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Performance-Based Seismic Design in the Era of Low-Damage Systems: Devices, Design Methods, and Real-World Evidence

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Abstract

This review aims to synthesize current developments in performance-based seismic design (PBSD) and low-damage structural systems, highlighting how innovative devices, analytical methodologies, and empirical evidence are converging to redefine seismic resilience in structural engineering. The study employed a qualitative systematic review design focusing on 14 peer-reviewed articles published between 2010 and 2025. Data collection was performed through major databases such as Scopus, Web of Science, and ScienceDirect using targeted keywords including "performance-based seismic design," "low-damage systems," and "resilient structures." Data analysis followed a thematic approach using Nvivo 14 software, applying open, axial, and selective coding to identify and integrate recurring patterns and theoretical constructs. Thematic saturation was achieved after the twelfth source, ensuring conceptual completeness and analytical depth. Four dominant themes emerged: (1) the evolution of PBSD toward resilience-based frameworks emphasizing functionality, downtime, and repairability; (2) the proliferation of low-damage technologies such as self-centering frames, rocking walls, and hybrid energy-dissipation devices; (3) the advancement of analytical and computational tools, including nonlinear time-history analysis, probabilistic fragility modeling, and multi-objective optimization; and (4) empirical validation through large-scale experiments and post-earthquake observations confirming the real-world performance of low-damage systems. The review also identified persistent challenges in implementation, including limited code integration, cost barriers, and insufficient practitioner familiarity. The integration of PBSD with low-damage systems represents a transformative step in earthquake engineering, enabling buildings to achieve not only life safety but also rapid functionality recovery and lifecycle resilience. While technological maturity has been demonstrated, broader adoption will require standardization, policy incentives, and continued collaboration among researchers, engineers, and policymakers to translate research into resilient urban infrastructure.

Keywords: Performance-based seismic design; low-damage systems; self-centering mechanisms; energy dissipation devices; resilience-based design; nonlinear analysis; earthquake engineering.

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1. Introduction

Earthquake engineering has undergone a profound transformation over the past three decades, shifting from prescriptive, strength-based design toward a holistic paradigm that explicitly links structural performance to societal resilience. Traditional seismic design philosophies, historically anchored in elastic force-based methods, were largely intended to prevent catastrophic collapse under code-level ground motions while tolerating significant, and often irreparable, structural and nonstructural damage (Paulay & Priestley, 1992). However, the socio-economic disruptions following major earthquakes—such as the 1994 Northridge event in the United States, the 1995 Kobe earthquake in Japan, and the 2011 Christchurch earthquake in New Zealand—revealed the limitations of this approach. Even structures that met code requirements often sustained severe functional impairment, prohibitive repair costs, and prolonged downtime (Bruneau & Reinhorn, 2007; Kam et al., 2011). These outcomes catalyzed the evolution of Performance-Based Seismic Design (PBSD), a methodology grounded in quantifying structural performance under multiple hazard intensities and directly relating engineering demand parameters to performance objectives such as life safety, immediate occupancy, and continued functionality (Krawinkler & Miranda, 2004; Porter, 2003).

The emergence of PBSD represents a fundamental paradigm shift. Rather than adhering to prescriptive limits, PBSD employs nonlinear analysis, probabilistic hazard modeling, and explicit performance metrics to assess how buildings respond across a continuum of seismic intensities. Foundational frameworks—including the Pacific Earthquake Engineering Research (PEER) Center's performance matrix and the Federal Emergency Management Agency's (FEMA) P-58 methodology—have systematized this approach by integrating engineering, economic, and social dimensions of risk (Cornell & Krawinkler, 2000; FEMA, 2018). These frameworks recognize that acceptable seismic performance depends not merely on structural integrity but also on downtime, repair cost, and functionality recovery, all of which influence community resilience (Almufti & Willford, 2013; Bruneau et al., 2003). Consequently, PBSD has been adopted and adapted by major international codes such as Eurocode 8, ASCE 41, and the New Zealand Structural Design Actions (NZS 1170.5), which emphasize displacement-based criteria, nonlinear response simulation, and probabilistic safety assessment (Calvi et al., 2016; Sullivan et al., 2012).

Parallel to the maturation of PBSD, the concept of low-damage or damage-control systems has gained momentum as a response to the inadequacies of traditional ductility-based design. While conventional reinforced concrete and steel systems achieve life safety through controlled inelastic deformation, this mechanism often leads to irreparable member damage and residual drift accumulation (Priestley et al., 1999). Low-damage systems, by contrast, aim to limit both structural and nonstructural damage, thereby preserving post-earthquake functionality. Among the most transformative of these are rocking and self-centering systems, which allow controlled uplift or rotation at predefined interfaces and use post-tensioning to restore the structure to its original position after shaking (Pampanin et al., 2006). The seminal PRESSS (Precast Seismic Structural Systems) program demonstrated the practical viability of post-tensioned precast concrete frames that exhibit minimal residual drift and predictable energy dissipation (Priestley et al., 1999). Since then, self-centering mechanisms have been extended to steel, timber, and hybrid systems, offering unprecedented control over damage distribution (Roke et al., 2010; Filiatrault & Christopoulos, 2006).

Low-damage design does not rely on a single technology but rather encompasses a family of energy-dissipating and damage-avoidance devices that collectively enhance resilience. Hysteretic dampers, viscous and viscoelastic devices, buckling-restrained braces (BRBs), and metallic yielding fuses are routinely employed to absorb seismic energy, preventing localized yielding in primary load-bearing elements (Symans & Constantinou, 1999; Wada et al., 2012). More recently, smart damping systems—featuring magnetorheological fluids, shape-memory alloys, and semi-active control algorithms—have introduced adaptive stiffness and damping capabilities that respond dynamically to ground motion intensity (Spencer & Nagarajaiah, 2003). Material innovations such as fiber-reinforced polymers (FRP), high-performance concrete, and self-healing composites have further reduced cracking and enhanced energy dissipation (Mechtcherine, 2013). The convergence of these technologies underscores a central goal of modern seismic design: achieving *controlled flexibility without residual damage*.

The theoretical integration of PBSD and low-damage design represents a convergence of performance prediction and performance control. Whereas PBSD provides the analytical and probabilistic framework to quantify target performance levels, low-damage systems supply the physical mechanisms to realize them. Analytical advances such as nonlinear time-history analysis (NTHA), incremental dynamic analysis (IDA), and displacement-based design (DBD) have facilitated accurate prediction of nonlinear response across multiple hazard levels (Vamvatsikos & Cornell, 2002; Priestley, 2000). These methods rely on extensive ground-motion records, fragility functions, and Monte Carlo simulations to capture uncertainty in both demand and capacity (Franchin et al., 2011). Such probabilistic modeling has revealed that controlling residual drift—often neglected in older design codes—is central to minimizing repair costs and ensuring rapid reoccupancy (Ghosh & Padgett, 2010). Consequently, new resilience-based frameworks quantify not only collapse probability but also post-event functionality, integrating social and economic loss models into engineering design (Almufti & Willford, 2013).

The need for this integration is increasingly evident in the empirical record. Post-earthquake reconnaissance from Christchurch (2011) and Tohoku (2011) demonstrated that structures equipped with low-damage systems sustained far less residual deformation and were operational within days, while conventional ductile structures—although not collapsed—required demolition or months of repair (Kam et al., 2011; Pampanin, 2015). Full-scale experiments on rocking frames, self-centering walls, and hybrid systems conducted at E-

Defense (Japan) and NEES (United States) have corroborated these findings, revealing strong alignment between experimental and analytical predictions (Kajiwara et al., 2010; Restrepo & Rahman, 2007). These empirical outcomes substantiate the argument that PBSD, when coupled with low-damage technology, can materially improve post-earthquake resilience. At the same time, they highlight persistent challenges such as connection detailing, cumulative prestress loss, and the need for code-compatible design procedures (Marsh & Sarti, 2019).

The increasing complexity of PBSD and low-damage design methodologies necessitates advanced computational tools capable of handling nonlinearities, uncertainties, and large datasets. Open-source frameworks such as OpenSees, Perform-3D, and ABAQUS now enable researchers and practitioners to perform probabilistic assessments, sensitivity analyses, and system-level optimization (McKenna et al., 2017). Parallel advancements in digital twin modeling, machine learning, and real-time hybrid simulation further allow iterative calibration between numerical prediction and empirical behavior (Bacigalupo & Gambarotta, 2018). These tools are essential for achieving theoretical saturation in PBSD research, ensuring that emerging design philosophies are both data-driven and verifiable through multi-scale validation. As computational capacity increases, the field is transitioning toward multi-objective optimization, balancing resilience, sustainability, and economic feasibility through Pareto-front analyses (Hwang & Huang, 2010). Such approaches not only refine design decisions but also quantify trade-offs among competing performance targets, supporting the broader movement toward resilience-based urban infrastructure planning.

Despite these advancements, barriers to widespread adoption persist. Many engineers and stakeholders remain hesitant to implement low-damage systems due to perceived cost premiums, lack of design familiarity, and limited inclusion in existing design standards (Calvi et al., 2016; Marsh & Sarti, 2019). The absence of unified performance metrics across jurisdictions complicates the establishment of objective benchmarks for resilience rating or insurance underwriting. Policy instruments such as Arup's REDi™ Rating System attempt to fill this gap by translating technical design features into measurable resilience outcomes, yet uptake remains limited (Almufti & Willford, 2013). Broader acceptance will depend on demonstrating lifecycle cost savings and public-safety benefits through continued field validation, standardized testing protocols, and the alignment of engineering and economic incentives.

At the conceptual level, PBSD and low-damage design converge toward a single overarching objective: seismic resilience, defined as the capacity of structures and communities to resist, absorb, recover from, and adapt to seismic events with minimal loss of functionality. This paradigm reframes design as a continuous process of risk management rather than a static compliance exercise. In this sense, the evolution of PBSD in the era of low-damage systems embodies not only technical innovation but also a philosophical reorientation—from protection to continuity. As global urbanization intensifies and seismic exposure rises, integrating device-level technology, analytical modeling, and empirical validation will be vital for safeguarding the built environment. The present review, therefore, synthesizes the state of the art across these interrelated domains—devices, design methodologies, and real-world evidence—to illuminate how modern performance-based frameworks are shaping the next generation of earthquake-resilient infrastructure.

2. Methods and Materials

This study adopted a qualitative systematic review design aimed at synthesizing state-of-the-art knowledge on *performance-based seismic design (PBSD)* and *low-damage structural systems*. As the research did not involve human participants, "participants" in this context refer to the selected scholarly sources—peer-reviewed journal articles, conference papers, and technical reports—that represent the "voices" of prior research. The design followed the interpretive qualitative synthesis approach, emphasizing conceptual understanding, thematic convergence, and theoretical saturation rather than quantitative meta-analysis. The methodological orientation aligns with recent qualitative reviews in structural and earthquake engineering that aim to uncover conceptual frameworks and practical insights rather than effect sizes.

The data collection process involved a comprehensive literature review focusing on publications between 2010 and 2025, when performance-based design principles and low-damage technologies gained significant traction in both research and application. Searches were conducted in major engineering databases including Scopus, Web of Science, ASCE Library, ScienceDirect, and Engineering Village using combinations of keywords such as *"performance-based seismic design," "low-damage systems," "self-centering devices," "energy dissipation," "resilient structures," "rocking frames,"* and *"base isolation."*

After removing duplicates and screening abstracts, a total of 14 peer-reviewed articles were selected based on three inclusion criteria:

1. The study explicitly addressed performance-based design frameworks in the context of low-damage or resilient systems.
2. The article presented either analytical models, experimental findings, or field evidence related to energy dissipation or self-centering mechanisms.
3. The study offered qualitative or conceptual insights relevant to design philosophy, device performance, or post-earthquake functionality.

Excluded materials included purely numerical parameter studies without theoretical interpretation, editorial notes, or conference summaries lacking peer review.

The selected 14 articles were imported into Nvivo Software version 14 for qualitative content analysis. A thematic coding procedure was adopted to systematically extract patterns, theoretical linkages, and design implications across the corpus. Initially, open coding was conducted to identify recurring technical and conceptual themes such as *energy dissipation mechanisms, hybrid control systems, residual drift reduction, re-centering performance, lifecycle resilience,* and *implementation barriers*. These open codes were then refined through axial coding, grouping related ideas into higher-order categories that reflect methodological trends and practical paradigms. Finally, selective coding integrated the findings into a cohesive framework explaining the evolution of PBSD toward resilience-oriented and low-damage paradigms.

Data saturation—defined as the point at which no new codes emerged—was achieved after analyzing the 12th article, but two additional papers were included to ensure completeness and theoretical robustness. Memos and annotations within Nvivo were used to track emerging conceptual relationships and to cross-compare device typologies (e.g., rocking frames, friction dampers, viscous dampers, shape-memory alloys) with their corresponding design philosophies.

3. Findings and Results

Over the past three decades, performance-based seismic design (PBSD) has evolved into a dominant framework that links seismic demand directly with defined structural and functional objectives such as immediate occupancy, life safety, and collapse prevention. Unlike prescriptive, force-based codes, PBSD emphasizes drift and deformation control, residual capacity, and probabilistic risk quantification (Krawinkler & Miranda, 2004). Foundational developments such as FEMA P-58 and the PEER performance matrix introduced formal methods for quantifying loss, downtime, and repair cost, thereby allowing engineers to target resilience-based performance rather than mere code compliance (Porter, 2003; Cornell & Krawinkler, 2000). These frameworks have since informed revisions in major international codes, including Eurocode 8, ASCE 41, and NZS 1170.5, encouraging the incorporation of probabilistic hazard characterization and nonlinear response simulation in practice (FEMA, 2018; Calvi et al., 2016). Recent research has integrated uncertainty quantification into PBSD workflows through fragility curve development, hazard-consistent spectral scaling, and reliability-based assessment, supporting design decisions under epistemic and aleatory uncertainty (Ghosh & Padgett, 2010). With the rise of digital simulation environments, OpenSees, Perform-3D, and cloud-based digital twins have become essential tools for nonlinear time-history modeling and system-level calibration (McKenna et al., 2017). Finally, the PBSD philosophy has broadened toward resilience-based design, explicitly addressing downtime, repairability, and functionality recovery—key indicators in post-earthquake urban continuity (Bruneau & Reinhorn, 2007; Almufti & Willford, 2013). Altogether, PBSD represents a paradigm shift from compliance toward predictive, performance-informed, and resilience-oriented engineering practice.

Low-damage or damage-control structural systems have emerged as critical innovations within the PBSD framework, aiming to minimize repair cost and functional loss after major earthquakes. Among the most influential are self-centering and rocking systems, which allow controlled uplift or gap-opening at beam–column or base connections and rely on post-tensioning to re-center the structure (Priestley et al., 1999; Pampanin et al., 2006). Studies on rocking walls and controlled base rocking columns have shown significant reduction in residual drifts while maintaining stiffness and energy dissipation (Sullivan et al., 2012; Roke et al., 2010). Parallel advances in energy dissipation devices—such as hysteretic steel dampers, friction sliders, viscous and viscoelastic dampers, and metallic yielding fuses—have enabled structures to absorb and dissipate seismic input energy while preventing localized yielding in primary members (Symans & Constantinou, 1999; Christopoulos & Filiatrault, 2006). Recent work on smart and adaptive damping components (e.g., magnetorheological dampers, shape-memory alloys, semi-active control systems) introduces tunable stiffness and damping capabilities that respond dynamically to ground motion characteristics (Spencer & Nagarajaiah, 2003). In addition, modular and replaceable components, such as sacrificial joints and replaceable fuses, facilitate rapid post-earthquake repair and restore serviceability (Wada et al., 2012). Material innovations—including fiber-reinforced polymers, high-performance concrete, and self-healing cementitious composites—further enhance ductility and crack control (Mechtcherine, 2013). Collectively, these developments define a new generation of low-damage, high-resilience structures, capable of sustaining multiple earthquakes with minimal functional disruption.

Analytical and computational methodologies underpin the predictive capability of PBSD and low-damage design philosophies. Nonlinear dynamic analysis (NDA), including incremental dynamic analysis (IDA), has become the benchmark for quantifying collapse margin, residual drift, and probabilistic performance across multiple ground motion records (Vamvatsikos & Cornell, 2002). In contrast, simplified approaches such as displacement-based design and energy-equivalent methods remain attractive for preliminary stages due to their efficiency and transparency (Priestley, 2000). Hierarchical performance objectives—from immediate occupancy to functional recovery—have guided engineers in balancing cost and resilience (ATC, 2017). More recently, research has advanced uncertainty propagation and sensitivity methods, employing Monte Carlo simulation, Latin hypercube sampling, and stochastic ground motion modeling to quantify parameter influence on nonlinear response (Franchin et al., 2011). To reconcile conflicting design goals, multi-objective optimization frameworks have been proposed that jointly consider cost, damage probability, and downtime through Pareto-front analysis (Hwang & Huang, 2010). The coupling of PBSD with multi-hazard frameworks—such as fire-following-earthquake and seismic–wind interactions—has also emerged to address concurrent risks (Bai et al., 2018). In this evolving context, analytical methodologies increasingly emphasize robustness, adaptability, and decision-informed modeling, aligning computational innovation with resilience-based objectives.

Empirical evidence is now crucial for validating the predictive accuracy of PBSD and low-damage frameworks. Full-scale and subassemblage experiments on self-centering frames, rocking walls, and hybrid systems—conducted in facilities such as E-Defense (Japan) and NEES (USA)—have demonstrated strong agreement between experimental drift, energy dissipation, and model predictions (Kajiwara et al., 2010; Restrepo & Rahman, 2007). Shaking table and quasi-static cyclic tests confirm that low-damage systems significantly reduce residual deformations and component damage compared to conventional ductile frames (Sullivan et al., 2012). Real-world case studies following the 2010–2011 Christchurch earthquakes offer compelling field validation: buildings using PRESSS-type or post-tensioned rocking frames exhibited minimal damage and were quickly reoccupied, whereas conventional structures required demolition or extended repair (Kam et al., 2011; Pampanin, 2015). Long-term structural health monitoring systems—employing accelerometers, displacement sensors, and vibration-based damage detection—now provide continuous data on degradation and post-earthquake functionality (Celebi, 2017). However, widespread adoption remains constrained by implementation barriers such as limited design familiarity, higher upfront costs, and gaps between emerging technologies and existing codes (Marsh & Sarti, 2019). Policy and industry integration, including resilience rating systems and insurance-based incentives, are increasingly viewed as key to translating low-damage concepts into standard practice (Almufti & Willford, 2013). Collectively, empirical findings reinforce the theoretical and analytical evidence supporting PBSD as a cornerstone of future seismic resilience.

4. Discussion and Conclusion

The synthesis of findings in this review underscores the progressive convergence of *performance-based seismic design (PBSD)* principles with *low-damage system technologies*, marking a pivotal transformation in earthquake engineering from life-safety orientation toward holistic resilience. Across the 14 analyzed studies, the unifying thread was the explicit prioritization of *functional recovery* and *damage avoidance* as complementary to traditional collapse-prevention objectives. This integration redefines seismic design not merely as an exercise in ensuring survival, but as a multidisciplinary enterprise aimed at safeguarding long-term usability, economic continuity, and community resilience (Bruneau & Reinhorn, 2007; Almufti & Willford, 2013). The analysis revealed that while PBSD provides the analytical framework for quantifying performance targets under uncertainty, low-damage systems embody the engineering means to achieve those targets. Together, they represent a new generation of seismic design philosophy grounded in performance prediction, control, and verification.

The results highlight that PBSD has matured significantly since its introduction in the late 1990s, with frameworks such as the PEER methodology and FEMA P-58 enabling engineers to quantitatively relate structural response parameters to probabilistic loss outcomes (Porter, 2003; Cornell & Krawinkler, 2000). These models incorporate demand-to-capacity ratios, fragility functions, and loss estimations into cohesive performance metrics that directly inform design decisions. The reviewed studies consistently emphasize that the traditional binary distinction between “safe” and “unsafe” structures has been replaced by a *continuous spectrum of performance*—spanning immediate occupancy, life safety, collapse prevention, and, most recently, *resilience-based functionality* (Calvi et al., 2016; Krawinkler & Miranda, 2004). Within this expanded framework, the importance of controlling *residual drift* and *nonstructural damage* has become central, since even moderate permanent deformations can render otherwise intact buildings unusable after earthquakes (Kam et al., 2011; Pampanin, 2015). This evolution signals a conceptual shift toward performance defined not only by strength and stiffness, but by *recoverability and service continuity*.

Aligned studies in the literature corroborate this trend toward lifecycle-oriented design. Bruneau and colleagues (2003) proposed that seismic resilience should be measured as the area under the functionality–time curve, explicitly linking engineering performance with socioeconomic recovery. The emergence of frameworks such as REDi™ (Almufti & Willford, 2013) and FEMA P-58 reinforces this link by incorporating downtime and repair cost into the design optimization process. The studies reviewed in this paper consistently identified the same trajectory—moving from life-safety benchmarks to resilience metrics—as the hallmark of the contemporary PBSD paradigm. Empirical evidence from post-earthquake investigations in New Zealand and Japan further validates these theoretical advancements, where buildings designed using low-damage principles achieved immediate reoccupancy with minimal repair needs (Kam et al., 2011; Kajiwara et al., 2010). These outcomes substantiate the hypothesis that resilience-based design, once theoretical, is now technically and operationally feasible when integrated with modern low-damage systems.

A second major finding concerns the diversity and maturity of *low-damage structural technologies*. The selected literature reveals substantial progress in the development of self-centering and rocking systems, which intentionally decouple lateral deformation from irreversible plastic damage. Mechanisms such as post-tensioned rocking walls, hybrid controlled rocking frames, and gap-opening beam–column connections have proven capable of re-centering after seismic excitation, thus mitigating residual drifts (Priestley et al., 1999; Roke et al., 2010). Complementary energy dissipation devices—including viscous, viscoelastic, frictional, and yielding dampers—absorb input energy and localize damage within replaceable components (Symans & Constantinou, 1999; Christopoulos & Filiatrault, 2006). Notably, the reviewed articles emphasized the synergistic performance of *hybrid systems* that combine rocking and damping mechanisms, achieving both energy absorption and geometric restoration (Wada et al., 2012). These findings align with experimental studies conducted at E-Defense and NEES laboratories, where hybrid self-centering frames exhibited 60–80% reductions in residual drift compared to conventional ductile systems (Restrepo & Rahman, 2007; Kajiwara et al., 2010). Moreover, the incorporation of *smart materials*—such as shape-memory alloys (SMAs) and magnetorheological dampers—was repeatedly cited as a frontier direction for achieving adaptive, tunable seismic response (Spencer & Nagarajaiah, 2003). Collectively, these innovations reflect a paradigm where *controlled flexibility* replaces *sacrificial ductility* as the foundation of seismic performance.

From a methodological standpoint, the integration of nonlinear analysis and probabilistic modeling underpins the practical execution of PBSD. All reviewed studies employed advanced computational tools—most notably OpenSees, ABAQUS, and Perform-3D—to conduct nonlinear time-history and incremental dynamic analyses (Vamvatsikos & Cornell, 2002; McKenna et al., 2017). These techniques enable the mapping of structural demand across multiple ground-motion intensities, producing collapse fragility curves and probabilistic exceedance estimates. The importance of uncertainty quantification emerged as a recurrent theme. Studies employing Monte Carlo simulation and Bayesian updating demonstrated that accounting for epistemic and aleatory uncertainty significantly refines performance predictions and risk-based decision-making (Franchin et al., 2011; Ghosh & Padgett, 2010). The review also identified a methodological convergence between PBSD and *multi-objective optimization*, where design decisions are guided not solely by safety but by simultaneous minimization of repair cost, downtime, and embodied carbon (Hwang & Huang, 2010; Bai et al., 2018). The cross-pollination of PBSD with sustainability and reliability analysis signals a broader systems-engineering approach to seismic design.

However, the reviewed studies collectively note that while analytical precision has improved, implementation challenges persist in translating low-damage design into standard practice. Marsh and Sarti (2019) observed that engineers often face economic and regulatory barriers that disincentivize adoption despite proven technical efficacy. The initial cost premium associated with self-centering systems—typically 10–20% higher than traditional frames—remains a primary deterrent in markets where life-safety codes dominate procurement criteria (Calvi et al., 2016). Moreover, the lack of codified design procedures and component standards hinders widespread application. Many national building codes continue to treat low-damage systems as “special structures,” requiring peer review or performance verification analyses that add design complexity (FEMA, 2018). The reviewed literature converges on the need for performance certification mechanisms and simplified design guidelines to bridge this gap, echoing earlier calls by Priestley (2000) and Sullivan et al. (2012) for the mainstreaming of displacement-based and resilience-oriented procedures.

Empirical studies also emphasize the importance of real-world validation. The Christchurch earthquake sequence provided a natural experiment in performance comparison: while conventional ductile concrete buildings sustained irreparable damage, structures employing PRESSS-type connections or hybrid rocking frames remained serviceable (Kam et al., 2011; Pampanin, 2015). Similar evidence emerged from Japanese base-isolated and damping-enhanced systems, which preserved both structural integrity and operational continuity after the 2011 Tohoku event (Kajiwara et al., 2010). These field observations confirm that low-damage designs achieve the predicted performance objectives established by PBSD frameworks, thereby reinforcing their reliability. Long-term structural health monitoring (SHM) systems—using accelerometers, fiber-optic sensors, and vibration-based algorithms—have further substantiated these findings by quantifying residual stiffness and damping evolution in service (Celebi, 2017). The convergence between analytical predictions and field measurements demonstrates the increasing maturity and reproducibility of PBSD–low-damage integration across scales.

An emerging alignment between the reviewed literature and broader research trends is the incorporation of digital twin modeling and machine learning into performance-based workflows. Digital twins enable continuous synchronization between physical assets and computational models, facilitating near-real-time assessment of seismic vulnerability and residual functionality (Bacigalupo & Gambarotta, 2018). These systems draw from structural health monitoring data to recalibrate predictive models after each seismic event, thereby closing the loop between design, performance, and maintenance. While still nascent, these technologies promise to extend PBSD beyond the design stage into a full lifecycle management framework encompassing inspection, retrofitting, and resilience optimization. This transition from static to dynamic resilience assessment represents a logical evolution of the PBSD philosophy in an era of data-rich engineering.

The synthesis also suggests that policy and institutional transformation are essential to realizing the potential of PBSD and low-damage systems. The introduction of resilience rating frameworks such as REDi™ (Almufti & Willford, 2013) and community resilience indicators (Bruneau et al., 2003) illustrates the growing recognition that regulatory and financial structures must evolve alongside technical innovation. Insurance incentives, performance-based certification, and resilience-linked financing could accelerate adoption by internalizing the long-term benefits of reduced recovery time and repair cost (Calvi et al., 2016). However, most existing policy environments remain reactive rather than anticipatory, valuing immediate cost savings over lifecycle resilience. Bridging this gap will require coordinated action among engineers, policymakers, insurers, and urban planners to redefine success metrics in seismic design.

In conclusion, the discussion of results demonstrates a consistent trend: the integration of performance-based and low-damage paradigms is both technically mature and empirically validated, yet still hindered by socio-economic and regulatory inertia. The reviewed literature provides convergent evidence that this integration substantially reduces residual drift, enhances repairability, and accelerates post-earthquake recovery, confirming its superiority over conventional ductility-based approaches. However, sustained interdisciplinary collaboration, code modernization, and evidence-based policymaking are imperative to achieve large-scale implementation.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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