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Aerodynamic and VIV responses of a twin-box bridge deck in smooth and small-scale turbulent flows

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SUMMARY
Experimental tests and 3D LES simulations of the Stonecutters Bridge bare deck have been carried out to obtain the force coefficients and pressure coefficient distributions for smooth incoming flow. Furthermore, an additional simulation has included an upstream rod to generate a 6% turbulence intensity small-scale turbulent flow impinging on the bridge deck. The mean force coefficients were lower for the small-scale turbulent flow, in agreement with previous experimental tests for this bridge. Also, fluid-structure interaction simulations were carried out to obtain the VIV response (amplitude of oscillation vs. reduced velocity) in smooth flow, obtaining a good agreement with equivalent experimental tests.

Keywords: wind tunnel, CFD small-scale turbulence, twin-box deck.

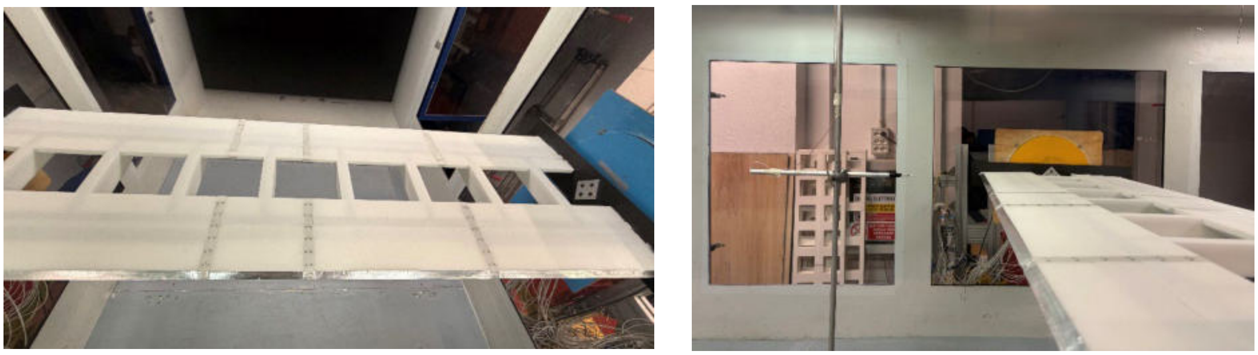
1. INTRODUCTION

Vortex-induced vibration (VIV) is an aeroelastic effect that occasionally may take place in light weight and flexible structures like long span bridges. Twin-box decks feature high critical flutter wind speed; however, they may be prone to VIV due to the impingement of the vortices shed from the upwind box on the downwind box. Wind tunnel testing has been so far the standard and trusted methodology to study wind effects in structures, although CFD simulations have demonstrated their suitability for modeling aerodynamic loads and even some fluid-structure interaction phenomena. However, modeling computationally VIV and the effects of freestream turbulent flow on bridges have proven to be challenging (Álvarez et al., 2019). Indeed, even within the experimental realm, limitations persist in our understanding about how certain flow characteristics, like turbulent length scale, may be impacting the flow-induced responses of structures. This abstract covers the CFD simulations and experimental tests of the bare Stonecutters Bridge deck. The aerodynamic responses of interest are the force coefficients, the pressure coefficient distributions and the VIV response (Larose et al., 2003), considering smooth flow and small-scale rod-induced incoming turbulent flow. A selection of results is reported next, which will be further enlarged at the conference.

2. WIND TUNNEL TESTS

An experimental campaign is currently taking place at the Giovanni Solari Wind Tunnel of the

University of Genoa. The 1/90 geometric scale sectional model features three strips of pressure probes, with an overall number of 90 pressure taps, 10 on each strip in the upstream box, and 20 on each strip in the downstream box. In this manner the downstream box, immersed in the wake of the upstream one, may be more accurately characterized. The overall aerodynamic forces are measured using high-precision force balances. The sampling frequency for pressures and the forces was 800 Hz. In Fig. 1, two images of the model in the wind tunnel are provided, one of which shows a hot-wire probe recording the wake velocity.



a) b)

Figure 1. Sectional model a) general view and b) a hot-wire probe placed in the wake of the deck.

3. COMPUTATIONAL MODELING

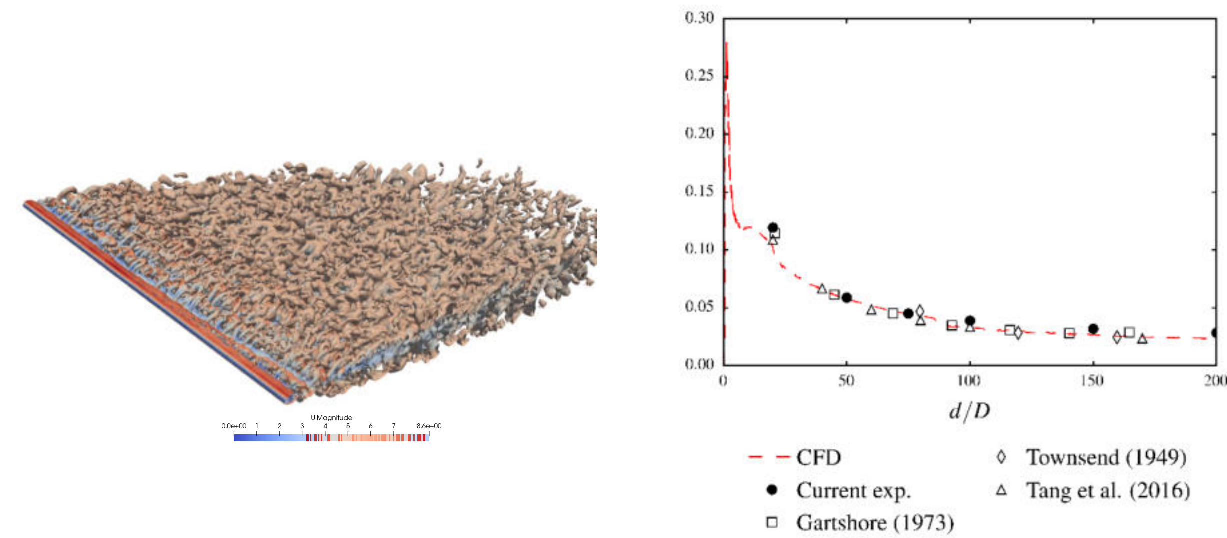
The selected CFD solver was OpenFOAM, adopting the arbitrary Lagrangian Eulerian (ALE) formulation for the VIV case. Three different 3D LES models have been considered, featuring different characteristics in the finite volumes mesh and numerical settings:

- Case 0: standard unstructured hexahedral mesh, extruded in the spanwise direction with uniform spanwise size: $\delta_z/C = 0.021$, being C the width of one box. Case 0 considers smooth incoming flow and the Smagorinsky LES model (Álvarez and Nieto, 2025).
- Case 1: structured hexahedral mesh graded in the spanwise direction with spanwise size on the deck surface $\delta_z/C = 5.77 \times 10^{-3}$ (near the corners of the deck this size is halved). Case 1 considers smooth incoming flow and the one-equation eddy LES model.
- Case 2: structured hexahedral mesh graded in the spanwise direction with spanwise size on the deck surface $\delta_z/C = 5.77 \times 10^{-3}$ (near the corners of the deck this size is halved), and spanwise size on the rod surface $\delta_z/D = 7.21 \times 10^{-4}$, being D the diameter of the rod. This case corresponds to small-scale rod-induced turbulent flow impinging on the deck as per the approach proposed in Gartshore (1973) and further applied in Kwok and Melbourne (1980) and Álvarez et al. (2025b). The model characteristics are the same as in Case 1.

4. SMALL-SCALE ROD-INDUCED TURBULENCE

One of the key aspects in this piece of research is the characterization of the turbulent wake downstream of the rod since the CFD implementation requires the high-fidelity reproduction of the turbulent intensity decay along the centerline in the wake of the rod. In this manner the distance between the rod and the twin-box deck placed downstream can be established based on the targeted turbulent intensity at the impingement point on the twin-box (Álvarez et al. 2025). In Fig. 2, the

CFD vorticity field in the wake of the rod is presented along with the decay of the along-wind turbulence intensity depending on the distance from the rod, including the experimental and CFD results for validation.

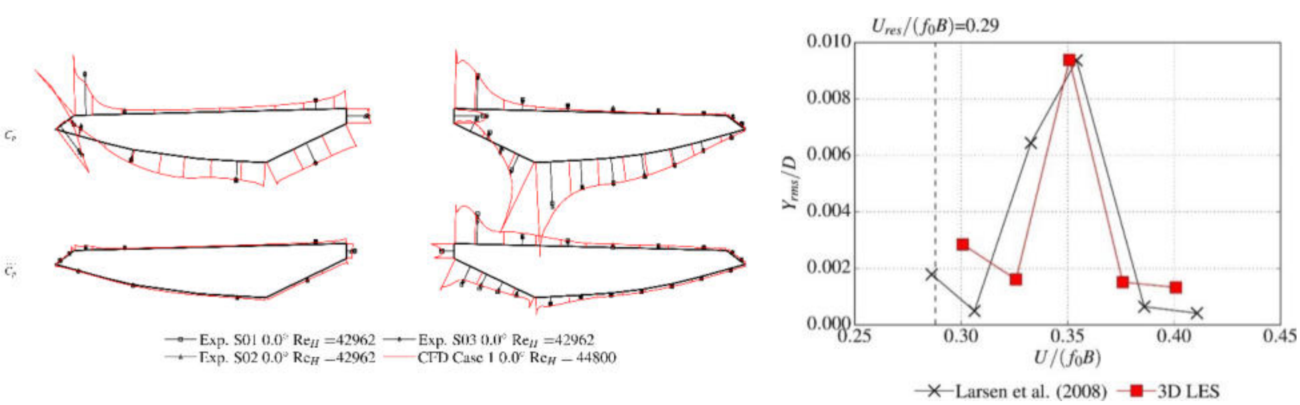


a) b)

Figure 2. Small-scale rod-induced turbulence a) Q-criterium for the turbulent wake of the isolated rod and b) turbulent intensity decay along the rod's wake centerline including experimental and CFD results.

5. INTEGRAL PARAMETERS AND PRESSURE COEFFICIENTS DISTRIBUTION

For the 0º angle of attack case, the mean force coefficients, and the Strouhal number are reported in Table 1 for the three CFD simulations considered herein, along with the experimental results. The geometric dimension considered for the nondimensionalization is the total width of the deck (53.3 m at real scale). Case 2 (6% turbulent incoming flow; distance between the rod and the deck of 50*D*) presents force coefficients that are lower than the ones obtained for Case 1 (smooth flow), which is consistent with the findings in Fok (2006). In Fig. 3a) the mean and fluctuating pressure coefficient distributions are provided at 0º angle of attack for the wind tunnel test and the Case 1 CFD model, showing a remarkable accuracy.



a) b)

Figure 3. a) Mean (up) and fluctuating (bottom) Pressure coefficient distributions (experiments and Case 1) for 0º angle of attack and b) amplitude of oscillation in the heave vs. reduced velocity (Case 0).

6. VIV RESPONSE IN SMOOTH FLOW

In Fig. 3b) the results obtained for the CFD simulation adopting the Case 0 model for a Scruton number equal to 32 in smooth flow are reported. The comparison with the experimental tests in Larsen et al. (2008) show a very good agreement, despite the relatively low peak amplitude of oscillation, which is roughly 1.5% of the deck's depth. The interested reader may find further details about these simulations in Álvarez and Nieto (2025).

Table 1. Integral parameters Stonecutters Bridge, 0º angle of attack

Case	Flow	C_d	C_l	C_m	St
Experiments	smooth	0.052	-0.114	0.011	0.26
Case 0	smooth	0.056	-0.095	0.028	0.24
Case 1	smooth	0.048	-0.142	0.018	0.27
Case 2	rod-induced	0.043	-0.127	0.022	0.25

7. CONCLUSIONS

The Stonecutters Bridge has been adopted as a case study for studying its aerodynamic response in smooth and small-scale turbulent flows experimentally and computationally by means of 3D LES simulations. Both approaches have provided very similar results, not only for the integral parameters, but also for the mean and fluctuating pressure coefficient distributions around the twin-box deck. Furthermore, the heave VIV response in smooth flow has been accurately provided by 3D LES simulations. The experimental results for the wind tunnel testing campaign adopting the rod-induced turbulent flow approach that is currently ongoing will provide additional inputs for assessing the impact of the turbulent length scale in the wind loads and VIV response.

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