# Exploring the Impact of Dynamic Winds on Bridge Safety

Luyuan Pei*

College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai,200000, China

*Corresponding author: 202210414057@stu.shmtu.edu.cn

**Abstract.** As a kind of infrastructure, bridges are of great significance in transportation connection, promoting regional economic development and enhancing cultural and economic development. However, bridges face safety issues such as structural aging and corrosion, the effects of natural disasters, and traffic overloading and vibration. Among them, the Tacoma Bridge in the U.S. unexpectedly collapsed in a wind environment far below the design strength. This has led experts and scholars to expand the design of bridges against the wind from the static wind level to the dynamic wind level. This paper explores the impact of dynamic wind on bridge safety in this research context. Four types of bridge vibration caused by dynamic wind and their damaging effects and hazards will be introduced from various dimensions. It will summarize the methods of wind tunnel testing and numerical simulation to assess the risk of wind exposure of bridges, and propose some relevant wind-resistant measures, such as adopting reasonable design means, strengthening wind load calculation, installing effective vibration-damping devices, and regular maintenance. The purpose of this paper is to provide help for the research on wind resistance of bridges and the construction of bridge projects.

**Keywords:** Bridge wind resistance; wind tunnel test; numerical simulation.

## 1. Introduction

Bridge construction is of great significance in promoting economic development and enhancing cultural exchanges. However, with the increase in the number of bridges, the safety problems of bridges have become more and more prominent, especially the impact of wind on bridges. The most famous incident is the Tacoma Strait Bridge in the United States. According to a study, the bridge opened to traffic on July 1, 1940, but during the opening period, there were instances of the bridge vibrating up and down in the wind. Eventually, the bridge was destroyed and collapsed on November 7th. Shockingly, according to studies, the wind speed experienced at the time of the bridge's collapse was only half of the design limit, and the static horizontal wind pressure was about one-sixth of the design standard [1-2]. It was this accident that led to the expansion of the study of wind resistance of bridges from the initial static effects to dynamic effects [3].

The problem of bridge accidents caused by wind has drawn the attention of many bridge workers to the wind-resistant design of bridges, e.g., the Kanmon strait bridge in Japan often restricts traffic on the bridge due to typhoons, the connecting bridge between Bahrain and Saudi Arabia across the Persian Gulf, where strong stormy weather often leads to restriction on the traffic, and the Hull River bridge, a famous large suspension bridge in the UK, which has been the scene of a traffic accident under strong wind conditions. For example, Dong et al. did a study on the suppression of vortex-excited vibration by installing wind flow hoods on rectangular steel box girders of railroad cable-stayed bridges [4]. Liu et al. did a study on the correlation between wind resistance and failure modes of semi-submersible offshore platforms during jack-up closure [5]. D. Kesavan et al. conducted a comfort assessment of wind-induced vibration of slender structures by means of on-site monitoring and numerical analysis [6].

This paper will investigate the impact of dynamic winds on bridge safety, and summarize the complex process of wind-induced vibration of these bridges and research methods. At the same time, based on the research results, the bridge wind protection measures are proposed.

## 2. Dynamic effects of wind on bridges

For large-span bridges, due to the increase in structural flexibility and the decrease of stiffness, their dynamic response under the action of wind becomes more significant, especially under the action of pulsating wind, which is more complicated. The dynamic effect of wind on the bridge structure is usually manifested as the wind-induced vibration of the bridge, which is a complex fluid-structure coupling process, i.e., the vibration behavior triggered by the interaction between the wind flow and the structure. In the process of wind-induced vibration, the coupling between the bridge structure and the wind flow leads to many types of vibration modes. These vibration modes can be categorized into four main forms: vortex vibration, chattering vibration, shaking vibration and chirping vibration [7].

### 2.1. Flutter

Bridge flutter vibration is a self-excited vibration phenomenon that occurs when a bridge is subjected to airflow under the action of a mean wind. This vibration occurs when the power absorbed by the bridge structure exceeds the energy that can be dissipated by the inherent damping of the bridge. With the gradual increase of wind speed, the main girder continuously absorbs energy, and the amplitude of vibration will increase, and eventually reach a critical point, when the wind speed exceeds the critical value, the accumulation of vibration energy will make the structure unable to withstand, resulting in the destruction of the bridge [8].

Bridge chatter does not only occur in specific types of main girder sections, it can occur in almost any shape of the main girder section, but different main girder section shapes will correspond to different critical wind speeds. In other words, although the occurrence of flutter is universal, the critical wind speed varies from one bridge structure to another, and therefore their sensitivity and tolerance to wind forces are also different.

### 2.2. Vibration

Bridge members oscillate more violently under the action of wind, a vibration phenomenon known as chirp vibration, which is characterized by a larger vibration amplitude and a lower frequency.

Bridge vibration is mainly manifested in two different forms: one is cross-flow vibration and the other is wake-flow vibration. Cross-flow vibration refers to the bridge components in the wind under the action of the wind along the lateral direction of the wind to occur a large swing, this vibration usually occurs in the case of low wind speeds, and is common in the lateral structure of the bridge is more weak. While the tail flow vibration occurs in the wind flow through the bridge members produced by the tail flow region, the bridge members in the tail flow under the influence of self-excited low-frequency oscillation, this vibration usually occurs in the wind speed is higher, the airflow is not stable in the environment, and the tail flow vibration is often easier than the cross-flow vibration to cause more substantial vibration.

The common feature of these two chi-square vibration phenomena is that they are caused by the complex interaction between wind flow and bridge structure, and usually manifest as vibration with large amplitude and low frequency, which may bring serious impacts on the safety and stability of bridges.

### 2.3. Vortex-excited vibration

Vortex-excited vibration is a common wind-induced vibration phenomenon in large-span bridge structures, which usually occurs under low wind speed conditions. From the point of view of hydrodynamics, vortex-excited vibration originates from the fact that a non-streamlined object will alternately generate vortices off the surface of the structure on both sides of the air flowing through the object at a constant wind speed.

For example, on June 18, 2024, a typical vortex-excited vibration phenomenon occurred at the Zhoushan Cross-sea Bridge in Zhejiang Province. As a result of eddy-current vibration, the vibration amplitude of the bridge exceeded the design safety limit, which led to the temporary closure of the bridge in both directions to ensure the safety of passing vehicles and pedestrians. Vortex-excited vibration is not only one of the technical challenges in the engineering field but also closely related to the aerodynamic design of bridges.

### 2.4. Chatter(Bridge shaking vibration)

Bridge shaking vibration refers to the random vibration phenomenon triggered by the influence of the pulsating wind spectrum in the gust belt of the space bridge structural system under the action of pulsating wind. This type of vibration is mainly caused by the instability of wind speed and the low-frequency components in the wind spectrum, and it is manifested as random oscillations of bridge members at different frequencies and amplitudes. Unlike other types of bridge vibration, shaking vibration is usually a forced vibration, i.e., it is subjected to the continuous action of external wind forces, and the amplitude is determined by the combination of wind speed and structural properties [9]. Although this type of vibration does not generally lead to aerodynamic instability of bridges, it induces a series of structural responses that may have an impact on the durability of bridges, especially under long-term effects.

Bridge shaking vibration is characterized by limited vibration amplitude, and generally does not reach destructive large-scale, belongs to the limited amplitude vibration. Due to the low wind speed but large vibration efficiency of shaking vibration, the long-term effect may result in localized fatigue damage to joints, bearings, or other critical construction details of bridge members. These localized fatigue damages may affect the structural integrity of the bridge or even, in extreme cases, lead to structural failure or the need for extensive repairs.

In addition, the chatter response of bridges not only affects the structure itself but may also jeopardize the safety of vehicles traveling on the bridge. Excessive vibration response can lead to irregular vibrations in the bridge deck, which may affect moving vehicles, especially at high speeds, where stability and maneuverability may be interfered with, increasing the risk of traffic accidents. In areas where wind conditions are poor or wind speeds change frequently, the potential threat of vibration shaking to the safety of bridge traffic cannot be ignored.

## 3. Methods for studying the effects of dynamic winds

For large-span bridges, the wind-induced dynamic response is one of the major safety issues for bridges, and therefore, predicting its behavior is crucial for safe design [10]. Two common methods for studying the effects of dynamic wind will be described below.

### 3.1. Wind tunnel testing

Among the many wind-induced vibration phenomena on large-span bridges, vortex-excited vibration (VIV) is considered to be a common and serious aerodynamic phenomenon.VIV generally manifests itself as small amplitude vibrations and rarely causes catastrophic bridge collapses, but at low wind speeds, due to the high frequency of occurrence of VIV, it can significantly affect driving comfort and may lead to long-term fatigue damage of the structure.VIV is closely related to a number of factors such as structural characteristics, wind speed, geometry, and aerodynamic features, which make the prediction of VIV more complicated. Occurrence is closely related to a number of factors, such as structural characteristics of the bridge, wind speed, geometry, and aerodynamic features, which make the prediction of VIV more complex. In the past decades, typical VIV phenomena have occurred in many actual bridges, such as the Kessock Bridge in Scotland, the Great Belt East Bridge in Denmark, and the West Back Gate Bridge in China [11-13]. Therefore, a more accurate probabilistic prediction method is needed to more effectively assess and manage the risk of large-span bridges and their life cycle [14].

Wind tunnel testing is a direct and effective method to observe the stress and deformation performance of the beam structure by simulating the actual wind speed and direction conditions in the wind tunnel, which can obtain the response of the structure under different wind loads.

The RWDI team, in collaboration with the design team, used a small rigid transport truck model for wind tunnel tests during the design of the Sazlidere cable-stayed bridge, aiming at determining the aerodynamic characteristics of the vehicle and its moment coefficient as a function of wind direction. Subsequently, these test data were combined with a numerical model of the rollover stability of high-side vehicles to analyze the critical wind speeds of the trucks traveling over the central span of the bridge under the influence of different wind speeds and wind directions [15].

### 3.2. Numerical simulation techniques

Numerical simulation techniques are utilized to study the dynamic response of beams in strong winds and the action of wind forces. This method is able to simulate the effects of actual wind fields on building girders and predict the performance of girders under different wind speeds, wind directions, and wind loads. For example, Bochao Cao et al. calculated the dynamic response of a large-span bridge in a typical unsteady wind environment using a time-domain approach, in which winds from a microburst approaching the bridge were simulated. Three different sizes of microbursts relative to the span of the bridge were considered and the wind generated from the simulated microburst events was used to generate the wind loads applied to the bridge and to calculate its response for comparison with a straight-line wind event with equivalent wind speed [16].

In order to study the flutter stability of main girder sections at high angles of attack, Zhiwen Liu et al. from Hunan University employed a numerical simulation method to analyze the flutter characteristics of thin plate and streamlined box girder sections at different angles of attack (0°, ±3°, ±5°, ±8°). In this process, a two-dimensional fluid-structure coupling (FSI) method was developed by combining ANSYS FLUENT user-defined functions (UDF) and dynamic meshing techniques and applied in conjunction with the Newmark-β method. Subsequently, the simulation results were compared with the wind tunnel test data. The results show that the critical flutter wind speeds of thin plate and streamlined box girder sections obtained from numerical simulation coincide with the wind tunnel experimental data, which verifies the validity and accuracy of this 2D FSI analysis method in the flutter stability study of bridge deck sections [17].

In comparison, wind tunnel tests can more realistically simulate the force of the bridge in the wind environment and provide more direct and reliable experimental data. However, wind tunnel tests can only be carried out on a certain scale model, which makes the conditions of wind tunnel tests limited, and at the same time, it needs to invest a large amount of facilities and equipment costs. Numerical simulation, on the other hand, is more flexible and less costly with a wider range of applications, but is highly dependent on the assumptions and initial conditions of the model. In practice, researchers can combine the two methods and use the numerical simulation results to verify and calibrate the wind tunnel test results, so as to obtain more accurate experimental results for bridge safety engineering.

## 4. Wind protection measures for bridges

Wind-resistant measures for bridges should be considered comprehensively from various aspects such as design, structural optimization, mechanical analysis and actual monitoring. By adopting reasonable design means, strengthening wind load calculation, installing effective vibration-damping devices and taking regular maintenance measures, the wind resistance of bridges can be significantly improved to ensure safe operation under strong winds or adverse weather conditions [18].

Use rational design tools. Optimize the cross-sectional shape of the bridge to make it more streamlined and reduce wind resistance. For example, design a streamlined windshield or profile on the upper part of the bridge so that the wind speed does not easily form a large-scale vortex on the surface of the bridge and reduce the wind pressure. Reasonable design of all parts of the bridge structure to reduce the impact of wind pressure, especially in the bridge tower, piers and other parts of the bridge, to minimize the sharp edges, to avoid the wind producing local turbulence. Design sufficient stiffness and strength for the bridge to ensure that the structure can resist the lateral and longitudinal forces of the wind and avoid large horizontal displacements or swaying of the bridge. During the design phase, use wind load analysis to calculate the impact of the bridge subjected to wind forces. Through wind tunnel experiments or numerical simulations, the dynamic response of the bridge is investigated for different wind speeds and directions. Understand the natural frequency of the bridge, wind-induced vibration patterns, and adjust the design according to the results. Two experts from the United States designed and evaluated the structural control on a more practical basis based on a comprehensive consideration of the effects of vehicles, wind speed, bridge structure and control system. The effect of tuned mass dampers on the performance of the bridge-vehicle system in a windy environment was investigated by parametric analysis of different control schemes. The possibility of developing temporary control measures is also developed for the prevention of rollover accidents of unloaded or partially loaded high-sided trucks under high wind conditions [19].

Installation of effective vibration damping devices. Add wind braces, wind ropes and other structures to the upper part of the bridge or tower columns for stabilizing and dispersing the wind force and reducing the deformation of the structure. Increase the stiffness and wind resistance of bridge bearings to ensure that the bridge remains stable in high wind conditions. Common practices include increasing the number of bearings or using high-strength materials.

Take regular maintenance measures. The effect of wind loads on the bridge structure may gradually increase as the bridge is used for a longer period of time. Therefore, regular bridge inspections and wind speed monitoring are essential. Especially after extreme weather events such as storms and typhoons, check the bridge structure for deformation, fatigue damage and other problems. In the event of minor damage to the bridge, timely repair and reinforcement are carried out to ensure the safety and stability of the bridge.

## 5. Conclusion

This paper synthesizes and analyzes the research on wind resistance of bridges affected by dynamic wind in recent years, and discusses the accident cases and causes of bridge damage caused by dynamic wind. This paper focuses on the causes and hazards of four types of wind-induced vibration. Flutter vibration and chirp vibration are relatively more dangerous, which may lead to serious damage or even collapse of the bridge. Vortex vibration usually leads to fatigue damage of bridges but is unlikely to cause immediate catastrophic consequences. Shivering vibrations are less hazardous, but may also have some structural impact on the bridge if they continue to occur. For bridge design and maintenance, preventing the occurrence of these vibration phenomena is key to ensuring the safety and long-term use of bridges.

In addition, wind tunnel testing and numerical simulation techniques, among others, have demonstrated significant advantages in wind protection design and detection and predictive prevention.

Despite the significant progress made by experts and scholars, there are still problems that need to be solved in terms of the design and wind resistance of bridges, and the design and protection programs have not yet been perfected. Future research can focus on the design, structural optimization, mechanical analysis and actual monitoring and other aspects of the comprehensive consideration, to take reasonable design means, the installation of effective vibration-damping equipment and regular maintenance to eliminate the occurrence of vibration and vibration to reduce the harm of vortex vibration and vibration, and to promote the comprehensive development of the field of wind resistance of bridges.

## References

[1] Wei W J, Wang N, Zhao Z S. Engineering failure and engineering science: An example of the Tacoma Strait Bridge accident. Engineering Research-Interdisciplinary Perspective on Engineering, 2020, 12(5): 488-498.

[2] Liu J L. Destruction of Tacoma bridge by wind vibration. Mechanics and Practice, 2007, (1): 13.

[3] Qian K R. Research on the evolution mechanism of nonlinear self-excited force and chattering pattern of three-tower suspension bridge [D]. Southeast University, 2020. DOI: 10.27014/d.cnki.gdnau.2020.000357.

[4] Dong J, Huang L, Liao H, Wang Q. Investigation on suppressing vortex-induced vibrations of the rectangular steel box girder for railway cable-stayed bridges by installing wind fairings. Journal of Wind Engineering and Industrial Aerodynamics, 2021, 219: 104821.

[5] Liu H J, Li H N, Fu X. Wind-resistant performance and failure modes for a semi-submersible offshore platform during jacking closure. Ocean Engineering, 2021, 241: 110102.

[6] Periyasamy D K, Shimpi V, Sivasubramanian M V. Comfort assessment of wind-induced vibrations for slender structures by field monitoring and numerical analysis. Journal of Safety Science and Resilience, 2024, 5(4): 383-399.

[7] Wu B F, Guo M, Qiao X Y. Research on wind resistance measures for large-span bridges. Construction Technology Development, 2020, 47(7): 127-128.

[8] Li P Z. Analysis and research on chattering vibration of large-span bridges [D]. Northeast Forestry University, 2006.

[9] Yang Y Y. Study on wind-induced vibration fatigue of large-span bridges [D]. Southwest Jiaotong University, 2008.

[10] Helgedagsrud T A, Bazilevs Y, Mathisen K M, Øiseth O A. ALE-VMS methods for wind-resistant design of long-span bridges. Journal of Wind Engineering and Industrial Aerodynamics, 2019, 191: 143-153.

[11] Owen J S, Vann A M, Davies J P, Blakeborough A. The prototype testing of Kessock Bridge: Response to vortex shedding. Journal of Wind Engineering and Industrial Aerodynamics, 1996, 60: 91-108.

[12] Frandsen J B. Simultaneous pressures and accelerations measured full-scale on the Great Belt East suspension bridge. Journal of Wind Engineering and Industrial Aerodynamics, 2001, 89(1): 95-129.

[13] Li H, Laima S, Zhang Q, Li N, Liu Z. Field monitoring and validation of vortex-induced vibrations of a long-span suspension bridge. Journal of Wind Engineering and Industrial Aerodynamics, 2014, 124: 54-67.

[14] Ge B, Ma R, Li F, Hu X, Chen A. Probabilistic vortex-induced vibration occurrence prediction of the twin-box girder for long-span cable-stayed bridges based on wind tunnel tests. Engineering Structures, 2022, 262: 114325.

[15] Ozkan E, Mattiello E, Dorigatti F, Taylor Z, Marble E, Istvan M, Yildizhan Y, Kantar O. Sazlidere Bridge Wind Tunnel Testing Assisted Design. IABSE Symposium Istanbul 2023: Long Span Bridges - Proceeding Book, 2023, 936–943.

[16] Cao B, Sarkar P P. Numerical simulation of dynamic response of a long-span bridge to assess its vulnerability to non-synoptic wind. Engineering Structures, 2015, 84: 67-75.

[17] Liu Z, Chen Y, Chen Z. Numerical simulation of critical flutter wind speed of typical bridge deck sections at high attack angles. Hunan Daxue Xuebao/Journal of Hunan University Natural Sciences, 2021, 48(1): 82-91.

[18] Liu X, Zeng J, Wang F. Comparative analysis of temporary wind-resistant measures for long-span cable-stayed bridge at construction stage. Journal of Railway Engineering Society, 2024, 41(1): 39-44, 52.

[19] Chen S R, Wu J. Performance enhancement of bridge infrastructure systems: Long-span bridge, moving trucks and wind with tuned mass dampers. Engineering Structures, 2008, 30(11): 3316-3324.