



WIND-RESISTANT STRUCTURES: BEYOND CONVENTIONAL DESIGN

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Article History: Received: 07.06.2022

Revised: 22.07.2022

Accepted: 07.09.2022

Abstract

This research study investigates the crucial field of wind-resistant structure design, exploring techniques that go beyond traditional approaches. Taking into account the increasing risk of extreme wind events due to climate change, this research looks for creative and long-lasting solutions for structure resilience. It begins with a summary of the importance of wind-resistant design and the drawbacks of conventional methods. By analyzing the changing wind patterns and environmental issues that call for a new design paradigm, the backdrop puts the study in context. The purpose of the study is to determine whether novel materials and cutting-edge modeling techniques can effectively increase wind resistance. A comprehensive literature study examines standard procedures, fsustainable integration, and pertinent theories and models, all guided by important research issues. The methodology section provides specifics on a thorough mixed-method strategy that emphasizes secondary data analysis. It emphasizes the significance of evaluating performance while taking into account economic and environmental factors and is backed by theoretical calculations and tables. Two case studies highlight how wind-resistant design ideas are used in practical situations. In light of evolving climatic trends, the paper's conclusion provides crucial insights into issues and potential solutions, along with suggestions for enhancing community resilience and wind-resistant architecture.

Keywords: Wind-resistant architecture, Sustainability, Innovative materials, Climate change, Structural resilience, Cutting-edge technology, Environmental impact

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1 Introduction

Wind is a strong natural force that affects structural design significantly, especially in locations that are vulnerable to strong winds, including coastal regions and tornado-prone areas. For the purpose of protecting people, maintaining property, and extending the life of infrastructure and buildings, wind-resistant construction is essential. To work on structural performance and resilience against wind pressures, this research article explores novel techniques that go past conventional design paradigms in the field of wind-resistant structures. The recurrence and intensity of wind-related cataclysmic events have increased as of late because of environmental change, making the research of wind-resistant structures more significant than any time in recent memory. These buildings must be sustainable and ecologically friendly in addition to being able to handle wind loads. Beyond engineering and architecture, this research is important because it addresses sustainability, material science, and the wider environmental effect of building from an interdisciplinary perspective. This study will look at the characteristics and benefits of various materials, as well as the difficulties in using them and how they may be used in practical situations. An extensive study will show how creative wind-resistant structure design affects life-cycle costs, sustainability, and environmental factors. The construction of wind-resistant buildings that go beyond conventional design principles becomes an essential requirement as the globe faces the difficulties posed by a changing climate. This paper lays the foundation for a deeper understanding of the ways that cutting-edge materials, sophisticated design techniques, and interdisciplinary teamwork can help create wind-resistant structures that not only withstand the forces of nature but also adhere to sustainable and environmentally conscious building principles.

2 Background of the study

One of the most powerful natural forces that has traditionally impacted both the safety of occupants

and the integrity of structures is wind. From ancient civilizations struggling with the effects of severe winds to modern society's expectations for sturdy, durable buildings, the necessity for wind-resistant constructions has been acknowledged throughout human history (Kareem, 2020). However, in the modern setting, changing elements including climate change, technology breakthroughs, and sustainability imperatives form the background of this subject.

Historical Perspectives: Throughout history, wind has caused structural damage that has prompted advancements in building methods and materials. Architectural traditions across many locations have been influenced by the ways that ancient builders used to survive powerful winds (Xu *et al.*, 2021). Wind-resistant elements became essential components of design, such as sloping roofs, bracing systems, and the use of regional materials.

Climate Change Impacts: The increasing importance of wind in structural design is a result of the intensification of weather patterns brought about by climate change. The frequency and severity of cyclones, hurricanes, typhoons, and tornadoes are rising, which emphasizes how urgent it is to build structures that can endure extremely high wind loads.

Technological Advancements: Technological advances have greatly improved engineering and design today, particularly with regard to computational tools for modeling, simulation, and wind load analysis. These developments make it possible to anticipate wind forces with greater accuracy, which helps to build creative solutions that are resistant to wind. **Sustainability and Environmental Concerns:** The basis of this study takes into account the environmental effect of construction techniques within the framework of sustainability (Zhao *et al.*, 2020). The key to solving wind-resistant structural design difficulties is to employ materials and design strategies that minimize waste, energy consumption, and greenhouse gas emissions.

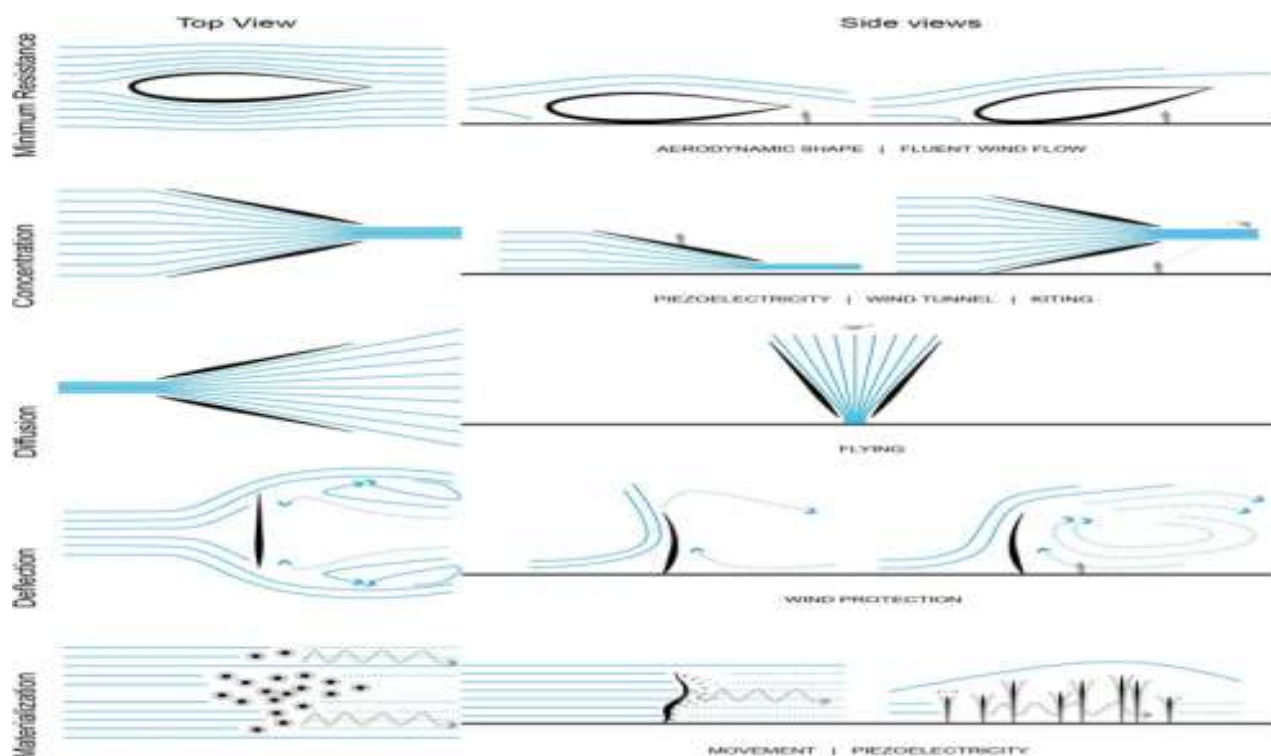


Figure 1: Architectural shape affecting the wind flow

(Source: www.researchgate.net)

3 Research Aim

With an emphasis on creating creative and sustainable solutions that may successfully lessen the impact of wind loads on infrastructure and buildings, the goal of this study is to increase understanding of wind-resistant structural design.

4 Research Question

1. How can the resilience of infrastructure and buildings against extreme wind occurrences be increased by improving wind-resistant structural design solutions beyond what is possible with traditional techniques?
2. Which cutting-edge building materials, technologies, and methods may be used to increase wind resistance in structural design?
3. How can wind-resistant structure design include sustainability to provide robust and ecologically conscious solutions?
4. What part do laws, guidelines, and multidisciplinary cooperation play in developing wind-resistant structure design that goes beyond traditional methods?

5 Research Objective

1. To evaluate and pinpoint the shortcomings and difficulties facing wind-resistant structure design as it is now.

2. Should look into cutting-edge building materials and methods that might improve a structure's ability to withstand wind while advancing sustainability.
3. To evaluate the financial and environmental effects of wind-resistant design options while taking long-term advantages and life-cycle costs into account.
4. To create useful guidelines and suggestions that legislators, engineers, and architects may use to incorporate cutting-edge wind-resistant techniques into the next building projects

6 Literature Review

6.1 Conventional Wind-Resistant Design Practices

Structural engineering has historically been built on the foundation of conventional wind-resistant design methods. These well-proven methods depend on established procedures for calculating wind loads, constructing structural elements, and including safety margins (Deng *et al.*, 2019). While traditional design has worked well in many cases, the research indicates that it may not always be sufficient to withstand the more frequent and severe high wind events brought on by climate change. Because conventional design approaches often rely on historical meteorological data, they may not adequately account for changing wind patterns and environmental conditions. Engineers have historically depended on guidelines and standards established by organizations such as the American

Society of Civil Engineers (ASCE) and the International Building Code (IBC) to ensure structural integrity under wind loads. These guidelines give valuable direction, yet they may not address specific issues connected with climate change, such as increased recurrence and intensity of wind events (Li *et al.*, 2020). Conventional design frequently focuses on individual structural parts such as beams and columns, frequently disregarding the total response of a structure to wind-incited stresses. This dual methodology can ignore any flaws in the structural system overall.

6.2 Innovative Materials and Technologies

The improvement of new materials and technologies offers a practical way toward the making of stronger, more wind-resistant constructions. These developments incorporate a wide scope of state-of-the-craftsmanship materials with enhanced strength, perseverance, and adaptability to dynamic wind pressures, including fiber-reinforced composites, shape-memory alloys, and sophisticated polymer coatings. Current structure methods, such as pre-assembled and measured systems, allow for speedier and more exact assembly, bringing the risk down to structures while they are being fabricated. The application of fiber-reinforced composites, which have exceptional strength-to-weight ratios and corrosion resistance, is one such model. These materials can be used to strengthen the resistance of various structural elements, such as building envelopes and reinforced concrete, against stresses caused by wind. Shape-memory alloys can possibly diminish structural harm by offering dynamic response mechanisms that empower structures to adjust to shifting wind conditions. Computational fluid dynamics (CFD) and wind burrow testing are two examples of cutting edge simulation and modeling technologies that are presently essential for building wind-resistant constructions (Wang *et al.*, 2021). With the use of these tools, engineers may evaluate a building's aerodynamic performance in a range of wind conditions, resulting in better-informed design choices and optimum forms and arrangements.

6.3 Sustainability in Wind-Resistant Design

In modern structural engineering, sustainability is a crucial and developing factor in wind-resistant design. With the increasing worldwide consciousness of environmental problems and climate change, it is becoming increasingly important to include sustainable methods in structural design. In addition to being able to sustain high wind loads, wind-resistant buildings also need to do so in an ecologically friendly way. A structure's lifespan carbon footprint may be minimized, energy-efficient designs can be implemented, and eco-friendly materials can be used in a variety of ways—all of which are included in

sustainable wind-resistant design. This strategy is in line with the overarching objective of reducing the environmental effect of the building and operations sector. Sustainable design elements are becoming more and more common among architects and engineers. Examples of these elements include natural ventilation systems, energy-efficient facades, and the use of recyclable or renewable construction materials. In order to capture wind energy and improve sustainability, the layout and positioning of wind turbines and other renewable energy sources on buildings are being investigated.

7 Theories and Models

7.1 Dynamic Wind Modeling:

A key concept in the construction of wind-resistant structures is dynamic wind simulation. It entails the investigation of wind behavior, particularly that which is dynamic and how it interacts with buildings and other structures. To help them understand how wind forces impact different components of a building, engineers and architects study wind flows around buildings using computational fluid dynamics (CFD) simulations (Schnuelle *et al.*, 2020). With the use of dynamic wind modeling, wind-induced forces may be accurately predicted by taking into account variables like wind direction, speed, and pressure distribution as well as turbulence. Designers may minimize wind-related difficulties and improve structural stability by optimizing a building's form, orientation, and facade through the analysis of dynamic wind behavior. Additionally, wind-resistant cladding, aerodynamic forms, and tunable mass dampers—features that reduce wind-induced vibrations and sway—all depend on dynamic wind modeling for their design.

7.2 Finite Element Analysis (FEA):

One modeling method that is frequently utilized in the design of wind-resistant structures is finite element analysis (FEA). Engineers may examine how these elements interact under different circumstances, such as wind loads, by using the numerical approach of Finite Element Analysis (FEA), which breaks down complicated structures into smaller, finite elements (Appadurai & Raj, 2021). When evaluating a structure's reaction to wind-induced forces such as vibrations, lateral loads, and uplift, finite element analysis (FEA) is crucial. FEA helps designers make well-informed decisions on material selection, cross-sectional dimensions, and reinforcing schemes by offering thorough insights into the distribution of stresses, strains, and displacements inside a building. Additionally, by using this modeling technique, possible structural failure spots may be predicted and designs that improve wind resistance can be optimized.

8 Methodology

Using a mixed-method approach, the study "Wind-Resistant Structures: Beyond Conventional Design" focuses mostly on secondary data analysis to fully answer the research goals and offer insightful information on creative wind-resistant structural design. The study begins with a thorough analysis of the body of literature, with particular attention to current case studies of wind-resistant buildings, new sustainable design strategies, and traditional wind-resistant design techniques. By analyzing the development of wind-resistant design throughout time and pointing out the shortcomings of traditional techniques, this secondary data analysis contributes to the establishment of the study's theoretical framework. Through a comprehensive analysis of pertinent scholarly publications, engineering guidelines, and business reports, the research acquires a deeper understanding of the difficulties presented by changing climatic circumstances as well as the constraints of current design methodologies. The identification of potential and limitations in the realm of wind-resistant structural design is made possible by this data-driven approach. This study's mixed-method approach, which combines theoretical understanding with empirical data where needed, enables a thorough analysis of wind-resistant structural design. The examination of secondary data offers a strong theoretical foundation, guaranteeing that the study's conclusions are firmly based on current knowledge and relevant to actual situations. This strategy addresses the problems brought on by climate change and encourages creative, sustainable solutions, all while advancing wind-resistant structure design.

9 Innovative Materials for Sustainable Structural Design

In the fields of architecture and civil engineering, sustainable structural design has become a top priority due to the pressing need to lessen the environmental effects of construction projects and improve the long-term viability of structures. This study explores the cutting-edge materials at the vanguard of environmentally friendly structural design, stressing their benefits, drawbacks, and revolutionary influence on the building sector.

9.1 Properties of Innovative Materials:

Cutting-edge materials have a variety of remarkable qualities that make them the foundation of sustainable structural design. These materials frequently have excellent strength-to-weight ratios, which guarantee that constructions may keep their structural integrity while putting on the least amount of weight possible. This is especially important for increasing building systems' efficiency and lowering

the amount of resources needed for construction. The environmentally friendly nature of sustainable materials, which are frequently derived from recycled or renewable resources, is what sets them apart. The construction industry's effective utilization of them is crucial in mitigating carbon emissions and promoting ecologically conscious building methodologies.

9.2 Advantages of Innovative Materials:

There are several benefits to using cutting-edge materials in structural design. Among these, sustainability comes first. Because of their efficient sourcing and production procedures, these materials greatly reduce the environmental effect of construction, which makes them compliant with global sustainability targets (Chen *et al.*, 2019). Cutting-edge materials improve a building's structural performance, guaranteeing longer lifespans and less upkeep. Because of the reduced resources required for transportation, its lightweight design can result in financial savings as well as ecologically responsible buildings.

9.3 Challenges in Adopting Innovative Materials:

The use of novel materials in sustainable structural design is advancing dramatically, yet there are still obstacles in the way of their widespread acceptance. Their use may be discouraged by financial limitations, such as greater startup costs. It could be necessary to modify building laws and regulations to allow for these new materials. Furthermore, a major problem is guaranteeing their compatibility with current building methods and materials. It may be necessary for construction professionals to get education and training in order to efficiently use these materials, as there is frequently resistance to change with developing technologies.

9.4 Impact on the Construction Industry:

The usage of innovative materials is causing a revolution in the building industry's approach to the design and construction of buildings. As environmental issues and laws become more urgent, using sustainable materials is becoming necessary rather than voluntary (Krauklis *et al.*, 2021). These materials enable engineers and architects to create more affordable, durable, and ecologically friendly building designs, ensuring that the construction industry can thrive in the sustainable era.

10 Performance Evaluation

Thorough performance evaluation is the cornerstone of designing wind-resistant structures. To guarantee the longevity and safety of buildings in high-wind conditions, it is crucial to evaluate the dependability and efficacy of materials and designs. This assessment includes a number of crucial steps, such

as laboratory testing, field testing, and thorough cost analysis.

10.1 Wind Load Analysis

Determining the wind loads that a building will experience is one of the main issues in constructing wind-resistant constructions. Examining the local wind environment, wind direction, and wind speed profiles are all part of wind load analysis (Tazay *et al.*, 2020). The impact of gusty winds and turbulent flow patterns must be taken into account. The wind loads that the structure must support are calculated using this data.

Wind Pressure Calculation: The wind pressure (P) on a structure's surface can be calculated using the formula:

$$P = 0.5 * \rho * V^2 * C_p * A$$

P is the wind pressure in pascals (Pa).

ρ (rho) is the air density in kg/m³.

V is the wind speed in meters per second (m/s).

C_p is the pressure coefficient, which depends on the shape and orientation of the surface.

A is the area of the surface in square meters (m²).

This formula helps to determine the force of the wind on a specific surface, which is crucial for assessing the structural load.

Wind Load on the Whole Structure: To find the total wind load on a structure, the wind pressures on all the surfaces. The formula is:

$$F = \Sigma P * A$$

F is the total wind load in newtons (N).

Σ denotes the sum over all surfaces.

P and A are as defined in the previous formula.

This gives the overall wind load the structure must resist.

Innovative Design Approaches

In today's changing environment, conventional design might not be enough to fulfill the demands of wind resistance. To improve a building's resilience and structural integrity, creative design techniques are needed. These methods might consist of:

Aerodynamic Shapes: By minimizing wind-induced pressure differences, structures may be designed with a reduced danger of uplift and lateral forces.

Smart Materials: By utilizing cutting-edge materials with characteristics that can adjust to shifting wind conditions, including shape-memory alloys, a structure's resistance to wind loads may be strengthened.

Damping Systems: By reducing structural vibrations and dissipating wind-induced energy, damping systems—such as viscous dampers or tunable mass dampers—may be included to improve stability.



Figure 2: Performance-Based Wind Engineering

(Source: www.frontiersin.org)

Modular building: By lowering the possibility of mistakes and increasing assembly precision, modular building methods may guarantee greater structural integrity.

Material Selection

It is crucial to use the appropriate materials for wind-resistant constructions. To withstand the forces imposed by strong winds, materials with great strength and durability are frequently used (Hu *et al.*, 2019). These materials need to be resistant to deterioration and corrosion over time. Better strength-to-weight ratios may be obtained by using

composite materials, such as fiber-reinforced plastics.

Stress Formula: The formula for stress (σ) in a material is:

$$\sigma = F / A$$

σ is the stress in pascals (Pa).

F is the force applied to the material in newtons (N).

A is the cross-sectional area of the material in square meters (m^2).

This formula helps to assess whether a material can withstand the forces, such as wind loads, applied to it.

Factor of Safety: To ensure that the material can safely withstand wind loads, you can use the factor of safety (FS). The factor of safety is typically determined by considering the maximum allowable stress ($\sigma_{\text{allowable}}$) for the material and the actual stress (σ) calculated using the above formula. The formula for the factor of safety is:

$$FS = \sigma_{\text{allowable}} / \sigma$$

FS is the factor of safety.

$\sigma_{\text{allowable}}$ is the maximum allowable stress.

σ is the calculated stress.

A factor of safety greater than 1 indicates that the material is safe under the given load.

10.2 Cost Analysis

Precise cost estimation is crucial when incorporating novel materials and designs into wind-resistant constructions. In addition to material prices, a thorough cost analysis should take into account labor costs, building methods, and ongoing maintenance over the life of the project (Esfeh *et al.*, 2021). Innovative solutions can typically result in significant long-term savings through enhanced durability and decreased maintenance, even with higher initial costs.

10.3 Performance Testing

The evaluation of wind-resistant constructions goes beyond abstract design principles. Confirming the structural soundness and stability of a design

requires performance testing, such as large-scale wind tunnel testing and field evaluations. In order to assess a structure's resistance to wind-induced forces, such as wind pressure, suction, and dynamic impacts, these tests replicate extremely high wind conditions.

Designing wind-resistant structures necessitates a multifaceted approach and goes beyond traditional methodologies. This method entails analyzing local wind patterns, using creative design techniques, choosing suitable materials, carrying out in-depth cost studies, and carrying out extensive performance testing. By adhering to these ideas, we can build buildings that will not only be resilient to the effects of climate change but also offer residents protection and security.

11 Environmental and Economic Considerations

When it comes to environmentally friendly structural design and the use of novel materials, careful analysis takes into account both economic and environmental factors. These factors are crucial to both the decision-making process and the materials' long-term survival.

11.1 Environmental Impact Assessment

Using cutting-edge materials frequently offers a chance to improve structural projects' environmental sustainability. Determining the ecological footprint of the materials is one of the main goals of environmental assessment. Examining the sources of raw materials, production methods, and the effects of using them over the course of the structure's lifespan are all part of this study. It also requires a review of the materials' suitability for recycling and reuse, which can help cut down on waste production and the burden on landfills (Yan *et al.*, 2021). In keeping with international efforts to slow down climate change, evaluating the possibility of reducing carbon emissions through the use of novel materials is also essential.

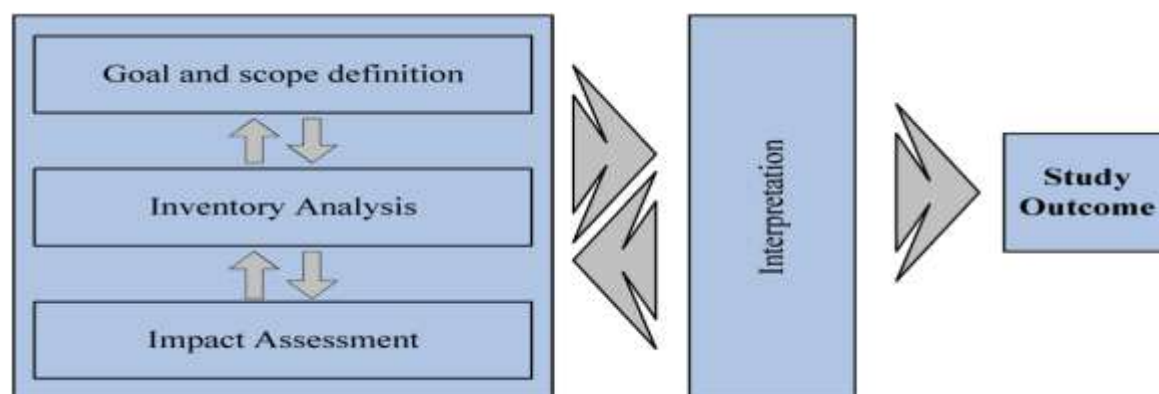


Figure 3: Life-Cycle Assessment and the Environmental Impact of Buildings

(Source: www.mdpi.com)

11.2 Economic Implications and Life-Cycle Analysis

A thorough economic study is necessary even if the initial expenses associated with incorporating new materials may be different from those associated with traditional materials. This study takes into account both the initial costs and the long-term financial effects. Examining life-cycle costs entails calculating the costs related to obtaining materials, building, maintaining, and maybe replacing or refurbishing a facility during its lifetime. It considers things like maintenance needs, longevity, and the effect on operating expenses. It also takes into account the possible financial advantages of employing novel materials. Over the course of the structure's existence, they might include lower maintenance costs, longer service life, and energy efficiency.

12 Case Study and Examples

12.1 Case Study 1: The Wind-Resistant Towers of the Burj Khalifa

Situated in Dubai, United Arab Emirates, the Burj Khalifa is a noteworthy example of a structural design that is resistant to wind. Its towering height, which makes it one of the highest structures in the world, offers particular technical difficulties. The Burj Khalifa's design and construction clearly demonstrate their creative approach to wind resistance. It has a sophisticated dampening mechanism and has a tapering design, two important aspects to reduce the impact of wind. The tower's streamlined, tapered shape improves the building's appearance while also increasing its wind resistance. The Burj Khalifa can successfully endure high wind speeds because it narrows as it climbs, reducing wind-induced forces.

12.2 Case Study 2: The Øresund Bridge - A Resilient Link

One of the best examples of wind-resistant structural design in the context of vital infrastructure is the Øresund Bridge, which connects Sweden and Denmark. The bridge, which spans the Øresund Strait, is exposed and has substantial wind concerns. In order to guarantee the bridge's safety and operation, wind resistance was given top priority throughout design and construction. The combination of structural engineering and aerodynamic concepts allows the bridge to withstand wind loads with resilience. Its sturdy yet lightweight construction reduces vibrations caused by wind and guarantees stability in strong gusts. The Resund Bridge is a prime example of how thoughtful consideration of wind-resistant design can result in the development of crucial infrastructure that continues to function even in adverse weather conditions.

13 Conclusion and Recommendations

The study emphasizes how important wind-resistant design is to guarantee the safety and structural integrity of important infrastructure and structures. Even while they work well in many situations, conventional design techniques might not be sufficient when it comes to changing wind patterns and harsh weather brought on by climate change. The literature emphasizes that in order to improve wind resistance, new materials, cutting-edge techniques, and environmentally friendly methods are required. Incorporating sustainability concepts into wind-resistant architecture promotes a more resilient built environment and is consistent with larger environmental objectives. The research provides a succinct list of suggestions to improve wind-resistant architecture. Wind resistance may be greatly increased by using innovative techniques like aeroelastic modeling and sophisticated dampening devices. To develop practical, long-lasting solutions, interdisciplinary cooperation between environmental scientists, meteorologists, and structural engineers is essential. It is crucial to prioritize sustainability by using green building techniques and renewable energy. Regular performance evaluations supported by defined standards are essential to guaranteeing wind-resistant constructions' continued efficacy and security. In order to enforce wind-resistant design requirements and increase community resilience, governments and legislators should update building rules and invest in wind-resistant infrastructure.

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