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Toward Low-Damage Seismic Performance: A Critical Synthesis of Column Base Behavior and Innovative Design Strategies

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Abstract

This article presents a critical synthesis of advanced seismic engineering strategies to enhance the resilience of multi-story steel buildings. It examines the shift in seismic design from traditional collapse prevention to prioritizing post-earthquake functionality and operational continuity. Through a focused review of column base behavior, this work addresses a significant gap in conventional design by synthesizing innovative solutions. It details the management of complex structural behaviors such as drift concentration, P-delta effects, and biaxial seismic response, along with their practical implications. The paper discusses low-damage self-centering systems and the Continuous Column Concept (CCC), explaining how column base flexibility can localize inelastic deformation to replaceable components and minimize residual drifts. It highlights significant challenges in practical application, including the need for improved modeling accuracy of column base behavior under multiaxial loading and for accounting for scaling effects in tall buildings. The review concludes by identifying key directions for future research, advocating for refined multi-axial demand modeling, standardization of new design methods, and the development of practical design tools to bridge the gap between cutting-edge research and current engineering practice, ultimately guiding the pursuit of truly resilient urban infrastructure.

Keywords: Continuous Column Concept, Base Flexibility, Low-Damage Design, Seismic Resilience, Drift Concentration.

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1- Introduction: Advancing Beyond Collapse Prevention – A Critical Perspective

The seismic engineering landscape is undergoing a significant shift. Traditionally, seismic design has primarily focused on collapse prevention to ensure life safety during extreme events, often accepting considerable structural damage, extensive downtime, and high repair costs (1). However, events like the Canterbury earthquakes have highlighted the shortcomings of this approach: even non-collapsed structures frequently sustained damage that rendered them functionally inoperable and uneconomical to repair, often leading to demolition (2). This has prompted a transition toward "damage-resistant" and "resilient" designs, which prioritize post-earthquake functionality and operational continuity (3), (4). Minimizing residual drift has become a key metric for achieving this goal (5). This paper advocates for a unified performance hierarchy that goes beyond mere collapse prevention, aiming for functional resilience.

This review article critically synthesizes the current knowledge of low-damage seismic design strategies, focusing on column base behavior in multi-story steel frames. It examines the shift in seismic design from traditional collapse prevention to prioritizing post-earthquake functionality and operational continuity. By reviewing column base behavior, this work addresses a significant gap in conventional design with innovative solutions. It details the management of complex structural behaviors such as drift concentration, P-delta effects, and biaxial seismic response, along with their practical implications. The paper discusses low-damage self-centering systems and the Continuous Column Concept (CCC), explaining how column base flexibility can localize inelastic deformation to replaceable components and minimize residual drifts. It highlights significant challenges in practical application, including the need for improved modeling of column base behavior under multiaxial loading and scaling effects in tall buildings. The review concludes by identifying key directions for future research, advocating for refined multi-axial demand modeling, standardization of new design methods, and the development of practical design tools to bridge the gap between cutting-edge research and current engineering practice, ultimately guiding the pursuit of resilient urban infrastructure.

While numerous reviews have explored seismic design principles and specific low-damage technologies (6-24), this work distinguishes itself through several key contributions:

- **Scope and Focus:** This article examines column base behavior in multi-story steel frames, in contrast to broader reviews that may include reinforced concrete or timber structures. This focused scope enables a deeper analysis of the unique challenges and solutions associated with this structure type.
- **Critical Synthesis over Description:** This review aims to evaluate and synthesize existing research rather than merely summarize it. It distinguishes between evidence-based and theoretical claims, integrates conflicting findings, and highlights the practical trade-offs inherent in various design strategies. The article critically assesses the practical implementation challenges and limitations that are often overlooked in descriptive accounts.
- **Bridging Research to Practice:** A primary objective is to translate complex analytical concepts into practical implications for engineers. This includes offering actionable guidance, real-world application contexts, and design considerations that inform actual design decisions beyond theory.
- **Structured Practical Deliverables:** The review concludes with comprehensive comparison tables, a conceptual flowchart, and a quantitative synthesis of reported trends designed to assist practitioners in evaluating design options and understanding the implications of their choices, thereby enhancing decision-making efficiency and facilitating knowledge transfer.

In response to design challenges, significant research has focused on developing low-damage, self-centering structural systems and energy dissipation technologies. These innovations aim not only to prevent collapse but also to ensure functionality and minimize economic loss. For example, Li and colleagues (25) developed a new seismic strategy for a strong-column-weak-beam design philosophy in RC frame structures. Their research showed that standard code-compliant force patterns often fail to prevent failures, highlighting the need for optimal seismic force patterns to achieve uniform drift distribution. Additionally, new seismic strategies, such as combining column strengthening with beam weakening, have been proposed to better control the sequence and location of plastic hinges (26).

The central focus of this review is to answer the question: How can a deep understanding of column base behavior in multi-story steel frames, combined with innovative seismic design strategies, effectively achieve low-damage performance, ensuring immediate occupancy and operational continuity post-earthquake?

This review is deliberately focused on:

- **Structural Type:** Multi-story steel frame buildings.
- **Key Component:** Column bases and their influence on global seismic response.
- **Design Philosophy: Low-damage,** resilient, performance-based seismic design focused on minimizing residual drifts and enhancing reparability**.**
- **Critical Behaviors:** Drift concentration, P-delta effects, biaxial seismic response, and the interaction of axial loads with bending**.**
- **Innovative Strategies:** Concepts such as the Continuous Column Concept (CCC), self-centering systems, base flexibility/rocking, energy dissipation devices at the base, and advanced modeling techniques.

This discussion focuses on column bases and their integration within the superstructure to ensure analytical depth. It excludes reinforced concrete, timber structures, and seismic retrofitting. While certain low-damage technologies, such as base isolation, are referenced for context, the primary emphasis remains on column bases.

2- Column Base Flexibility: A Critical Nexus for Seismic Performance

Conventional seismic design often relies on simplified assumptions for column bases, treating them as perfectly pinned or fixed (17). However, empirical observations from seismic events and numerous experimental studies show that real-world connections exhibit semi-rigid behavior. This flexibility, stemming from the base plate, anchor bolts, foundation, and soil-structure interaction, significantly alters a structure's lateral stiffness, natural period, and moment distribution (17, 27). Ignoring this flexibility can lead to inaccurate predictions of drift demands and plastic hinge locations, potentially compromising seismic performance. For instance, studies indicate that assuming fixed bases without adequate detailing for anchor stretch can result in premature concrete crushing, while nominally "pinned" bases have non-negligible rotational stiffness due to anchor bolts and base plate interaction, affecting period calculations (28). This highlights a critical departure point: true behavior lies in the intermediate range, necessitating explicit modeling of base rotational spring (29).

Base flexibility presents a significant trade-off in structural design. Increased flexibility can extend the natural period of a structure and reduce base shear demand, particularly in short-period structures subjected to long-period ground motions, helping to avoid resonance with predominant earthquake frequencies. However, greater flexibility often increases inter-story drifts, particularly in lower stories, thereby increasing susceptibility to P-delta effects (30). This drift amplification is a primary concern for maintaining serviceability and preventing soft-story mechanisms. Research indicates that neglecting base flexibility can considerably underestimate displacement demands, with top displacements potentially reaching up to 1.64 times those of fixed-base structures for the same period (14).

Innovative strategies like "Base Dissipation" (BD) developed by Petti et al. (31) aim to address this trade-off by decoupling the superstructure from ground motion through a damping hinge interface. Although effective in localizing energy dissipation and protecting the superstructure, the practical implementation and codification of these specialized damping interfaces are still evolving. Similarly, controlled rocking bases, which allow uplift to limit forces, require sophisticated detailing to ensure reliable re-centering and manage potential instabilities during uplift. The literature often presents these as standalone solutions; however, their synergistic integration with other low-damage concepts, such as self-centering or continuous columns, requires further investigation (32).

A notable knowledge gap exists in accurately modeling the combined effects of axial loads and biaxial bending on column bases. Seismic events typically do not involve unidirectional shaking; rather, bidirectional ground motions create complex stress paths that can significantly increase demands on column bases (33). Moreover, axial forces are not static during an earthquake; they fluctuate dynamically because of overturning moments (34). These fluctuating axial forces directly affect the strength and deformation capacity of structural members, particularly in composite columns like concrete-filled tubes (CFTs) (35, 36). In friction-based connections, increased axial compression can enhance energy dissipation; however, excessive compression may lead to joint locking (32). The complex P-M-M interaction under biaxial cyclic loading is a critical area that requires improvement in both current design practices and modeling accuracy, particularly for advanced low-damage base systems.

Figure 1 illustrates the differences in deformation and drift in: a. conventional fixed-base frames, b. uniform controlled rocking patterns, and c. self-centering systems.

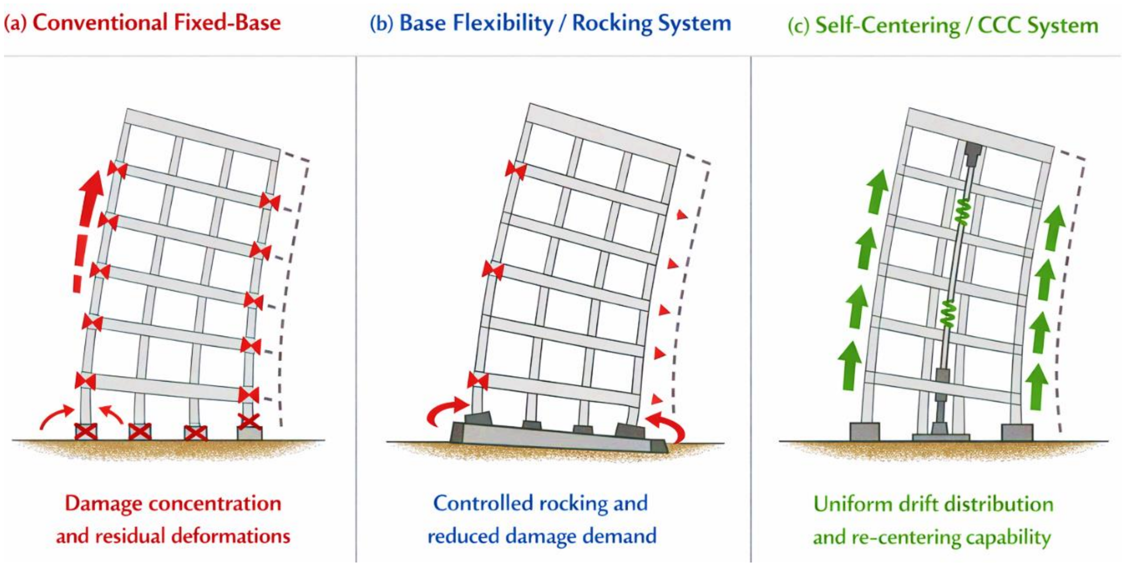

Figure 1. Conceptual Comparison of Deformation Mechanisms in Conventional and Low-Damage Seismic Design Strategies

As shown in Fig. 1, conventional fixed-base frames typically experience drift concentration in the lower stories, resulting in significant damage and residual deformations. In contrast, systems with base flexibility or controlled rocking mechanisms redistribute seismic demand by allowing foundation rotation, reducing member-level damage. Additionally, self-centering and continuous-column strategies promote a more uniform drift distribution along the height and minimize residual deformations through restoring-force mechanisms.

Practical Implications for Engineers:

- **Explicitly Model Base Restraint:** Move beyond idealized pinned/fixed assumptions. Use rotational springs calibrated from experimental data or advanced connection models (e.g., CBFEM) to represent realistic base stiffness.
- **Consider P-Delta Effects:** In both flexible and tall structures, P-delta analysis is crucial for stability, particularly in self-centering systems where it can counteract re-centering capabilities.
- **Account for Axial Load Variations:** Recognize that axial loads fluctuate significantly during seismic events, affecting base connection behavior, particularly in CFT columns and friction-based systems.
- **Embrace 3D Analysis for Complex Systems:** For advanced base connections (rocking, sliding, and fuses) integrated with CFT columns, 3D coupled analysis is essential due to complex load paths under biaxial cycling.

3- Drift Management: The Continuous Column Concept and its Critical Role

Drift concentration (DCE) is a key challenge in multistory frame design, characterized by excessive inter-story displacements at certain levels. This phenomenon, often caused by stiffness irregularities, non-uniform mass distribution, or inadequate lateral stiffness, results in localized plasticity and damage. The consequences include increased residual drift, compromised structural stability, and a higher risk of progressive collapse. Conventional capacity design methods, typically applied level-by-level, often fail to prevent DCE, especially in steel frames where member stiffness-to-strength ratios differ significantly from those of concrete. The reliance on simplified force patterns can further exacerbate this issue (25, 26).

Column Concept (CCC) provides a robust, stiffness-based alternative to traditional strength-focused capacity design. By prioritizing the continuity of columns across multiple stories, CCC enhances global stiffness and stability, effectively mitigating drift concentration. This methodology recognizes that all continuous columns and walls play a significant role in contributing to overall stiffness .

Unlike capacity design, which identifies plastic hinge locations, the concept of Continuous Column Control (CCC) focuses on preventing undesirable yielding in critical areas by ensuring sufficient global stiffness. This is accomplished by maintaining at least one continuous column line that remains elastic, thereby providing a restoring force. A critical aspect of CCC's effectiveness is its emphasis on stiffness as the primary mechanism for controlling deformation, while strength primarily serves to uphold that stiffness. This paradigm shift has significant implications:

- **Holistic Frame Behavior:** CCC takes into account the entire frame height rather than focusing on individual levels, integrating the stiffness of all continuous columns, including gravity columns, which significantly improves overall stiffness and stability (7).
- **Dynamic Stability:** The continuous stiffness offered by CCC is essential for dynamic stability, minimizing the risk of significant permanent displacements due to P-delta effects. Research demonstrates that continuous columns deliver positive effective post-elastic stiffness, effectively counteracting the negative post-elastic stiffness that may arise from localized yielding (37).
- **Synergy with Other Technologies:** CCC's emphasis on global stiffness positions it as a key enabler for various low-damage technologies. It provides the stable elastic framework needed for efficient energy dissipation through friction dampers and promotes more uniform patterns of plastic deformation (38).

The effectiveness of CCC is directly tied to the non-dimensional column stiffness ratio, α. Higher α values, achieved by increasing column stiffness or adding gravity columns, drive the Drift Concentration Factor (DCF) toward unity (7). For typical steel frames, α is usually sufficient to significantly reduce DCE. However, for exceptionally tall frames, achieving a DCF close to unity may require considerable column stiffness.

Some of the Practical Design Guidance and Trade-offs with CCC include:

- **Integration of Gravity Columns:** Consider the stiffness contribution of gravity columns, as their inclusion can significantly reduce the required stiffness of seismic columns for a given DCF .
- **Detailing for Continuity:** Ensure robust connections between continuous columns and foundations, as well as between columns and floor diaphragms, to effectively transfer stiffness.
- **Beyond Basic Pushover Analysis:** While CCC provides a conceptual framework, a detailed analysis, such as Non-linear Time History Analysis (NLTHA), is essential to accurately quantify actual DCF and column demands, particularly for tall or complex structures.
- **Trade-off:** Although CCC effectively controls drift, the increased global stiffness it provides may require a review of seismic force levels if not adequately considered in load patterns. Additionally, it may result in larger demands on other components if not carefully integrated, as its primary goal is to prevent yielding in columns.

Despite the well-established concept of CCC for limiting drift and enhancing stability, extensive experimental validation remains necessary, particularly for :

- **Complex Frame Geometries:** Investigating the effectiveness of CCC in irregular plan layouts and high-rise buildings where three-dimensional effects are prominent .
- **Integration with Advanced Base Systems:** Assessing the synergistic benefits and potential conflicts that may arise when CCC is combined with advanced base isolation, rocking, or friction damping systems .
- **Material Variations:** While CCC applies to various materials, obtaining specific experimental data for advanced implementations in concrete or timber structures would be beneficial.

4- Bridging Research to Practice: Practical Design Tools for Low-Damage Systems

This section simplifies complex concepts into practical tools and considerations for engineers. It offers a quantitative overview of reported trends and clearly defines performance objectives for seismic design strategies.

Table 1 presents quantitative trends from various studies. The "Mean/Typical Value" column mostly shows N/A, as many results relate to specific case studies or simulations, complicating the determination of a true statistical mean without a meta-analysis. Sensitivity factors are crucial for understanding variability.

Table 1. Integrated Design and Modeling Recommendations for Resilient Steel Frames

Parameter	Reported Range	Mean/Typical Value (if applicable)	Key Sensitivity Factors
Displacement Demand Increase (Flexible Base)	Up to 1.64 times fixed base	N/A	Base stiffness, Period of structure, Ground motion frequency
Story Drift Increase (Splice Flexibility)	Up to ~11%	N/A	Splice detail, Location of splice, Frame stiffness
Residual Drift Reduction (SC Systems)	Near zero to < 1%	< 0.5%	SC mechanism effectiveness, P-delta effects, Height
Overstrength Factor (Friction Systems)	~1.15 (reported for specific applications)	N/A	Clamping force calibration, Friction material properties
Collapse Prevention Limit (Implied)	Beyond Level 1 of hierarchy	N/A	Seismic demand exceeding capacity, Localized failure

Table 2 offers design recommendations that connect seismic challenges to suitable strategies and modeling requirements, providing critical guidance to bridge the gap between research and practice.

Table 2. Integrated Design and Modeling Recommendations for Resilient Steel Frames

Design Challenge	Recommended Design Strategy	Modeling Requirement (Fidelity)	Key References
Drift Concentration & Soft Story	1. Continuous Columns (CCC): Ensure column continuity over multiple stories. 2. Weak Beam-Strong Column: Use explicit capacity reduction factors for beams.	TPMC: Use Theory of Plastic Mechanism Control to predict collapse mode rather than simple pushover.	MacRae et al. (CCC) Li et al. (Weakening) Dell'Aglio (TPMC)
P-Delta Instability	Elastic Column Spine: Maintain at least one elastic column line to provide positive post-yield stiffness.	Rigorous 2nd Order Analysis: Calculate P-Delta based on deformed shape at collapse, not just elastic multipliers.	Latham & Andrews MacRae & Kawashima
Connection Reality	Low-Damage Detailing: Use replaceable fuses (LYPS, Friction) with clear extraction paths.	Semi-Rigid Springs: Model base and connection stiffness explicitly (e.g., using CBFEM or experimental data).	Awkar & Lui SCNZ Guidelines
Splice Effects	Splice Location: Locate splices away from high-moment zones or detail for full capacity.	Flexible Splice Model: Account for splice rotation in global drift checks (expect ~11% drift increase).	Ladani & MacRae
Complex Loading	Bi-directional Resilience: Detail columns (esp. CFT) for biaxial bending interaction.	3D Coupled Analysis: Essential for assessing corner column demands and rocking base stability.	Anderson & Mahin Montuori et al.

To provide a clear framework for comparing seismic design strategies, the following hierarchy is proposed, progressing from basic safety to full operational capability post-earthquake:

- **Level 1 – Collapse Prevention:** Life safety is ensured; significant structural damage is acceptable, and the structure is likely uneconomical to repair (traditional approach's minimum).
- **Level 2 – Controlled Damage:** Damage is limited to prevent collapse, but residual drifts may be significant, leading to substantial downtime and repair costs. Performance primarily focuses on life safety.
- **Level 3 – Low Damage:** Inelastic deformation is localized to replaceable components or controlled mechanisms, minimizing damage to primary structural elements. Repair is feasible, and downtime is reduced.
- **Level 4 – Immediate Occupancy:** Minimal structural and non-structural damage; the building can be safely occupied immediately after the earthquake with negligible repairs needed.
- **Level 5 – Functional Resilience:** The building sustains minimal damage and remains fully operational for its intended purpose (e.g., hospital, data center, and emergency services).

Table 3 compares ranges of practical design parameters and their associated trade-offs.

Table 3: Practical Design Parameter Ranges and Trade-offs: A Comparative Overview

Strategy	Core Mechanism	Primary Benefit(s)	Practical Design Considerations	Key Limitations / Trade-offs
Conventional Fixed Base	Strength-based, Ductility dissipation	Well-established codes, economical for standard structures.	Predictable behavior (historically), simple analysis.	High damage, significant residual drift, high repair costs, potential for soft-story mechanisms, limited post-event functionality (2), (11)
Base Flexibility/ Rocking	Controlled rotation/ uplift at foundation	Reduced base moments, localized energy dissipation, protection of superstructure.	Requires careful SSI modeling, specialized foundation detailing, and potential sensitivity to ground motion characteristics (vertical).	Increased inter-story drift, P-Delta amplification, limited codified guidance, potential for instability if not re-centered (30), (39)
Continuous Column Concept (CCC)	Stiffness continuity along column height	Uniform drift distribution, enhanced global stability, discourages soft-story mechanism.	Demands precise detailing of column-foundation and column-slab connections; analysis needs to account for all continuous columns.	Primarily stiffness-based, may still require significant column sizes if stiffness is limited; effectiveness depends on α ratio (8)
Self-Centering Systems	Restoring forces (tendons, rocking, SMAs)	Minimal residual drift, rapid post-earthquake re-occupancy.	Higher initial cost, requires advanced nonlinear analysis, complex connection design, and maintenance.	SC capability diminishes with height (P-Delta), may require global stiffness strategies, sensitive to cumulative deformations (12)
Friction-Based Systems	Friction slip at designated interfaces	Stable hysteretic behavior, high energy dissipation, no stiffness degradation.	Requires precise calibration of clamping forces, needs stable elastic frame for minimal residual drift, detailed performance checks	Can be sensitive to joint stiffness degradation and bolt tension consistency; potential for "stick-slip" behavior (32), (38)
Low-Yield-Point (LYP) Steel Fuses	Controlled yielding in replaceable components	Localized, ductile damage in fuses, protecting primary members.	Design of fuse geometry and placement, ensuring "fuse extraction" feasibility post-earthquake	Fuses are sacrificial, requiring replacement; performance can be affected by strain hardening and material variability (40)

The strategies outlined in this review can be categorized by their capabilities and applications:

- **Conventional Fixed-Base Systems:** These systems primarily target Level 1 (Collapse Prevention), with some designs achieving Level 2 (Controlled Damage) through ductility. However, they often fail to reach lower damage levels due to uncontrolled plastic hinge formation and significant residual drifts (1), (11).
- **Continuous Column Concept (CCC):** This approach enhances Level 2 (Controlled Damage) and enables Level 3 (Low Damage) by reducing drift concentration and improving global stability. Its main strength lies in preventing detrimental soft-story mechanisms.
- **Friction Fuses/Connections:** These systems aim for Level 3 (Low Damage) by localizing yielding to replaceable fuses, minimizing damage to primary members and facilitating easier repairs.
- **Self-Centering Systems:** These systems target Level 4, especially when integrated with CCC (Immediate Occupancy), and potentially Level 5 (Functional Resilience) by minimizing residual drifts and enabling rapid re-occupancy. Their integration with CCC improves effectiveness by providing essential global stiffness.
- **Base Flexibility/Rocking:** This strategy contributes to Level 3 (Low Damage) by reducing force demands on the superstructure. However, achieving higher performance levels typically requires integration with re-centering mechanisms.

A decision matrix for selecting low-damage base strategies enhances understanding of the process.

Designs that explicitly target re-centering and avoid column plastic hinging at the base can effectively mitigate soft-story mechanisms. Rocking walls/cores and stiffened boundary frames serve as complementary strategies to regulate story drift profiles and prevent concentration(41, 42). Recent studies indicate that controlled rocking with self-centering devices can nearly eliminate residual drifts in single-story prototypes and significantly reduce concentration in multistory systems. This is further supported by new energy-based design frameworks for pinned-rocking systems, which provide mechanisms to balance strength, re-centering, and energy dissipation. These innovative approaches align with the overarching goals of resilience benchmarks and loss-based design philosophies (43, 44).

Integrated approaches that manage P-delta effects, control drift distribution, and utilize advanced technologies are essential for enhancing a building's resilience against multiaxial loading and concentrated drift. While re-centering mechanisms effectively minimize residual drifts, designers must rigorously evaluate stability under conditions of temporary uplift and device nonlinearity (45). The flowchart in Figure 2 outlines a conceptual pathway for engineers to consider when choosing suitable low-damage base strategies, highlighting key decision points and their implications.

Some practical design guidance beyond theory includes:

- **Embrace Modeling Fidelity:** Always use models that account for realistic base flexibility, connection semi-rigidity, and splice flexibility. Simplified models (e.g., pinned/fixed bases, rigid connections) are insufficient for performance-based, low-damage design (46) ,(34).
- **Prioritize Ductility in Designated Locations:** If yielding is unavoidable, ensure it occurs in predictable, replaceable components (e.g., beams, specific fuses) rather than in columns or critical connections (40).
- **Quantify Drift Limits:** Understand code-specific drift limits for immediate occupancy and re-occupancy. Design strategies should explicitly aim to meet these limits, rather than solely avoiding collapse.
- **Consider Life-Cycle Costs (LCC):** While low-damage systems may incur higher initial costs, they often yield significantly lower long-term repair costs and reduced downtime. LCC analysis is essential for justifying these investments.
- **Detail for Reparability:** Design connections and fuses to facilitate ease of inspection, testing, and replacement post-earthquake.

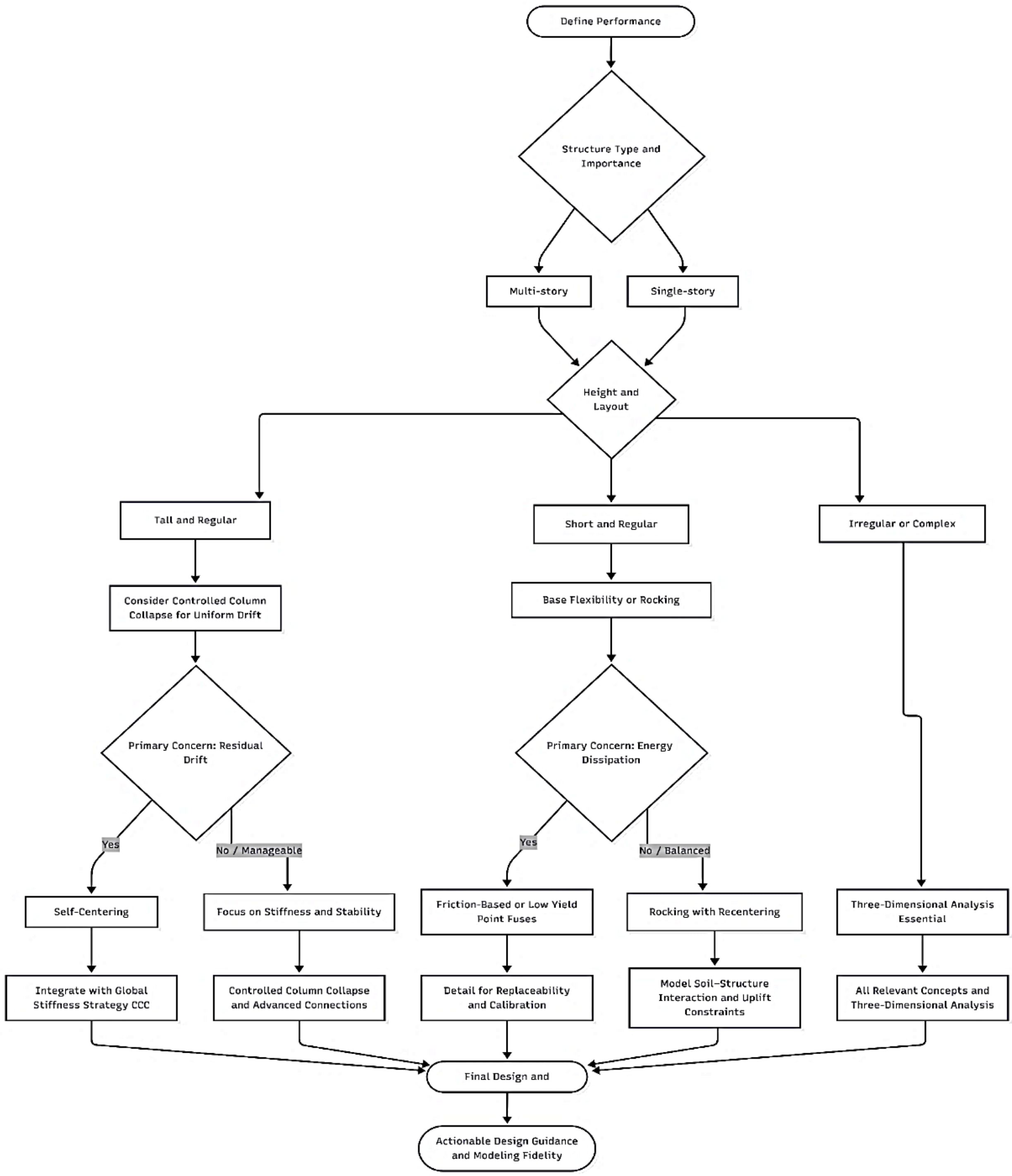

Figure 2: Decision Matrix for Selecting Low-Damage Base Strategies

5- Knowledge Gaps and Future Research Directions

The reviewed literature highlights significant advancements; however, several critical areas necessitate further research to fully harness the potential of low-damage seismic design in multi-story steel frames.

5-1. Multiaxial and Combined Loading Validation:

- **Experimental Data for CFT Bases:** There is a significant lack of experimental data on low-damage (rocking/sliding) CFT column bases under realistic three-dimensional loading conditions (33). To develop accurate P-M-M interaction models, targeted subassembly tests incorporating realistic axial cycling are essential (35, 36).

- **Interaction of Low-Damage Systems with Biaxial Shaking:** How do systems such as self-centering connections, rocking bases, or repairable fuses respond to coupled biaxial bending and fluctuating axial loads? Existing code provisions and analysis methods frequently do not adequately address these nonlinear complexities (17, 18), (47).

5-2. Long-Term Resilience and Performance Degradation:

- **Self-Centering (SC) Capability in Tall Buildings:** The degradation of SC capability in tall buildings due to cumulative P-delta effects and higher-mode contributions requires further investigation. Developing height-dependent modification factors for SC systems is a priority.
- **Durability and Maintenance of Devices:** The long-term performance, durability, and maintenance of specialized seismic devices (e.g., friction dampers, SMA actuators) in real-world conditions are not well documented.

5-3. Multi-Hazard Integration and Robustness Assessment:

- **Performance under Multiple Hazards:** How do low-damage seismic details perform under other extreme events, such as progressive collapse, post-earthquake fire, or blast loads (48, 49)?
- **AI-Driven Robustness Assessment:** Using Machine Learning (ML) and Artificial Intelligence (AI) to predict progressive collapse potential in irregular frames and efficiently simulate dynamic increase factors after the loss of critical elements offers a promising alternative to costly deterministic methods (50), (51)

5-4. Standardization and Code Development:

- **Standardization of New Design Methods:** The gap between advanced research and current practice remains significant. There is a critical need to standardize new design methods, criteria, and detailing practices to facilitate adoption by the engineering community.
- **Codification of Practical Implementation:** While concepts like CCC are validated, their explicit inclusion and detailed implementation guidelines in seismic design codes are often lacking, hindering widespread adoption.

Conclusions

This review critically explored the evolution of multistory steel frame design, shifting from conventional strength-based methodologies to advanced low-damage and resilience-focused approaches. A comprehensive analysis of recent literature highlights the need for a paradigm shift in seismic performance assessment: achieving seismic resilience necessitates more than high-capacity individual components. It requires transcending simplified boundary conditions (fixed/pinned) to integrate "Modeling Fidelity," which includes splice flexibility, semi-rigid connections, and intricate stiffness interactions.

- **Drift Management vs. Component Strength:** To address the vulnerability of multistory frames to drift concentration (soft-story effects), the Continuous Column Concept (CCC) offers a strong structural solution by ensuring stiffness continuity and mitigating soft-story mechanisms. This approach redistributes plastic demands and provides the necessary restoring forces to maintain global stability. Additionally, analytical strategies like the Optimal Seismic Force Pattern effectively complement this by considering higher-mode effects during the design phase.
- **Real-world Connections:** Vast research critically challenges assumptions such as "perfectly rigid" or "perfectly pinned." Ignoring connection semi-rigidity or splice flexibility can lead to an underestimation of story drifts by over 10%, which can adversely affect fundamental periods and compromise the design of drift-sensitive, low-damage fuses. Adopting calibrated spring models that accurately reflect the intermediate fixity of column bases is essential for improved design practices.
- **Complex Loading Realities and the Axial-Biaxial Nexus:** Simplified combination rules, such as the 100%+30% approach, and two-dimensional analyses, are no longer adequate for modern low-damage structural systems. Research indicates that bidirectional seismic shaking and near-fault pulses induce coupled nonlinear responses, resulting in amplified axial forces and cross-axis drift, necessitating fully integrated three-dimensional modeling. The performance of advanced base connections—such as self-centering or friction-based systems—is highly sensitive to variations in axial load and the effects of bidirectional shaking. Consequently, design methodologies must advance beyond two-dimensional uncoupled assumptions to accurately account for the complex P-M-M interaction paths that are critical for the integrity of base plates and anchors.

- **Post-Earthquake Reparability:** Detailing must advance to prioritize the feasibility of "Fuse Extraction," ensuring that energy dissipators can be replaced with minimal downtime and without reliance on the gravity system.

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- **Author’s Contribution:** The sole author was entirely responsible for the conceptualization, computational modeling, data analysis, and manuscript preparation.
- **AI Usage:** Artificial intelligence tools were utilized strictly for grammatical verification and linguistic refinement. The author conducted a comprehensive review of the edited text and assumes full responsibility for the integrity, accuracy, and original content of the published work.
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References

[1] Andrew H. Buchanan DB, Rajesh Dhakal,, Greg MacRae AP, Stefano Pampanin. Base Isolation and Damage-Resistant Technologies for Improved Seismic Performance of Buildings. University of Canterbury, Failure tRCoIiB, Earthquakes CbtC; 2011 2011.

[2] Mieler DHU, S. R; Wright, K. C., Overcoming the barriers to uptake of low damage construction: Perceptions from researchers, industry professionals, and end users. GNS Science Report 2014. Contract No.: 38.

[3] Montuori R, Nastri E, Tagliafierro B. Residual displacements for non-degrading bilinear oscillators under seismic actions. Mechanics Research Communications. 2021; 111.

[4] Ashkan Hashemi RL, Setu Agarwal, Soheil Assadi, and Pierre Quenneville. Friction-Based Bracing Systems for Low-Damage and Economic Design of High-Importance Structures in Australia. Australian Earthquake Engineering Society National Conference; 20–22 November 2025; Melbourne, Victoria, Australia2025

[5] Edoardo Cosenza GMaGMV. A new strategy for the seismic assessment of existing RC buildings. ANNALS OF GEOPHYSICS. 2002; 45.

[6] Leelataviwat S. DRIFT AND YIELD MECHANISM BASED SEISMIC DESIGN AND UPGRADING OF STEEL MOMENT FRAMES: The University of Michigan; 1998.

[7] MacRae GA. The Continuous Column Concept - Development and Use. Proceedings of the Ninth Pacific Conference on Earthquake Engineering; 14–16 April; Auckland, New Zealand: Building an Earthquake-esilient Society; 2011.

[8] MacRae GA, Kimura Y, Roeder C. Effect of Column Stiffness on Braced Frame Seismic Behavior. Journal of Structural Engineering. 2004; 130(3):381–91.

[9] Ikago K. Dynamic instability in high-rise steel structures subjected to strong ground motions: A review.

[10] T. Hansoulle' NB, R. Gonçalves, D. Camotim, J.P. Jaspart. DESIGN OF BEAM-COLUMNS IN STEEL SWAY FRAMES: FROM THE ACTUAL MEMBER TO A SIMPLY SUPPORTED EQUIVALENT ONE. Annual Technical Session & Meeting; April 2007; New Orleans2007

[11] S. Dehghanian GAM, A. S. Moghadam P-delta or P-theta analysis? NZSEE 2024 Annual Conference: New Zealand Society for Earthquake Engineering; 2024.

[12] Safaei S, MacRae GA, Moghadam AS. Column Base Flexibility Effects on the Seismic Performance of Single-bay Single-story Steel Moment Frames. Journal of Earthquake Engineering. 2022; 27(8):2279–97

[13] Borzouie J, Chase JG, MacRae GA, Rodgers GW, Clifton GC. Spectral Assessment of the Effects of Base Flexibility on Seismic Demands of a Structure. Advances in Civil Engineering. 2016;2016:1–8.

[14] Borzouie J, Rodgers G, Macrae G, Clifton G, S. Moghadam A. Base Connections Seismic Sustainability and Base Flexibility Effects. Steel Innovations Conference; Christchurch, New Zealand2013.

[15] Borzouie J, MacRae G, Chase G, Rodgers G, Clifton C, editors. The effect of base flexibility on demands of the structure. New Zealand Society of Earthquake Engineering Annual Conference; 2013.

[16] Tjahjanto H, MacRae G, Abu A, Clifton C, Beetham T, Mago N, editors. Behavior of External Diaphragm Connections for Square CFST Columns Under Bidirectional Loadings. The 8th International Conference on Behavior of Steel Structures in Seismic Areas; 2015; Shanghai, China.

[17] Stathas N, Di Sarno L, Wu J, Freddi F, D'Aniello M, Bousias S, et al. Biaxial seismic response of base-column connections in sub-standard steel buildings: dataset. Open Res Eur. 2024; 4:161

[18] Eyitayo A. Opabola KJE, and Santiago Pujol. Influence of Biaxial Lateral Loading on Seismic Response of Reinforced Concrete Columns. ACI Structural Journal. 2020; 117(6)

[19] Faramarz KHOSHNOUDIAN MP. RESPONSES OF THREE DIMENSIONAL BUILDINGS UNDER BIDIRECTIONAL AND UNIDIRECTIONAL SEISMIC EXCITATIONS. 13th World Conference on Earthquake Engineering; August 1–6, 2004; Vancouver, B.C., Canada2004

[20] Krawinkler BAaH. EFFECTS OF NEAR-FAULT GROUND MOTIONS ON FRAME STRUCTURES. Stanford University, Engineering CaE; 2001. Report No.: 138.

[21] Jin J, Nagae T, Chung Y-L. Seismic and collapse behavior of existing high-rise steel buildings under long-period earthquakes. Journal of Constructional Steel Research. 2023; 211:108151.

[22] G. A. MacRae EVA, J. D. Pettinga, B. Deam and V. Sadashiva. A simple design method for yielding structures subject to torsion. The 14th World Conference on Earthquake Engineering October 12–17; Beijing, China2008

[23] MacRae GA, Urmson CR, Walpole WR, Moss P, Hyde K, Clifton C. Axial shortening of steel columns in buildings subjected to earthquakes. Bulletin of the New Zealand Society for Earthquake Engineering. 2009; 42(4):275–87.

[24] Hatami M, Borzouie J, Macrae G, Yekrangnia M, Abubakar S. Finite Element Analysis of Column Base Weak Axis Aligned Asymmetric Friction Connection. 8th International Conference on Behavior of Steel Structures in Seismic Areas July 1–3, 2015; Shanghai, China2015.

[25] Li F, Li Y, Luo W, Lei C, Pan W, Ji S. A new seismic strategy for strong column-weak beam design philosophy in RC frame structures. Structures. 2025; 77.

[26] Montuori R, Nastri E, Tagliafierro B. An Optimal Seismic Force Pattern for Uniform Drift Distribution. Buildings. 2019; 9(11)

[27] Salem A, Elserwi A, El Dib F, editors. In-Plane Stability Considerations of Column Braced Steel Frames. Annual Stability Conference; 2011 May 10–14; Pittsburgh, Pennsylvania: Structural Stability Research Council.

[28] Hyland C. Portal Frame Design Tips Seminar Proceedings. Steel Construction New Zealand Inc. 2010(Steel Advisor GEN7001).

[29] Dell'Aglio G, Montuori R, Nastri E, Piluso V. Consideration of second-order effects on plastic design of steel moment resisting frames. Bulletin of Earthquake Engineering. 2019;17(6):3041–70.

[30] rigorian CE, Grigorian M. Performance Control and Efficient Design of Rocking-Wall Moment Frames. Journal of Structural Engineering. 2016; 142(2).

[31] Luigi Petti AL, Bruno Palazzo. A New Strategy To Control The Seismic Response Of Buildings: The Base Dissipation. International Journal of Engineering and Technology (IJET). 2014;6.

[32] Colajanni P, La Mendola L, Monaco A, Pagnotta S. Low-Damage Friction Connections in Hybrid Joints of Frames of Reinforced-Concrete Buildings. Applied Sciences. 2023;13(13).

[33] Li B-y, Yang Y-L, Chen Y-F, Cheng W, Zhang L-B. Behavior of connections between square CFST columns and H-section steel beams. Journal of Constructional Steel Research. 2018;145:10–27.

[34] Pan J, Huang R, Xu J, Wang P, Wang Z, Chen J. Behavior of exposed column-base connections with four internal anchor bolts under seismic loading. Structures. 2021; 34:105–19.

[35] Li X, Zhou T, Li J, Kuang X-B, Zhao Y-W. Seismic behavior of encased CFT column base connections. Engineering Structures. 2019;182:363–78.

[36] Liu J, Zhou X, Zhang S. Seismic behaviour of square CFT beam–columns under biaxial bending moment. Journal of Constructional Steel Research. 2008; 64(12):1473–82.

[37] Ji X, Kato M, Wang T, Hitaka T, Nakashima M. Effect of gravity columns on mitigation of drift concentration for braced frames. Journal of Constructional Steel Research. 2009; 65(12):2148–56.

[38] Bagheri H, Hashemi A, Quenneville P, Yan Z, Clifton G, Zarnani P, et al. Full-scale shaking table testing of a low-damage steel structure using Resilient Slip Friction Joint. NZSEE Annual Conference; 2020: New Zealand Society for Earthquake Engineering; 2020.

[39] Henry RS, Zhou Y, Lu Y, Rodgers GW, Gu A, Elwood KJ, et al. Shake-table test of a two-storey low-damage concrete wall building. Earthquake Engineering & Structural Dynamics. 2021; 50(12):3160–83.

[40] Hao-Xiang He, Li-Can Liao, and Shi-Tao Cheng. Damping performance experiment and damage analysis of replacement connection with low yield-point steel. Advanced Steel Construction. 2021; 17:169–80.

[41] Classification of Multi-Storey Frames. European Structural Design Education PartnershipSTRUCTURAL SYSTEMS: BUILDINGS. Available from: Classification of Multi-Storey Frames. European Structural Design.

[42] iQ, Zou A, Zhang H. A simplified method for stability analysis of multi-story frames considering vertical interactions between stories. Advances in Structural Engineering. 2016;19(4):599–610.

[43] Ronald O. Hamburger HK, James O. Malley, Scott M. Adan. Seismic Design of Steel Special Moment Frames: A Guide for Practicing Engineers2009.

[44] Larry Griffis RS. Fast and Efficient Design for Stability. The Steel Conference; 2020; Virtual Conferen: NASCC; 2020.

[45] Lettieri A, Elettore E, Freddi F, Latour M, Rizzano G. Performance-based assessment of seismic-resilient steel moment resisting frames equipped with innovative column base connections. ce/papers. 2021;4(2-4):1736–46

[46] Fahimeh Tork Ladani GM, Geoffrey Chase. EFFECTS OF COLUMN SPLICE LOCATION ON SEISMIC DEMANDS IN STEEL MOMEMNT FRAMES CONSIDERING SPLICE FLEXIBILITY. 8th International Conference on Behavior of Steel Structures in Seismic Areas; July 1–3, 2015; Shanghai, China2015.

[47] Cui J, Lee C, MacRae G. Strong-axis and weak-axis buckling of buckling restrained braces under bidirectional loading. Pacific Conference on Earthquake Engineering2019. p. 4–6.

[48] Pantidis P, Hill T, Gerasimidis S, editors. The impact of gravity connections on the progressive collapse response of steel framed and concrete composite buildings. Annual Stability Conference, Structural Stability Research Council; 2018 April 10–13; Baltimore, Maryland.

[49] Rezania J, Torkzadeh P. Evaluation of Progressive Collapse Performance in Double layer Diamatic Domes. Civil Engineering Journal. 2019;5(10):2167–79.

[50] Javid Rezania MH, Alireza Rasekhi. Investigating the Application of Artificial Intelligence in Civil Engineering and Progressive Collapse. Civil and Project. 2023;5(9):11–22.

[51] Possidente L, Freddi F, Tondini N. Dynamic increase factors for progressive collapse analysis of steel structures considering column buckling. Engineering Failure Analysis. 2024; 160.