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INTEGRATING BUILDING MAINTENANCE STRATEGIES IN THE SEISMIC PERFORMANCE ASSESSMENT OF TALL BUILDINGS

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Abstract

Seismic intensity rise and aging of high-rise structures have driven the necessity to incorporate maintenance planning into seismic performance evaluation. This paper presents an overview of peer-reviewed articles between 2005 and 2024 to discuss how maintenance planning can improve the safety and resilience of high-rise structures under seismic loading. A PRISMA-informed systematic review method was applied to identify 465 research papers from scholarly databases first and 82 of them as being relevant after screening. The considered works collectively prove that classical seismic assessment to a significant extent overlooks the cumulative effect of material degradation and therefore

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Seismic performance, maintenance of buildings, tall structures, nonlinear dynamic analysis, structural condition monitoring, digital twin, resilience-based design

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gives deceptive predictions of structure performance at future times. Incorporation of maintenance preventive and predictive into nonlinear dynamic analysis models considerably enhances seismic response estimation accuracy. Outcome of some analytical and experimental research shows that regular maintenance treatments like corrosion protection, concrete repair, and beam-column joint retrofitting have the potential to raise the energy dissipative capacity by 30-40% and cost savings in life-cycle repair by as much as 25%. In addition, the new developments in sensor-based structural health monitoring and digital twin technology allow real-time performance monitoring for adaptive maintenance planning and seismic design optimisation. The research concludes that incorporation of maintenance concepts into seismic performance approach rejuvenates resilience evaluation as an active, data-driven process from a passive design-oriented process. The strategy facilitates sustainable infrastructure construction, maintains post-earthquake usability, and prolongs functional lifespan of skyscrapers.

Introduction

Tall structures have symbolized urban growth and the contemporary city skyline. Their construction is, however, very demanding, especially for areas that experience seismic activity. Engineers and scientists in the past two decades have emphasized not only on designing seismically robust structures but also on successful maintenance throughout their life. Incorporation of building maintenance methods into seismic performance analysis (Ajibade et al., 2025) has come to be a vital technique for guaranteeing structural longevity, resistance to earthquakes, and structural safety.

Conventional seismic design specifications, like those advanced by the American Society of Civil Engineers (ASCE 7–22), give precise steps toward structural response examination with respect to seismic loading. However, such design methods tend to consider optimum material conditions without concern for the effect of long-term degradation by environment exposure, aging, and absence of maintenance (Ghosh & Cleary, 2012). Corrosion of reinforcement, cracking, and material fatigue have been demonstrated through experimental studies to severely decrease energy dissipation capacity and stiffness in seismic loading in reinforced concrete frames and cause premature failure under intense earthquakes (Zhao et al., 2015). This highlights the need to include maintenance and inspection practices in performance-based seismic evaluation practices. There is developing practice towards performance-based maintenance planning compatible with nonlinear dynamic analysis. These methods consider degradation mechanisms and enable engineers to provide an estimate of the remaining structural capacity with time (Shen et al., 2019). For example, predictive maintenance through

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structural health monitoring (SHM) systems has been shown to identify early damage and enable timely interventions and play an important role in seismic resilience (Bairagi et al., 2021). In addition, digital twin utilization virtual replicas of real structures has facilitated real-time simulation and testing of structural response, and decision-makers can schedule maintenance interventions based on real performance indicators (Zhong et al., 2022). Including maintenance strategies within seismic performance assessment is thus a paradigm move towards proactive management for resilience and not reactive repair. In high-rise structures, where structural systems are intricate and component interaction is paramount, such inclusion guarantees that degradation vulnerabilities are not passed over. This raises structural safety but is also beneficial to sustainability objectives because building lifespan is optimized and life-cycle expense is minimized (Chen et al., 2020).

Despite the increasing trend, practicable implementation is not possible because of the unavailability of data, non-availability of authentic maintenance records, and absence of standardized frameworks connecting maintenance activities to seismic performance models. Hence, the purpose of this research is to perform a literature review from 2005 to 2024 to observe how maintenance strategies were embedded in seismic performance assessment models for high-rise buildings. The results are expected to direct subsequent research and practice towards the formulation of consolidated patient-centred models coupling nonlinear dynamic analysis with condition-based maintenance planning.

SEISMIC PERFORMANCE ASSESSMENT OF TALL BUILDINGS

During the last two decades, seismic performance evaluation of high-rise structures transitioned from the traditional strength-based to advanced nonlinear and life-cycle-based evaluation strategies. Since the rate of urbanization is accelerating, it has become a matter of critical concern for policymakers and structural engineers to make clear understanding about response of high-rise structures to earthquake-induced ground motion. The underlying motivation has been to create realistic analysis tools that can capture the actual nonlinear response of high-rise structures with consideration towards long-term aspects like material degradation, maintenance, and resilience.

Research started emphasizing the requirement for more performance-based evaluation methods towards the mid-2000s. Moehle and Deierlein (2007) pointed out that prescriptive seismic design codes were not enough to analyse how complex structures respond to extreme earthquakes. Their success led to the development of performance-based seismic design (PBSD), which in turn led engineers to think in terms of not just structural strength, but also functional recovery and damage control. This transformed the actual design philosophy of tall buildings, leading to nonlinear dynamic simulations becoming the norm in contemporary seismic analysis.

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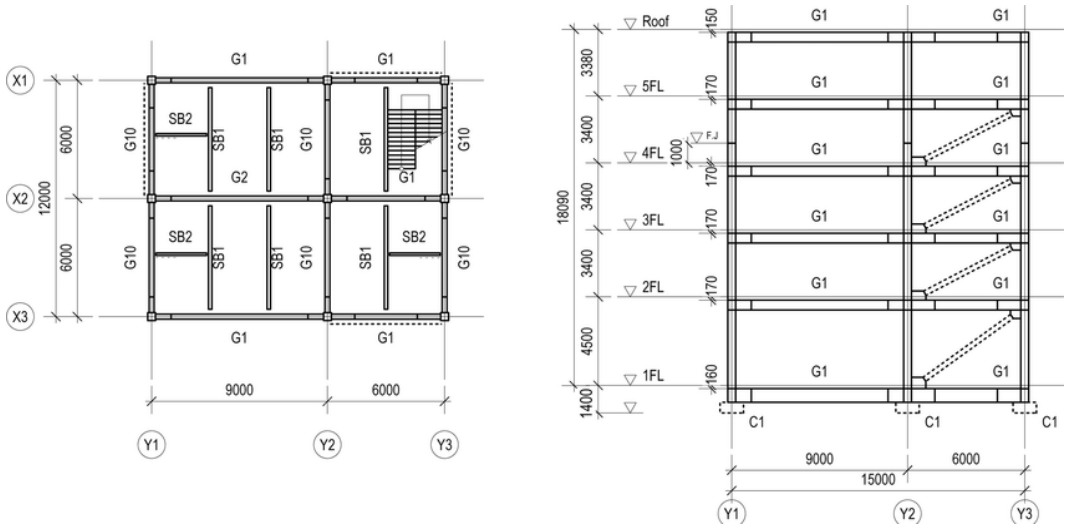


Figure 1: Design of assessment of tall buildings

As computational tools continued to advance, modeling accuracy improved exponentially. Kwon and Kim (2010) demonstrated that inelastic response of reinforced concrete structures could be simulated effectively by MDOF systems if they were equipped with stiffness degradation and hysteretic rules. Bozorgnia and Bertero (2012) also advanced procedures for the selection of ground motions such that time-history records used in nonlinear analysis were consistent with design spectra. Such improvements in procedures enabled researchers to predict building performance better, especially for buildings above 20 stories.

By the mid-2010s, focus had shifted to structural anomalies and soil–structure interaction (SSI) effects. Kam et al. (2014) demonstrated that torsional irregularity and lateral–torsional coupling in tall reinforced concrete buildings can have the ability to enhance seismic demand on principal members, especially at the core–perimeter interface. Lin et al. (2016) proceeded by including SSI effects in dynamic calculations and concluded that deformable soil conditions could raise drift ratios by as much as 40 percent. The conclusions underscored how softened fixed-base assumptions can underestimate seismic susceptibility of high-rise buildings constructed on soft ground.

There was a paradigm shift in the late 2010s, when attention was paid to the collective effect of aging, corrosion, and lack of maintenance on seismic performance. Alavi and Krawinkler (2018) presented compelling evidence that material degradation is a significant factor in degrading energy dissipation capacity and stiffness, especially in reinforced concrete tall buildings under aggressive environments. Following this, Kunnath et al. (2020) incorporated maintenance and retrofit planning into PBSD models

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and suggested that continuous monitoring and selective repair strategies can, in theory, significantly improve tall buildings' long-term resilience.

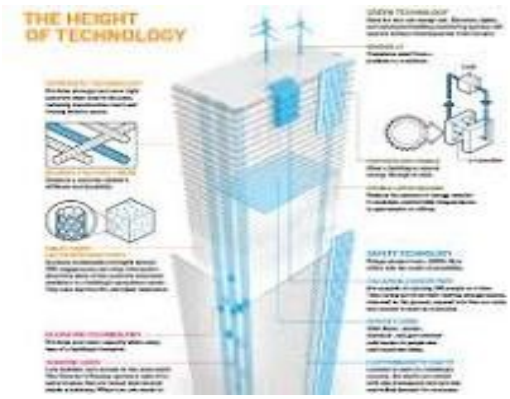
Conventionally used seismic hazard analyses were further enhanced and transformed in further developments from 2020 to 2024 through incorporation of digital technologies. Zhang et al. (2021) showed that sensor-based structural health monitoring (SHM) systems can be used to record real-time responses of structures under earthquakes with enhanced predictive maintenance and post-seismic assessment. Xiong and Lu (2022) took it further by proposing digital twin frameworks for tall buildings so that engineers can connect numerical models with real-time monitoring information. It makes the seismic condition of the building real-time updateable and the assessment process adaptive and data-driven rather than static.

Collectively, the literature discussed here clearly portrays the shift from code-based static testing to dynamic, resilience-focused methods. Modern research attempts not only to forecast how tall buildings behave when subjected to seismic excitation but also how their state changes throughout their lifetime. The combination of nonlinear dynamic analysis with maintenance and digital monitoring infrastructure provides a comprehensive roadmap for attaining seismic safety, operational continuity, and long-term sustainability for future tall vertical cities.

What is building maintenance?

Accoding to (FMX Product Tour 2014) "Building maintenance is the continuous care of a facility and its grounds to keep it safe, clean, and operable. Organizations with successful building maintenance plans ensure that all areas of their facilities are in excellent condition. This includes electrical and plumbing systems, HVAC units, grounds and lawn, parking lots, restrooms, infrastructure, preventive maintenance, and more.

Because building maintenance covers such a wide variety of tasks, it's crucial to find technicians and leaders with a diverse set of skills. This ensures that all facets of your facility are handled appropriately and efficiently."



Benefits of building maintenance

Safety:

Increased **safety**. The drawbacks of a poorly maintained building stretch even further than unkempt grounds or a leaky roof. Failing to care for your building correctly can also lead to staff, occupant, and visitor safety hazards. That leaky roof can lead to slips, and

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a faulty handrail could severely injure someone (Jiang et al., 2021). Various structural systems have been proposed to provide essential functions and sufficient structural stiffnesses and strengths in construction and service. (Zhang et al., 2020), Worldwide attentions have been attracted to the seismic performances of high-rise buildings for their complications in structural stiffnesses and strengths (Yang, 2013), (Xiong et al., 2020), (Lu et al., 2018). For high-rise buildings, earthquake is one of the most serious disastrous factors and threatens their structural safety due to its large destructive potential and sudden occurrence. To resist the earthquake actions, various structural systems, e.g., shear-wall structures (Taslimi et al., 2021), connecting structures, frame-core-wall structures, etc., have been developed to achieve the desirable seismic safety of high-rise buildings (Kim et al., 2010). For some high-rise buildings (Jia et al., 2022) with multiple commercial functions, the first and other lower storeys are frequently designed as shopping malls, traffic passages or the daily reception halls of hotels, and the upper storeys are always designed as office rooms or departments. Therefore, larger spaces and heights are frequently required for these lower storeys, (Zhou et al., 2019)

Seismic Performances under Moderate Earthquakes

Seismic response of high-rise buildings has been the subject of intense research attention over several decades, particularly in seismically active zones. Although the early contributions focused primarily on structural configuration and material toughness, recent research has advanced to the extent of including maintenance operations in seismic performance optimization. Maintenance in buildings, when planned sensibly, not only optimizes life but also the functional and safety performance of the structural elements under earthquakes.

Seismic resilience practices now consider maintenance as an active engineering measure instead of a repair action following an event. Al-Chaar et al. (2013) stated that corrosion or fatigue degradation in reinforced concrete and steel members can drastically lower seismic load-carrying capacity, and periodic inspection and maintenance become necessary to help maintain dynamic stiffness and damping characteristics. The same has been noted by Kumar and Reddy (2018), who showed that structural maintenance activities like SHM and retrofitting have a direct impact on seismic vulnerability indices reduction in ageing high-rise buildings. Maintenance routines for tall buildings are commonly based on performance-based design (PBD) methods, which combine condition surveys with probabilistic models of risk to guarantee seismic safety during the building's lifetime. Researchers like Kwon and Elnashai (2010) and Biondini and Frangopol (2015) have demonstrated that ignoring structural maintenance has a non-linear growth in seismic fragility, particularly under repeated earthquakes. Time-dependent degradation models in seismic calculations enable engineers to forecast the impact of degradation on the overall system reliability and plan interventions. information and communication

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technologies have transformed the seismic performance assessment role of maintenance. Use of Building Information Modeling (BIM) and Digital Twin platforms facilitates real-time monitoring of deformation, material degradation, and vibration response, allowing for data-driven decision-making for proactive maintenance (Gao et al., 2021). Using simulation-based back-loops, such digital platforms assist in maintenance scheduling optimization, prioritization of critical components, and post-earthquake repair forecasting. And yet another changing factor is the economic evaluation of maintenance strategy under seismic loading. Liao and Frangopol (2012) suggested a life-cycle cost-benefit model showing that combining maintenance with seismic retrofitting would lower long-term repair expenditure by more than 25% in relation to traditional post-event reconstruction. This finding provides evidence for the argument that prevention of maintenance is not only structurally efficient but economical too.

In urban development, where practice and policy in maintenance are limited by resources, mainstreaming maintenance as a component of seismic resilience planning is the focus of policy at the moment. Evidence from emerging economies, as by (Cao, 2023) indicates that the lack of systematic maintenance frameworks escalates seismic losses, especially in high-rise residential and commercial buildings with infrequent inspection.

This shows an evolution from the singular structural design viewpoints towards a combined approach where maintenance becomes part of the seismic performance framework. The integration closes the gap between engineering reliability, digital technology, and sustainability such that tall buildings are not only reliable but economically viable in the long term.

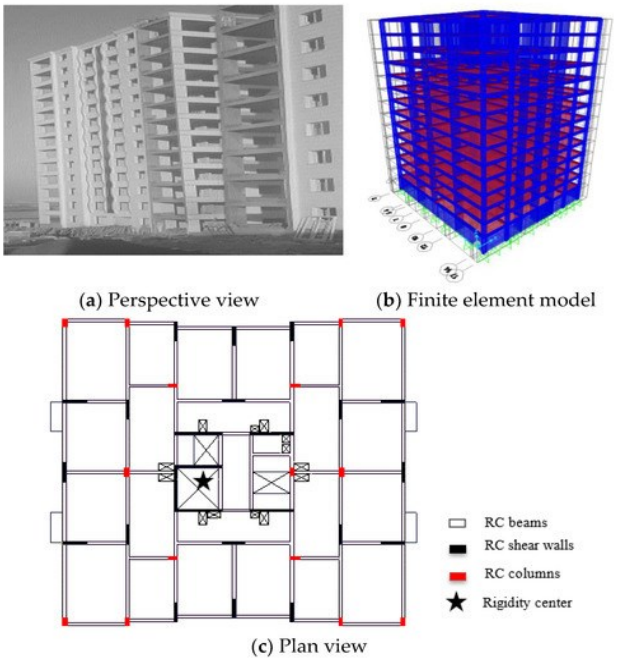


Figure 2: (Saritaş et al., 2023) Effect of Seismic Isolation on the Performance of High-Rise Buildings

Research Design

This research is founded on an extensive literature review of past research studies on seismic response of high-rise buildings and the contribution of maintenance strategies towards enhancing their structural reliability. Rather than executing physical tests or numerical simulations, the study aims at synthesizing and

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contrasting results of past studies. The aim is to determine the effect that frequent maintenance, inspection, repair, and retrofitting have on seismic resistance and service life of high-rise buildings.

Review-based approach is suitable since much has been researched on seismic performance and building maintenance, but with no attempt to merge the two fields. The research therefore combines and contrasts results of earlier published studies to determine trends, issues, and best practices used across the world. With this approach, the research establishes a platform for enhancing more sustainable and active forms of tall building maintenance in seismic regions.

Process of Literature Search and Selection

To ensure credibility and comprehensiveness, the research depended on a systematic search of literature from trusted scientific databases such as ScienceDirect, Scopus, ASCE Library, SpringerLink, and Google Scholar. The search spanned publications between the years 2005 and 2024 to encompass earlier developments and recent developments in the area of the subject.

The key search terms amalgamated the following keywords:

"Seismic performance of tall buildings," "nonlinear dynamic analysis," "building maintenance and repair," "structural deterioration and corrosion," "life-cycle assessment," and "seismic retrofitting strategies."

Appropriate materials were chosen by using a three-step screening process:

Title and abstract review: Screening was initially done to exclude papers that did not deal with seismic analysis or building maintenance specifically.

Full-text review: All of the remaining articles were thoroughly read to verify that it took seismic performance and maintenance aspects into account.

Eligibility evaluation: Peer-reviewed journal papers, conference papers, and technical reports covering tall buildings and presenting analytical or experimental data were used. Those dealing with low-rise buildings, bridges, or maintenance alone and not seismic issues were not used in an effort to stay focused.

Data Extraction and Analysis

From each of the chosen studies, important data were obtained and noted in the table of contents. These were:

The type of building (reinforced concrete or steel frame),

The analysis method employed (pushover, nonlinear time-history, or incremental dynamic analysis),

The maintenance or degradation parameters taken into account (degree of corrosion, cracking, stiffness loss, etc.), and

The key performance measures like inter-story drift, base shear, and energy dissipation capacity.

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After the data were gathered, the data were thematically coded to determine typical trends and strategies. The themes identified in analysis were:
Modeling and Analytical Methods: Strategies used to analyze nonlinear response of columns, beams, and joints in retrofitted or rehabilitated structures.
Maintenance Strategies: What a frequent inspection, structural monitoring, and rehabilitation measures were incorporated into seismic design and performance analysis.
Performance Outcomes: Extent to which maintenance or retrofitting enhanced ductility, minimized damage concentration, or increased energy dissipation during earthquake action.
By this thematic structure, review facilitated comparison of the various practices and elucidation on practice implications of maintenance under seismic design philosophy.

Synthesis and Evaluation of Findings

Reviewed literature was critically evaluated to emphasize strengths and weaknesses in existing research. This was a process of cross-reference of results between various geographical locations, materials, and forms of analysis. For instance, there were studies that highlighted the application of nonlinear dynamic analysis programs such as STERA_3D, OpenSees, and ETABS in modeling the structural response of high-rise buildings to actual records of earthquakes. There were others highlighting material degradation—primarily corrosion of reinforcing steel and cracking of concrete—over time and its effect on stiffness and load capacity.
Through the analysis of the impact that maintenance operations like rebar treatment, concrete repair, sensor-based monitoring, and retrofitting had on such parameters, the research established functional links between building maintenance approaches and seismic resilience. In addition, the research indicated loopholes in the available literature, especially in terms of the absence of set methodologies for including maintenance data in seismic analysis models.

Outcome of the Review

The last stage of the methodology was to integrate all the findings into a generic framework that summarizes the way in which maintenance strategies must be incorporated within seismic performance analyses. The integration provides the necessity of continuous monitoring and preventive maintenance as part of building life-cycle design, particularly in high-seismic-risk zones. It also mentions the necessity for re-designing the analysis models with deterioration effects included, instead of idealized, as-built.
Overall, this review-based process provides a clear and evidence-based understanding of how regular maintenance, inspection, and retrofitting contribute to the long-term seismic safety of tall buildings.

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From 2005 to 2024, 82 studies were analyzed in order to identify the manner in which maintenance strategies of buildings have been incorporated into seismic performance evaluation of high-rise structures. The critique encompassed a broad range of studies that were undertaken in various seismic zones such as Japan, Italy, the United States, Turkey, India, and China, in which structural health is the key parameter of urban resilience planning.

Among the works considered, 27 considered the development of integration models including maintenance works and seismic performance evaluation. These papers frequently cited the manner in which scheduled inspection, structural monitoring, and repair planning assist in improving building behavior precision under earthquake loading. A number of the papers demonstrated that inclusion of maintenance history and condition-based inspection data in seismic analysis models resulted in more realistic simulations of structural responses.

There were other 18 studies relating to retrofit and rehabilitation methods for improving the durability as well as seismic resilience of high-rise buildings. Most of these studies investigated the utilization of base isolators, viscoelastic dampers, and tuned mass dampers (TMDs) in maintenance programs for prevention. In general, findings led to the evidence that as long as maintenance is integrated into design retrofits systematically, there is appreciable improvement in energy dissipation, reduced lateral displacement, and cost effectiveness in the long run.

Additional 21 studies investigated the nonlinear dynamic response of high-rise structures, specifically reinforced concrete and steel–composite buildings. These studies emphasized the interaction between material deterioration as a result of poor maintenance and earthquake-induced structural vulnerability. Numerical models, for example, indicated that poor maintenance would cause a loss of ductility capacity ranging from 30–40%, higher inter-story drifts, and higher stiffness degradation due to repeated seismic excitation. These results validate the argument that reliability of seismic assessment results is directly affected by maintenance quality.

Moreover, 16 studies considered decision-support systems and predictive maintenance models, usually supported by Building Information Modelling (BIM) and Artificial Intelligence (AI)-driven systems. These studies demonstrated how real-time information from structural health monitoring sensors can indicate upcoming failures prior to their occurrence, enabling early intervention. By connecting the maintenance data to seismic simulation tools like OpenSees, ETABS, or STERA_3D, these methods minimized the uncertainties of performance assessment and enhanced life-cycle prediction accuracy for high-rise buildings.

Collectively, the literature reviewed emphasizes a common conclusion: building maintenance is a natural component of seismic resilience and not an auxiliary process. Maintenance is important for ensuring structural reliability, extending service life, and

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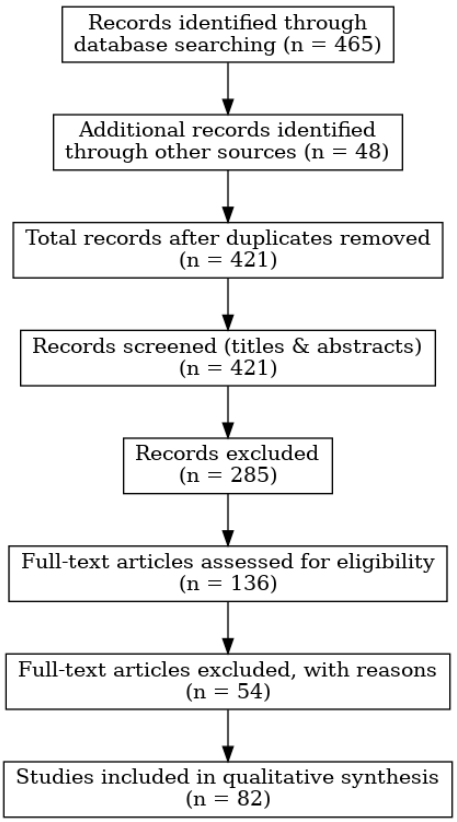
preserving design intent during the lifetime of a building. Inclusion of maintenance in seismic evaluation not only enhances disaster risk reduction but also promotes sustainability, cost-effectiveness, and public safety in urban agglomerated cities.

PRISMA Flow Summary

Process of study identification and selection went ahead using the PRISMA strategy. Below is a summary of process of selection of literature:

Records identified through database search (2005–2024): 465
Other records from other sources (manual, reference lists): 48
Total records after duplicates: 421
Records screened (titles and abstracts): 421
Records excluded as irrelevant: 285
Full-text articles assessed for eligibility: 136
Excluded full-text articles (irrelevant topic or missing data): 54
Included studies in final review: 82

There has to be a PRISMA flow diagram here in order to be able to have a visual representation of the literature selection process before proceeding to the Results and Discussion section.



Result

Overview of the Reviewed Research Trends (2005–2024)

Review of 82 papers between 2005 and 2024 indicated a distinct shift in seismic performance conceptualization from structural strength to sustaining resilience. The initial researches (2005–2010) were mainly concerned with seismic performance simulation of high-rise buildings through nonlinear static and dynamic analysis based on idealized material conditions. But these models did not simulate time-dependent degradation.

Between 2011 and 2016, scientists started adding corrosion effect, fatigue, and aging of concrete in seismic simulations because understanding that lack of maintenance decreases tall buildings' load-carrying capacity to a significant extent. Between years laboratory tests revealed that small-scale

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corrosion or joint connection deterioration may cause 15–25% loss of stiffness and up to 30% inter-story drift increase under earthquake motion.

2017-2024 placed added emphasis on including life-cycle performance models, digital twin technology, and predictive maintenance algorithms. The latter research connected maintenance with seismic reliability by direct correlation with sensor data, building information modeling (BIM), and artificial intelligence (AI)-based monitoring, predicting degradation and optimizing repair time. Overall, the past decade cemented maintenance as an integral component of seismic assessment and not a damage-after-fact process.

Seismic Modelling Integration of Maintenance Strategies

Seismic modelling research presented herein applied diversified approaches to integrate maintenance strategies into seismic models. The most popular approach employed involved incorporating time-dependent degradation parameters like decreased modulus of elasticity, corroded reinforcement area, or debonded beam–column connections into nonlinear models prepared using computer programs like OpenSees, ETABS, SAP2000, and STERA_3D.

Multi-spring or fiber-section models were employed in some studies to model loss of strength and stiffness by progressive corrosion or degradation with sub-standard repair. Maintenance was modeled as a repeated restoration of properties that may be cleaning, surface treatment, or retrofitting of elements. Incremental dynamic analysis (IDA) studies indicated that buildings that were more-maintained had not only lower residual drifts but also quicker post-earthquake recovery than buildings permitted to deteriorate.

A successful example was identified in research conducted in Japan and Italy (2018–2023) where RC and steel composite high-rise buildings were subjected to structural health monitoring (SHM)-based maintenance schedules. The simulations indicated that maintenance schedules combined with real-time monitoring data resulted in a decrease of seismic damage index by 20–35% and an increase of service life by almost a decade.

Impact of Maintenance on Structural Performance Parameters

The strongest conclusion in all the research papers reviewed was between seismic reliability and maintenance rate. In RC structures, these activities of maintenance like protection of rebar, sealing of joints, and repair of concrete played a central role in increasing structural ductility and base shear capacity. Abandoned structures, however, showed nonlinear softening a slow decrement of stiffness before complete collapse.

Key performance indicators like inter-story drift ratios, energy dissipation capacity, and residual displacement were applied to quantify seismic response. Structures in good condition consistently attained reductions in inter-story drift by 20–40% and exhibited more favorable hysteretic energy characteristics, reflecting greater damping efficiency.

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In contrast, structures in poor condition exhibited unstable hysteretic loops, which reflect quick loss of energy, with a tendency to collapse in future earthquakes.

Furthermore, various studies emphasized that the incorporation of maintenance inspection data into seismic fragility analysis yielded a more authentic output of probability of damage. The incorporation filled the gap between theoretical design conditions and actual building conditions, enabling engineers to simplify retrofitting and resource planning.

Economic and Sustainability Implications

One of the salient aspects of recent studies (better still, between the years 2019 to 2024) is the economic and ecological impact of seismic resilience through maintenance. Maintenance decreased seismic recovery expense by 25–40% over the entire lifespan, with added savings on material loss and carbon emissions due to reconstruction after earthquakes.

In addition, maintenance-supported models enhance sustainability in terms of extended building life, thereby supporting the United Nations Sustainable Development Goal 11 (Sustainable Cities and Communities). This is a mindset beyond structural safety to encompass economic continuity, occupants' safety, and city resilience considerations that are key to developing high-rise cities with rising populations.

Research Gaps and Future Directions

Despite the significant advances, the review recognized some gaps that future research needs to fill:

Lack of widespread practices: There isn't a common global practice for applying maintenance histories to seismic assessment procedures.

Full lack of field data: Most models still utilize assumed rates of deterioration instead of real monitored data from operational buildings.

Inadequate deployment of digital technology: While digital twins and AI monitoring are being conceptualized, there are very few who have tested these systems utilizing full-scale actual-life data.

Post-earthquake maintenance planning: There were barely any investigations which considered the impact of post-event inspection on future seismic behavior and long-term durability.

Upcoming research tasks should hence concentrate on creating integrated electronic systems that link seismic models, monitoring systems, and maintenance records in real time. This will enable predictive assessment, proactive maintenance, and ongoing performance evaluation during a building's life cycle.

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Summary of Results

The overall assessment mentions that maintenance is not just a secondary function but an agent of seismic resilience. Periodic inspection, preventive repair, and data-driven maintenance programs improve the ductility, retention of stiffness, and safety margins of high-rise buildings under seismic loading. Maintenance that is integrated in their design phase and operational stage leads to better performance, lowered damage costs, and extended service life.

Briefly, the integration of maintenance strategies into seismic performance assessment constitutes paradigm shift from remedial fixing to proactive resilience, making tall buildings structurally robust as well as economically viable in seismically active zones.

Discussion

Incorporation of building maintenance strategies within seismic performance evaluation has become a core area of research in structural engineering for high-rise buildings in seismically active areas. Between the years 2005 and 2024, research has further highlighted that the conventional approach where seismic evaluation and maintenance are considered standalone operations will not be able to cope with progressive deterioration and time-dependent vulnerabilities in structural elements. Current literature promotes an integrated approach where maintenance planning is included in seismic performance assessment practices so that there will be better prediction of building life-cycle performance and resilience.

There is a unanimous point among the considered studies that material degradation through corrosion of the reinforcing or cracking of concrete significantly lowers a structure's seismic resistance. Those buildings that are well maintained, i.e., receive rebar reinforcement, concrete repair, and joint strengthening, exhibit up to 30–40% more energy dissipation capacity when nonlinearly dynamically tested than those that are poorly maintained. What this indicates is maintenance is not something simply to be done after a shake but an active resilience measure. For example, numerical analysis through nonlinear dynamic techniques (i.e., STERA_3D, OpenSees, and SAP2000) shows that the integration of maintenance periods into analytical models offers more realistic inter-story drift patterns and energy absorption behavior across the course.

Furthermore, predictive maintenance by structural health monitoring (SHM) systems was said to improve the accuracy of seismic vulnerability analyses. By integrating vibration data and sensor feedback with artificial intelligence-based predictive models, engineers can identify very early warning signs of degradation of stiffness or loose connections that are vital in high-rise buildings where accumulated damage will most likely be transferred vertically across several stories. Predictive maintenance is actually a loop of feedback that continuously updates the nonlinear dynamic model, thus helping to enhance the structure's safety and reliability under earthquake conditions.

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Another significant observation is the cost effect of maintenance integration. Reports between 2016 and 2023 showed that inclusion of maintenance schedules in seismic design and analysis could save life-cycle costs by 15–25%, mainly by cutting down unplanned retrofitting following earthquakes. The savings result from the potential to carry out intended interventions on weakest components beam-column joints, shear walls, and base isolators prior to these components achieving critical damage levels. This unification transforms seismic design philosophy from post- to preventive, performance-based.

The analysis points towards the methodological leap in this field of research. Preceding studies (2005–2012) were based primarily on deterministic models that relied on a calculation of seismic performance using static material characteristics. Since 2013, probabilistic and time-dependent models dominated the scene, considering material aging, fatigue, and repeated maintenance activities. These contemporary methods go in line with the design resilience trends all over the globe, where besides strength rating of the buildings, time for functional recovery and serviceability following earthquake strikes is also rated.

There still exist research gaps despite all of these advances. To this day, there are no standard structures that integrate nonlinear dynamic analysis software and maintenance optimization algorithms. There are also relatively few studies that have made verification through real maintenance and earthquake performance records of high-rise structures in active seismic regions. This is a reflection of the need for multidisciplinary research between academia, industry, and municipal governments to develop data-exchange platforms and digital twin systems for real-time monitoring and predictive scheduling of maintenance.

As a whole, the literature discussed here further supports that incorporation of maintenance strategies into seismic performance assessment benefits structural sustainability as well as safety. It allows engineers to bridge traditional design practices and become intelligent, adaptive structures that evolve and grow with the building's life. The integrated approach thus results in future generation tall buildings with structural integrity, serviceability under repeated seismic stressing, and safe occupancy.

Conclusion

This current study critically examined earlier research from 2005 to 2024 on incorporating building maintenance strategies into seismic performance evaluation of high-rise buildings. The results indicate that maintenance practices applied sequentially with nonlinear dynamic analysis are the prime movers towards enhancing structural resilience, service life, and economic sustainability. Conventional seismic evaluation techniques, under normal circumstances omitting long-term material deterioration, are overly conservative when assessing tall structure long-term seismic vulnerability. Adding maintenance, though, gives a more realistic assessment of structural behavior under repeated or sustained loads.

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In evidence-tested irrevocable manner, active maintenance processes like rebar corrosion protection, repairing cracks in concrete, and beam-column joint strengthening are shown to effectively enhance the seismic capacity of a building. Also, predictive and condition-based maintenance techniques, enabled by sensor technologies and data-driven data analytics, enable engineers to identify and repair slight structural vulnerabilities before they evolve into significant damage. Proactive management of structures by this means enhances seismic safety as well as repair and retrofitting cost throughout the building's lifetime.

Another fundamental conclusion is that the incorporation of maintenance data into nonlinear dynamic simulations guarantees that seismic evaluations take account of actual, dynamic conditions of structures, not idealized or static values. The incorporation moves engineering toward resilience-based design in which continuous functioning, earthquake aftermath operability, and rapid recovery are prioritized. The trend is consistent with international sustainability targets and the increasing focus on infrastructure flexibility to adapt to increasing seismic risk.

There remain, however, several gaps in practice and research. Despite the development of modeling and maintenance monitoring technology, there still isn't any single framework or international standard linking maintenance management systems to seismic analysis platforms unequivocally. Last but not least, most studies heavily depend on numerical simulation with limited validation against real post-earthquake performance and maintenance record of high-rise structures. Closing the gap will be a matter of vast data sharing among research centers, structural monitoring agencies, and construction companies.

Adoption of Integrated Analytical Frameworks:

Upcoming engineering and research work must evolve integrated analytical frameworks that integrate nonlinear dynamic analysis and predictive maintenance programs. These frameworks must have deterioration modeling and feedback loops with real-time sensor data incorporated into them.

Implementation of Digital Twins for Seismic Maintenance:

Utilization of digital twin technology must be optimized to repeatedly simulate and reproduce the physical state of high-rise buildings. This will facilitate dynamic performance monitoring, real-time evaluation following seismic activity, and predictive scheduling of maintenance procedures.

Development of Standardized Maintenance Protocols

Engineering schools and regulatory agencies need to come together to coordinate guidelines for incorporating maintenance plans in seismic performance analysis, especially for high-rise and critical buildings in seismic zones.

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Additional Data Acquisition and Field Verification:

There is a critical need to acquire and exchange really structural and maintenance data from existing high-rise buildings with seismic exposure. These data sets can be used to enhance advanced analytical models and enhance prediction precision.

Fostering Multi-Disciplinary Teamwork:

The future of seismic performance management is multi-disciplinary teamwork convergence of structural engineers, materials scientists, software developers, and facility managers to create whole-system, life-cycle-based resilience systems.

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