales, loading protocols, and boundary conditions. Consequently, numerical outcomes such as reductions in drift, acceleration, fragility, damage, or loss cannot be treated as directly comparable effect measures across studies unless the underlying structural and hazard conditions are sufficiently similar. For this reason, the present review does not pool these values or use them to produce numerical rankings of retrofit technologies. Instead, quantitative findings are retained within their original study contexts and interpreted together with the governing failure mechanism, intervention scale, performance objective, applicability conditions, and reported uncertainty.

7. Conclusions

This review brought together 64 recent studies on earthquake-resistant structural design and building retrofit. Taken as a whole, the literature favours performance, loss and recovery objectives over reliance on minimum code compliance alone. Isolation, supplemental damping, bracing, self-centring systems, FRP, jackets and masonry or timber strengthening address different mechanisms. Their effectiveness depends on the gov-

erning failure mode, the building load path, ground-motion characteristics, uncertainty, constructability and the required post-earthquake function.

Retrofit technology should be chosen only after the hazard, site effects and structural and nonstructural weaknesses have been established. Performance targets then need to be considered together with life-cycle loss, carbon, cost and disruption. The framework developed in this review arranges those decisions from assessment through intervention to the intended resilience outcome. The next priority is stronger full-scale validation and more comparable measures of recovery and life-cycle performance. These conclusions come from a preliminary synthesis of 64 studies. They are meant to give insight into similar retrofit problems and do not replace the case-specific investigation that any individual building still requires. Looking forward, closing that gap will most directly change practice if it happens along four fronts: hazard and site characterisation that is propagated, not assumed fixed, into every downstream fragility and loss estimate; vulnerability assessment that reports device and model uncertainty alongside the point estimate; performance objectives that are stated explicitly enough to be checked against functional-recovery and downtime targets, not only life safety; and intervention families that are compared on the same evidence-appraised basis used in this review, rather than argued for individually. Progress on these fronts, more than any single new device or material, is what would let the resilience outcomes discussed throughout this review be predicted with confidence rather than illustrated with case examples.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/buildings16214256/s1: PRISMA 2020 checklist [66].

Author Contributions: Conceptualisation, E.E.B.M.N.; methodology, E.E.B.M.N. and S.K.B.A.A.; validation, S.K.B.A.A.; formal analysis, E.E.B.M.N. and S.K.B.A.A.; investigation, E.E.B.M.N., S.K.B.A.A.; data curation, S.K.B.A.A.; writing-original draft preparation, E.E.B.M.N. and S.K.B.A.A.; writing—review and editing, E.E.B.M.N.; visualisation, E.E.B.M.N. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Study Summary Table

Table A1. Characteristics and extracted findings of all included studies.

ID	Study	Title	Method	Theme	Extracted Finding	DOI
1	Kazemi et al. (2023) [5]	Machine learning-based seismic fragility and seismic vulnerability assessment of reinforced concrete structures	Numerical/analytical	Performance-based seismic design	Performance indicators showed that the algorithms of Artificial Neural Networks (ANNs), Extra-Trees Regressor (ETR), Extremely Randomized Tree Regressor (ERTR), Bagging Regressor (BR), Extreme Gradient Boosting (XGBoost), and Histogram-based Gradient Boosting Regression (HGBR) had higher performance, which achieved acceptable accuracy and fitted to actual curves.	10.1016/j.soildyn.2023.107761
2	Freddi et al. (2021) [28]	Innovations in earthquake risk reduction for resilience: Recent advances and challenges	Analytical/design study	Performance-based seismic design	The SFDRR encourages better access to technological innovations combined with increased DRR investments in developing cost-effective approaches and tackling global challenges.	10.1016/j.ijdrr.2021.102267
3	Pohoryles et al. (2022) [10]	Integrated seismic and energy retrofitting of existing buildings: A state-of-the-art review	Review	Life-cycle and multi-performance retrofit	Through renovation, it is possible to improve their energy-efficiency, hence reducing their significant impact on the total energy household and associated greenhouse gas emissions.	10.1016/j.jobe.2022.105274
4	Bapir et al. (2023) [3]	Soil-structure interaction: A state-of-the-art review of modeling techniques and studies on seismic response of building structures	Review	Performance-based seismic design	In addition, with the aim of helping new researchers to improve previous findings, the research gaps and future research tendencies in the SSI field are pointed out.	10.3389/fbuil.2023.1120351
5	Miglietta et al. (2021) [32]	Full-scale shake-table tests on two unreinforced masonry cavity-wall buildings: effect of an innovative timber retrofit	Experimental	Masonry and heritage retrofitting	This paper describes in detail the bare and retrofitted specimens, compares the experimental results obtained through similar incremental dynamic shake-table test protocols up to near-collapse conditions, and identifies damage states and damage limits associated with displacements and deformations.	10.1007/s10518-021-01057-5

Table A1. *Cont.*

ID	Study	Title	Method	Theme	Extracted Finding	DOI
6	Ruggieri et al. (2022) [6]	Analytical-mechanical based framework for seismic overall fragility analysis of existing RC buildings in town compartments	Numerical/analytical	Performance-based seismic design	The results show overall fragilities curves for the investigated town compartments, which are obtained in a different way from the existing procedures, by avoiding an a priori selection of one or more index buildings to represent the specific building portfolio and the definition of a specific building taxonomy.	10.1007/s10518-022-01516-7
7	Hu et al. (2023) [17]	Life-cycle benefits estimation for hybrid seismic-resistant self-centring braced frames	Analytical/design study	Bracing and self-centring systems	HSBFs show better life-cycle benefits than SCBFs when the building's lifetime is not lower than 50 years.	10.1002/eqe.3914
8	Shi et al. (2023) [19]	Design, manufacturing, and testing of a hybrid self-centring brace for seismic resilience of buildings	Experimental	Bracing and self-centring systems	The results indicate that the developed SMA-based hybrid self-centring braces provide an average of 9% equivalent viscous damping at different loading amplitudes with a complete self-centring characteristic.	10.1002/eqe.3821
9	Bhatta et al. (2023) [4]	Seismic damage prediction of RC buildings using machine learning	Numerical/analytical	Performance-based seismic design	The machine learning models are trained using the simulation results.	10.1002/eqe.3907
10	Menna et al. (2021) [9]	Review of methods for the combined assessment of seismic resilience and energy efficiency towards sustainable retrofitting of existing European buildings	Review	Life-cycle and multi-performance retrofit	Finally, a critical evaluation is provided, highlighting what can be used for future developments toward a sustainable and resilient retrofitting of existing European buildings.	10.1016/j.scs.2021.103556
11	Zhang et al. (2021) [38]	Review of Seismic Risk Mitigation Policies in Earthquake-Prone Countries: Lessons for Earthquake Resilience in the United States	Review	Performance-based seismic design	The result is a set of best practice recommendations that are organized conceptually around key stages of the seismic retrofit process: (1) risk assessment; (2) knowledge transfer; (3) setting targets; (4) implementation; and (5) monitoring.	10.1080/13632469.2021.1911889
12	De Domenico et al. (2021) [33]	Multi-level performance-based design optimisation of steel frames with nonlinear viscous dampers	Analytical/design study	Dampers and energy dissipation	However, using drift-based UDD approach generally results in a better seismic performance.	10.1007/s10518-021-01152-7

Table A1. *Cont.*

ID	Study	Title	Method	Theme	Extracted Finding	DOI
13	Di Sarno et al. (2021) [31]	Fragility assessment of existing low-rise steel moment-resisting frames with masonry infills under mainshock-aftershock earthquake sequences	Numerical/analytical	Masonry and heritage retrofitting	The evaluation of the efficiency of commonly used intensity measures of aftershocks was also carried out as part of the second phase of assessment.	10.1007/s10518-021-01080-6
14	Chen et al. (2023) [16]	Enhanced design and experimental investigation of disc spring-based self-centring buckling-restrained braces with a compounded combination mode	Experimental	Bracing and self-centring systems	The experimental results demonstrate that the improved design can provide accurate estimations of the spring friction in the brace design and that the proposed brace can exhibit a stable and favourable flag-shaped hysteretic response with negligible residual deformations throughout the loading protocol.	10.1002/eqe.3912
15	Golias et al. (2021) [20]	Effectiveness of the Novel Rehabilitation Method of Seismically Damaged RC Joints Using C-FRP Ropes and Comparison with Widely Applied Method Using C-FRP Sheets—Experimental Investigation	Experimental	FRP, jacketing and advanced materials	Extensive comparisons and discussion of the test results derive new quantitative and qualitative results concerning the seismic capacity and the service life extension of the strengthened RC members using the proposed retrofitting scheme.	10.3390/su13116454
16	Sorrentino et al. (2018) [2]	Seismic behaviour of ordinary masonry buildings during the 2016 central Italy earthquakes	Analytical/design study	Masonry and heritage retrofitting	Observed damage patterns showed that masonry typology, connections, diaphragm action, and construction details strongly governed the seismic response of ordinary buildings during the 2016 Central Italy earthquakes.	10.1007/s10518-018-0370-4
17	Patsialis et al. (2021) [35]	Tuned-mass-damper-inerter optimal design and performance assessment for multi-storey hysteretic buildings under seismic excitation	Analytical/design study	Dampers and energy dissipation	To reduce the computational burden, a reduced order model (ROM) is based on the original FEM, using the framework proposed recently by the first and second authors.	10.1007/s10518-021-01236-4
18	Hu et al. (2022) [18]	Machine learning-aided peak and residual displacement-based design method for enhancing seismic performance of steel moment-resisting frames by installing self-centring braces	Numerical/analytical	Bracing and self-centring systems	Machine-learning surrogate models reproduced peak and residual displacement demands and supported displacement-based sizing of self-centring braces for steel moment-resisting frames.	10.1016/j.engstruct.2022.114935

Table A1. *Cont.*

ID	Study	Title	Method	Theme	Extracted Finding	DOI
19	Ping et al. (2021) [48]	Seismic robustness of self-centring braced frames suffering tendon failure	Analytical/design study	Bracing and self-centring systems	Considering a residual drift threshold of 0.5%, the probability of exceedance of the same structures over the same life span increases from 1.78–3.54% to 5.46–9.71%.	10.1002/eqe.3421
20	Caruso et al. (2021) [29]	Integrated economic and environmental building classification and optimal seismic vulnerability/energy efficiency retrofitting	Analytical/design study	Life-cycle and multi-performance retrofit	The illustrative application of the framework to an existing school building is then carried out, investigating alternative retrofitting solutions, including either sole structural retrofitting options or sole energy refurbishments, as well as integrated strategies that target both objectives, with a view to demonstrate its practicality and to explore its ensuing results.	10.1007/s10518-021-01101-4
21	Cattari et al. (2021) [30]	Benchmarking the software packages to model and assess the seismic response of unreinforced masonry existing buildings through nonlinear static analyses	Analytical/design study	Masonry and heritage retrofitting	While other papers from the teams involved in the research project delve on the specific results achieved on each of these case studies, this paper illustrates an overview on such benchmark structures, their purpose and the standardized criteria adopted to compare the results.	10.1007/s10518-021-01078-0
22	Gharagoz et al. (2025) [67]	Explainable machine learning (XML) framework for seismic assessment of structures using Extreme Gradient Boosting (XGBoost)	Numerical/analytical	Performance-based seismic design	The approach improves transparency using XAI methods like SHAP and LIME.	10.1016/j.engstruct.2025.119621
23	Işık et al. (2024) [1]	Seismic Performance and Failure Mechanisms of Reinforced Concrete Structures Subject to the Earthquakes in Türkiye	Analytical/design study	Performance-based seismic design	Soft/weak story, short column, insufficiently reinforced-concrete, and poor workmanship are the primary causes of structural damage, which cause earthquake weaknesses in these buildings.	10.3390/su16156473
24	Ademović et al. (2022) [58]	Post-Earthquake Assessment and Strengthening of a Cultural-Heritage Residential Masonry Building after the 2020 Zagreb Earthquake	Case study	Masonry and heritage retrofitting	Good consistency was obtained between the numerical modelling, visual inspection, and on-site testing.	10.3390/buildings12112024

Table A1. *Cont.*

ID	Study	Title	Method	Theme	Extracted Finding	DOI
25	Ponzo et al. (2021) [27]	Advanced Modelling and Risk Analysis of RC Buildings with Sliding Isolation Systems Designed by the Italian Seismic Code	Numerical/analytical	Base isolation	Results pointed out that in the case of new buildings the GC and UPD conditions occur almost at the same seismic intensity, while for the cases of the existing building, the UPD is the dominant limit state, being reached at an intensity level lower than GC.	10.3390/app11041938
26	De Domenico et al. (2024) [34]	Displacement-based design procedure for the seismic retrofit of existing buildings with self-centring dissipative braces	Analytical/design study	Dampers and energy dissipation	As demonstrated in recent seismic sequences, there might be not enough time to restore (e.g., though hydraulic actuators and a reaction frame) the undeformed configuration of the structure before a subsequent shock.	10.1016/j.istruc.2024.106174
27	Saingam et al. (2021) [36]	Experimental dynamic characterization of friction brace dampers and application to the seismic retrofit of RC buildings	Experimental	Dampers and energy dissipation	The analysis results suggest that the proposed retrofit design method and friction brace dampers are effective in reducing the maximum story drift.	10.1016/j.engstruct.2021.112545
28	Pertile et al. (2021) [59]	Seismic and Energy Integrated Retrofitting of Existing Buildings with an Innovative ICF-Based System: Design Principles and Case Studies	Analytical/design study	Masonry and heritage retrofitting	The results of the analyses show a considerable increase in lateral stiffness of the retrofitted buildings that, considering the non-dissipative behavior of the elements, leads to a relevant reduction of seismic deformation demand on existing structural elements.	10.3390/su13169363
29	Won et al. (2021) [15]	Machine Learning-Based Approach for Seismic Damage Prediction Method of Building Structures Considering Soil-Structure Interaction	Numerical/analytical	Performance-based seismic design	This data generation method with high accuracy and speed can be utilized as a regional seismic assessment tool for safe and sustainable structures against natural disasters.	10.3390/su13084334
30	Mota-Páez et al. (2021) [45]	Seismic Response of RC Frames with a Soft First Story Retrofitted with Hysteretic Dampers under Near-Fault Earthquakes	Analytical/design study	Dampers and energy dissipation	It is concluded that the maximum displacements can be easily predicted from the energy balance of the structure by using appropriate values for the parameter that reflects the influence of the impulsivity of the ground motion: the so-called equivalent number of cycles.	10.3390/app11031290

Table A1. *Cont.*

ID	Study	Title	Method	Theme	Extracted Finding	DOI
31	Kallioras et al. (2023) [60]	Seismic performance of a full-scale five-story masonry-infilled RC building subjected to substructured pseudodynamic tests	Experimental	Masonry and heritage retrofitting	Abstract: This paper discusses the results of a series of hybrid earthquake tests on a full-scale reinforced-concrete (RC) building with masonry infills.	10.1002/eqe.3940
32	Shin et al. (2022) [22]	Optimum retrofit strategy of FRP column jacketing system for non-ductile RC building frames using artificial neural network and genetic algorithm hybrid approach	Analytical/design study	FRP, jacketing and advanced materials	Based on the investigation, the geometric conditions-related stiffness parameters within a low confinement level were increased rather than increases in the confinement parameters.	10.1016/j.jobe.2022.104919
33	Freddi et al. (2021) [52]	Device uncertainty propagation in low-ductility RC frames retrofitted with BRBs for seismic risk mitigation	Numerical/analytical	Bracing and self-centring systems	The results show that, for the considered case study structure, these uncertainties could lead to an increase of fragility up to 21% and a variation in seismic risk estimates up to 56%.	10.1002/eqe.3456
34	Titirla (2023) [11]	A State-of-the-Art Review of Passive Energy Dissipation Systems in Steel Braces	Review	Dampers and energy dissipation	The efficacy of all of these types of dampers has been proved, as they have been used all around the world, and their comparison in experimental or numerical studies, applications, and optimisation shows that there is no unilateral solution, as the appropriate selection of effective retrofit strategies takes into account parameters such as cost, duration, technical aspects, architectural needs, etc.	10.3390/buildings13040851
35	Kallioras et al. (2024) [21]	Cross-laminated timber for seismic retrofitting of RC buildings: Substructured pseudodynamic tests on a full-scale prototype	Experimental	FRP, jacketing and advanced materials	The experiments yielded promising results, showing that the suggested retrofit solution significantly increased displacement and energy dissipation capacity.	10.1002/eqe.4222
36	Wang et al. (2021) [23]	Experimental Research on Bond Behaviour of Fabric Reinforced Cementitious Matrix Composites for Retrofitting Masonry Walls	Experimental	FRP, jacketing and advanced materials	One way of providing seismic resistance upgrading is through the application of the proposed FRCM system on existing masonry infill walls to increase their stiffness and integrity.	10.1186/s40069-021-00460-1
37	Bianchi et al. (2022) [62]	A probabilistic-based framework for the integrated assessment of seismic and energy economic losses of buildings	Analytical/design study	Life-cycle and multi-performance retrofit	The research outcomes demonstrate the effectiveness of the probabilistic approach for decision making in building projects.	10.1016/j.engstruct.2022.114852

Table A1. *Cont.*

ID	Study	Title	Method	Theme	Extracted Finding	DOI
38	Dal Lago et al. (2021) [47]	Tension-only ideal dissipative bracing for the seismic retrofit of precast industrial buildings	Analytical/design study	Bracing and self-centring systems	The efficacy of the CSM is critically analysed through the comparison with the results of a set of nonlinear dynamic analyses.	10.1007/s10518-021-01130-z
39	Işık et al. (2022) [68]	Architectural Characteristics and Seismic Vulnerability Assessment of a Historical Masonry Minaret under Different Seismic Risks and Probabilities of Exceedance	Analytical/design study	Masonry and heritage retrofitting	While the same seismic and structural analysis results were obtained for the selected settlements in the same earthquake zone in this study, remarkable differences were observed for these settlements using the geographical-location-specific design spectrum.	10.3390/buildings12081200
40	Nguyen et al. (2022) [26]	Machine learning-based prediction for maximum displacement of seismic isolation systems	Numerical/analytical	Base isolation	Machine-learning models predicted the maximum displacement demand of seismic isolation systems from ground-motion and system parameters, offering an efficient alternative to repeated nonlinear response-history analyses.	10.1016/j.jobe.2022.104251
41	Dauda et al. (2022) [12]	Understanding the impediments to sustainable structural retrofit of existing buildings in the UK	Analytical/design study	Life-cycle and multi-performance retrofit	The findings of this study contribute to the broader discussion of sustainability within the built environment by increasing awareness of the key barriers to overcome to promote sustainable structural retrofit of existing buildings.	10.1016/j.jobe.2022.105168
42	Micozzi et al. (2021) [25]	Risk Assessment of Reinforced Concrete Buildings with Rubber Isolation Systems Designed by the Italian Seismic Code	Analytical/design study	Base isolation	The results point out that all isolation systems work effectively in limiting damage, while they show a quite low margin with respect to collapse, regardless of the dominant failure mode, which is governed by the more fragile component among isolation system and superstructure.	10.1080/13632469.2021.1961937
43	Granata (2024) [54]	Seismic Retrofit of Concrete Buildings Damaged by Corrosion: A Case Study in Southern Italy	Case study	FRP, jacketing and advanced materials	The adoption of CFRP wrapping at the lower edge of the beams implies a limited increase in thickness and the limited interventions of partial demolition from the existing structural members.	10.3390/buildings14041064

Table A1. *Cont.*

ID	Study	Title	Method	Theme	Extracted Finding	DOI
44	Kitayama et al. (2022) [24]	Performance evaluation of seismically isolated buildings near active faults	Analytical/design study	Base isolation	It is also demonstrated that the seismic isolation systems that have the best collapse performance for far-field motions are not necessarily the best for the near-field pulse-like ground motions.	10.1002/eqe.3602
45	Passoni et al. (2022) [13]	The LCT Challenge: Defining New Design Objectives to Increase the Sustainability of Building Retrofit Interventions	Analytical/design study	Life-cycle and multi-performance retrofit	The results of the comparative analyses confirm that LCT-based retrofit solutions are less impactful than both the traditional seismic retrofit interventions and the demolition and reconstruction scenario.	10.3390/su14148860
46	Kabashi et al. (2025) [8]	Advancements in Fiber-Reinforced Polymer (FRP) Retrofitting Techniques for Seismic Resilience of Reinforced Concrete Structures	Analytical/design study	FRP, jacketing and advanced materials	These results emphasize the critical role of tailored FRP retrofitting strategies in enhancing seismic resilience, offering valuable insights for future retrofitting practices in seismic-prone regions.	10.3390/buildings15040587
47	Aljawhari et al. (2025) [61]	Beyond Direct Economic Losses: An Integrated Approach to Seismic Retrofit Considering Sustainability and Indirect Losses	Analytical/design study	Life-cycle and multi-performance retrofit	It allows users to specify their desired seismic risk level (in terms of losses) and returns the corresponding nominal performance that must be targeted during the design process.	10.1002/eqe.4324
48	Rubini et al. (2024) [63]	Direct loss-based seismic retrofit of reinforced concrete frames	Numerical/analytical	Life-cycle and multi-performance retrofit	Benchmark loss estimates are calculated using non-linear time-history analyses of refined, multi-degree-of-freedom models showing satisfactory results: the simplified loss estimate introduces an overestimation maximum equal to 15.4% among the four illustrative applications.	10.1007/s10518-024-02027-3
49	Karabini et al. (2023) [14]	Seismic Tests of Full Scale Reinforced Concrete T Joints with Light External Continuous Composite Rope Strengthening—Joint Deterioration and Failure Assessment	Experimental	FRP, jacketing and advanced materials	The composite strengthening, increases the structural performance of the joint up to 4% drift which corresponds to 68 mm of beam-end displacement and shear deformation of the joint equal to 10×10^{-4} rad.	10.3390/ma16072718
50	Yan et al. (2024) [51]	Seismic life-cycle cost evaluation of steel-braced frames: Comparing conventional BRBF with emerging SCVDF and HBF systems	Analytical/design study	Bracing and self-centring systems	In most scenarios, HBFs demonstrate superior economic benefits over SCVDFs.	10.1016/j.engstruct.2024.118256

Table A1. *Cont.*

ID	Study	Title	Method	Theme	Extracted Finding	DOI
51	Tsang (2022) [42]	Analytical design models for geotechnical seismic isolation systems	Numerical/analytical	Base isolation	The application of the proposed analytical design models has been illustrated through response history analyses, and a detailed hand-calculation design procedure has also been outlined and demonstrated.	10.1007/s10518-022-01469-x
52	Rahgozar et al. (2023) [49]	Functional recovery evaluation of hybrid self-centring piston-based braced frames	Analytical/design study	Bracing and self-centring systems	The study findings indicate that BRBFs suffer more significant collapse losses than SC-PBBFs.	10.1002/eqe.4042
53	Majumder et al. (2024) [55]	Sustainable Retrofitting Solutions: Evaluating the Performance of Jute Fiber Nets and Composite Mortar in Natural Fiber Textile Reinforced Mortars	Analytical/design study	FRP, jacketing and advanced materials	TC tests have demonstrated the moderate insulation capacity of these composite mortar samples, and the TC values obtained from the tests range from 0.110 (W/mK) to 0.121 (W/mK).	10.3390/su16031175
54	Pohoryles et al. (2021) [56]	Effect of slab and transverse beam on the FRP retrofit effectiveness for existing reinforced concrete structures under seismic loading	Analytical/design study	FRP, jacketing and advanced materials	The slab and transverse beam altered the force-transfer mechanism and the effectiveness of FRP joint retrofit; component-level assessment that omits these members may misrepresent the building response.	10.1016/j.engstruct.2021.111991
55	Belbachir et al. (2023) [39]	Enhancing the Seismic Response of Residential RC Buildings with an Innovative Base Isolation Technique	Analytical/design study	Base isolation	These findings underscore the effectiveness of incorporating FVDs in conjunction with HDRBs as a means to enhance the seismic response of reinforced-concrete buildings.	10.3390/su151511624
56	Chiaro et al. (2022) [40]	Seismic response of low-rise buildings with eco-rubber geotechnical seismic isolation (ERGSI) foundation system: numerical investigation	Numerical/analytical	Base isolation	The eco-rubber geotechnical isolation layer and rubberised-concrete raft reduced seismic demand in the investigated two-storey RC frames while offering a low-cost route for reusing waste rubber.	10.1007/s10518-022-01584-9
57	Mazzon et al. (2023) [44]	Effectiveness of Tuned Mass Damper in Reducing Damage Caused by Strong Earthquake in a Medium-Rise Building	Analytical/design study	Dampers and energy dissipation	It is therefore demonstrated that a TMD is a valid solution for the retrofit of medium-rise existing buildings.	10.3390/app13116815

Table A1. *Cont.*

ID	Study	Title	Method	Theme	Extracted Finding	DOI
58	Ahmadie Amiri et al. (2023) [46]	Life cycle cost-based optimization framework for seismic design and target safety quantification of dual steel buildings with buckling-restrained braces	Numerical/analytical	Bracing and self-centring systems	Comparison of optimized buildings with the two design approaches in terms of structural responses and seismic consequences demonstrates that fulfilling the minimum code requirements at a given seismic hazard level is not sufficient to minimize lifetime seismic losses of steel SMRF-BRBs.	10.1002/eqe.3864
59	Shendkar et al. (2025) [57]	Seismic evaluation and retrofit of reinforced concrete structures	Analytical/design study	FRP, jacketing and advanced materials	Also, the ultimate capacity and over strength factor of the retrofitted single-storey RC existing building are found 2.04 times and 1.82 times increased in X and Y direction as compared to the building without retrofit because of the RC jacketing and FRP sheet wrapping.	10.1186/s43065-024-00114-y
60	Issa et al. (2024) [7]	Unveiling the Seismic Performance of Concentrically Braced Steel Frames: A Comprehensive Review	Review	Bracing and self-centring systems	The work finally highlights the advancements and challenges in achieving more sustainable solutions for the built environment.	10.3390/su16010427
61	Imran et al. (2021) [41]	Seismic performance of reinforced concrete buildings with double concave friction pendulum base isolation system: case study of design by Indonesian code	Case study	Base isolation	The double-concave friction-pendulum system reduced seismic response relative to the fixed-base RC building and demonstrated the feasibility of isolation design under the Indonesian code.	10.1016/j.istruc.2021.07.084
62	Vailati et al. (2021) [43]	Integrated Solution-Base Isolation and Repositioning-for the Seismic Rehabilitation of a Preserved Strategic Building	Analytical/design study	Base isolation	Possible ideas for new research and developments are also highlighted.	10.3390/buildings11040164
63	Abraik et al. (2022) [53]	Seismic Performance of Hybrid Corrosion-Free Self-centring Concrete Shear Walls	Analytical/design study	FRP, jacketing and advanced materials	The hybrid walls not only solved the durability problem but also significantly improved the seismic performance.	10.3390/su14020712
64	Sorace et al. (2023) [50]	Seismic assessment and dissipative bracing retrofit-based protection of infills and partitions in RC structures	Analytical/design study	Bracing and self-centring systems	Dissipative bracing reduced deformation demand and improved protection of masonry infills and partitions, linking structural retrofit design to nonstructural damage control.	10.1016/j.engstruct.2023.115781

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