International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Seismic Behaviour of High-Rise Mega-Braced Frame-Core Buildings

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ABSTRACT

This review paper provides an in-depth analysis of the seismic response of high-rise mega-braced frame-core buildings, drawing upon the comprehensive study conducted by Brunesi et al. (2016). Using nonlinear time history analysis (NLTHA) and response spectrum analysis (RSA), the study examines the behaviour of 30 and 60-story prototypes designed according to European seismic codes. This paper discusses the modelling approach, structural configurations, seismic input, global and local responses, implications for seismic design, and recommendations for future research. It emphasizes the importance of incorporating advanced analysis techniques and realistic modelling in seismic evaluation and design.

Key words: - Seismic performance, High-rise buildings, Mega-bracing system, Outrigger system, Nonlinear time history analysis (NLTHA)Performance-based seismic design, Tall building dynamics.

1. Introduction

With increasing urbanization and technological advancements, high-rise buildings have become a hallmark of modern cities. These structures often utilize mega-braced frame-core systems and include structural features such as outriggers and belt trusses to resist lateral forces, especially in seismic regions. The complexity and flexibility of these tall buildings pose unique challenges for seismic design, necessitating advanced analytical tools beyond the scope of conventional seismic codes. Traditional seismic design approaches struggle to account for long-period behaviour, higher mode participation, and nonlinear interactions. Moreover, as buildings exceed conventional height thresholds, their behaviour becomes increasingly sensitive to geometric nonlinearity, stiffness discontinuities, and dynamic interactions. Engineers are required to employ sophisticated modelling strategies that simulate the actual behaviour of the structure under seismic excitation. The study by Brunesi et al. offers a timely investigation into these challenges by integrating detailed finite element modelling and nonlinear analysis to assess the seismic resilience of high-rise mega-frame structures. Their methodology serves as a benchmark for performance-based design, enabling practitioners to develop structures that not only comply with design codes but also exhibit robust behaviour under extreme seismic demands.

2. STRUCTURAL CONFIGURATION AND DESIGN APPROACH

2.1 Building Prototypes: Brunesi et al. analysed two high-rise building prototypes: HR-01, a 30-story structure standing 120 meters tall, and HR-02, a 60-story structure at 240 meters. Both buildings are symmetric in plan with a 6x6 bay layout and feature internal concentrically braced cores. Outriggers are strategically placed every 15 stories, linked with belt trusses to enhance lateral load distribution and minimize inter-story drift. This configuration is reflective of real-world practices in seismic-prone regions where the primary objective is to control deflections while maintaining structural safety. The internal braced core is tasked with handling the majority of lateral forces, while the outriggers serve to redistribute these forces across the structure, particularly toward the perimeter columns. This approach mitigates excessive demand on any single structural subsystem. The use of such hybrid systems also introduces redundancy, which enhances seismic resilience by offering alternative load paths. Furthermore, the symmetry and regularity in plan and elevation aid in achieving uniform seismic performance, reducing the likelihood of torsional responses. The comprehensive detailing and structural articulation employed in the design of HR-01 and HR-02 serve as a template for future high-rise buildings aiming for optimal seismic performance.

2.2 Material and Sectional Properties: The prototypes employ a strategic selection of steel profiles, optimizing strength-to-weight ratios and structural efficiency. IPE400 beams, HD profiles, and hollow structural sections (HSS) are utilized throughout, with material grades ranging from S275 for beams to high-strength S700 for columns and braces. This careful gradation in material properties corresponds to the performance demands at different building heights. Lower stories, subjected to higher gravity and seismic loads, employ stronger, heavier sections, while upper stories use lighter members to reduce mass and construction cost. The differential member sizing not only adheres to capacity design principles but also reflects an economic balance between material cost and performance requirements. High-strength steel in braces and outriggers enables greater energy absorption and improved ductility, which are crucial for mitigating seismic damage. Additionally, the steel sections are chosen for their favourable cyclic behaviour, enhancing the building's ability to withstand repeated seismic excitations without significant strength degradation. This tailored material application underscores the study's alignment with modern performance-based design philosophies.

2.3 Connection Systems: Recognizing the critical role of connections in seismic performance, the study meticulously models joint behaviour using advanced techniques. Beam-column and brace-to-frame connections are characterized with bolted and welded gusset plates, represented in the model by zero-length springs and fibre-based elements to simulate nonlinear behaviour. This includes stiffness degradation, strength loss, and rotational capacity, ensuring that connection failure modes are realistically portrayed. The modelling accounts for bolt slippage, gusset plate flexibility, and potential weld fractures, all of which are pivotal under cyclic loading. The validation of this modelling approach through experimental benchmarks and prior literature lends credibility to the study’s findings. In high-rise buildings, where cumulative deformations and load reversals can compromise joint integrity, such realistic connection modelling becomes indispensable. It allows engineers to identify potential weak links in the load path and address them through improved detailing. Overall, the rigorous approach to connection modelling reinforces the necessity of moving beyond simplified elastic representations, particularly in performance-critical seismic applications.

3.MODELING METHODOLOGY

3.1 Finite Element Modelling in OpenSees: OpenSees, an open-source software framework designed for simulating the seismic response of structures, is employed for finite element modelling. Brunesi et al. leverage force-based fibre beam-column elements to simulate the nonlinear behaviour of structural members, capturing both material and geometric nonlinearity. This level of detail is crucial for high-rise buildings where assumptions of linearity can significantly misrepresent the system's dynamic response. The modelling includes distributed plasticity, strain hardening, and stiffness degradation, thus enabling a comprehensive representation of inelastic behaviour. Structural hierarchy is respected in the meshing: critical load-resisting members like columns are modelled with one element per story, while beams have finer discretization to capture curvature effects. Mass is lumped at nodes to replicate dynamic characteristics realistically. Additionally, the model incorporates corotational transformations for large displacements and P-Delta effects, accounting for second-order influences. These choices reflect an advanced understanding of the seismic mechanics of tall structures and ensure fidelity in simulation results.

3.2 Brace and Gusset Plate: Representation Braces are a primary energy-dissipating element in the studied buildings and are modelled using nonlinear beam-column elements with initial imperfections to simulate out-of-plane buckling. The brace behaviour is enhanced using the Menegotto-Pinto steel model, which captures Bauschinger effects, isotropic hardening, and cyclic degradation. These features are critical in representing the hysteretic behaviour of bracing elements under reversed cyclic loads. Gusset plates connecting braces to the frame are modelled with rigid offsets and zero-length springs that simulate plate flexibility. This nuanced approach enables the model to replicate not just axial yielding but also local deformations and buckling-induced strength loss. The configuration captures complex phenomena like pinched hysteresis and asymmetric strength degradation, making it particularly valuable for assessing low-ductility or brittle failure modes. Overall, this detailed representation of brace-gusset assemblies allows for high-fidelity assessment of both local and system-wide responses.

3.3 Damping and Analysis Configuration: Rayleigh damping is used to simulate energy dissipation through modal damping, calibrated to the first two modes to capture both fundamental and higher-mode effects. The damping matrix is updated iteratively to reflect changes in stiffness due to damage progression during seismic events. This dynamic calibration helps avoid over- or under-estimation of damping effects, which is especially relevant for nonlinear time history analyses. The selected ground motions are applied using a suite of ten real earthquake records scaled to match the EC8 displacement spectra. These time histories span a wide range of intensities and frequency contents, ensuring a robust understanding of the structural behaviour under varying seismic conditions. Time integration is performed with precise time steps and convergence is ensured using energy and displacement norms. The combination of sophisticated damping, realistic loading, and robust convergence checks results in highly reliable simulations suitable for design verification and performance evaluation.

4.SEISMIC INPUT SELECTION

4.1 Ground Motion Characteristics: The selection of ground motion records significantly influences the accuracy and applicability of nonlinear seismic analysis. Brunesi et al. chose ten ground motions from the PEER NGA database, representative of magnitude 6.2 to 7.6 events. These motions were selected to emulate realistic seismic scenarios for high-seismicity European sites, aligned with EC8 soil type C classifications. Importantly, the motions reflect a wide range of rupture mechanisms, source-to-site distances, and site amplification characteristics. This diversity enhances the robustness of the simulations by encompassing both near-fault and far-field effects. Each record is scaled to the EC8 displacement spectrum in the 1 to 8-second period range, which is especially relevant for tall buildings that exhibit long fundamental periods. This careful calibration ensures that the selected records preserve natural variability while remaining spectrally consistent with code-based design expectations.

4.2 Spectral Compatibility: To maintain the physical integrity of the seismic inputs, the motions are scaled without altering their frequency content. Brunesi et al. ensure spectrum compatibility by minimizing the average coefficient of variation (COV) across the long-period range. The COV values remain below 0.25, indicating low dispersion and consistent response demands across different ground motions. Spectral matching is achieved through uniform scaling, allowing meaningful comparison of nonlinear responses and reducing statistical noise in performance metrics. Such a rigorous selection and scaling protocol ensures that the structural response is not biased by any individual motion and supports reliable extrapolation of the findings to broader design applications.

5.GLOBAL STRUCTURAL PERFORMANCE

5.1 Inter-Storey Drift and Displacement Profiles: Analysis of inter-storey drift profiles reveals the profound impact of nonlinearities and higher-mode effects, especially in the upper portions of the towers. HR-01 exhibits peak drifts of approximately 0.75%, while HR-02 reaches up to 1.00% under the strongest motions. These values are within acceptable limits but highlight the increasing drift demand with height. RSA, by contrast, underestimates drift values by as much as 50%, failing to capture stiffness discontinuities and modal coupling introduced by outrigger levels. Displacement profiles show distinct kinks at outrigger locations, emphasizing their effect on structural dynamics. These results underscore the importance of using NLTHA for tall buildings and call into question the adequacy of RSA-based design in these contexts.

5.2 Floor Accelerations: Maximum floor accelerations are critical for assessing non-structural damage and occupant safety. The study finds that floor accelerations often peak near the outrigger levels due to localized stiffness increases. NLTHA results show average peak accelerations of 1.09g for HR-01 and 0.68g for HR-02, with significant variability across motions. RSA, in some instances, overpredicts these values due to its linear assumptions. The implications are far-reaching: sensitive equipment, interior partitions, and architectural finishes may suffer damage even when the primary structure remains intact. Therefore, acceleration demands should be factored into both structural and architectural design, with possible use of isolation systems or damping devices to mitigate extreme responses.

5.3 Storey Shear and Bending Moment: The concentration of shear forces and bending moments at outrigger levels is a notable finding. NLTHA reveals that these discontinuities induce abrupt force redistributions, potentially leading to localized overstressing of structural components. RSA fails to predict these concentrations accurately due to its inability to model inelastic stiffness reductions and redistribution phenomena. Designers must therefore reinforce outrigger interfaces with enhanced detailing, including oversized gusset plates, higher-capacity bolts, and ductile welds. Furthermore, storey shear and moment profiles should guide vertical segmentation of the structure, ensuring that each segment is independently stable under severe loading scenarios.

6.LOCAL COMPONENT RESPONSE

6.1 Brace Behaviour and Hysteresis: Braces in both prototypes exhibit pseudoelastic behaviour with limited inelastic energy dissipation. Hysteresis loops demonstrate notable pinching, indicative of stiffness degradation and restrained ductility. Peak axial forces in braces reach 5000–7000 kN, with brace slenderness and boundary conditions playing key roles in response variability. The limited energy dissipation aligns with the medium ductility class design and raises questions about the trade-off between stiffness and ductility. To enhance seismic performance, future designs could explore higher-ductility brace configurations, such as buckling-restrained braces (BRBs), which provide more stable hysteresis and better energy dissipation capacity.

6.2 Outrigger-Induced Axial Loads: Outriggers introduce significant additional axial loads to perimeter columns, redistributing moment and shear demands from the central core. The induced axial loads can increase by up to 40% at the outrigger levels and taper off with height. These variations challenge conventional design practices, as they require localized increases in column capacity and connection strength. Foundation design must also account for these fluctuations, particularly in terms of axial uplift and differential settlement risks. Designers should implement load-path continuity and capacity design principles to prevent column overstress and potential failure at transfer zones.

6.3 Connection Demands: Connections experience heightened forces under NLTHA compared to RSA, with increases up to 40% in gusset plates, bolts, and welds. This discrepancy is particularly pronounced at transitions between the core and perimeter frames. The EC8 code's prescriptive overstrength factors do not adequately capture these nonlinear demands. Consequently, design validation should include NLTHA-based force demands, particularly for performance-critical joints. Detailing must emphasize ductility, energy dissipation, and redundancy. Incorporating nonlinear spring models in design-phase simulations can also help predict and mitigate potential failure mechanisms.

7.DESIGN IMPLICATIONS AND RECOMMENDATIONS

7.1 Shortcomings of RSA: RSA remains a cornerstone of conventional seismic design but proves insufficient for capturing the nuanced behaviour of high-rise systems under real earthquakes. It systematically underestimates drift, shear, and joint forces, especially where nonlinearities and modal interactions are significant. To improve safety and reliability, performance-based design approaches that incorporate NLTHA should become mandatory for structures exceeding a certain height or irregularity threshold. Where RSA is used, correction factors or supplemental checks should be employed to address known deficiencies.

7.2 Capacity Design and Detailing: Achieving a resilient structure requires consistent overstrength ratios and robust detailing across all critical components. Outrigger levels demand special attention due to their role in force redistribution and dynamic interaction. Detailing must ensure ductile failure modes in braces, beams, and connections. Brunesi et al. recommend advanced joint detailing techniques, including reduced beam sections and slotted connections. Redundancy should be embedded at all levels, enabling load transfer in the event of local failures. These measures collectively reduce the risk of progressive collapse and enhance seismic robustness.

7.3 Future Code Developments: This study presents compelling evidence for refining seismic design codes. EC8 and similar standards should integrate height-based adjustment factors, require NLTHA for complex geometries, and provide explicit guidance on nonlinear joint modelling and ground motion selection. Additionally, code provisions should encourage or mandate performance-based verification using probabilistic and scenario-based frameworks.

As the industry advances, codes must evolve to incorporate empirical insights and simulation data, moving beyond simplified formulas to reflect the real behaviour of modern tall buildings.

8.FUTURE RESEARCH DIRECTIONS:

Future work should aim to model local buckling and fracture using shell or solid elements, enabling a more precise assessment of component-level failure. Progressive collapse simulations are essential to understanding cascading failure scenarios and developing mitigation strategies. Probabilistic fragility analysis can inform retrofit prioritization and insurance modelling. Finally, diaphragm flexibility and façade-structure interaction merit investigation to quantify their effects on lateral stiffness, damping, and overall dynamic behaviour. These research directions will advance the state of knowledge and provide actionable insights for improving seismic resilience in high-rise buildings.

Conclusion:

Brunesi et al.'s study highlights the necessity of advanced nonlinear modelling and performance-based design in high-rise seismic engineering. Mega-braced frame-core systems with outriggers provide an effective means of controlling drift and distributing seismic forces. However, simplified linear methods like RSA fall short in capturing the complexity of tall building behaviour. This review underscores the critical importance of incorporating realistic material models, joint detailing, and ground motion records in seismic simulations. By embracing NLTHA and refining design codes accordingly, engineers can achieve safer, more resilient structures capable of withstanding the demands of future earthquakes.

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