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High Rise Building Retrofitting Optimization Against Wind Loads: A Review

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ABSTRACT

The purpose of this review paper is to discuss development studies and problems in upgrading tall buildings for increased resilience against wind loads. With the growing frequency of strong wind occurrences, it is critical to understand the impact of wind load on the structural integrity of these buildings. This work thoroughly examines wind load types, the impacts accompanying such loads, and dynamic factors such as vibrations and sway that may affect the stability of the buildings. Innovative retrofitting approaches, including structural reinforcements, tuned mass dampers (TMDs), and facade alterations, have been used to mitigate the negative effects of wind. There is a strong focus on cutting-edge materials such as fiber-reinforced polymers (FRPs), carbon nanotubes (CNTs), and smart materials that promise improved performance and adaptability. Iconic skyscrapers such as Taipei 101, Burj Khalifa, and One World Trade Center serve as examples of case studies. These buildings demonstrate the utility of these retrofitting efforts in terms of wind resistance and structural safety. Emerging developments in computational tools, predictive modeling, and the incorporation of smart systems are also addressed in the context of future retrofitting solutions. Thus, this analysis finishes with an emphasis on sustainable practices and the ability of resilient retrofitting to satisfy high-rise building performance targets in the face of more severe wind events. The study provides a detailed perspective on the rapidly expanding area of renovating tall buildings to improve wind resistance while maintaining long-term structural integrity.

Keywords High-rise building, Optimization, Wind loads, Retrofitting Techniques, Innovative Materials

1. Introduction

Extreme wind occurrences are becoming more frequent and intense, emphasizing the need to optimize retrofitting solutions for high-rise buildings. Wind forces, in the form of gusts and turbulence, have presented significant obstacles to tall structures, resulting in structural failures, safety issues, and costly damages. Aside from the degeneration and deterioration of many buildings, it poses considerable risk and financial issues for the sites where most high-rise buildings are located and are overcrowded with people. As a result, improving retrofitting tactics in the building sector is a problem of safety and economic viability. Addressing such difficulties would necessitate a comprehensive strategy that includes breakthroughs in computational methodologies, performance-based design, life-cycle cost analysis, and next-generation structural systems.

For one, among the many indicated optimization strategies, the computation algorithms are the swiftest and most effective tool in getting wind resistance in high-rise buildings. Li et al. [1] reached out to the effectiveness of genetic algorithms for achieving the performance criterion of structures and economy. This technique evaluates the different potential design possibilities for wind-induced entry, their material properties, and structural restrictions. By executing the majority of design possibilities and iterating possible design solutions, the genetic algorithm can identify the best configuration for wind effect reduction. This technique is a versatile yet efficient tool for engineers looking to optimize their retrofit efforts. It ensures that high-rise buildings are unaffected by violent winds at a low cost that is unlikely to be excessively expensive; hence, it serves as a practical option for new buildings or renovating existing ones.

In addition to computational optimization, performance-based design strategies are gaining significant traction for improving the resilience of high-rise buildings against wind loads. These strategies focus on assessing the building's overall performance rather than adhering to prescriptive design codes. Alinejad et al.[2] emphasize the critical role of aerodynamic treatments in improving wind resistance. Techniques such as corner modifications and façade adjustments help reduce wind-induced forces by altering the airflow around the building, mitigating vortex shedding and aerodynamic instability. By integrating these aerodynamic treatments into the design process, performance-based strategies offer a more nuanced and dynamic approach to retrofitting, where the building's response to wind conditions is the central focus. These treatments, when optimized and tested through simulation, provide tailored solutions to minimize wind-induced damage while enhancing building safety and comfort.

Computational optimization and performance-based design techniques are also becoming more popular ways to increase high-rise buildings' resistance to wind loads. Instead of imposing design regulations, they seek to understand the whole performance of the structure. The importance of better aerodynamic treatments for the building in terms of wind resistance was emphasized by Alinejad et al.[2], Aerodynamic Treatments. By altering the airflows that are channeled around the building and lowering vortex shedding and aerodynamic instability, techniques that alter the façade position and execute corner alterations aid in the reduction of wind-induced forces. Aerodynamic treatment is combined with performance-based methodologies and included in the design process. Retrofitting becomes more dynamic and fine-tuned in reaction to wind conditions as a result. By optimizing and evaluating these treatments through simulation, we can create tailored solutions for decreasing wind damage while improving safety and comfort.

Meanwhile, Wang and Giaralis[3] worked on integrated optimization, which considers structural and aerodynamic aspects holistically. It ensures that all components of the building's geometry, material attributes, and wind load analysis are developed simultaneously. Computational fluid dynamics (CFD) combined with optimization techniques improves wind behavior forecast results, resulting in significantly more accurate building performance. Furthermore, by taking structural and aerodynamic aspects into account, this framework provides the foundation for engineers to establish the most efficient and successful retrofitting procedures for developing resilient structures that can resist a variety of wind conditions while being cost-effective.

In addition to computational and performance-based approaches, life-cycle cost optimization is critical to ensuring that refurbishment solutions are not only effective in the near term but also economically viable in the long run. Micheli et al.[4] emphasized that, in addition to initial building expenses, long-term operational costs must be calculated. Tuned mass dampers are commonly employed in constructions to decrease wind-induced vibrations and structural movements due to dynamic stress. Indeed, incorporating such dampening systems can improve performance while also saving money on maintenance and repair expenditures throughout the building's life. The approach optimizes life-cycle costs, ensuring that retrofitting solutions stay economically feasible during the entire life of the building, thereby addressing both safety.

However, Estrado et al.[5] limited those issues to high-rise buildings with very irregular geometries and advanced geometry. Twisting and asymmetry are examples of unusual forms that contribute to torsional wind effect instability and discomfort for occupants. The emphasis of this study was demonstrated to be crucial in advanced wind load analysis approaches, such as wind tunnel testing and CFD simulations, for forecasting the effects of wind influences on complicated geometries. As a result, incorporating these advanced wind loading assessment processes into retrofitting programs would ensure that engineers could develop site-specific, tailor-made solutions to such wind load difficulties. This ensures that even the most complex high-rise structures are maintained with the best possible structural integrity and resilience.

Other retrofitting options involve reinforcing structures with specialized structural features such as shear walls and bracing systems. In reality, Aziz and Hidayat[6] have demonstrated clearly that the use of steel plate shear walls increases a building's ability to withstand static and dynamic stresses. They would eventually help to increase lateral stiffness in the building, minimizing sway caused by wind forces and lowering the possibility of structural damage from the two. Steel plate shear walls are an effective solution for reducing wind resistance in new and existing high-rise buildings; they provide a more direct and cost-effective method of boosting structural resilience.

Kodakkal et al. [7] also provided a risk-averse design methodology that accounts for the inherent uncertainty of wind loads. The method ensures that buildings are constructed to withstand the majority of potentially variable wind conditions while minimizing the structural failure risk under extreme weather events using probabilistic modeling and the consideration of different wind scenarios during the design process. In this regard, this strategy will provide a more robust solution to wind resistance by considering all of the uncertainties that are commonly encountered when anticipating wind behavior.

Hassanzadeh et al.[8] have emphasized the need to use performance-based designs in conjunction with advanced simulations and optimization methods to optimize structural components. Bracing systems and dampers could be adjusted, enhancing building responsiveness to wind loads and overall performance by increasing resilience. This design process is sufficient for a comprehensive refit, ensuring that tall structures can endure not just harsh wind conditions, but also meet performance criteria for safety, comfort, and functionality for the occupants.

It turns out that structural retrofitting for high-rise buildings is best built for wind loads by taking a multi-pronged approach to optimization that includes computational optimization, aerodynamic treatments, structural systems, and life-cycle cost considerations. This work reviews several ways to improve wind resistance with advanced computational algorithms and performance-based design principles on structural upgrades based on performance-theoretical designs in the extensive literature. Unfortunately, the integration of all of these disparate approaches into a fully functional framework did not occur. The current research thus proposes an entirely new integrated optimization framework that incorporates performance-based design concepts, computational techniques, and life-cycle costs into an integrated approach for retrofitting high-rise structures for increased wind resistance. It will also look at how modern aerodynamic treatments and structural systems are specifically designed for different types of buildings to maximize wind resistance practices.

2. Understanding Wind Loads on High-Rise Buildings

Wind loads are indeed one of the factors that constitute a primary parameter and play a vital role in the safety of tall buildings. Above all, to develop effective design procedures concerning these kinds of loads, engineers must be fully aware of the various types of wind loads, understand the factors affecting such loads, and appreciate the dynamic effects imposed by such loads on structures. In discussing all of these issues at length, the present section forms the basis for dealing in depth with wind loading at high-rise buildings.

2.1 Types of Wind Loads

Wind loads on buildings of greater height, generally, are classified into two types static loads and dynamic wind loads; static wind loads are forces acting on a structure without the moving part of the wind within it. The forces are calculated primarily on the shape of the building, its height, and orientation concerning wind direction. The static wind load varies widely depending on geographical location and environmental factors.[9].

Dynamic wind loads are loads induced due to the losses in wind speed and direction leading to time-varying movements on a structure. These movements are harder to predict and usually require complex computing models for more accurate estimations. Overall, the dynamic nature of wind load distribution across a tall building makes varying pressures into actions that can end up causing oscillations or vibrations in the building itself [10].

Gust loading factors understand dynamic wind loads. These are given by a transient measuring factor for gust wind speed and usually, this factor is even more significant when dealing with tall structures and during major storms or turbulent wind conditions. High-speed wind gusts can cause oscillation in high-rise buildings and might lead to structural defects if not considered properly during design [11].

2.2 Factors Affecting Wind Loads

Many factors determine wind load magnitudes and distributions on high-rise buildings. The most important attributes are the height, shape, position, and surrounding environment of the building. On Building Shape and Geometry: The shape and geometry of a building significantly influence wind-induced loadings. For example, among other types of shapes, square or cylindrical tall buildings are subjected to higher resistance forces from wind than tapered or rounded shapes. This is due to their sharp corners where flat surfaces redirect wind flow, thereby increasing local pressure and wind load [12]. Aerodynamic treatments, such as corner chamfers and streamlined shape buildings, have found much application in reducing wind loads by creating smoother airflows around buildings [13].

Building Height: Height also determines the extent of exposure of winds towards a building. The taller the building becomes, the more the winds are higher in elevation, which causes more wind-induced motions on the structure [14]. This is more so in conditions where the winds are of very high velocity and turbulence conditions such as coastal or mountainous regions. Moreover, the aerodynamic behavior of a tall building may be highly influenced by its height, thus shifting the focus of wind load distribution within the building itself [15].

Surrounding Environment: Another important point that stands in defining wind loads up on buildings is their location. For instance, an urban area with numerous high structures may produce very complicated wind dynamics due to vortex shedding and wind tunneling effects. However, the buildings found in open fields are more exposed to high wind velocities but considerably receive consistent wind patterns [16]. Localized increases can develop as a function of the site terrain and other obstacles such as mountains or buildings [10].

2.3 Dynamic Effects and Vibrations

High-rise buildings represent a significant challenge in structural engineering, the most serious aspect of which is wind. Wind-induced vibrations may lead to long-term structural damage as well as the discomfort experienced by the users. The cause of all these effects is the regularity in time of the dynamic wind loads which become equal to the natural frequencies of the building. The most common dynamic effects include gust-induced vibrations and along-wind and across-wind oscillations in general [17].

Wind-Induced Vibrations- Such vibrations can produce deflections in the structure that may be uncomfortable for its occupants. Dampers are often installed in high-rise buildings to limit their amplitude. Devices such as tuned mass dampers (TMD) or active control systems have been used to counteract the effects of wind for the construction of tall buildings, especially for a superstructure of more than 150 m in height [18]. Such systems must be designed based on dynamic studies of the particular building's natural frequencies and damping ratios.

Along and across the direction of the wind: In typical cases, most sways of tall buildings are due to wind's across-wind and along-wind oscillation. Each type affects some aspects of the building's characteristics, such as across-wind oscillation which occurs when wind flows directly along the entire length of a high-rise building and the movement caused by this effect swings the building in the direction of wind, or along with corresponding against main wind directions. Across the wind, oscillations happen when the wind strikes perpendicularly to the building causing lateral displacements up and downwards. The two motions can greatly influence the stability and serviceability of the structure when not effectively kept at bay [19].

Sets of widely used frequency-based optimization techniques in resonant structures are used for designing structures with reduced wind-induced vibration effects. Elimination of the resonance would effectively achieve very high performance of such buildings and meet the goal of safe performance of any high-rise buildings under a type of dynamic application-wise wind load [20].

2.4 Wind Load Prediction and Design Methods

Prediction of wind loads and formulation of design methods have been vital in protecting the buildings from being structurally unsafe or dysfunctional in their use at a truly high end. Several current prediction models and design methods have evolved to predict as well as alleviate wind load effects on tall structures.

Computational Fluid Dynamic: CFD models allow extensive simulation of wind flow around a high-rise building in an effort to assist in its wind load distribution predictions, as well as zones of high-pressure accumulation. This kind of setup can study wind behavior in complicated environments, for example in an urban canyon or with a great deal of topographical variation [21]. CFD engineers have the rulers of wind-safety comfort to optimize designs, making buildings' construction more convenient and improving safety levels.

Design Optimization: Wind load optimization is a key aspect of the design of high-rise buildings. Structural optimization methods like genetic algorithms (GA) have been implemented to design a structure that can efficiently resist wind-induced forces. The methods take into consideration all necessary criteria to arrive at the best design options to minimize wind-induced vibrations while keeping structural performance [22]. For example, Li et al. [23] integrated the analysis of wind-induced responses with structural optimization, showing how important this approach is for tall building designs under different wind conditions.

Wind Load Provisions: the most common guideline available for designing buildings for wind load is the clause in various codes or standards. For instance, the ASCE 7-16 guidelines offer wind load provisions that include complete instructions to calculate wind loads by type of building, height, geographic location, and wind speed [24]. These code requirements are now widely used by engineers to build structures, judged against whether they will survive more than hurricane and tornado conditions. Such safety factors include load factors as well as resilience measures so that buildings are designed to encounter normal or even extreme wind conditions [25].

It is important to note that understanding wind loads on high-rise buildings is among the most complex components of structural design. Engineers are also challenged by the need to consider a variety of wind load types and dynamic effects caused by variables of the site from the outset of design. As wind-load-harnessing prediction models and design strategies change over time, newer technologies combined with optimizing techniques will advance the prospect of buildings withstanding the most powerful forces of nature. High-performance computing and design strategies have significant implications for bringing efficient design solutions and resilience to high-rise buildings in terms of wind loading.

3. Challenges Posed by Wind Loads to High-Rise Buildings

Inherently, high-rise constructions are prone to the effect of wind loads because of their large surface areas and heights and also because their height includes exposure to unhealthy atmospheric conditions. As wind interacts with tall structures, it causes vibrations and structural failures in some extreme cases, aggravating the material degradation over time, which can lead to damage in the long run. Thus, this section discusses the challenges that wind loads impose on high-rise buildings: wind-induced vibration and sway; structural failure; aging and degradation of materials; and increased intensity of wind events.

3.1 Wind-Induced Vibrations and Sway

These phenomena of vibrations and sway are normally related to tall buildings in regions with high winds and severe winds. The exposure of tall buildings to these dynamic wind forces stimulates vibrations, which differ in intensity because of the shape of the buildings, height, and direction alignment to the winds. The larger purview surface of a tall building has a greater tendency to be affected by lateral wind forces, which are immediately visible in sway and vibrations within the structure. If not controlled, these movements can cause discomfort among the occupants and in extreme cases, lead to possible building failure or collapse [26].

Interference in aerodynamics in between neighboring tall buildings magnified to enhanced sway and vibrations due to wind. According to Solari and Repetto's [27], there is a gust buffeting effect on buildings characterized by wind gusts that interact with structures and create the transmission of vibrations toward the structure's frame. Transmission could bring about phenomena of resonance, leading to considerable displacement levels at some heights. A thorough knowledge of aerodynamics on structures is important in minimizing them. Aerodynamic treatments and structural modifications are used to overcome the behaviors mentioned above. Sharma et al. [28] have reviewed various modifications for aerodynamic design aimed at preventing wind-induced sway, in terms of modifications to the building's aerodynamic shape, surface roughness, or damping systems. The primary focus of these modifications is on decreasing the extent of vibrations and keeping the building within the limits of oscillation safety anticipated during periods of severe wind events.

3.2 Structural Failures and Damages

Structural failures in tall buildings occur when the wind loads acting on these structures exceed the design limits. Most structural failures of tall buildings occur as a result of cumulative dynamic stresses over a period or when there are extreme wind conditions like storms and typhoons. Although high-rise buildings are designed to resist wind forces at a certain point in time, excessive dynamic response of the structure has got that leading to large values of deflection which may, in turn, cause structural damage [29].

Pope[30] illustrated the consequences of structural deficiencies in cooling towers subjected to wind-induced loads, which in turn caused failures in the UK power stations. These instances are reminders of the necessity to consider wind load applications in the design and maintenance of high-rise buildings. According to Vickery et al. [29], the mode shape of buildings is a major contributor to their response to wind loads because certain configurations are more prone to resonant vibrations that lead to damage or even failure.

Further, Tamura et al. [31] also tackled the dynamic wind-induced responses of structures, noting that wind-induced torsional and lateral vibrations could severely harm the structure should these not be adequately accounted for in the design. The study emphasized that effective modeling and prediction are required regarding the forces or effects of wind on tall buildings to prevent occurrences of disasters.

3.3 Aging Buildings and Material Degradation

The performance of high-rise buildings under wind loads is likewise influenced by aging amounts of materials and the degradation of structural components with time. The deterioration that occurs with time is in the form of prolonged exposure of concrete, steel, and glass to environmental impacts such as wind, rain, and temperature changes. This leads to a reduction in structural capacity, thus exposing buildings to wind-induced forces [32]. Zhao et al. [33] studied how one could reduce model shape corrections for wind load estimations in old buildings, to achieve the material degradation effects. Thus, when the load is applied to these buildings, their structural elements weaken and tend to behave more flexibly and deforming condition under wind load conditions with enhanced sway and amplified vibrations that would aggravate the risk of damage to the structure. In this regard, Zhi et al. [34] outlined some methodologies for the estimation of wind load based on inverse modeling that takes into consideration materials degradation. Thus the actions have enabled the engineers to evaluate the condition of a building perfectly all the time concerning any variations in changes in wind loads, making it safer with time.

3.4 Increasing Intensity of Wind Events

Located high above the ground, high-rise buildings now stand as the only structures that unfortunately suffer from the increasing intensity and frequency of wind events, especially due to climate change. While towers stand tall and proud, such extreme events have higher impacts, including worse and stronger storm events and typhoons. These are directly linked to exceeding the design limits of the buildings due to the increased intensity and unpredictability of wind forces. Wang et al. [35] cites field studies of super-tall buildings that determined that intensity wind loads were increasing during extreme events during the last few decades, showing an urgent need to reshape building codes and strategies for design enhancements due to these changes.

It is not unusual, according to Takayama and Donadei [36], to observe that increased acceleration of wind speeds and gusts in urban environments are seen, often worsened by an "urban canyon" effect. However, the funneling, conjoining, or marching between tall buildings can lead to much higher wind pressures than those presumed: To buildings, this leads to increased forces on them, with even much greater objectives possible for wind excitation vibrations or sway, possible structural damage during great winds, and eventual failure.

As Tamura et al. [31] iterated, understanding how structures need to be adapted to wind-induced effects in design codes is crucial for buildings to be able to withstand and outlast these more frequent, intense wind events. It can be expected that the evolution of knowledge will benefit in both avoiding failure and making things well marketed in high-rise buildings with metamorphosing futurities in the complex new environments these be developed. For that matter, high-rise buildings now in the throes of wind loads resulting from several factors: wind-induced vibrations and sways, structural failure possibility, the gradual degradation of materials, and effects of climate change intensifying wind events. Such problems require continuous research and advanced design practice between current and future wind conditions.

4. Retrofitting Techniques for High-Rise Buildings

It has been observed that retrofitting techniques for high-rise structures have grown tremendously to cope with increasing requirements for sustainability, resilience, and structural performance. These structures are highly wind-loaded, making it necessary for them to adopt innovative retrofit techniques to improve response and functionality. This section provides a comprehensive review of some of the major retrofitting techniques, such as structural reinforcements, implementation of tuned mass dampers (TMDs), facade modifications, and performance-based retrofitting approaches.

4.1 Overview of Retrofitting

Retrofitting is essentially an intervention of a "critical" kind, which is necessary for the adequacy of structural capacity and performance of existing buildings to conform to newer standards and withstand environmental loads, such as that of wind forces. The retrofitting of high-rise buildings engages various challenges such as those concerned in increasing their lateral stiffness, reducing their dynamic responses, and realizing cost-effectiveness without compromising aesthetic architecture-value. Alkhatib et al. [37] demonstrated the application of computational fluid dynamic (CFD)-improved genetic algorithms in optimizing tall irregular buildings for wind resistance. The modern analytical tool has its role in retrofitting design. Elshaer et al. [38] pointed out how urban developments affect tall buildings in terms of wind loads that need retrofitting to make environmental conditions adaptive. Sharma et al. [28] studied aerodynamic modification to avoid wind-induced vibration concerns in a comprehensive retrofit approach.

4.2 Structural Reinforcements

For retrofitting high-rise buildings, structural reinforcements are a very essential part of the strategy to strengthen, stiffen, and make buildings more resilient. Among the techniques used are bracing systems, concrete jacketing, and steel plate bonding. Different bracing systems for the wind- and seismic-performance enhancement of tall structures were investigated by Kim and Hu [39]. Their results showed that the single diagonal bracing configuration drastically increases the lateral stability of the structure but is cost-effective at the same time. Also, Vafai et al. [40] presented evidence that the single diagonal brace has considerable improvement in the lateral response of high-rise buildings due to the wind load. Huang et al. [41] proposed an optimization framework for developing wind-sensitive buildings which includes uncertainties in design variables. This emphasizes the need to adopt probabilistic methods to make retrofitted structures perform in reality satisfactorily under wind loads. Another technique for retrofitting is introduced by Karihoo et al. [42], which involves the application of fiber-reinforced polymer to give strength without adding excess weight.

4.3 Tuned Mass Dampers (TMDs)

Tuned mass dampers (TMDs) are popular applications in tall buildings due to their effectiveness in controlling wind-induced vibrations. These systems consist of a mass connected to the building with a spring and damper in opposition to its motion so that dynamic responses can be diminished. As mentioned by Zhang and Li [43], TMD implementation on a 600-meter-high skyscraper achieved significant results concerning wind loads: "The performance of the system has indicated that optimal location and tuning of the TMD are essential for enhancing efficiency". Li et al. [44] analyzed the dynamic behavior of Taipei 101 and concluded that its TMD alleviated occupant discomfort as well as structural stresses. Yang et al. [45] proposed a general optimum design methodology for passive supplemental dampers, such as TMDs, based on performance criteria. This makes such TMD systems not only efficient but also economically justifiable. Xu et al. [46] have begun actual investigations of hybrid-TMD systems incorporating both passive and active elements.

4.4 Facade Modifications

This is a cutting-edge method of retrofit involving the transformation of high-rise buildings such that aerodynamic properties could reduce wind loads and help in improving energy efficiency; it consists of an array of techniques ranging from adding aerodynamic elements, modifying corners, and installing advanced facade materials.

Sharma et al. [28] discuss various types of aerodynamic modifications that could be made to reduce shear forces caused due to wind Beveling of corners, heightened turns, and tapering are some of the techniques recommended. Their study works between architectural design and structural optimization. Gu and Quan [15] conducted research on across-wind loads for some prototypical tall buildings and proposed modifications on facades to lessen the effects. Hou and Jafari [47] mentioned using sustainable facade materials for retrofit projects. Their study provided that in addition to reducing wind pressures, the integrated advanced glazing systems and double-skin facades would also increase thermal performance. Finally, Elshaer et al. [48] showed how urban aerodynamics affect the performance of facades and argued for retrofit strategies.

4.5 Performance-Based Retrofitting

Performance Based Retrofitting (PBR) involves newer methodologies aimed at pursuing the achievement of targeted specific performance objectives, such as limiting drift, minimization of energy dissipation, or enhancement of occupant comfort under wind loads, thereby using analytical tools, simulations, and optimization algorithms to customize retrofitting solutions. Chan et al. [49] developed an integrated framework for aerodynamic load determination and stiffness optimization in tall buildings and showed how wind tunnel tests should couple with numerical simulations for accurate predictions and effective retrofitting design. Li et al. [10] also proposed optimization of it for wind-induced responses based on irregular-shaped buildings using genetic algorithms to find the best retrofit configuration.

Comparative studies of international wind codes and standards were carried out by Kwon and Kareem [50] to show how performance criteria vary and how they affect retrofitting. This implies keeping localized PBR, which means the region has to be brought into consideration, for example, the wind climates and building regulations. Xu et al. [20] introduced frequency-constrained optimization for tall buildings which showed its capability to control dynamic responses while keeping the integrity of structures. Miano et al. [51] also compared different retrofit methods for reinforced concrete structures and included important insights into the choice of the best solution based on performance with associated costs.

Retrofitting of high-rise buildings under wind loads requires diversely integrated conventional means along with innovative solutions. Structural alterations, TMDs, facade alterations, or performance-based methods, which could offer different approaches toward improving the resilience and functionality of the structures, include a variety of techniques. These integrated tools empower engineers to drive site-specific strategies alongside the limited futuristic potential investments that have been gained from modern advanced computational tools.

5. Innovative Retrofitting Materials

Retrofitting tall buildings against wind hazards constitutes a key area of concern in keeping the safety and longevity of contemporary infrastructure. Building materials for retrofitting improve structure performance, resilience, and energy efficiency with the passing years or changing climatic conditions. Innovative retrofitting materials would produce solutions that add wind resistance, durability, and sustainability to high-rises so that they can at least, if not more, accommodate today's and tomorrow's design demands. Some of the most advanced materials used in retrofitting application research, like fiber-reinforced polymers (FRPs) and carbon nanotubes (CNTs), advanced composites, and smart materials, are discussed in this section above. These new materials can provide amazing structural strength, flexibility, and adaptation capacity resulting from their contribution to improving wind load resistance in tall buildings.

5.1 Fiber-reinforced polymers (FRPs)

Fiber-reinforced polymers (FRPs) mean composite materials, which comprise polymer matrices reinforced with fibers such as glass, carbon, or aramid. Their characteristics involve a combination of high strength-to-weight ratio and superior corrosion resistance coupled with good general versatility, which has made FRPs a very reliable choice for retrofitting applications in structural engineering. It has been well documented in the available literature that FRPs substantially enhance the mechanical performance of structural elements.

FRPs, on the other hand, found the best application in enhancing the strength of reinforced concrete (RC) structures. Jawed Qureshi [52] stated that FRP composites are practically capable of increasing the load-carrying capacity of RC beams, slabs, and columns. The application of FRPs as an external reinforcer improved flexural and shear strength while preserving the original integrity of the structure. This method is also minimally invasive, thus maintaining the aesthetics of retrofitted elements.

Mahboubizadeh et al. [53] discussed advancements in FRP composite manufacturing processes, which thereby broaden their application opportunities in retrofitting. Some of these include pre-stressing of FRP systems, hybrid composites, and advanced bonding mechanisms, which ensure effective adhesion between the FRP system and the substrate. According to the authors, it is also worth noting that computational modeling plays a crucial role in designing and applying FRPs for particular structural deficiencies.

FRPs are another benefit since they have the property of being durable under extreme environmental conditions. According to Rajak et al. [54], FRPs can be used in a marine environments as well as in industrial conditions because they show excellent resistance to chemical degradation as well as environmental degradation. In addition to that, FRPs are lightweight; thus, they tend to lower dead load on structures and can therefore be used very effectively in the event of seismic retrofitting interventions.

But all these advantages come along with certain challenges when using FRPs in retrofitting. Bai and Keller [55] professed that such problems include high initial cost, requirement for skilled labor, and fire resistance concerns whereas there are the benefits of increasing effectiveness and reducing cost efficiencies in the use of FRP systems. Mahboubizadeh et al. [53] maintained that their future feasibility as retrofittable material would benefit even further from durable and recyclable FRP material research.

5.2 Carbon Nanotubes (CNTs)

The realization of such a wide range of applications in composite materials should be attributed to the phenomenal mechanical and lightweight properties of carbon nanotubes in structural retrofitting systems. Taczak et al. [56] dealt with the technical issues and disciplines of research in nanomaterial composites concerning their aerospace applications, shedding light on CNTs promising a possible reinforcement to polymers in structural retrofitting. Their exceptional mechanical properties include terrific tensile strength as well as stiffness, which make CNTs ideal for increasing load-bearing ability in various retrofitting materials. Moreover, it has an added potential with the currently developing field of multifunctional CNT-composite, namely, as a load-bearing material that serves a sensing function for damage or material property change.

Mikhalchan and Vilatela [57] described in detail this novel class of materials and their potential applications, as well as the transition of CNTs toward macroscopic applications. CNT fibers are compared to the typical high-performance fiber from which they derive their genesis, and it will be shown that the performance of the CNT fibers is incomparably better in structural applications requiring high durability and harsh environmental resistance. Kundalwal [58] complemented such versatility in inciting CNT-reinforced composites through his elaboration on the thermomechanical behavior of hybrids and their potential. These composites promise great future retrofitting solutions providing a range of properties for strength, durability, and multi-functionalism.

5.3 Advanced Composites

Mostly nowadays, advanced composites such as carbon-fiber-reinforced polymers (CFRPs) and CNT reinforcements are assuming their important role in structural retrofitting. Huang et al. [59] elaborated on a perceptive review regarding the present directions of research in advanced composites intended for structural strengthening and about new materials, design improvements, and optimization techniques very much reshaping the retrofitting landscape of today. Structural performance is enhanced in mechanical properties and the resilience of existing structures over earthquakes, extreme weather, and other environmental impacts. Advanced composites were often lightweight yet high-strength solutions where their performance would not be compromised by being ideal for such structural repair and upgrade.

Luo et al. [60] attempted the incorporation of nanomaterials as fillers to improve the mechanical properties of CFRP composites. They display the improvement of certain properties from using nanofillers, for instance, strength, stiffness, and resistance to degradation that collectively make these composites outperform traditional materials. Consequently, the use of CFRPs has been increasing as a perfect option for strengthening core structural elements such as beams, columns, and slabs meant to ensure better long-term performance and durability. Vijayan et al. [61] discussed the same aspect of CFRPs in civil engineering that presents their manifold applications in retrofitting and strengthening infrastructures of civil engineering. They also put forth, as growing recognition to CFS, that these have proven a viable, economical solution for strengthening existing structures without major overhauls.

5.4 Smart Materials and Adaptive Systems

Structural retrofitting using smart materials and adaptive systems is an exciting territory in which structures would be able to monitor and repair themselves in real-time. Lopes et al. [62] presented the development of CFRP composites that, apart from reinforcing structures, detect damage and respond to it. These smart composites are equipped with sensors for condition monitoring of the structure, early damage detection, and process initiation for self-healing. Such materials could lead to higher efficiency of maintenance activities concerning less manual inspection and timely intervention.

Research on smart materials in CNTs is also growing, as noticed in the one conducted by Ou et al. [63]. Their study discusses the incorporation of CNTs into the interlayer structure of CFRP that produces laminate toughness and damage resistance. These improvements to microstructural mechanics yield adaptive materials for environmental stressors and load or damage changes in response. Collectively, these advances in smart and adaptive materials have set the stage for the next generation of technologies to enable retrofitting infrastructure with more responsive and resilient solutions.

6. Case Studies on Retrofitting High-Rise Buildings

Retrofitting high-rise buildings for wind resistance and structural safety has been a critical focus in architectural and engineering fields. The following case studies provide insights into innovative approaches adopted in Taipei 101, Burj Khalifa, and One World Trade Center to tackle challenges posed by wind loads.

6.1 Case Study 1: Taipei 101 – Retrofitting with a Tuned Mass Damper (TMD)

Taipei 101 is one of the tallest skyscrapers in the world between typhoons and earthquakes. These make wind-induced vibrations a significant engineering problem. To tackle this, engineers incorporated within the structure a tuned mass damper (TMD) that weighs 660 metric tons and is suspended between the 87th and 92nd floors. This TMD plays a pivotal role in counteracting and absorbing vibrations induced by wind load. As Kourakis [64] stated, the TMD dampens the sway and, therefore, maintains a steady stabling structure and comfort for the occupants. The further review of Vibration Control in a 101-story Building Using a Tuned Mass Damper brings into light how the swinging pendulum movement of the TMD acts under varying external wind pressures. As a countermeasure to external forces, the TMD reduces oscillation amplitude up to a maximum of 40 percent, which shows excellent efficiency. Aesthetically, the incorporation of TMD also within the public observational site proves a wise integration of functionality with design [65].

Moreover, it created a precedent on how public interaction can be achieved through engineering solutions. This interaction may be a peek into the actions of TMD as an exhibit in Taipei 101, allowing building users to engage in appreciating the engineering marvel involved in the building. The public read of the design team's decision to secure a visible damper affirms the importance of education in high-rise building design [64].

6.2 Case Study 2: Burj Khalifa – Retrofitting for Wind Resistance

It is quite a burden carried by the tallest building in the world - namely, the Burj Khalifa, as it has to endure all its extreme height and slender aerodynamic concerns. Engineers designed a whole variety of design changes and retrofitting techniques so that they could mitigate these body winds. One interesting strategy discussed in The Wind Engineering of the Burj Dubai Tower was that which reshaped the structure of the tower to confuse and diffuse wind flow. The staggered setbacks and spiral shape of the building are so designed to prevent vortex-shedding, a process that can intensify vibrations brought about by wind-induced [66].

The aerodynamic design also Confusing The Wind: The Burj Khalifa, Mother Nature, and Modern skyscrapers reveal wind tunnel testing proved to have a fundamental role in the environmental optimization of the building tower. The original design rotated about 120 degrees with a remarkable reduction of wind loads against the structure would have been realized from its alignment with the prevailing wind directions. Reinforced concrete cores and outriggers form part of these measures, which represent a new form of retrofitting design integration for stability and safety [67].

Referring to the above, Burj Khalifa also employs high-performance materials and advanced damping systems to enhance wind resistance. Another factor that contributes to lateral stability within the building is the density of the reinforced concrete, which is stiffer than steel. Also, high-strength adhesives and sealants were included to sustain the cladding system against wind pressure as discussed in Confusing The Wind. Some of those aspects indicate the importance of material selection when retrofitting constructions above example [67].

6.3 Case Study 3: One World Trade Center – Wind Resistance and Structural Safety

One World Trade Center in New York seems to be one of the best master plans for wind-resistant design and retrofitting. Combining reinforced concrete core with steel framing, the hybrid structural system of the building resists high wind load and seismic force. This is more advantageous in case of high lateral stiffness, thus, minimal sways which make the occupants more comfortable during a strong wind event as detailed in Case Study: One World Trade Center, New York. Its aerodynamic features for the tower are chamfered corners and a tapering design which reduces wind-induced pressures. As put in The Rise of One World Trade Center, these much extensive wind tunnel testing guides such design choices. In addition to being energy efficient, the high-strength glazing of the façade withstands very high wind pressures and is therefore an example of the entire retrofitting approach to resilience and sustainability [68].

Integration of advanced monitoring systems by One World Trade Center boasts of another remarkable innovation. Sensors in the whole structure can continuously record the wind loads and building response to allow proactive maintenance and performance optimization. This advancement again shows how smart technologies play their roles in retrofitting practices today [69].

Broader Implications of Case Studies

This collection of case studies brings forth the changing strategies and technologies in the retrofitting of high-rise structures. Supplementary damping systems are tangible solutions to wind vibrations, and Taipei 101's TMD is one such example. The aerodynamic modifications in the Burj Khalifa highlight the benefit of integrating wind engineering into its initial design phase. One World Trade Center sets a bar for integrating structural innovations with smart monitoring systems.

These constructions also enhance the relationship between engineering, architecture, and materials science. Retrofitting high-rise buildings goes beyond the technical aspect; it's a multidisciplinary affair. To understand the collaborative model by which retrofitted high-rise buildings are created, there commonly revolves a series of learning from these iconic structures that would eventually lead to future projects for an urban environment to live resiliently in events with increasing winds and other environmental challenges.

Thus, these monuments serve stakeholders in the construction industry to interpret such landmark designs in terms of how the retrofitting technique affects structural performance and occupant comfort. Future research will necessarily build on current explorations in emerging materials and technologies, such as adaptive systems and predictive modeling, to push the performance envelope for high-rise buildings under wind loads even further.

7. Future Directions and Emerging Technologies in Retrofitting

The field of retrofitting high-rise buildings is rapidly advancing, with emerging technologies and methodologies enhancing structural resilience, sustainability, and efficiency. This section explores future directions in retrofitting, focusing on advancements in computational tools, resilient and sustainable practices, smart system integration, and predictive modeling, supported by recent scholarly research.

7.1 Advancements in Computational Tools

With breakthroughs such as the inclusion of machine learning algorithms in the effectual use of artificial intelligence to improve evaluation, design, or retrofitting for advanced complex structures, computation has indeed turned the game for structural analysis and design making them more complex. For example, recently launched explainable AI for the seismic assessment and retrofitting of structures that employ data-driven performance prediction of structures under seismic loading [70]. In addition to this are reinforcement learning frameworks for active control systems, enabling real-time decision-making under dynamic loads [71]. This improves the design of adaptative systems meant to live up to the environment-added resolutions for high-rise buildings.

7.2 Resilient and Sustainable Retrofitting Practices

Sustainable retrofitting strategies are the need of the hour for minimizing the environmental burden posed by existing buildings. Literature review and assessment included various energy retrofitting technologies aiming at building performance enhancement, such as advanced HVAC systems, high-performance insulation, and energy-efficient lighting. A well-built implementation of these technologies is known to confer massive reductions in energy consumption and greenhouse gas emissions. Furthermore, the integration of renewable resources such as photovoltaics and wind energy into retrofitting projects improves compliance with global sustainability goals. Urban Building Energy Modeling (UBEM) tools are developed for large-scale simulation of energy performance, offering insights for sustainable urban design and energy-efficient cities worldwide [71].

7.3 Integration of Smart Systems

Incorporating smart systems in retrofitting projects has been known to improve the performance of buildings and the comfort of occupants. Real-time monitoring of structural health and environmental conditions is made possible by the Internet of Things for predictive maintenance and optimization. Smart technologies were reported to achieve more than 20% energy savings in retrofitted office buildings [72]. Building Information Modeling (BIM) supports the retrofitting process by providing detailed visual data for precision interventions. A new class of advanced materials, including shape-memory alloys and piezoelectric composites, increases the adaptability and resilience of retrofitted structures by dynamically responding to environmental variations and enhancing safety to the occupants [73].

7.4 Predictive Modeling and Simulation

Predictive modeling and simulation are primordial in anticipating and preventing risks in any retrofitting project. Computational fluid dynamics (CFD) simulations analyze airflow and pressure patterns; hence, informing the improvement in aerodynamics and structure. These digital twins are virtual replicas of physical structures, facilitating real-time monitoring and continuous optimization of retrofitting practices [73]. Hence, cost reduction, refinement in designs, and assurance for the long-term safety and performance of high-rise buildings are made possible. By embracing such technologies, this construction industry is moving forward in building a brighter and safer future for all high-rise buildings around the world.

Broader Implications for the Future

This revolution in retrofits is high-rise. Wind loads, along with other environment-induced challenges, can be addressed through a combination of computational tools with green practices or smart systems and predictive modeling. This revolution is expected to improve structural safety and resilient, sustainable urban environments. Engineers must work with architects, material scientists, and technology developers to fully realize the full potential of these emerging technologies in society. The rapid and seemingly endless pace of urbanization implies that heavier demands for creative solutions will require more innovative retrofitting measures in the coming years. Therefore, it is paramount to invest in research and development in this area. Future research must strongly focus on how to blend these technologies into a unified framework rooted in forward-looking adaptable practices for retrofitting. These advancements can offer the construction industry a more positive and safer environment for the emerging future of high-rise structures worldwide.

8. Conclusion

This assertion cannot be overemphasized about buildings. Wind-induced forces, including pressure, suction, and dynamic effects, make up a significant threat to structural integrity and safety for tall buildings particularly as the wind patterns have become even more erratic because of climate change. The need for resilient infrastructure has, therefore, become even more imperative as cities keep on expanding and the urban environment is subject to change. High-rise buildings, as important components of modern cities, should be designed and retrofitted toward the forces of nature, balancing functionality, safety, and durability throughout time.

Key innovations in retrofitting high-rise buildings have made it possible to solve these problems very effectively. Among the major proven structural reinforcements have used tuned mass dampers, shear walls, and bracing systems, which reduce wind-induced vibrations and ensure stability during strong winds. Advanced materials such as fiber-reinforced polymers (FRPs) and carbon nanotubes (CNTs) have made a major revolution in retrofitting because they improve strength and durability with little additional weight. Other design modifications are aerodynamic changes to the building facades, combined with the new smart materials and adaptive systems, which are becoming more and more applied to improve the wind load resistances of buildings. These materials do not only improve high wind resistance properties but also achieve sustainability advantages, hence going with the trend of energy-efficient and environmentally friendly construction worldwide.

The future of retrofitting technologies looks quite bright in the hitherto promising developments that would eventually augment the resilience of high-rise buildings even more. One of the most thrilling areas for growth is the application of prediction tools on simulation models which take into actual data for predictive winds and load impacts and give proactive measures to retrofit. The benefit of AI and machine learning in such predictive methodologies would allow engineers to add even better tuning to the retrofit technique, and thereby assuredly get more effective and pointed interventions. The other huge benefit of real-time structural health monitoring systems will be that continuous data will be available concerning the performance of retrofitted structures, identifying early weaknesses with a direct effort to repair damage before it occurs.

It seems the retrofitting technologies will continue to develop in the long term, along with the growing concerns toward sustainability that will play a significant role in making high-rise buildings safer, better-performing, and with enhanced lives. In the growing public awareness about the environment and construction, low-carbon solutions and greener materials would be the main thrusts of future retrofit practices. The additional integration of intelligent technologies into building systems would proactively respond to the wind stresses, immediately adapting to any number of real-time conditions and ensuring the long-term viability of these high-rises against changing climate conditions.

In conclusion, retrofitting proves quite an important aspect of urban development as it becomes a critical measure associated with the steady increase in wind loads on high-rise buildings. In this perspective, the forthcoming innovative retrofitting materials and techniques, along with further developments in predictive modeling and smart systems, will keep these buildings safe, resilient, and sustainable in the decades to come. High-rise buildings will be subjected to accelerated urbanization forces and its geotechnical wind issues aggravate with time and therefore, retrofit will continue to be an innovative approach in contributing to ensuring the structural robustness and integrity as well as safety in the high-rise building towards the establishment of more resilient and adaptable urban environments.

References

[1] Y. Li, R. B. Duan, Q. S. Li, Y. G. Li, and X. Huang, "Wind-resistant optimal design of tall buildings based on improved genetic algorithm," *Structures*, vol. 27, no. August, pp. 2182–2191, 2020, doi: 10.1016/j.istruc.2020.08.036.

[2] H. Alinejad, B. Ahn, and T. H.-K. Kang, "Performance-Based Wind Design of Tall Buildings Considering Corner Modification and Inelastic Behavior," *J. Struct. Eng.*, vol. 150, no. 7, 2024, doi: 10.1061/jsendh.steng-13100.

[3] Z. Wang and A. Giaralis, "A Novel Integrated Optimization-Driven Design Framework for Minimum-Weight Lateral-Load Resisting Systems in Wind-Sensitive Buildings Equipped with Dynamic Vibration Absorbers," *Struct. Control Heal. Monit.*, vol. 2023, pp. 1–19, Feb. 2023, doi: 10.1155/2023/3754773.

[4] L. Micheli, A. Alipour, and S. Laflamme, "Life-cycle cost optimization of wind-excited tall buildings using surrogate models," *Struct. Des. Tall Spec. Build.*, vol. 30, no. 6, pp. 94–100, Apr. 2021, doi: 10.1002/tal.1840.

[5] E. Estrado, M. Turrin, and P. Eigenraam, "Optimization of complex-geometry high-rise buildings based on wind load analysis," *Simulation*, vol. 99, no. 11, pp. 1133–1146, 2023, doi: 10.1177/00375497221109577.

[6] R. R. Aziz and A. I. Hidayat, "The effect of retrofitting high-rise buildings with steel plate shear walls," *E3S Web Conf.*, vol. 426, 2023, doi: 10.1051/e3sconf/202342601028.

[7] A. Kodakkal *et al.*, "Risk-averse design of tall buildings for uncertain wind conditions," *Comput. Methods Appl. Mech. Eng.*, vol. 402, 2022, doi: 10.1016/j.cma.2022.115371.

[8] A. Hassanzadeh, S. Moradi, and H. V. Burton, "Performance-Based Design Optimization of Structures: State-of-the-Art Review," *J. Struct. Eng.*, vol. 150, no. 8, pp. 1–22, 2024, doi: 10.1061/jsendh.steng-13542.

[9] J. D. Holmes, "Effective static load distributions in wind engineering," *J. Wind Eng. Ind. Aerodyn.*, vol. 90, no. 2, pp. 91–109, 2002, doi: 10.1016/S0167-6105(01)00164-7.

[10] Y. Li and Q. S. Li, "Wind-induced response based optimal design of irregular shaped tall buildings," *J. Wind Eng. Ind. Aerodyn.*, vol. 155, pp. 197–207, 2016, doi: 10.1016/j.jweia.2016.06.001.

[11] A. G. Davenport, "Gust Loading Factors," *J. Struct. Div.*, vol. 93, no. 3, pp. 11–34, Mar. 1967, doi: 10.1061/JSDEAG.0001692.

[12] K. C. S. Kwok, "EFFECT OF BUILDING SHAPE ON WIND-INDUCED RESPONSE OF TALL BUILDING," *Adv. Wind Eng.*, pp. 381–390, Jan. 1988, doi: 10.1016/B978-0-444-87156-5.50049-7.

[13] Y. Li, Y. G. Li, Q. S. Li, and K. F. Tee, "Investigation of wind effect reduction on square high-rise buildings by corner modification," *Adv. Struct. Eng.*, vol. 22, no. 6, pp. 1488–1500, 2019, doi: 10.1177/1369433218816111.

[14] Y. Li, C. Li, Q. S. Li, Q. Song, X. Huang, and Y. G. Li, "Aerodynamic performance of CAARC standard

tall building model by various corner chamfers," *J. Wind Eng. Ind. Aerodyn.*, vol. 202, no. April, 2020, doi: 10.1016/j.jweia.2020.104197.

[15] M. Gu and Y. Quan, "Across-wind loads of typical tall buildings," *J. Wind Eng. Ind. Aerodyn.*, vol. 92, no. 13, pp. 1147–1165, 2004, doi: 10.1016/j.jweia.2004.06.004.

[16] C. M. Chan and J. K. L. Chui, "Wind-induced response and serviceability design optimization of tall steel buildings," *Eng. Struct.*, vol. 28, no. 4, pp. 503–513, 2006, doi: 10.1016/j.engstruct.2005.09.005.

[17] Q. S. Li, D. K. Liu, J. Q. Fang, and C. M. Tam, "Multi-level optimal design of buildings with active control under winds using genetic algorithms," *J. Wind Eng. Ind. Aerodyn.*, vol. 86, no. 1, pp. 65–86, 2000, doi: 10.1016/S0167-6105(00)00004-0.

[18] W. H. Melbourne and T. R. Palmer, "Accelerations and comfort criteria for buildings undergoing complex motions," *J. Wind Eng. Ind. Aerodyn.*, vol. 41, no. 1–3, pp. 105–116, 1992, doi: 10.1016/0167-6105(92)90398-T.

[19] Q. S. Li, D. K. Liu, J. Tang, N. Zhang, and C. M. Tam, "Combinatorial optimal design of number and positions of actuators in actively controlled structures using genetic algorithms," *J. Sound Vib.*, vol. 270, no. 4–5, pp. 611–624, 2004, doi: 10.1016/S0022-460X(03)00130-5.

[20] J. Y. Fu, B. G. Wu, A. Xu, J. R. Wu, and Y. L. Pi, "A new method for frequency constrained structural optimization of tall buildings under wind loads," *Struct. Des. Tall Spec. Build.*, vol. 27, no. 18, 2018, doi: 10.1002/tal.1549.

[21] S. Huang, Q. S. Li, and S. Xu, "Numerical evaluation of wind effects on a tall steel building by CFD," *J. Constr. Steel Res.*, vol. 63, no. 5, pp. 612–627, 2007, doi: 10.1016/j.jcsr.2006.06.033.

[22] D. E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*. Addison-Wesley, 1989.

[23] Q. S. Li, X. K. Zou, J. R. Wu, and Q. Wang, "Integrated wind-induced response analysis and design optimization of tall steel buildings using Micro-GA," *Struct. Des. Tall Spec. Build.*, vol. 20, no. 8, pp. 951–971, Dec. 2011, doi: 10.1002/tal.569.

[24] E. Simiu, *Design of Buildings for Wind: A Guide for ASCE 7-16 Wind Load Provisions*, 1st editio. Wiley, 2017.

[25] E. Simiu and D. Yeo, *Wind Effects on Structures*. Wiley, 2019. doi: 10.1002/9781119375890.

[26] Y. Quan, J. Chen, and M. Gu, "Aerodynamic interference effects of a proposed taller high-rise building on wind pressures on existing tall buildings," *Struct. Des. Tall Spec. Build.*, vol. 29, no. 4, 2020, doi: 10.1002/tal.1703.

[27] G. Solari and M. P. Repetto, "General tendencies and classification of vertical structures under gust buffeting," *J. Wind Eng. Ind. Aerodyn.*, vol. 90, no. 11, pp. 1299–1319, 2002, doi: 10.1016/S0167-6105(02)00259-3.

[28] A. Sharma, H. Mittal, and A. Gairola, "Mitigation of wind load on tall buildings through aerodynamic modifications: Review," *J. Build. Eng.*, vol. 18, no. September 2017, pp. 180–194, 2018, doi: 10.1016/j.jobe.2018.03.005.

[29] P. Vickery, A. Steckley, N. Isyumov, and B. Vickery, "The effect of mode shape on the wind-induced response of tall buildings," *Proc., 5th US Natl. Conf. Wind Eng.*, 1985.

[30] R. A. POPE, "STRUCTURAL DEFICIENCIES OF NATURAL DRAUGHT COOLING TOWERS AT UK POWER STATIONS. PART 1: FAILURES AT FERRYBRIDGE AND FIDDLERS FERRY.," *Proc. Inst. Civ. Eng. - Struct. Build.*, vol. 104, no. 1, pp. 1–10, Feb. 1994, doi: 10.1680/istbu.1994.25675.

[31] Y. Tamura, A. Kareem, G. Solari, K. C. S. Kwok, J. D. Holmes, and W. H. Melbourne, "Aspects of the dynamic wind-induced response of structures and codification," *Wind Struct.*, vol. 8, no. 4, pp. 251–268, Aug. 2005, doi: 10.12989/was.2005.8.4.251.

[32] L. Zhi, P. Yu, Q. S. Li, B. Chen, and M. Fang, "Identification of wind loads on super-tall buildings by Kalman filter," *Comput. Struct.*, vol. 208, pp. 105–117, 2018, doi: 10.1016/j.compstruc.2018.07.002.

[33] R. Zhao, A. Xu, W. Sun, and X. Lan, "Model shape correction method for high-frequency force balance technique," *J. Vibroengineering*, vol. 19, no. 3, pp. 1665–1679, 2017, doi: 10.21595/jve.2017.17938.

[34] L. Zhi, M. Fang, and Q. S. Li, "Estimation of wind loads on a tall building by an inverse method," *Struct.*

Control Heal. Monit., vol. 24, no. 4, p. e1908, Apr. 2017, doi: 10.1002/stc.1908.

[35] C. Wang *et al.*, "Field research on thewind-induced response of a super high-rise building under Typhoon," *Appl. Sci.*, vol. 9, no. 11, 2019, doi: 10.3390/app9112180.

[36] X. Xu, Q. Yang, A. Yoshida, and Y. Tamura, "Characteristics of pedestrian-level wind around super-tall buildings with various configurations," *J. Wind Eng. Ind. Aerodyn.*, vol. 166, pp. 61–73, Jul. 2017, doi: 10.1016/j.jweia.2017.03.013.

[37] F. Alkhatib, N. Kasim, S. Qaidi, H. M. Najm, and M. M. Sabri Sabri, "Wind-resistant structural optimization of irregular tall building using CFD and improved genetic algorithm for sustainable and cost-effective design," *Front. Energy Res.*, vol. 10, no. October, 2022, doi: 10.3389/fenrg.2022.1017813.

[38] A. Elshaer, G. Bitsuamlak, and A. El Damatty, "Aerodynamic optimization to reduce wind loads on tall buildings," *Proceedings, Annu. Conf. - Can. Soc. Civ. Eng.*, vol. 3, pp. 1749–1759, 2016.

[39] D. K. Kim and J. W. Hu, "Bracing systems for seismic and wind performance of tall buildings," *Adv. Mater. Res.*, vol. 650, pp. 667–672, 2013, doi: 10.4028/www.scientific.net/AMR.650.667.

[40] A. Vafai, H. Estekanchi, and M. Mofid, "The use of single diagonal bracing in improvement of the lateral response of tall buildings," *Struct. Des. Tall Build.*, vol. 4, no. 2, pp. 115–126, 1995, doi: 10.1002/tal.4320040203.

[41] M. F. Huang, C. M. Chan, and W. J. Lou, "Optimal performance-based design of wind sensitive tall buildings considering uncertainties," *Comput. Struct.*, vol. 98–99, pp. 7–16, 2012, doi: 10.1016/j.compstruc.2012.01.012.

[42] B. L. Karihoo, F. J. Alaee, and S. D. P. Benson, "A new technique for retrofitting damaged concrete structures," *Proc. Inst. Civ. Eng. Struct. Build.*, vol. 152, no. 4, pp. 309–318, 2002, doi: 10.1680/stbu.152.4.309.40812.

[43] J. W. Zhang and Q. S. Li, "Mitigation of wind-induced vibration of a 600 m high skyscraper," *Int. J. Struct. Stab. Dyn.*, vol. 19, no. 2, 2019, doi: 10.1142/S0219455419500159.

[44] Q. S. Li, L.-H. Zhi, A. Y. Tuan, C.-S. Kao, S.-C. Su, and C.-F. Wu, "Dynamic Behavior of Taipei 101 Tower: Field Measurement and Numerical Analysis," *J. Struct. Eng.*, vol. 137, no. 1, pp. 143–155, 2011, doi: 10.1061/(asce)st.1943-541x.0000264.

[45] J. N. Yang, S. L. Lin, J. H. Kim, and A. K. Agrawal, "Optimal design of passive supplemental dampers based on H∞ and H 2 performances," *Struct. Congr. 2000 Adv. Technol. Struct. Eng.*, vol. 103, pp. 1–8, 2004, doi: 10.1061/40492(2000)8.

[46] A. Xu, W. X. Sun, R. H. Zhao, J. R. Wu, and W. Q. Ying, "Lateral drift constrained structural optimization of an actual supertall building acted by wind load," *Struct. Des. Tall Spec. Build.*, vol. 26, no. 6, pp. 1–13, 2017, doi: 10.1002/tal.1344.

[47] F. Hou and M. Jafari, "Investigation approaches to quantify wind-induced load and response of tall buildings: A review," *Sustain. Cities Soc.*, vol. 62, no. September 2019, p. 102376, 2020, doi: 10.1016/j.scs.2020.102376.

[48] A. Elshaer, A. Gairola, K. Adamek, and G. Bitsuamlak, "Variations in wind load on tall buildings due to urban development," *Sustain. Cities Soc.*, vol. 34, pp. 264–277, 2017, doi: 10.1016/j.scs.2017.06.008.

[49] C. M. Chan, J. K. L. Chui, and M. R. Huang, "Integrated aerodynamic load determination and stiffness design optimization of tall buildings," *Struct. Des. Tall Spec. Build.*, vol. 18, no. 1, pp. 59–80, 2009, doi: 10.1002/tal.397.

[50] D. K. Kwon and A. Kareem, "Comparative study of major international wind codes and standards for wind effects on tall buildings," *Eng. Struct.*, vol. 51, pp. 23–35, 2013, doi: 10.1016/j.engstruct.2013.01.008.

[51] A. Miano, H. Sezen, F. Jalayer, and A. Prota, "Performance-based comparison of different retrofit methods for reinforced concrete sructures," *COMPDYN 2017 - Proc. 6th Int. Conf. Comput. Methods Struct. Dyn. Earthq. Eng.*, vol. 1, pp. 1515–1535, 2017, doi: 10.7712/120117.5510.17150.

[52] J. Qureshi, "A Review of Fibre Reinforced Polymer Structures," *Fibers*, vol. 10, no. 3, pp. 4–6, 2022, doi: 10.3390/fib10030027.

[53] S. Mahboubizadeh, A. Sadeq, Z. Arzaqi, O. Ashkani, and M. Samadoghli, "Advancements in fiber-

reinforced polymer (FRP) composites: an extensive review," *Discov. Mater.*, vol. 4, no. 1, 2024, doi: 10.1007/s43939-024-00091-9.

[54] D. K. Rajak, D. D. Pagar, P. L. Menezes, and E. Linul, "Fiber-reinforced polymer composites: Manufacturing, properties, and applications," *Polymers (Basel).*, vol. 11, no. 10, 2019, doi: 10.3390/polym11101667.

[55] T. Keller and Y. Bai, "Structural performance of FRP composites in fire," *Adv. Struct. Eng.*, vol. 13, no. 5, pp. 793–804, 2010, doi: 10.1260/1369-4332.13.5.793.

[56] M. D. Taczak, "A Brief Review of Nanomaterials for Aerospace Applications: Carbon Nanotube-Reinforced Polymer Composites," *Group*, no. May, 2006.

[57] A. Mikhalchan and J. J. Vilatela, "A perspective on high-performance CNT fibres for structural composites," *Carbon N. Y.*, vol. 150, pp. 191–215, 2019, doi: 10.1016/j.carbon.2019.04.113.

[58] S. I. Kundalwal, "Hierarchical modeling of multifunctional novel carbon nanotube reinforced hybrid composites for next generation polymeric composites," *arXiv*, 2017.

[59] X. Huang, S. Su, Z. Xu, Q. Miao, W. Li, and L. Wang, "Advanced Composite Materials for Structure Strengthening and Resilience Improvement," *Buildings*, vol. 13, no. 10, p. 2406, Sep. 2023, doi: 10.3390/buildings13102406.

[60] M. Jami, R. Rupakhety, S. Elias, B. Bessason, and J. T. Snæbjörnsson, "Recent Advancement in Assessment and Control of Structures under Multi-Hazard," Appl. Sci., vol. 12, no. 10, 2022, doi: 10.3390/app12105118.

[61] D. S. Vijayan, A. Sivasuriyan, P. Devarajan, and E. Koda, "Carbon Fibre-Reinforced Polymer (CFRP) Composites in Civil," 2023.

[62] C. Lopes *et al.*, "Smart Carbon Fiber-Reinforced Polymer Composites for Damage Sensing and On-Line Structural Health Monitoring Applications," *Polymers (Basel).*, vol. 16, no. 19, 2024, doi: 10.3390/polym16192698.

[63] Y. Ou, C. González, and J. J. Vilatela, "Understanding interlaminar toughening of unidirectional CFRP laminates with carbon nanotube veils," *Compos. Part B Eng.*, vol. 201, 2020, doi: 10.1016/j.compositesb.2020.108372.

[64] I. Kourakis, "Structural systems and tuned mass dampers of super-tall buildings: case study of Taipei 101," pp. 43–58, 2007, [Online]. Available: http://dspace.mit.edu/handle/1721.1/38947

[65] A. Y. Tuan and G. Q. Shang, "Vibration control in a 101-storey building using a tuned mass damper," *J. Appl. Sci. Eng.*, vol. 17, no. 2, pp. 141–156, 2014, doi: 10.6180/jase.2014.17.2.05.

[66] P. A. Irwin and W. F. Baker, "The wind engineering of the Burj Dubai tower," *CTBUH 2005 - 7th World Congr. Renewing Urban Landscape, Proc.*, 2005.

[67] J. C. Feblowitz, "Confusing The Wind: The Burj Khalifa, Mother Nature, and the Modern Skyscraper," *Inquiries Journal/Student Pulse*, 2010. http://www.inquiriesjournal.com/a?id=124

[68] K. Lewis and N. Holt, "a Study on One World Trade Center," *Int. Res. J. Mod. Eng. Technol. Sci.*, 2023, doi: 10.56726/irjmets34459.

[69] A. Rahimian and Y. Eilon, "The Rise of One World Trade Center," *Glob. Interchang. Resurgence Skyscraper City*, pp. 66–71, 2015.

[70] K. Shabbir, M. Noureldin, and S. Sim, "Data-driven model for seismic assessment, design, and retrofit of structures using explainable artificial intelligence," *Comput. Civ. Infrastruct. Eng.*, vol. 40, no. 3, pp. 281–300, Jan. 2025, doi: 10.1111/mice.13338.

[71] S. S. Eshkevari, S. S. Eshkevari, D. Sen, and S. N. Pakzad, "RL-Controller: a reinforcement learning framework for active structural control," 2021, [Online]. Available: http://arxiv.org/abs/2103.07616

[72] M. Azouz and S. Elariane, "Towards energy efficiency: retrofitting existing office buildings using smart technologies," *J. Eng. Appl. Sci.*, vol. 70, no. 1, pp. 1–17, 2023, doi: 10.1186/s44147-023-00327-0.