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Experimental and numerical analyses of the effects of complex topography and tree canopy on the wind responses of the CNW cycling-pedestrian bridge

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SUMMARY:
A comprehensive aerodynamic assessment was performed by RWDI to assist the design of the proposed CNW cycling-pedestrian suspension bridge in Luxembourg. This is signature suspension bridge that crosses a narrow valley at an elevation of ~50 m with spans of 135 m and 65 m supported by a single 72 m high pylon. Featuring a slender and lightweight design and subject to unconventional wind conditions due to the complex topography and significant vegetation of its location, the bridge warranted detailed aerodynamic investigations. Wind climate analyses were conducted, together with wind tunnel tests on a topographic model, a deck sectional model and a pylon rigid model. A novel bespoke approach was developed to model at scale and measure in the wind tunnel the flow conditions determined at the bridge site by the complex topography in the presence of a deciduous tree canopy within the valley. Significant differences were found in the mean wind speed, mean angle of wind incidence and turbulence levels along the bridge and between summer and winter seasons due to the presence/absence of the foliage on the trees. The sensitivity of the bridge aerodynamic responses to such complex wind conditions was assessed through numerical stability and buffeting simulations.

Keywords: Wind tunnel testing, Deciduous trees scale modelling, Buffeting analysis in non-uniform flow field

1. INTRODUCTION

The proposed CNW cycling-pedestrian bridge is a 200 m long suspension bridge between the Cents and the Weimershof-Neudorf districts in Luxembourg. The bridge will cross the narrow Neudorf valley at an elevation of ~50 m, with a main span of 135 m and a short span of 65 m supported by a central pylon 72 m tall. It will be a steel structure with a concrete plate-like deck, approximately 6 m wide and 0.3 m thick, equipped with pre-tensioned tendons (Fig. 1).

As a slender, lightweight and highly flexible structure, the CNW bridge warranted aerodynamic stability assessment and evaluation of the wind-induced dynamic responses for strength and serviceability verification. To support the structural design RWDI carried out wind climate analysis and topographical model wind tunnel testing, followed by sectional model testing of the deck, rigid model testing of the pylon and numerical buffeting simulations of the full bridge for wind load derivation. In addition, full-bridge aeroelastic model testing is currently underway. During the project a novel bespoke approach was developed to obtain representative predictions of the complex wind conditions determined on-site by the terrain exposure, the complex valley topography, and tree canopy within the valley (including the seasonal effects associated with presence/absence of the foliage on the deciduous trees). In addition, the sensitivity of the bridge responses to such complex wind conditions was assessed through aerodynamic stability and buffeting numerical analyses.

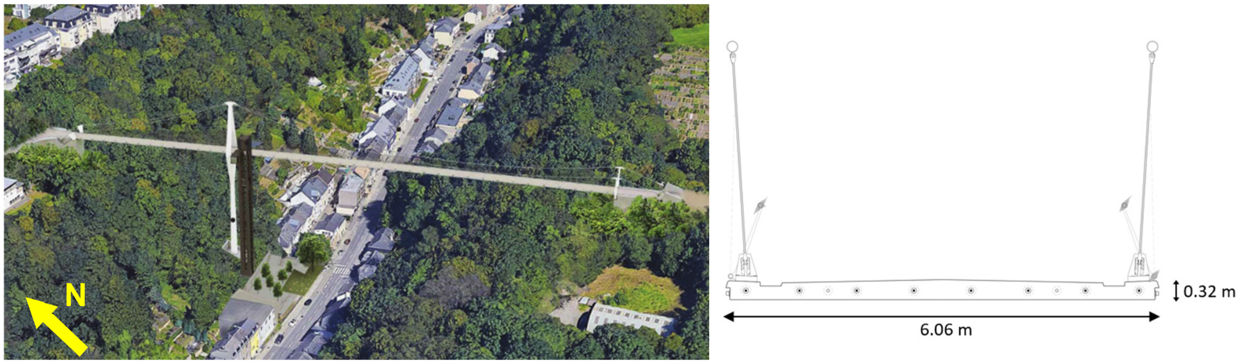


Figure 1. Rendering on the CNW bridge within the Neudorf valley (left) and bridge deck cross-section (right) (www.vdl.lu).

2. TOPOGRAPHIC MODEL STUDY

A 1:400 scale topographic model reproducing a full-scale radius of ~1300 m from the bridge site was tested in RWDI's 7.3 m x 2.4 m Irwin atmospheric boundary layer wind tunnel. As both sides of the valley are covered by deciduous trees up to 20 m tall, two configurations of the topographic model were tested to assess seasonal variations of the wind conditions due to the presence/absence of the foliage on the trees.

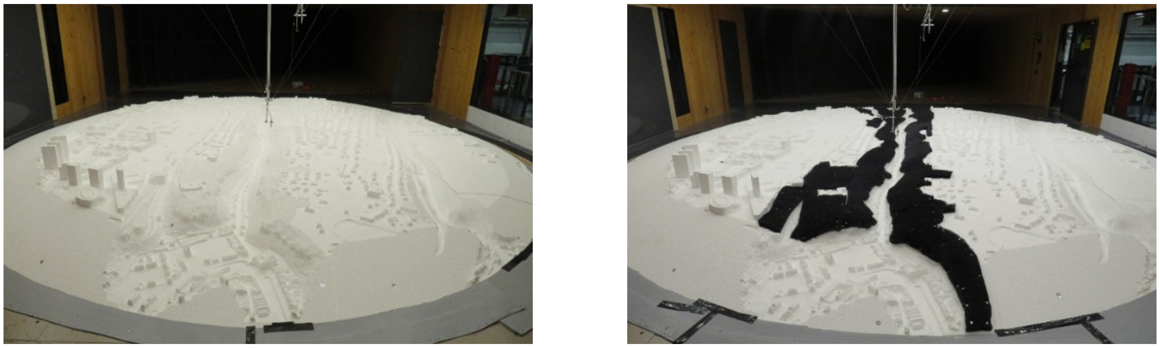
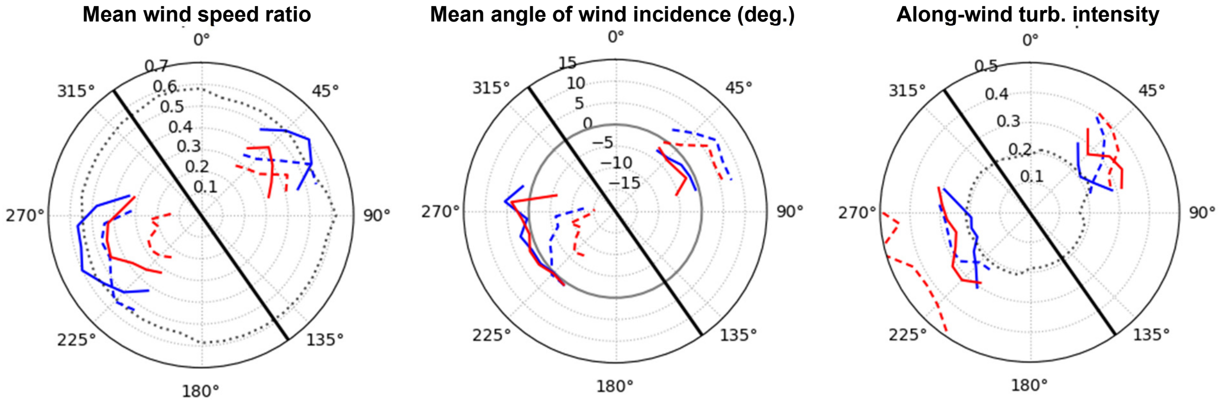


Figure 2. Views of the 1:400 scale topographic model of the proposed CNW bridge site in the winter (left) and summer (right) trees configurations in RWDI's Irwin boundary layer wind tunnel.

The full-scale equivalent aerodynamic roughness and displacement height for the trees were estimated based on the characteristics of the trees along the valley (Crockford and Hui, 2007). They were then modelled at scale by machining a bespoke roughness on the model surface, for leafless trees in the winter, and by employing a porous foam installed on the model surface, for the trees with leaves in the summer (Fig. 2). Both modelling techniques are in-line with current best practices (McAuliffe and Larose, 2012) and were calibrated through dedicated boundary layer flow measurements over various surface roughness. Flow measurements were carried out using multi-hole fast-response pressure probes (TFI Cobra probes) supported by an automated and remotely controlled traverse system. Measurements were taken at three spanwise locations: at the centre of each span (at deck level) and the pylon location (at multiple elevations). The two critical sectors including wind directions along the valley were investigated (i.e., winds from North-East and South-West), with additional measurements at the pylon location collected also for winds along the bridge.

Fig. 3 compares the flow conditions measured at the centre of both bridge spans in summer and winter. Due to the combined effects of the valley topography, vegetation and surrounding terrain, the mean wind speed, turbulence intensity and mean angle of wind incidence in the vertical plane were found to vary along the bridge span and to change depending on the season. Also, compared to the undisturbed wind conditions, higher mean wind speeds and wider ranges of turbulence intensities and angles of wind incidence (of approximately ±10° at the centre of the short span) were predicted at the bridge site.


Mean wind speed ratio

Mean angle of wind incidence (deg.)

Along-wind turb. intensity

Figure 3. Polar plots of wind conditions at deck elevation of the proposed CNW Bridge based on topographic model tests at the centre of the main span (solid lines) and short span (dashed lines), in the winter (blue) and summer (red), compared to undisturbed oncoming flow (dotted black line) and relative to the bridge alignment (solid black line)

3. WIND TUNNEL DECK SECTIONAL AND PYLON RIGID MODEL TESTING

A 1:20 scale bridge deck sectional model (Fig. 4) was tested in smooth flow and in calibrated turbulent flow to verify the aerodynamic stability of the proposed deck to vortex-shedding induced oscillations, flutter and galloping. Also, static aerodynamic force and moment coefficients and aerodynamic derivatives for the deck (initial displacement method) were measured, which were later used in the buffeting analysis for derivation of design wind loads. All the tests were carried out over an extended range of angles of attack, as determined by the results of the topographic study. No vortex-shedding induced vibrations or divergent aerodynamic instabilities were observed during the tests. A subset of the static aerodynamic coefficients measured for the deck over a ±25° range of angle of attack is shown in Fig. 4.

A 1:60 scale rigid model of the bridge pylon (Fig. 4) was also tested in the wind tunnel on a base-mounted multi-component force balance to obtain the static aerodynamic force and moments coefficients. These coefficients were used in the buffeting analysis for derivation of the wind loads.

4. NUMERICAL STABILITY AND BUFFETING ANALYSIS

Time-domain numerical simulations were performed to confirm the bridge aerodynamic stability and predict the wind-induced buffeting responses, from which the wind loads were derived (Stoyanoff and Dallaire, 2013). Input data to these analyses included the bridge dynamic properties, as provided by the structural engineer Ney & Partners, as well as the static aerodynamic coefficients for the deck and the pylon and the aerodynamic derivatives for the deck, as obtained via wind tunnel tests. Also, virtual time series of the turbulent wind approaching the bridge were simulated at multiple bridge node locations to reproduce the complex wind conditions measured from the topographic study, which presented spanwise-varying mean wind speeds, mean angle of wind incidence and turbulence intensities. The buffeting analysis method employed for buffeting analyses of the CNW bridge was optimized to account for such wind conditions and sensitivity analyses were completed to assess their effect on the aerodynamic responses of the bridge in comparison to when they remain uniform along the entire bridge span.

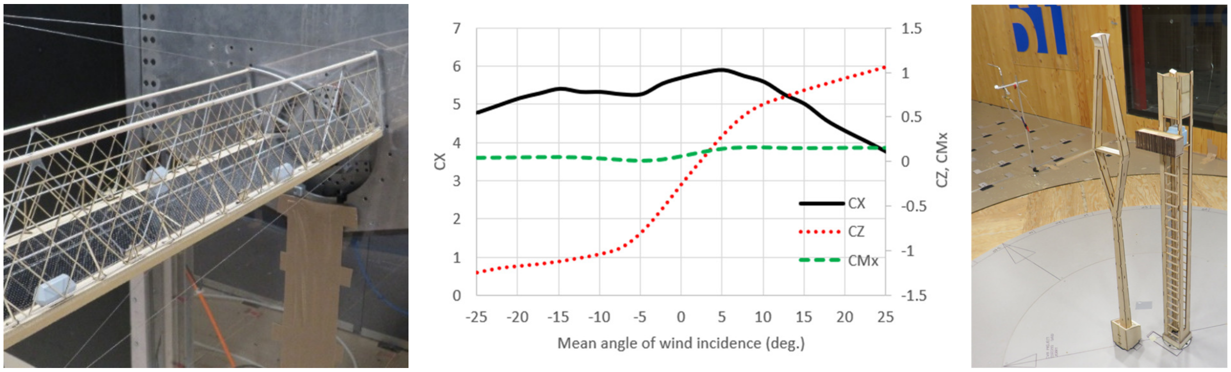


Figure 4. Wind tunnel sectional model (left) and static aerodynamic coefficients (centre) for the deck; wind tunnel pylon rigid model in the presence of the adjacent elevator shaft (right).

4. CONCLUSIONS

Upon completing a comprehensive series of numerical and experimental analyses on the proposed CNW footbridge, RWDI was able to confirm that the bridge meets the aerodynamic stability criteria and derived a series of wind loads to inform the structural design. Results from topographic wind tunnel model testing indicated that the combined effects of the valley topography, vegetation and surrounding terrain determine complex on-site wind conditions, which change largely along the bridge deck. In addition, a significant contribution from the foliage of trees was identified, which causes the site wind conditions to vary significantly from winter to summer. In this regard, undertaking an appropriate topographic assessment in the early stages of the project has proven to be critical to define effectively the scope and methods of the entire wind investigation campaign.

ACKNOWLEDGEMENTS

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