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A Review of Performance-Based Seismic Evaluation of Core-Wall Tall Buildings with and Without Belt-Truss Systems Considering Different Configuration and Location

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Abstract—
Core-wall systems are widely adopted in tall buildings owing to their efficiency in resisting gravity and lateral loads, architectural adaptability, and construction practicality. However, as structural height and slenderness increase, standalone core-wall systems may exhibit excessive lateral drift, residual deformation, and concentrated seismic demand that undermines serviceability and post-earthquake repairability. Belt-truss and outrigger mechanisms are therefore introduced to engage perimeter columns, enhance overturning resistance, and improve seismic performance across multiple hazard levels. This review synthesizes representative peer-reviewed research on the performance-based seismic evaluation of core-wall tall buildings with and without belt-truss systems, emphasizing configuration type, vertical placement, stiffness distribution, analytical framework, and engineering demand parameters. The literature demonstrates that belt-truss effectiveness is governed by core stiffness, perimeter column stiffness, outrigger rigidity, supplemental damping, soil–structure interaction, and the chosen performance objective. Optimal placement is response-metric dependent: lower-level positioning may reduce base overturning moment, while mid-height or upper-level placement may better moderate story drift or floor acceleration. Nonlinear time-history analysis and fragility-based procedures offer substantially greater reliability than simplified elastic methods. The review identifies critical knowledge gaps and proposes a research agenda to advance resilient, low-damage tall building design.

Keywords— performance-based seismic design; tall building; core wall; belt truss; outrigger; nonlinear time-history analysis; seismic evaluation

I. INTRODUCTION

Tall-building design has progressively transitioned from strength-oriented code compliance toward performance-oriented decision-making, driven by the recognition that extreme seismic events demand not only life safety but also controlled damage, structural repairability, post-event service continuity, and long-term community resilience. In reinforced concrete and composite tall buildings, the structural core wall remains among the most efficient primary lateral-force-resisting systems. Yet, as slenderness increases, pure core-wall behavior may prove insufficient to satisfy drift, acceleration, or damage-control requirements across multiple design-level seismic hazards. Structural engineers therefore supplement the core with outriggers, belt trusses, belt walls, mega-columns, supplemental damping devices, or hybrid lateral systems to increase effective flexural depth and redistribute overturning actions more favorably [1], [2], [3], [4].

The present review focuses on the performance-based seismic evaluation of core-wall tall buildings with and without belt-truss systems. Three recurring design questions motivate this review: (1) Under what structural and geometric circumstances does a standalone core wall provide adequate seismic performance, and when does belt-truss augmentation become necessary? (2) How do differing configurations and vertical locations of the belt-truss system influence engineering demand parameters under multi-level seismic hazards? (3) Which analytical frameworks are sufficiently rigorous and reliable for journal-quality performance assessment and design recommendations [1], [2], [5], [6], [7]?

II. SCOPE AND REVIEW METHODOLOGY

This review constitutes a focused analytical synthesis of representative studies addressing core-wall tall buildings, outrigger-belt-truss systems, virtual outrigger configurations, and performance-based seismic evaluation procedures. Emphasis is placed on investigations that explicitly examine: (a) the comparative seismic performance of core walls with and without an outrigger or belt-truss mechanism; (b) variation of structural response with the location, number, stiffness, or type of outrigger or belt-truss element; (c) nonlinear or performance-based assessment frameworks, including pushover analysis, nonlinear time-history analysis, fragility analysis, or explicit performance-level checking; and (d) practical implications for optimal system configuration in tall-building design.

III. STRUCTURAL BACKGROUND AND PERFORMANCE-BASED FRAMEWORK

3.1 Standalone Core-Wall Tall Buildings

A standalone core-wall tall building resists lateral forces primarily through flexural, shear, and coupling-beam action within the structural core. Its seismic response is governed by wall aspect ratio, coupling beam behavior and ductility capacity, boundary element confinement, higher-mode participation, floor diaphragm stiffness, and the stiffness contrast between the core and the surrounding gravity framing system. Such configurations may perform adequately for moderate height ranges or for buildings with favorable plan geometry and aspect ratios; however, they become progressively more susceptible to large drift demand, concentration of inelastic deformation in lower stories, and potentially unfavorable residual deformations as building height and structural slenderness increase [4], [6], [7], [8], [9].

3.2 Core Wall with Belt-Truss and Outrigger Mechanisms

In a conventional outrigger system, a stiff horizontal truss, deep beam, or structural wall directly connects the building core to perimeter columns at one or more discrete levels. A belt truss positioned at the perimeter distributes the outrigger-induced axial forces among the exterior columns and thereby improves the overall efficiency of the outrigger action. In a virtual outrigger arrangement, the belt truss or belt wall engages floor diaphragms and the perimeter framing so that overturning resistance is mobilized indirectly, without requiring a continuous direct structural link between the core and exterior columns [1], [2], [3], [10], [11].

3.3 Performance-Based Seismic Evaluation Framework

Performance-based seismic evaluation (PBSE) for tall buildings typically considers multiple seismic hazard levels paired with multiple structural performance states. Common performance targets include Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), each accompanied by prescribed global and component-level acceptance criteria. The literature consistently demonstrates that, owing to the pronounced higher-mode effects, significant period elongation, and stiffness degradation sensitivity inherent to tall buildings, nonlinear dynamic procedures offer substantially greater reliability than elastic analysis methods when the objective is publication-quality performance assessment [2], [6], [7], [12].

IV. COMPARATIVE SUMMARY OF REPRESENTATIVE STUDIES

Table 1. Summary of representative studies on core-wall and belt-truss seismic performance.

Study	System / Building	Methodology	Key Variables	Principal Seismic Findings
Samadi & Jahan (2021)	28- and 56-story; braced core or RC wall core + outrigger	Modal RSA vs. NLTHA	Core type, height, outrigger level	Elastic spectrum may overestimate drift-reduction; RC wall-core buildings showed more consistent displacement reduction.
Zhou & Xing (2021)	Frame-core; single viscous damper-outrigger	RSA with CCQC method; calibrated against FEM and NLTHA	Outrigger/core stiffness, damper coefficient, height, vertical location	Optimal location shifts with stiffness ratio and damping; upper-half placement can increase modal damping ratio.
Amoussou et al. (2021)	80-story core-wall; mega-columns and belt trusses; outrigger vs. ladder	Optimization-assisted PBSD with NLTHA under SLE and MCE	Distributed vs. concentrated stiffness; IO, LS, CP checks	Distributed ladder system reduced displacement and base shear more; external components showed greater plastic demand under MCE.
John & Kamath (2023)	40-, 60-, 80-story RC core; hybrid conventional and virtual outrigger	Static and NLTHA under wind and seismic	Outrigger position, stiffness, arm length	Optimal location is demand-parameter dependent; level minimizing drift is not optimal for acceleration or base moment.
Pujari et al. (2024)	G+30 RC building; frame-shear-wall system	PBSD using linear and nonlinear analyses; fragility curves	Performance levels; seismic demand; nonlinear modeling	PBD provides richer damage understanding than conventional code-based linear analysis.

V. EFFECT OF CONFIGURATION: CORE-WALL SYSTEMS WITH AND WITHOUT BELT TRUSS

The primary distinction in the available literature lies between standalone core-wall systems and core-wall systems augmented by outrigger-belt-truss mechanisms. Core-wall-only systems provide an essential benchmark for performance evaluation, as the lateral force path is concentrated within the wall core and coupled wall subassemblies. Under seismic loading, this typically produces larger global displacement and a pronounced concentration of deformation demand in the lower third of the building. For performance-based design, such behavior may remain acceptable when the governing target is collapse prevention under a rare seismic event; however, it proves significantly more challenging to satisfy low-damage, immediate-occupancy, or serviceability-oriented objectives [6], [7], [13].

The introduction of a belt truss fundamentally alters the structural mechanics by activating perimeter columns in axial tension and compression. This engagement increases effective structural depth, reduces core rotation, and generally decreases peak interstory drift. Nevertheless, such improvements are accompanied by trade-offs: the belt-truss levels attract large local forces and generate abrupt changes in story shear distribution. Samadi and Jahan (2021) [5] demonstrated that the perceived performance benefits inferred from elastic modal response spectrum analysis can differ substantially from those obtained via nonlinear time-history analysis, underscoring the danger of relying exclusively on simplified linear procedures for design decisions.

VI. INFLUENCE OF VERTICAL LOCATION AND NUMBER OF BELT-TRUSS LEVELS

The vertical position of the outrigger or belt-truss level represents one of the most extensively investigated parameters in the literature. A consistent finding across the reviewed studies is that no single universally optimal location exists. The most effective placement depends on the selected objective function, structural height, core typology, relative stiffness ratios among system components, damping assumptions, and whether the foundation is idealized as fixed or modeled as deformable [1], [2], [5], [14].

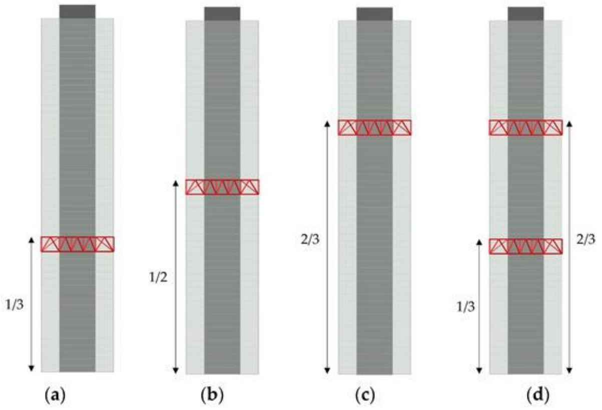

Figure 1. Influence of belt-truss vertical location on three seismic response metrics: (a) H/3 lower placement, (b) H/2 mid-height placement, (c) 2H/3 upper placement, and (d) dual placement.

Figure 1 illustrates that the optimal belt-truss location is strongly dependent on the chosen engineering demand parameter. Lower placement (H/3) tends to be more effective for base overturning moment reduction, mid-height placement (H/2) offers a compromise between drift and moment control, while upper placement (2H/3) may better serve acceleration-related performance objectives, and dual placement proves effective for controlling drift, acceleration, and base shear simultaneously. These conclusions are consistent with findings reported by Kamgar et al. [14] and John and Kamath [15].

VII. PERFORMANCE-BASED SEISMIC EVALUATION METHODS

The reviewed studies employ a broad spectrum of analysis methodologies, ranging from approximate closed-form analytical formulations to fully nonlinear dynamic simulation frameworks. Simplified analytical models are useful in preliminary design and parametric optimization studies; however, they generally cannot capture higher-mode interaction, connection nonlinearity, record-to-record variability, residual drift accumulation, or stiffness and strength degradation under cyclic loading [1], [2], [5], [6], [16], [17].

Modal response spectrum analysis (MRSA) remains prevalent in design practice owing to its computational efficiency and compatibility with prescriptive code procedures. Nevertheless, Samadi and Jahan (2021) [5] demonstrated its significant limitations for predicting outrigger system benefits under strong seismic excitation. Their direct comparison with NLTHA revealed that MRSA can unconservatively overestimate drift-reduction effects in certain system configurations — a finding of particular importance for tall buildings with complex stiffness distributions [18].

VIII. SYNTHESIS OF MAJOR FINDINGS

Table 2. Synthesis of principal findings and implications for future research.

Issue	**Observed Trend**	**Interpretation**	**Implication for Future Research**
Core-wall vs. belt-truss-assisted response	Belt truss generally reduces roof displacement and interstory drift by engaging perimeter columns.	Performance benefit must be evaluated against target performance state rather than elastic stiffness gain alone.	Compare peak and residual demands at IO, LS, and CP levels under multiple ground-motion suites.
Optimal vertical location	No universal optimum exists; effective	Location must be treated as a multi-	Apply Pareto-based optimization under multiple hazard levels.

	location depends on demand parameter, stiffness ratio, building height, and SSI.	objective optimization problem.	
Direct vs. virtual vs. hybrid systems	Direct outriggers are mechanically efficient but architecturally intrusive; virtual systems offer greater flexibility.	Different force paths alter damage accumulation patterns.	Investigate diaphragm flexibility, connection detailing, and damage transfer in 3D models.
Reliability of elastic methods	Elastic spectrum methods may overestimate outrigger benefits in certain configurations.	Conclusions should not rely exclusively on MRSA for tall buildings.	Benchmark simplified methods against NLTHA; identify conditions where simplified approaches are unconservative.
Damped and SSI-sensitive systems	Viscous dampers and SSI modify optimal location and can improve global response, but trends remain parameter dependent.	PBSE should treat foundation flexibility and supplemental damping as coupled design variables.	Develop integrated models combining nonlinear soil springs, supplemental dampers, and ground-motion uncertainty.

Across the reviewed literature, four conclusions recur with notable consistency. First, the effectiveness of belt-truss systems is strongly conditional rather than universal. Second, optimal placement is response-metric dependent. Third, nonlinear behavior is consequential: studies relying exclusively on elastic analysis may misrepresent both the magnitude and spatial distribution of seismic demand. Fourth, interaction effects are critical: soil flexibility, supplemental damping, core typology, and the configuration of multiple outrigger levels can substantially alter conclusions that might otherwise appear stable under simplified assumptions [1], [2], [5], [6], [14].

IX. RESEARCH GAPS

Despite substantial progress in understanding the seismic behavior of core-wall tall buildings with belt-truss systems, the current body of literature retains several significant gaps:

– Residual drift and post-earthquake reparability are systematically underreported relative to peak drift and roof displacement.

– Plan irregularity effects, torsional coupling, and three-dimensional load redistribution remain insufficiently explored.

– Detailed connection behavior at outrigger and belt-truss floor levels is rarely modeled explicitly.

– Nonlinear soil-structure interaction, particularly for soft or layered soil profiles, has not been routinely integrated into performance-based optimization.

– Systematic uncertainty quantification is limited across the reviewed literature.

– A widely accepted multi-objective optimization framework has not yet been established for core-wall and belt-truss systems.

– Experimental validation of numerical models remains sparse, particularly for hybrid and virtual outrigger configurations.

X. FUTURE RESEARCH DIRECTIONS

Future research should transcend single-metric optimization paradigms and embrace multi-hazard, multi-objective, and lifecycle-aware evaluation frameworks. A comprehensive next-generation performance-based study could systematically evaluate an array of 40-, 60-, and 80-story reinforced concrete core-wall tall buildings — with and without belt-truss systems — under both far-field and near-fault ground-motion suites, while varying belt-truss type, number of levels, and vertical placement. The resulting seismic response database could then be interpreted not only through peak interstory drift and base shear but also through residual drift distribution, floor acceleration profiles, wall strain demand, component damage classification, and expected repair cost [2], [5], [6].

Another high-priority research direction involves the systematic integration of supplemental damping devices with belt-truss systems. Damped outriggers incorporating viscous fluid dampers, yielding metallic fuses, buckling-restrained braces, or low-damage replaceable link elements may permit designers to retain the global stiffness benefit of the belt-truss mechanism while simultaneously mitigating damage concentration in core-wall boundary elements [1], [19].

XI. CONCLUSIONS

The following principal conclusions are drawn from the preceding synthesis of representative literature:

– Core-wall systems remain fundamental to tall-building seismic resistance; however, their standalone performance may become inadequate as structural slenderness increases and performance expectations extend beyond life safety to encompass serviceability, repairability, and resilience.

– Belt-truss and outrigger mechanisms generally enhance lateral stiffness and reduce displacement demand by engaging perimeter columns; however, their benefits are performance-state dependent and may introduce local force concentrations and connection detailing challenges.

– The optimal configuration and vertical location of a belt-truss system cannot be determined by a single generalized rule. Available evidence demonstrates that the most effective placement is sensitive to the target engineering demand parameter, building height, stiffness distribution, damping characteristics, and soil-structure interaction conditions.

– Elastic analysis procedures retain utility for preliminary design and early-stage optimization; however, nonlinear time-history analysis is essential for credible performance-based seismic evaluation of tall buildings incorporating complex force-transfer mechanisms such as outrigger and belt-truss systems.

– The literature supports the conclusion that belt-truss systems can significantly enhance the seismic performance of core-wall tall buildings, but only when their configuration and location are selected through a performance-based, multi-objective, and nonlinear-analysis-driven design process.

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