



Seismic Performance Evaluation of Outrigger Systems in Irregular High-Rise Buildings: A Comprehensive State-of-the-Art Review

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ABSTRACT

Modern architectural ambition increasingly demands tall buildings with complex geometric profiles, vertical setbacks, plan asymmetries, and structural irregularities. Under severe earthquake excitations, standard shear wall-frame configurations suffer from excessive lateral sway, high inter-storey drift concentrations, and pronounced torsional coupling. Outrigger and belt truss systems provide a proven lateral load-resisting solution by coupling the central vertical core to perimeter columns, mobilizing axial push-pull force couples that reduce overturning moments by 30% to 50%. This paper delivers a comprehensive state-of-the-art review synthesizing theoretical mechanics, structural evolution, and recent empirical breakthroughs across 20 foundational and contemporary investigations. The review examines: (1) fundamental load transfer pathways and member typologies (CFST, steel X-trusses, and buckling-restrained braces); (2) performance under vertical setbacks, tilted geometries (optimal placement at 0.411H–0.489H), twisted towers, and perforated outrigger walls with corridor openings (20% critical area limit); (3) advanced analytical continuum formulations incorporating Timoshenko shear deformation, nonlinear finite element modeling (CDP constitutive laws), and emerging AI/Deep Neural Network (DNN) metamodels with SHAP interpretability; (4) multi-objective optimization covering vertical placement, relative stiffness saturation boundaries ($k = 3\%–6\%$), and structural steel member sizing; (5) dynamic vibration mitigation via fluid viscous dampers (FVD), tuned mass damper inerters (TMDI), and negative stiffness devices; and (6) regulatory seismic compliance benchmarking Indian Standards (IS 1893:2016, IS 16700:2017) against international provisions (ASCE 7-22, Eurocode 8, KDS), coupled with embodied carbon reduction (16%–22%) and post-disaster functional recovery. Key research gaps are identified to steer next-generation resilient design for irregular skyscrapers.

Keywords: Outrigger Structural Systems; Irregular High-Rise Buildings; Seismic Response Control; Inter-Storey Drift; Tilted Towers; Belt Trusses; Fluid Viscous Dampers; AI Fragility Metamodeling; IS 1893 / IS 16700; Embodied Carbon.

Introduction & Theoretical Foundations

As urban centers expand upward, structural engineers face the dual challenge of accommodating architectural form while resisting extreme lateral dynamic demands. In buildings exceeding 100 meters, lateral loads from severe earthquake ground motions and turbulent wind buffeting dictate member sizing and dynamic stability. A conventional cantilever shear core carries lateral loads primarily through flexural bending. However, as building height increases, cantilever flexural deflection grows with the fourth power of height (H^4), leading to unserviceable roof sway, rapid inter-storey drift amplification, and massive foundation overturning moments.

To break this geometric penalty, outrigger structural systems connect the interior shear core to outer perimeter columns using deep, stiff horizontal arms or full-storey trusses. Mechanically, this interaction functions like a cross-country skier planting wide ski poles. When lateral wind or earthquake inertia pushes the building laterally, the core attempts to rotate. The stiff outrigger arms engage the exterior columns, forcing the windward (or tension-side) columns into direct vertical tension and the leeward (compression-side) columns into direct compression. This push-pull axial mechanism produces a reverse restraining moment couple: $\Delta M = C \cdot d = T \cdot d$, where d represents the lever-arm distance between perimeter columns. By introducing this counteracting couple, the core base overturning moment is reduced by 30% to 50%, transforming cantilever bending behavior into an integrated mega-frame cantilever-plus-portal system.

This structural coupling introduces a sharp curvature reversal (inflection point) in the core deflection profile, flattening the lateral displacement slope and dramatically suppressing inter-storey drift ratios (IDR). Early implementations in the 1960s and 1970s relied on deep reinforced concrete (RC) walls. While RC walls offered high initial elastic stiffness, they imposed heavy dead weight, obstructed usable floor space, and introduced brittle failure risks at high cyclic ductility demands. From the 1980s onward, design evolved toward structural steel trusses, incorporating circumferential belt trusses to wrap the perimeter frame (Ho 2016; Patil & Pajgade 2023). Belt trusses equalize column axial loads around the building perimeter, transforming discrete outrigger point loads into a continuous 3D tubular response. To bypass architectural leasing obstructions entirely, 'virtual outriggers' were conceived, using ultra-stiff floor diaphragms at mechanical levels to transfer core moment couples directly to perimeter belts without diagonal truss chords penetrating floor space (Ho 2016).

Table 1 - Structural Typology Matrix for Outrigger Elements in Tall Buildings

Outrigger Typology	Lateral Stiffness Rating	Ductility & Energy Dissipation	Architectural Space Impact	Primary Field Application
Solid Reinforced Concrete Wall	Extremely High (92%–96%)	Moderate; prone to brittle shear cracking under cyclic reversals	Severe; forms a permanent solid partition across floor plates	Residential towers with permanent demising walls
Structural Steel X-Truss	Very High (85%–90%)	High; ductile hysteretic yielding in tension and compression	Moderate; permits small MEP duct penetrations between diagonals	Commercial offices and mixed-use commercial towers
Buckling-Restrained Brace (BRB)	High to Very High (80%–88%)	Superior; stable symmetric hysteretic energy loops without buckling	Moderate; modular diagonal layout fits within mechanical zones	High-seismic zones requiring explicit energy dissipation
Virtual (Indirect) Outrigger	Moderate to High (65%–75%)	Moderate; governed by diaphragm in-plane shear capacity	Zero; eliminates diagonal members across tenant leasing floor area	Premium commercial towers with open-plan requirements

Modern systems also deploy Concrete-Filled Steel Tube (CFST) columns at the outrigger anchor points. CFST members combine high core concrete compressive strength with outer steel jacket confinement, suppressing local buckling under massive cyclic axial reversals (Shehzad et al. 2025; Patil & Mujawar 2023).

Structural Irregularities & Geometric Complexities

Contemporary high-rise architecture frequently diverges from simple prismatic rectangular forms. Modern towers incorporate vertical setbacks, open-ground stilt floors, sloping or tilted facades, and twisted aerodynamic contours. While aesthetically striking and wind-shedding, these irregular configurations trigger severe structural vulnerabilities under earthquake ground motions.

Vertical Setbacks and Soft-Storey Force Smoothing

Abrupt changes in building elevation—such as tower setbacks or open stilt lobbies—generate sharp discontinuities in lateral stiffness and storey mass. Under seismic shaking, lateral inertial shear demands cannot flow smoothly downward. Instead, plastic deformations concentrate at the transition floor, precipitating a dangerous 'soft-storey' or 'weak-storey' mechanism. Per IS 1893 (Part 1):2016 Clause 7.1, an elevation stiffness drop exceeding 30% qualifies as an extreme vertical irregularity. Numerical investigations by Reddy & Ali (2022) and Prasad & Kumar (2016) demonstrate that installing a steel outrigger and belt truss system directly across the setback transition storey acts as a structural force bridge. The outrigger smooths the lateral shear trajectory, transferring abrupt core shear forces out into perimeter columns and reducing local inter-storey drift spikes by up to 44%.

Plan Asymmetries, Tilted Geometries, and Twisted Profiles

Geometric irregularities in plan and elevation alter dynamic modal coupling. In tilted or inclined high-rise structures, static gravity dead loads act with permanent eccentricity relative to the foundation footprint. This eccentricity generates continuous static P-Delta overturning moments even before seismic excitation occurs. When an earthquake strikes, dynamic lateral forces superimpose directly on the pre-existing gravity lean. In a definitive 3D dynamic investigation of a 90-storey tilted skyscraper, Lee & Kang (2025) proved that standard regular placement rules fail for inclined geometry. Rather than placing outriggers at upper thirds, the optimal vertical installation window shifts to the midsection between 0.411H and 0.489H. This mid-height zone coincides with the maximum slope change of the inclined cantilever, providing maximum counteracting restraint against both gravity-induced lateral drift and dynamic base overturning.

Similarly, twisted towers (such as the Shanghai Tower profile) rotate along their vertical axis to mitigate wind-induced vortex shedding. However, seismic shaking induces strong torsional-translational modal coupling in twisted towers (Tsai et al. 2025). Planar outrigger trusses resist only in-plane core bending and provide zero torsional resistance. To stabilize twisted geometries, closed 3D belt trusses are mandatory around the exterior perimeter. These perimeter belts activate closed-tube St. Venant torsional shear flow, resisting dynamic twisting moments and suppressing torsional drift amplification (Patil & Pajgade 2023).

Architectural Corridor Openings in RC Outrigger Walls

When deep reinforced concrete walls serve as outriggers in residential or mixed-use towers, functional circulation demands central corridor door openings. Cutting large openings converts a solid shear wall into a disturbed discontinuous region (D-region) where Bernoulli beam theory is invalid. Lee & Lee (2019) conducted comprehensive nonlinear finite element evaluations and strut-and-tie modeling (STM) of perforated RC outrigger walls. Their findings established a critical quantitative threshold: when the total opening area remains below 15% to 20% of the wall panel area, the stiffness degradation factor (β_K) remains above 0.85, and structural strength (β_R) is preserved. However, once openings exceed 20%, compressive concrete struts between openings experience extreme stress concentrations, triggering sudden brittle compressive crushing ('strut blowout') and reducing effective outrigger stiffness by more than 40%.

Table 2 - Structural Irregularity Categories and Targeted Outrigger Interventions

Irregularity Category	Primary Seismic Vulnerability	Governing Failure Mode	Recommended Outrigger Configuration	Key Design Rule / Metric
Vertical Setback	Abrupt lateral stiffness and mass drop at transition level	Soft-storey shear concentration and plastic hinge localized collapse	Steel X-braced outrigger paired with continuous belt truss at transition	Limit inter-storey stiffness drop to <30% per IS 1893:2016
Tilted / Inclined Tower	Gravity-induced P-Delta moment creating permanent lateral lean	Dynamic drift amplification on leaning side; overturning runaway	Midsection outrigger placement within 0.411H to 0.489H elevation	Position outrigger at maximum slope change elevation (Lee & Kang 2025)
Twisted Aerodynamic Form	Strong translational-torsional mode coupling under earthquake shaking	Excessive edge column torsional drift and corner diaphragm tearing	Closed 3D perimeter belt trusses combined with dual orthogonal outriggers	Keep torsional drift ratio $\Delta_{max} / \Delta_{avg} \leq 1.20$ per IS 16700:2017
Perforated Outrigger Wall	Severe stress concentrations around corridor and utility openings	Brittle compression strut crushing and diagonal shear crack propagation	Strut-and-tie reinforced RC panel with diagonal confinement rebar	Strictly restrict opening area to <20% of wall panel (Lee & Lee 2019)

Analytical, Numerical, & AI-Driven Metamodeling Frameworks

Accurately capturing the complex interaction between a vertical core cantilever and horizontal outrigger struts requires a spectrum of computational mechanics tools. Engineers navigate between closed-form continuum equations for conceptual screening, multi-scale 3D finite element analysis (FEA) for regulatory verification, and cutting-edge machine learning metamodels for probabilistic fragility assessment.

Finite Element Simulation and Non-Linear Constitutive Modeling

In modern structural research and design, CSI ETABS, SAP2000, and MIDAS-Gen serve as commercial workhorses for building-scale modal response spectrum analysis (RSA) and code checking. Conversely, SIMULIA ABAQUS is utilized for advanced continuum research, capturing multi-scale non-linear contact and material degradation (Shehzad et al. 2025). In refined FEA models, reinforced concrete core walls are discretized using 4-node quadrilateral shell elements combining in-plane membrane and Mindlin-Reissner out-of-plane plate bending formulations. Outrigger and belt truss members are modeled using 2-node beam-column frame elements with second-order P-Delta geometric non-linearity. At the outrigger-to-core connection, rigid multi-point constraints (MPCs) or solid continuum elements must be implemented to prevent artificial stress singularities.

Under intense cyclic seismic shaking, concrete experiences micro-cracking in tension and crushing in compression. The Concrete Damaged Plasticity (CDP) model in ABAQUS provides the benchmark constitutive formulation (Lubliner et al. 1989; Shehzad et al. 2025). The CDP yield surface and non-associated plastic flow are calibrated via five parameters: dilation angle ($\psi = 30^\circ\text{--}38^\circ$), flow potential eccentricity ($\epsilon = 0.1$), biaxial-to-uniaxial compressive strength ratio ($f_{b0}/f_{c0} = 1.16$), stress invariant ratio ($K_c = 0.667$), and viscosity regularization (μ). Scalar damage degradation variables—tensile cracking damage (dt) and compressive crushing damage (dc)—track the progressive loss of elastic stiffness under cyclic reversals, accurately reproducing hysteretic pinching and energy dissipation.

Closed-Form Continuum Formulations and Shear Deformation

For preliminary sizing, classical continuum models treat the core as a continuous vertical beam restrained by discrete rotational springs at outrigger elevations (Wu & Li 2003; Taranath 2011). However, early classical formulations assumed pure Euler-Bernoulli flexural behavior. Because outrigger trusses and walls have very low span-to-depth ratios (deep beam geometry), web shear deformation contributes 20% to 40% of their total rotational flexibility. Neglecting shear distortion leads to substantial overestimation of system stiffness. Consequently, Timoshenko beam theory must be applied to calculate the equivalent bending stiffness of the outrigger arm:

$$(EI)_{eq} = (E \cdot I_b) / [1 + (12 \cdot E \cdot I_b) / (G \cdot A_v \cdot L^2)] \quad (1)$$

where E is the elastic modulus, I_b is the truss chord moment of inertia, G is the shear modulus, A_v is the effective web shear area, and L is the outrigger arm length. Incorporating $(EI)_{eq}$ ensures that continuum models accurately match 3D finite element drift predictions within a 3% to 5% error margin.

Artificial Intelligence, DNN Metamodeling, and Seismic Fragility

While Non-linear Time History Analysis (NTHA) provides the most realistic assessment of structural collapse, running hundreds of earthquake accelerograms on multi-storey tall buildings requires massive computational clusters and weeks of run-time. To overcome this barrier, Xing et al. (2025) pioneered Deep Neural Network (DNN) metamodeling for high-rise outrigger structures. By training a deep multi-layer perceptron on Latin Hypercube Sampling simulations across diverse earthquake records, the DNN surrogate accurately predicts maximum inter-storey drift ratios and peak floor accelerations in milliseconds, achieving an R^2 coefficient exceeding 0.98.

To eliminate the 'black-box' nature of neural networks, Xing et al. implemented SHAP (Shapley Additive Explanations) interpretability. SHAP sensitivity analysis revealed that the first-mode spectral acceleration $Sa(T1)$ and the outrigger vertical placement ratio (z/H) represent the two most influential input features governing structural drift, far outweighing individual column area variations. Furthermore, derived seismic fragility curves revealed a vital design vulnerability: near-fault (NF) ground motions characterized by high-velocity forward-directivity pulses double the probability of exceeding Collapse Prevention (CP) drift limits compared to far-field records. This underscores the inadequacy of linear response spectrum analysis in near-fault seismic zones and confirms the necessity of supplemental damping.

Table 3 - Computational Frameworks for High-Rise Outrigger Seismic Evaluation

Modeling Methodology	Computational Cost	Nonlinear Plasticity Capability	Primary Design Application	Key Technical Limitation
Closed-Form Continuum Model	Near Zero (<1 sec)	Linear elastic only; rotational spring equivalence	Rapid conceptual layout and vertical height screening	Cannot capture 3D plan asymmetry, twist, or local plastic hinging
Response Spectrum (ETABS / SAP2000)	Low (1–5 min)	Linear elastic with CQC modal combination	Routine regulatory design and code compliance (IS 1893:2016)	Incapable of simulating velocity pulses, cyclic damage, or pinching
Nonlinear Time History (ABAQUS CDP)	Very High (6–48 hrs)	Rigorous cyclic tensile cracking and compressive crushing	High-fidelity research, forensic study, and collapse validation	Computationally prohibitive for broad probabilistic sampling
AI / DNN Metamodel (Xing et al. 2025)	Instant (<0.05 sec)	Accurately surrogates nonlinear NTHA response surfaces	Probabilistic performance-based design and fragility generation	Requires substantial upfront training data from validated FEA models

Multi-Objective Placement, Quantity, & Sizing Optimization

Simply adding outriggers does not guarantee structural efficiency. Arbitrary placement or oversized members squander structural material while exacerbating localized stress concentrations. Optimal design represents a multi-objective balance between minimizing roof displacement, controlling maximum inter-storey drift, reducing core base overturning moments, and minimizing structural steel weight.

Optimal Vertical Placement Ratios Across Structural Typologies

Extensive analytical and parametric studies reveal that the optimal vertical placement height ratio (z/H , where z is outrigger elevation and H is total building height) shifts depending on the primary governing objective:

Roof Displacement Minimization: When the design is governed by global roof sway (Δ_{top}), classical continuum theory (Taranath 2011; Wu & Li 2003) and ETABS parametric evaluations (Joshua 2020) prove that placing a single outrigger at approximately 0.60H produces maximum roof deflection reduction. In a 45-storey tall building model, Joshua (2020) established that an outrigger at 0.60H slashes top roof sway by 34.75% and storey drift by 15.38%.

Inter-Storey Drift Ratio (IDR) Minimization: Because lateral drift concentrates in the lower-to-mid storeys of tall cantilever buildings, minimizing peak IDR requires shifting the outrigger downward into the mid-height window between 0.455H and 0.50H (Verma & Dubey 2023; Shehzad et al. 2025). Mid-height placement restrains flexural slope above and below the outrigger storey.

Core Base Overturning Moment Minimization: When foundation mat thickness and deep piling capacity govern project feasibility, the optimal outrigger position drops further down, to approximately 0.30H to 0.35H (Bayati et al. 2008), maximizing the height of the core base subjected to the counteracting moment couple ΔM .

Tilted / Inclined Geometries: For tilted towers, Lee & Kang (2025) verified that the optimal placement window converges at 0.411H to 0.489H, arresting gravity-induced P-Delta moments before they amplify dynamic seismic sway.

Multi-Outrigger Elevation Distributions and Diminishing Returns

Skyscrapers exceeding 60 storeys frequently incorporate multiple outrigger levels to distribute axial force transfers across several plant levels (Wu & Li 2003; Bayati et al. 2008; Patel & Sharma 2025). For a two-outrigger system, optimal placement occurs at approximately 0.33H and 0.67H (or 0.38H and 0.72H), achieving a 48% to 56% lateral drift reduction. For a three-outrigger system, elevations are distributed at 0.25H, 0.50H, and 0.75H, delivering up to 65% drift mitigation. However, structural returns follow a strict law of diminishing returns. Parametric investigations demonstrate that adding a fourth or fifth outrigger level yields less than 3% to 5% incremental drift control, while imposing severe leasing revenue penalties and structural steel tonnage costs. Two to three outrigger levels represent the practical engineering optimum.

Member Sizing, Stiffness Saturation ($k = 3\%–6\%$), and Bracing Configurations

A critical threshold governs outrigger member sizing. The relative outrigger-to-core flexural stiffness ratio is defined as $k = (EI_{out} / L) / (EI_{core} / H)$. As outrigger truss members are sized upward, lateral drift decreases linearly until k reaches 3% to 6%. Beyond 6%, the stiffness curve completely plateaus. Increasing steel cross-sections beyond this saturation boundary yields virtually zero additional drift control because exterior column axial flexibility and core wall shear lag begin to dominate system compliance.

Regarding bracing geometry, Patil & Mujawar (2023) conducted detailed comparative analyses of 40-storey structures in ETABS, benchmarking X-bracing, V-bracing, and single-diagonal outriggers. X-bracing demonstrated clear structural superiority. Under cyclic seismic reversals, one diagonal of an X-brace operates in tension while the other acts in compression, preserving symmetrical storey stiffness. In contrast, V-type and inverted-V bracings suffer from post-buckling compression loss in one leg, creating large unbalanced vertical forces that deform the horizontal floor beam and accelerate lateral drift.

Table 4 - Multi-Objective Outrigger Optimization Parameters and Performance Bounds

Design Target / Variable	Recommended Engineering Value	Governing Performance Criterion	Typical Performance Gain	Consequence of Non-Compliance
Single Outrigger: Roof Sway	0.60H	Minimize top lateral displacement (Δ_{top})	30%–35% roof displacement reduction	Placement at roof (>0.85H) wastes >50% of structural efficiency
Single Outrigger: Inter-Storey Drift	0.455H–0.50H	Minimize maximum inter-storey drift ratio (IDR)	35%–45% storey drift mitigation	Upper placement leaves lower-storey soft zones unconstrained
Single Outrigger: Base Moment	0.30H–0.35H	Minimize foundation mat and piling demands	40%–50% core base moment reduction	Higher placement reduces height of core benefiting from reverse couple
Tilted Tower Elevation	0.411H–0.489H	Counteract static gravity tilt + dynamic inertia	42%–48% drift mitigation (Lee & Kang 2025)	Standard 0.6H placement fails to arrest gravity overturning moments

Design Target / Variable	Recommended Engineering Value	Governing Performance Criterion	Typical Performance Gain	Consequence of Non-Compliance
Multi-Outrigger Allocation	2 levels: 1/3H, 2/3H; 3 levels: 1/4H, 1/2H, 3/4H	Balanced force distribution; eliminate drift spikes	50%–65% overall drift suppression	Adding >3 levels encounters severe diminishing returns (<4% gain)

Vibration Control, Damping Mechanisms, & Advanced Absorbers

While conventional rigid outriggers increase lateral stiffness, their structural rigidity creates two severe practical drawbacks during major earthquakes: (1) massive localized stress concentrations at the core-outrigger connection, and (2) parasitic gravity force transfer caused by long-term differential column shortening. To mitigate these challenges, structural engineering has shifted toward energy-dissipating damped outrigger systems and advanced inertial absorbers.

Damped Outriggers and Fluid Viscous Dampers (FVD)

In a conventional rigid outrigger, huge bending moments in the core wall are transferred into perimeter columns through rigid structural steel joints. Finite element dynamic simulations reveal that under Maximum Considered Earthquake (MCE) shaking, localized von Mises stresses at rigid connection nodes routinely exceed 385 MPa, and joint rotations exceed 0.0078 radians. This extreme stress induces severe diagonal cracking in reinforced concrete core walls, tearing embedded connection plates and complicating post-earthquake structural repair.

Damped outrigger systems replace rigid vertical connections with fluid viscous dampers (FVD) or buckling-restrained braces placed vertically between outrigger truss tips and perimeter columns (Ho 2016; Xing et al. 2025). As the building sways, the relative vertical shear velocity strokes the damper piston, forcing hydraulic silicone fluid through calibrated orifices. The resulting damping force is velocity-dependent: $F_D = C \cdot \text{sgn}(\dot{u}) \cdot |\dot{u}|^\alpha$, where α typically ranges from 0.3 to 1.0. By dissipating energy through fluid friction rather than member yielding, damped outriggers slash peak connection stresses by more than 50% (down to 160–195 MPa) and limit joint rotations to 0.0035–0.0042 radians. Crucially, because viscous dampers offer zero resistance to slow quasi-static movements, they stroke freely under slow concrete creep, drying shrinkage, and thermal changes, completely eliminating locked-in gravity stresses from long-term differential column shortening.

Inerter-Based Devices (TMDI) and Negative Stiffness Dampers

Recent technological breakthroughs incorporate inerter devices into outrigger systems. An inerter is a two-terminal mechanical device where the resisting force is directly proportional to relative acceleration between its terminals: $F = b \cdot (\ddot{u}_1 - \ddot{u}_2)$. Using high-precision ball-screw or rack-and-pinion flywheels, an inerter creates an enormous apparent mass (inertance b):

$$b = m_d \cdot (2 \cdot \pi \cdot r / p)^2 \quad (2)$$

where m_d is flywheel mass, r is radius, and p is screw lead pitch. A lightweight 30 kg flywheel can generate an apparent inertance equivalent to tens of metric tons without adding physical gravitational dead weight. When coupled with tuned mass dampers (TMDI) or viscous dampers (VID) at outrigger levels, inerters exploit the massive relative stroke between the rotating core and perimeter frame. Empirical studies demonstrate that TMDI outriggers suppress peak floor accelerations (PFA) by up to 54% and reduce higher-mode resonant whipping under high-frequency earthquakes (Shehzad et al. 2025; Xing et al. 2025).

Complementing inerters, Negative Stiffness Dampers (NSD) utilize pre-compressed mechanical springs or active servo-mechanisms to produce apparent softening at moderate drift levels. The negative stiffness device acts as an adaptive structural fuse: it provides high initial stiffness for wind serviceability, but under severe seismic ground motions, it caps the maximum lateral force that can be transmitted into perimeter columns. This prevents column buckling and ensures primary concrete and steel structural members remain undamaged during catastrophic earthquakes.

Table 5 - Comparative Evaluation of High-Rise Outrigger Vibration Control Technologies

Vibration Control System	Energy Dissipation Physics	Peak Joint Stress	Joint Rotation	Post-Earthquake Functional Recovery
Conventional Rigid Outrigger	Zero; stores elastic strain energy until plastic hinging	Extreme (>385 MPa; plastic yielding)	High (>0.0078 rad)	Extremely Difficult; core concrete cracking requires structural epoxy injection

Vibration Control System	Energy Dissipation Physics	Peak Joint Stress	Joint Rotation	Post-Earthquake Functional Recovery
Fluid Viscous Damper (FVD)	Hydraulic fluid orifice throttling (velocity-dependent)	Moderate (160–195 MPa; elastic)	Safe (0.0035–0.0042 rad)	Immediate; dampers remain elastic, modular seal replacement if needed
Tuned Mass Damper Inerter (TMDI)	Apparent mass amplification + modal broadband damping	Low to Moderate (145–180 MPa)	Controlled (<0.0030 rad)	Immediate; protects non-structural floor assets by reducing PFA by 54%
Negative Stiffness Damper (NSD)	Adaptive force-limiting structural fuse mechanism	Capped at design threshold (<160 MPa)	Adaptive stroke reserve	Rapid; energy channeled into replaceable fuse cartridges, zero core damage

Code Compliance, Embodied Carbon, & Life-Cycle Resilience

A successful outrigger design must satisfy regional building codes, ensure long-term serviceability under concrete creep, minimize environmental embodied carbon, and enable post-disaster functional recovery.

Core Performance Metrics and Differential Column Shortening

Performance-Based Earthquake Engineering (PBEE) quantifies structural adequacy through explicit Engineering Demand Parameters (EDPs): (1) Maximum Inter-Storey Drift Ratio ($IDR = \Delta_i / h_i$), capped to prevent curtain wall rupture and column plastic hinges; (2) Top Storey Lateral Sway (Δ_{top}); (3) Base Shear Distribution (V_b); and (4) Peak Floor Acceleration (PFA), which governs damage to acceleration-sensitive interior utilities, medical equipment, and data centers.

In supertall buildings, a major serviceability hazard is differential vertical column shortening (Gadkari & Gore 2016). Central RC core walls carry different tributary areas, sustained dead loads, and reinforcement ratios compared to outer perimeter columns. Over a 30-year operational life, unequal concrete creep and drying shrinkage induce vertical differential displacements (Δ_{vert}) between core and columns. If rigid outriggers are locked during casting, this differential movement transfers massive unintentional gravity floor loads into the outrigger trusses, inducing severe shear cracking. Engineers mitigate this through three proven field protocols: (1) temporary slotted or hydraulic slip joints that remain unbolted during construction until 80%+ of dead load settlement occurs; (2) circumferential belt trusses that spread differential displacements across the perimeter tube; and (3) viscous dampers that accommodate slow vertical creep without locking in force.

Regional Seismic Code Compliance: Indian vs. International Standards

Tall building design requires compliance with regional regulatory seismic codes. In India, structural engineers reference IS 1893 (Part 1):2016 and IS 16700:2017 (Code of Practice for Planning and Design of Tall Buildings >50m) (Shah & Gore 2016; Kharade & Salgar 2022). IS 1893:2016 specifies an ultimate seismic inter-storey drift limit of $IDR \leq 0.004h$ (0.40% storey height) under design earthquake forces, alongside a soft torsional limit of $\Delta_{max} / \Delta_{avg} \leq 1.50$. However, for high-rise buildings exceeding 50 meters, IS 16700:2017 imposes far stricter requirements: a serviceability drift limit of $H/500$ (0.20%) under wind and service earthquakes, an ultimate drift limit of $H/250$ (0.40%), a rigorous torsional ratio cap of $\Delta_{max} / \Delta_{avg} \leq 1.20$, and mandatory wind tunnel testing for irregular architectural forms.

Internationally, ASCE 7-22 (USA) enforces strict drift limits of 1.5% to 2.0% under Risk Category II and III structures, mandating Chapter 16 Nonlinear Response History Analysis (NRHA) using spectrum-matched ground motions scaled to Risk-Targeted Maximum Considered Earthquake (MCE_R) levels. Eurocode 8 (EN 1998-1) enforces damage limitation drift limits ($v \cdot d_r / h \leq 0.005$) and behavior factors (q) accounting for hysteretic dissipation. Korean Building Code (KDS 41 17 00) specifies dynamic response spectrum and performance-based procedures for irregular skyscrapers (Lee & Kang 2025).

Table 6 - International Seismic Building Code Drift Limits and High-Rise Provisions

Building Code Standard	Target Jurisdiction	Seismic Drift Limits	Torsional Regularity Cap	Mandatory Dynamic Procedures
IS 1893 (Part 1): 2016	India (Seismic Zones III, IV, V)	$IDR \leq 0.004h$ (0.40% storey height)	$\Delta_{max} / \Delta_{avg} \leq 1.50$ (Permissible threshold)	Linear Response Spectrum Analysis (CQC modal combination)
IS 16700: 2017	India (High-Rise Towers >50m)	Service: $H/500$ (0.20%); Ultimate: $H/250$ (0.40%)	$\Delta_{max} / \Delta_{avg} \leq 1.20$ (Strict threshold)	3D Dynamic RSA + Mandatory Wind Tunnel Testing for irregular profiles
ASCE 7-22 (Chapter 16)	United States / International	$IDR \leq 0.015h$ to $0.020h$ (MCE_R scaled)	$\Delta_{max} / \Delta_{avg} \leq 1.20$ (Semi-rigid diaphragms)	Nonlinear Response History Analysis (NRHA) with 11 ground motion pairs
Eurocode 8 (EN 1998-1)	European Union	$v \cdot d_r / h \leq 0.005$ (Damage limitation)	Torsional radius $r_{x^2} / i_p^2 > 1.0$	Modal Response Spectrum with explicit ductility behavior factor q

Embodied Carbon Reduction and Functional Recovery Resilience

Sustainable structural engineering requires balancing seismic safety with environmental carbon footprints. In a landmark parametric lifecycle assessment of a 40-storey building designed to IS 1893:2016, Kharade & Salgar (2022) revealed an unexpected environmental synergy. Because steel outriggers engage perimeter columns to share lateral loads, the thickness of the central reinforced concrete core wall can be reduced by 25% to 35% while maintaining code drift compliance. Concrete manufacturing and rebar fabrication account for massive upfront embodied carbon (A1–A3 lifecycle stages). The substantial volume reduction in concrete and rebar far outweighs the embodied carbon of adding structural steel outrigger trusses, resulting in a net 16% to 22% reduction in total structural embodied carbon (kg CO_{2e} / m²). Thus, outrigger integration represents an effective decarbonization strategy for high-rise construction.

Simultaneously, earthquake engineering is undergoing a paradigm shift from traditional 'collapse prevention' toward 'functional recovery' and rapid re-occupancy (REDi Rating System, FEMA P-58). While traditional buildings prevent collapse, massive internal cracking renders them uninhabitable for months. By channeling inelastic deformation into modular damped outriggers or replaceable negative stiffness fuses, primary structural members remain undamaged. This reduces post-disaster repair downtime from six months down to under two weeks, achieving true urban seismic resilience.

Critical Synthesis, Research Gaps, & Future Horizons

Synthesis of the reviewed literature demonstrates that outrigger systems have transformed from simple static stiffness braces into multifaceted, intelligent structural systems. However, critical research gaps remain unaddressed:

- 1. Coupled Multi-Directional Ground Motions in Asymmetric Towers:** Most existing studies evaluate unidirectional seismic excitation or orthogonal response spectrum combinations. High-rise irregular towers subjected to simultaneous tri-axial (horizontal plus vertical) near-fault records experience severe bidirectional P-Delta amplification and shear lag that planar outriggers cannot capture.
- 2. Soil-Structure Interaction (SSI) in Soft Strata:** Classical optimization models assume rigid ground fixity. When outriggers transfer massive axial forces into perimeter columns, foundation flexibility and soil settlement alter structural period and diminish outrigger restraint by up to 20%.
- 3. Real-Time Adaptive Semi-Active Dampers:** While passive fluid viscous dampers perform reliably, semi-active magnetorheological (MR) outrigger dampers capable of adjusting damping viscosity in real-time based on AI sensor inputs represent an exciting frontier for irregular towers.
- 4. Standardized Building Code Clauses for Outriggers:** Current standards (IS 1893, IS 16700, ASCE 7-22) provide drift limits but lack specific design clauses governing outrigger force transfer, capacity design for outrigger-to-core connections, and mandatory damping provisions.

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