IN-VENTO 2026
International Conference of the Italian Association for Wind Engineering
Bari, September 13th – 16th, 2026

Experimental Investigation of Bridge Deck Aerodynamics under Time-Varying Wind Conditions

Maria Antonietta Pace[a], Jinxin Cao[b], Tommaso Argentini[c], Daniele Rocchi[d]

[a]*Politecnico di Milano, Milan, Italy, mariaantonietta.pace@polimi.it*
[b]*Tongji University, Shanghai, China, jinxin@tongji.edu.cn*
[c]*Politecnico di Milano, Milan, Italy, tommaso.argentini@polimi.it*
[d]*Politecnico di Milano, Milan, Italy, daniele.rocchi@polimi.it*

SUMMARY:
Long-span bridges are exposed to non-synoptic wind events, such as thunderstorms and downbursts, characterized by rapid variations in wind speed and direction. Conventional aerodynamic characterization is generally based on steady wind conditions and may therefore be inadequate to describe bridge response under transient flows. This study presents an experimental investigation on sectional models derived from the Hardanger Bridge and the Julsundet Bridge under controlled non-stationary wind conditions. The testing campaign includes low-frequency variations, bi-harmonic inflow conditions and turbulent transient wind fields, with the aim of characterizing the aerodynamic behavior of the deck sections. The results are intended to quantify the sensitivity of deck aerodynamics to wind non-stationarity and to provide a consistent experimental basis for validating numerical models for transient buffeting response.

Keywords: bridge aerodynamics, non-synoptic winds, wind tunnel testing, long-span bridges

1. INTRODUCTION

Long-span bridges are required to perform safely under complex environmental loading, among which extreme wind events remain one of the most critical challenges [Fenerci and Øiseth, 2018]. Among these, thunderstorms, downbursts, and other non-synoptic wind phenomena are attracting increasing attention because their transient nature may significantly affect bridge safety and performance [Calamelli et al., 2024, Di Lenardo et al., 2026].
Conventional bridge aerodynamic assessment is largely based on steady-state wind conditions, from which static aerodynamic coefficients and flutter derivatives are typically derived through stationary wind tunnel testing [Diana et al., 2015]. While this approach supports current design practice effectively, it may not adequately represent the response of bridge decks subjected to rapidly varying, non-stationary wind fields [Kareem et al., 2019].
Non-synoptic winds are characterized by strong temporal fluctuations in wind speed and angle of attack, which may alter both aerodynamic loads and aeroelastic behavior. Although several studies have highlighted these effects, systematic experimental validation remains limited due to the difficulty of reproducing transient wind conditions in a controlled laboratory environment. Recent developments in wind tunnel technologies offer new possibilities for generating non-stationary inflow conditions and for investigating bridge deck response under transient winds [Cao et al., 2002, Cao and Cao, 2017]. On this basis, the present study aims to experimentally characterize bridge deck aerodynamics under controlled non-synoptic wind conditions and to support the validation of numerical models for transient buffeting and aeroelastic response.

2. METHODS

2.1. Testing Strategy

The experimental campaign is aimed at characterizing the aerodynamic behavior of bridge deck sections under controlled non-stationary wind conditions, with a focus on static force coefficients, flutter derivatives and aerodynamic admittance functions. Two complementary configurations are considered: a suspended-model setup and a forced-motion setup with prescribed vertical and torsional oscillations. The tests are carried out on two bridge deck sections representative of the Hardanger Bridge and the Julsundet Bridge. Throughout the experimental campaign, the bridge deck models are maintained at a horizontal angle of attack equal to $0deg$. The adopted inflow conditions are introduced with increasing complexity, from low-frequency variations of the mean wind speed to mixed-frequency and turbulent non-stationary wind fields.

2.2. Wind Tunnel Facility

The experimental campaign is conceived with reference to the actively controlled multiple-fan wind tunnel (TJ-5) at Tongji University, specifically developed for the generation of non-stationary and transient wind fields [Cao and Cao, 2017].

The facility is an open-circuit wind tunnel including a multiple-fan section, a settling chamber with damping meshes, and a modular test section. The working section is 1.5 m wide, 1.8 m high and 10 m long, with adjustable effective length depending on the testing requirements. The driving system consists of 120 independently controlled fans arranged in a 10×12 grid, allowing the reproduction of prescribed wind velocity histories.

2.3. Reference bridge sections

Two bridge deck sections representative of the Hardanger Bridge and the Julsundet Bridge are selected as reference cases. For both bridges, rigid sectional models at reduced scale are adopted, with geometric and inertial properties defined consistently with the aerodynamic testing programme (Table 1).

Table 1. Main properties of the reference bridge sections.

	Hardanger Bridge	Julsundet Bridge
Bridge length and Deck chord [m]	1625 - 27.5	1308 - 18.3
Model scale	1:70	1:50
1st mode [Hz]	0.0508 (lateral)	0.0422 (lateral)
2nd mode [Hz]	0.1426 (vertical)	0.1183 (vertical)
3rd mode [Hz]	0.3711 (torsional)	0.2803 (torsional)

2.4. Non-stationary wind flow

The horizontal inflow conditions are defined with progressively increasing complexity in order to investigate the aerodynamic response of the bridge deck sections under non-stationary wind excitation. Steady-wind cases are first considered as benchmark conditions for comparison with the subsequent time-varying inflow cases.

The non-stationary inputs are then organized into single-frequency and dual-frequency cases. In the single-frequency tests, low-frequency and high-frequency excitations are considered separately in order to isolate the effects associated with different temporal scales of the inflow. In the dual-frequency cases, the two components are combined to reproduce more complex wind histories. The imposed inflow signals are validated by comparing the reproduced velocity histories with the target ones, confirming the accuracy of the generated wind input (Fig. 1). The main characteristics of the adopted wind conditions are summarized in Table 2. All inflow conditions are generated with a unidirectional wind field.

Table 2. Summary of the wind input conditions adopted in the experimental campaign.

Case	Description	Mean speed	Amplitude	Frequency
Steady benchmark	Constant wind velocity	6–12 m/s	–	constant
Single-frequency LF	Low-frequency oscillation	8.5 m/s	3.5 m/s	1/18 Hz, 1/72 Hz
Single-frequency HF	High-frequency oscillation	8 m/s	2 m/s	0.3, 1, 2, 3 Hz
Dual-frequency	Superposition of LF and HF components	8.5 m/s	combined	2 LF × 4 HF cases

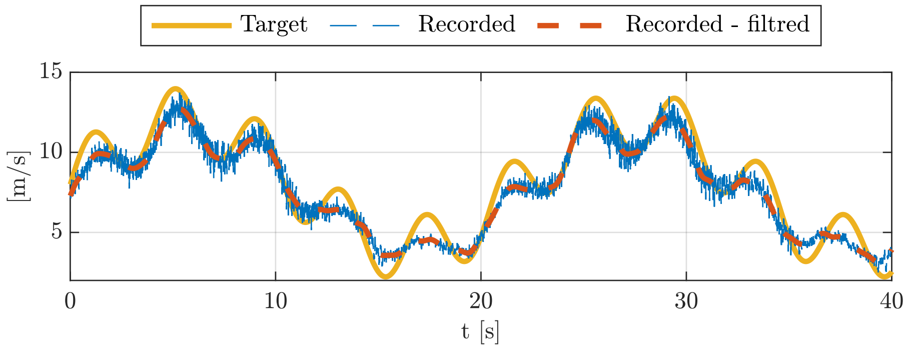

Figure 1. Wind Input Comparison - Dual Frequency, $f_{LF} = 1/18$ Hz , $f_{HF} = 0.3$Hz .

3. PRELIMINARY RESULTS

3.1. Forced-motion configuration

For the forced-motion configuration, preliminary results are presented in terms of the aerodynamic forces and moment measured under prescribed wind inputs (Tab. 2).
Under steady inflow, the measured loads provide the baseline reference. Under non-stationary inflow, the force histories exhibit time-varying amplitudes and phase changes, with the dual-frequency cases showing the most evident unsteady features. Representative force histories for wind input reported in Fig. 1 are reported in Fig. 2.

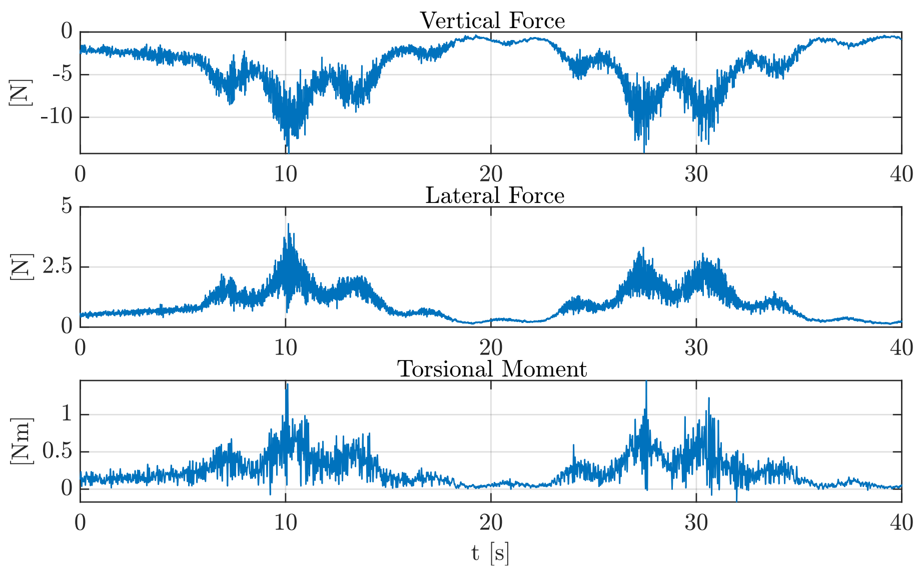

Figure 2. Representative time histories of measured aerodynamic forces and moment in the forced-motion configuration of the Julsundet Bridge under non-stationary wind input shown in Fig. 1.

3.2. Suspended-model configuration

For the suspended-model configuration, the response is described through the measured time histories of vertical displacement and torsional rotation under the wind input conditions (Tab. 2).

Under steady inflow, the response is nearly stationary and provides the reference condition. Under non-stationary inflow, both vertical displacement and torsional rotation show a clear transient modulation, which becomes more pronounced in the dual-frequency cases. Representative response histories for wind input reported in Fig. 1 are shown in Fig. 3.

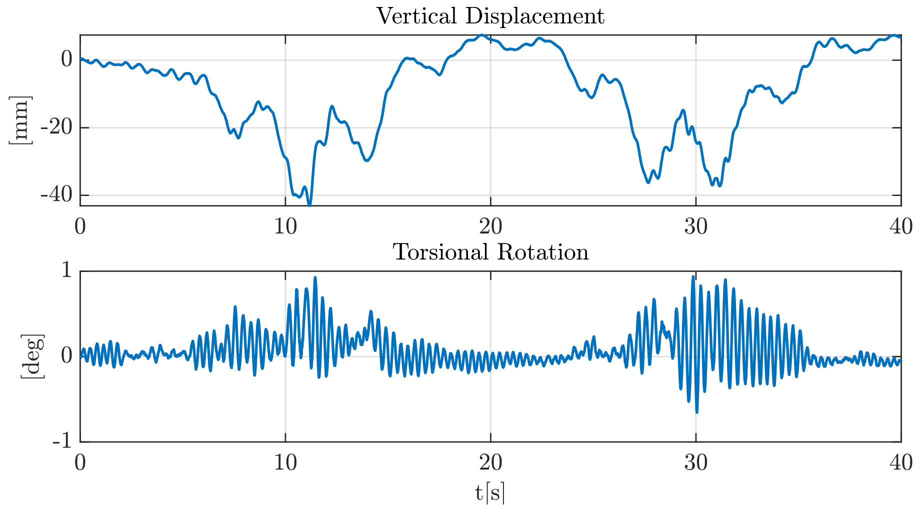

Figure 3. Representative time histories of vertical displacement and torsional rotation measured in the suspended model of the Julsundet Bridge under non-stationary wind input shown in Fig. 1.

4. CONCLUSIONS

The preliminary results confirm the feasibility of the proposed experimental approach for investigating bridge deck response under controlled non-stationary wind conditions. The measured displacement, rotation, force, and moment histories provide a first basis for the aerodynamic characterization of bridge deck sections in unsteady wind flow. These data will be used to support the identification of aerodynamic parameters and the validation of numerical models for transient bridge response.

ACKNOWLEDGEMENTS

Access to the wind tunnel facility at Tongji University is gratefully acknowledged.

REFERENCES

Calamelli, F., R. Rossi, T. Argentini, D. Rocchi, and G. Diana (2024). A nonlinear approach for the simulation of the buffeting response of long span bridges under non-synoptic storm winds. Journal of Wind Engineering and Industrial Aerodynamics 247, 105681.

Cao, S. and J. Cao (Dec. 2017). Toward Better Understanding of Turbulence Effects on Bridge Aerodynamics. Frontiers in Built Environment 3.

Cao, S., A. Nishi, H. Kikugawa, and Y. Matsuda (Dec. 2002). Reproduction of wind velocity history in a multiple fan wind tunnel. Journal of Wind Engineering and Industrial Aerodynamics 90, 1719–1729.

Di Lenardo, F., M. A. Pace, T. Argentini, and D. Rocchi (Sept. 2026). Aeroelastic response of long-span bridges to downburst wind fields: a nonlinear time-domain investigation. Proceedings of EURODYN 2026.

Diana, G., D. Rocchi, and T. Argentini (Sept. 2015). Buffeting response of long span bridges: numerical-experimental validation of fluid-structure interaction models. IABSE Symposium Report 105, 1–8.

Fenerci, A. and O. Øiseth (2018). Strong wind characteristics and dynamic response of a long-span suspension bridge during a storm. Journal of Wind Engineering and Industrial Aerodynamics 172, 116–138.

Kareem, A., L. Hu, Y. Guo, and D. K. Kwon (Oct. 2019). Generalized Wind Loading Chain: Time-Frequency Modeling Framework for Nonstationary Wind Effects on Structures. Journal of Structural Engineering 145, 04019092.