

Evaluation of bridge deck aerodynamic coefficients in a short open-section wind tunnel

C O H Meyer-Johansen¹, J R Bell², N Daniotti³, J T Snæbjörnsson^{1,4}
and J B Jakobsen¹

¹Department of Mechanical and Structural Engineering, University of Stavanger, Stavanger, Norway

²Institute of Aerodynamics and Flow Technology, German Aerospace Center, Göttingen, Germany

³Svend Ole Hansen ApS, Copenhagen, Denmark

⁴Department of Engineering, Reykjavík University, Reykjavík, Iceland

E-mail: carl.o.meyer-johansen@uis.no

Abstract. The present work examines flow interaction with a streamlined bridge-girder model in a short open-section wind-tunnel facility, specifically the side-wind module of the DLR Tunnel Simulation Facility Göttingen, [selected for its ability to reproduce the effects of flow on vehicles crossing the bridge in strong winds](#). A 1:15 sectional model of the Lysefjord Bridge, equipped with 21 surface-pressure taps, was investigated in three configurations at varying flow-incidence angles. Since the model and jet are fixed, the mean inflow angle is imposed using adjustable flaps, and the resulting effective angle of attack is deduced from the data from a traversing five-hole probe. Sectional forces, approximated by integrating the measured surface pressures, are compared with closed-section force-balance data and a full-scale monitoring record. The windward-face pressures approximately match the full-scale distribution. [Re-integrating the model pressures over the twelve-tap subset that mirrors the full-scale array roughly halves the lift and moment offsets from the full-scale values, whereas the drag stays well below the closed-section reference and lift and moment vary little with incidence.](#) The open-jet facility can therefore reproduce the windward flow and loading needed for the moving-vehicle study, but has limitations for determining girder force coefficients.

1 Introduction

Static force coefficients (drag, lift and moment) are essential to assess the aerodynamic stability of long-span suspension bridges, which depends on how they vary with the angle of attack [1].

The present work belongs to a wider experimental programme concerned with the safety of vehicles crossing the bridge in strong winds [2, 3, 4]. Before moving vehicle models will be introduced in later tests, it is necessary to understand the aerodynamic environment around the bare bridge deck in its different configurations.

The Lysefjord Bridge spans a fjord east of Stavanger on Norway's south-western coast, with a single main span of about 446 m carrying two traffic lanes and a pedestrian footpath. Its deck is a streamlined, closed steel box girder, 12.3 m wide and 2.7 m deep, with a shallow aerodynamic cross-section typical of medium- and long-span crossings. Completed in 1997, the bridge sits in complex fjord terrain, and the approaching wind is often both yawed and vertically inclined, so that the representative angle of attack at the girder departs from the nominal horizontal.

This exposed setting has drawn the University of Stavanger to use the bridge as a full-scale laboratory. Since 2013, wind turbulence data from sonic anemometers spaced along the span have been recorded, together with deck acceleration response [5, 6] and, later, three pressure strips were installed on the bottom part of the bridge deck [7]. The resulting [body of literature](#)¹ documents the local turbulence, the mean flow angle, and the buffeting response of the structure, thereby providing a full-scale dataset that may be used to validate theoretical models (e.g., buffeting theory) alongside reduced-scale experimental data and CFD simulations.

The wind tunnel campaign took place in a compact open-jet facility that is part of the Tunnel Simulation Facility Göttingen (TSG) at the German Aerospace Center (DLR). Unlike the long closed-section boundary layer wind tunnels normally used for sectional-model tests of bridge decks, this facility has a short, wide, open-ended test section and limited flow conditioning, because its primary purpose is to launch models along a rail that passes through a 5 m stretch used to generate exposure to transient crosswinds. A 1/15-scale model of the bridge deck and part of one tower was 3D printed and fixed to the vehicle rail, crossing the wind jet. The angle of attack cannot be imposed by rotating the model or by tilting the flow, as both the rail and the tunnel are fixed; instead, an upstream row of adjustable flaps was installed to deflect the jet over the fixed model to adjust the mean inflow inclination. Since the facility is central to the planned moving-vehicle-model work, the paper aims to provide an initial assessment of the wind conditions for a range of angles of attack and evaluate the associated static force coefficients (drag, lift and moment) of the Lysefjord girder recovered from this arrangement. These coefficients, obtained here from surface pressures on the 1:15-scale model, are compared with force-balance measurements from an earlier 1:50-scale campaign in a closed-section boundary layer wind tunnel, as well as with pressure data and load coefficients from the full-scale monitoring system on the bridge. [To the authors' knowledge, this campaign is the first use of a short open-jet moving-model facility to study wind effects on vehicles crossing a bridge deck. The present paper focuses on the deck surface pressures.](#)

The paper is organised as follows. Section 2 describes the facility, the sectional model and the flap system. Section 3 discusses the reduction of the pressure signals to sectional force coefficients and the calculation of an angle of attack representative for these tests. Section 4 characterises the inflow produced by the flap array. The measured surface-pressure distributions and the derived force coefficients are then presented and compared with the closed-section and full-scale references, and the main findings are summarised in the concluding section.

2 Experimental setup

2.1 Short open-section wind tunnel facility

The side-wind module of the TSG moving-model facility [2, 3], shown in Figure 1. The open jet runs 5 m along the rail, 3 m across the crosswind direction, is 1 m in height, and produces a horizontal mean wind of up to 20 m s^{-1} .

The facility was designed to produce transient side winds for moving vehicle and train models travelling along the rail. The flow regime had not previously been systematically investigated, conditioned, or characterised. The jet can be shifted vertically but not rotated; it was positioned with its lower edge 250 mm beneath the girder underside, so that the model sits fully in the flow while space remains above the deck for free-stream measurement as a vehicle passes.

The wind is measured at three points, shown in Figure 1 and tabulated in Table 1. A fixed pitot-static tube above the deck, U_{ref} , supplies the reference static pressure for the surface-pressure transducers and the reference dynamic pressure. A five-hole probe ($\text{Ø}7 \text{ mm}$ straight

¹<https://windengineeringuis.github.io>

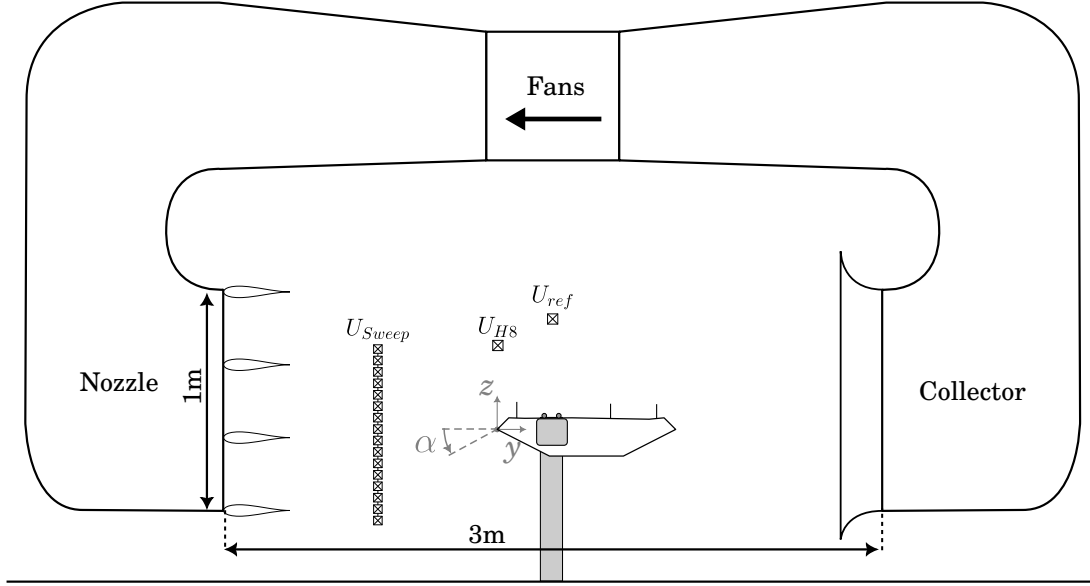


Figure 1. Cross-section of the side-wind test section seen along the rail: the nozzle with the flap array (Section 2.4), the girder model on its support, and the three wind-measurement positions listed in Table 1.

Vectorflow 5-hole multi-hole pressure probe) was placed at a location corresponding to the position of the full-scale anemometer H08E (see [7]), U_{H08} , and provided the reference flow measurement used in this comparison. The same five-hole probe was mounted on a two-axis traverse 0.62 times the width of the deck in front of the leading edge of the bridge and swept vertically (U_{Sweep}), giving three components of the wind velocity, including the angle of attack.

Table 1. Wind-measurement positions marked in Figure 1, at model scale. The coordinates are as defined in Figure 1.

Symbol	Instrument	Position	z (mm)	y (mm)
U_{Sweep}	Five-hole probe	traverse	-380 to 370	-510
U_{H08}	Five-hole probe	fixed	400	0
U_{ref}	Pitot-static tube	fixed	500	250

2.2 Sectional model and test configurations

The campaign used a 1:15 sectional model of the Lysefjord Bridge girder throughout, giving a model width $B_m = 0.82$ m and depth $D_m = 0.18$ m, with $B = 12.3$ m and $D = 2.7$ m. The model includes the girder, along with its traffic- and pedestrian-side railings, and was printed using fused deposition modelling in polylactic acid. The model was initially used in the proof-of-concept study of the facility [4, 3], where its construction and surface finish are documented in detail.

The coordinate system's origin is at the windward leading edge of the deck, with both the horizontal and vertical axes defined normal to the bridge axis. Following the usual convention in bridge aerodynamics, the angle of attack (AoA) is taken as positive when the flow is directed upward toward the deck, corresponding to wind approaching from below.

Unlike a conventional sectional-model rig, the model cannot be inclined or yawed. It wraps around the launch rail of the moving-model system, which is fixed to the tunnel floor at 5 m spacing, so the geometric incidence of the deck stays at 0° (Figure 1); a continuous slot in the deck section accommodates the rail and the carriage of the moving vehicle, visible in Figure 2. The model axis follows the rail, so the crosswind meets the deck side almost normally (zero yaw). The model spans the entire test section, and no end plates or similar were used because the measurements were taken well away from the tunnel ends. It is installed with the north-north-east (NNE) face of the prototype to windward and the pedestrian lane downstream. The model can be turned around to represent south-south-west (SSW) exposure.

A generic lorry model, at the same 1:15 scale as the bridge deck model, stands in for a heavy vehicle parked in the windward traffic lane (cf. Figure 2). It is a single solid body, wheels included, roughly 12.2 m, 2.6 m and 3.6 m in prototype length, width and height, with 0.5 m ground clearance, and is positioned so that it crosses the instrumented section.

Three configurations were tested, summarised in Table 2: the bare girder; the girder with both railings; and the girder with railings and the static vehicle in place.

Table 2. Tested configurations.

id	Configuration	Railings	Static vehicle
(i)	Bare girder	absent	absent
(ii)	Girder with railings	present	absent
(iii)	Girder with railings and static vehicle	present	present



Figure 2. Image of the tunnel section with the bridge model installed in configuration (iii), the flap system seen on the right, and both the pitot-static tube and five-hole probe in the middle. Note: the truck model was added to this image from another similar image by OpenAI, *ChatGPT*, August 2026 (<https://chat.openai.com>).

The deck fills approximately 18 % of the 1 m jet, and about 22 % with the vehicle. While a closed-section wind tunnel confines and accelerates the flow with its walls, an open jet instead has a free shear-layer boundary, so the displaced flow would typically spill outwards, and the model is expected to experience an effective over-expansion, along with extra jet deflection and nozzle- and collector-proximity effects [8, 9]. This is high relative to standard open-jet blockage corrections, so the wake and leeward pressures – and, with them, the drag – are expected to be distorted. The goal is instead to reproduce the upstream flow and the windward-face loading correctly and to determine the effective full-scale angle of attack, with the remaining influence assessed against the closed-section and full-scale references (Section 3).

2.3 Surface pressure instrumentation

A single chordwise strip of 21 taps at mid-span of the model measured the surface pressures. Twelve of these taps have the same positions as the taps on the full-scale pressure-strip at Lysefjord Bridge [7], allowing a direct model-to-full-scale comparison; the other nine were added to resolve the pressure distribution more finely, six on the upper deck surface and three on the soffit and the lower inclined faces of the box. Each pressure tap is pneumatically connected to a differential pressure transducer, Endevco 8510B, with a range of ± 6.89 kPa, which uses the static backing pressure from the pitot static tube above the deck model (at U_{ref}).

Each transducer was calibrated in place against a reference pressure calibrator at four set points spanning ± 1.9 kPa, and a linear least-squares fit supplied the channel gain. Offset values were simply removed before each run. All signals – the deck taps, the five-hole probe, the pitot-static tube and the ambient temperature and pressure – were logged together on one Dewetron DEWE-501 recorder (32 channels), amplified and sampled at 5 kHz over a 30-second record per test point, equivalent to 7 minutes at full scale at the chosen wind speed. Most channels used a differential (double-ended) mode, which rejects common-mode pick-up and lowers the noise floor.

2.4 Flap system for inflow control

Since neither the model nor the jet can be inclined, an attempt was made to introduce a mean horizontal inflow angle through an array of adjustable flaps at the nozzle exit (Figure 1). Four aerofoil-section flaps span the 1 m nozzle height and extend over the full 5 m length; each pivots about a span-wise axis, turning the emerging jet as a whole. The deflection is set by hand using a jig that fixes the trailing-edge rise over a fixed chord-wise base, yielding nominal geometric settings in steps of 3° . The pivoting of the flaps was kept within a range of $\pm 18^\circ$.

The geometric flap setting does not equal the effective inflow angle at the model, as the deflected jet spreads and mixes before reaching the deck. The resulting local flow angle is smaller and varies across the model; this is examined further in Section 4.

2.5 Test programme

The campaign ran at the TSG in June 2026. For each of the three configurations in Table 2, the surface-pressure distribution was recorded at zero flap setting over a range of reference wind speeds, to test Reynolds-number sensitivity, and then through the full flap sweep at a fixed reference speed of about 10 m s^{-1} ; for the bare girder and the girder with railings, the $\pm 9^\circ$ settings were also repeated at the other speeds (Table 3). In all, this amounts to some 60 surface-pressure records.

Using the deck depth D , the tested wind speeds cover a Reynolds number of about $0.8\text{--}2 \times 10^5$, roughly an order of magnitude below the full-scale values.

Table 3. Surface-pressure test matrix. Flap settings are geometric; the corresponding effective inflow angles are given in Section 4.

Configurations id	Flap setting	Reference wind speed
(i), (ii), (iii)	0°	$\approx 7, 10, 14, 17 \text{ m s}^{-1}$
(i), (ii), (iii)	0 to $\pm 18^\circ$, 3° steps	$\approx 10 \text{ m s}^{-1}$
(i), (ii)	$\pm 9^\circ$	$\approx 7, 10, 14 \text{ m s}^{-1}$

The sections that follow draw on two more sets of measurements from the same campaign: the five-hole-probe inflow surveys (Section 4), made at the same flap settings and speeds, and a series of moving-vehicle runs (configuration (iii)) with the lorry travelling along the deck). Only the static configurations are treated here; the moving-vehicle results are reported separately.

3 Data processing

3.1 Pneumatic tubing correction

Each tap connects to its transducer through tubing. The amplitude ratio $H = p_m/p$ and the phase (taken over true pressure) were computed with the Bergh–Tijdean model [10] from the tubing segment lengths, bores and cavity volume of the transducer (Figure 3).

For the deck taps, $|H|$ stays close to unity only below 10 Hz and falls to half by 60 Hz. Inverting it boosts the signal about $5\times$ at 200 Hz, but beyond about 500 Hz, the surface pressure carries too little energy to be recovered even with the very low transducer noise floor. The signals were thus downsampled to 500 Hz after the correction.

The five-hole probe rolls off in much the same way as the pressure taps, but with a far steeper phase loss. It was therefore also downsampled to 500 Hz after applying the correction.

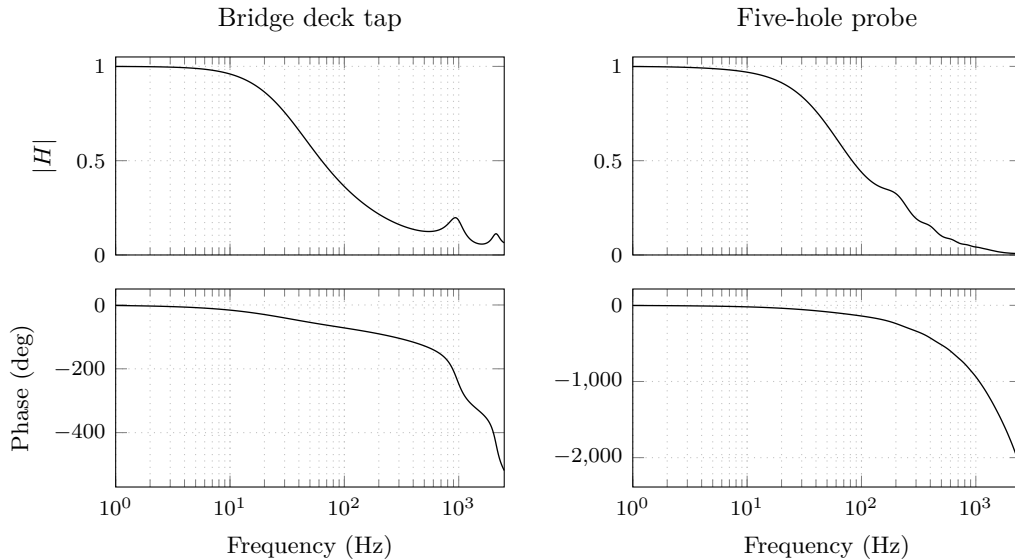


Figure 3. Pneumatic tubing transfer function $H = p_m/p$ (measured over true pressure), Bergh–Tijdean model [10] at 25°C , 101.3 kPa (weakly sensitive to both). Left: deck tap; right: five-hole probe. Top: amplitude; bottom: phase.

3.2 Reference flow and pressure coefficients

Air density is calculated from the measured ambient temperature and pressure. During the inflow surveys at U_{Sweep} , the five-hole probe provides the reference velocity and dynamic pressure, q_{ref} , as the sampling of pitot-static velocity was flawed in these tests. During the bridge-pressure measurements, the five-hole probe is fixed at U_{H08} , while the tap pressures are measured relative to the free-stream static pressure supplied by the pitot-static tube. The pressure coefficient, therefore, follows as $C_p = p/q_{\text{ref}}$.

3.3 Sectional force coefficients

Integrating the mean pressure around the section contour gives estimates of the sectional forces F_D , F_L and F_M per unit span, which are defined as follows:

$$C_L = \frac{F_L}{q_{\text{ref}}B}, \quad C_D = \frac{F_D}{q_{\text{ref}}D}, \quad C_M = \frac{F_M}{q_{\text{ref}}B^2}. \quad (1)$$

For the calculation of forces, each of the 21 taps (Figure 4) carries a tributary length extending halfway to its neighbours, a fixed outward normal and a uniform pressure, and the moment is taken about the shear centre, 1.45 m above the soffit at full scale [11]. **Drag and lift are resolved in the mean-flow frame, i.e. rotated from the deck axes by α_{eff} , consistent with the closed-section and full-scale references.**

4 Flow characterisation

This section describes the modelled wind flow: the inflow across the jet, mapped with the five-hole probe on the traverse, and, where relevant, the flow at the fixed U_{H08} position that is used as reference for the surface-pressure tests. Mean profiles and turbulence intensities come first, then the velocity spectra.

4.1 Effective angle of attack and inflow profiles

The AoA is set through the geometric flap setting, which overstates the actual inflow inclination at the model. To estimate the angle of attack representative for this model, the set flap angle is plotted against the measured one, as in Figure 5. The measured AoA is shown there at every swept position, together with the value at the H08 position, across the range -9° to 9° . The AoA at the other traverse heights appear in grey, with the upper lines corresponding to the highest measurement positions and the reverse. The set-to-measured relation varies substantially with vertical position, indicating a parabolic field that flattens out at the top and becomes steeper in the lower end at the inlet nozzle. In this work, the effective AoA, α_{eff} , is defined as a linear fit to the values measured at the leading-edge height, as these are the most relevant; this angle is adopted from here on. **As the inflow sweep only covered set flap angles of $\pm 9^\circ$, the values for α_{eff} are extended beyond this range, up to $\pm 18^\circ$, by extrapolation from this fit.**

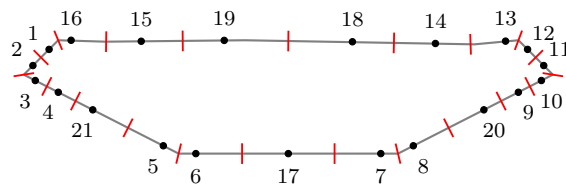


Figure 4. Sectional-model cross-section: the 21 pressure taps and their numbering ($\bullet$), and the tributary-segment boundaries used for the pressure integration ($\times$).

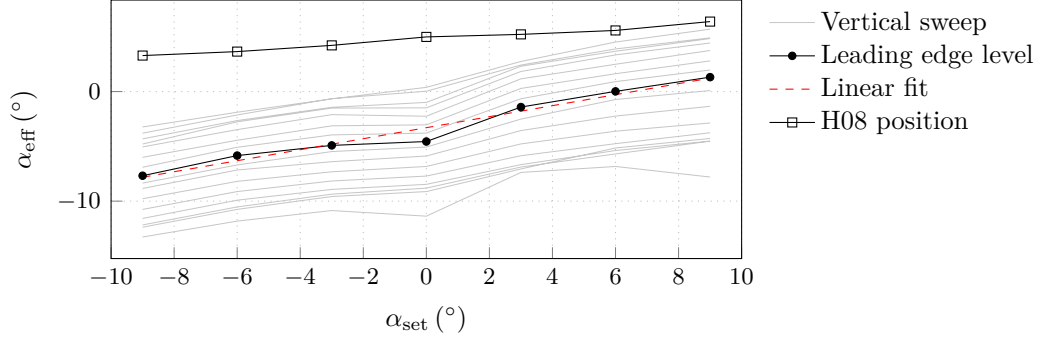


Figure 5. Effective (model-scale) angle of attack, α_{eff} , against the set flap angle, α_{set} : The five-hole probe positioned $0.63B$ upstream from leading edge at various heights, at leading-edge height and at the H08 position. Linear fit $\alpha_{\text{eff}} \approx 0.5 \alpha_{\text{set}} - 3^\circ$ at leading edge level.

Figure 6 plots the profiles against the traverse height y , with $y = 0$ at the leading-edge.

The first row holds the mean velocity components and the turbulence intensities. Above the floor shear layer ($y \gtrsim -250$ mm, depending on the AoA), the streamwise speed u and the magnitude U_{mag} are uniform to within about $\pm 7\%$, so most of the model is in a nearly uniform flow. The lateral component is small, $|v| \lesssim 1 \text{ m s}^{-1}$, pointing to a few degrees of yaw that arise

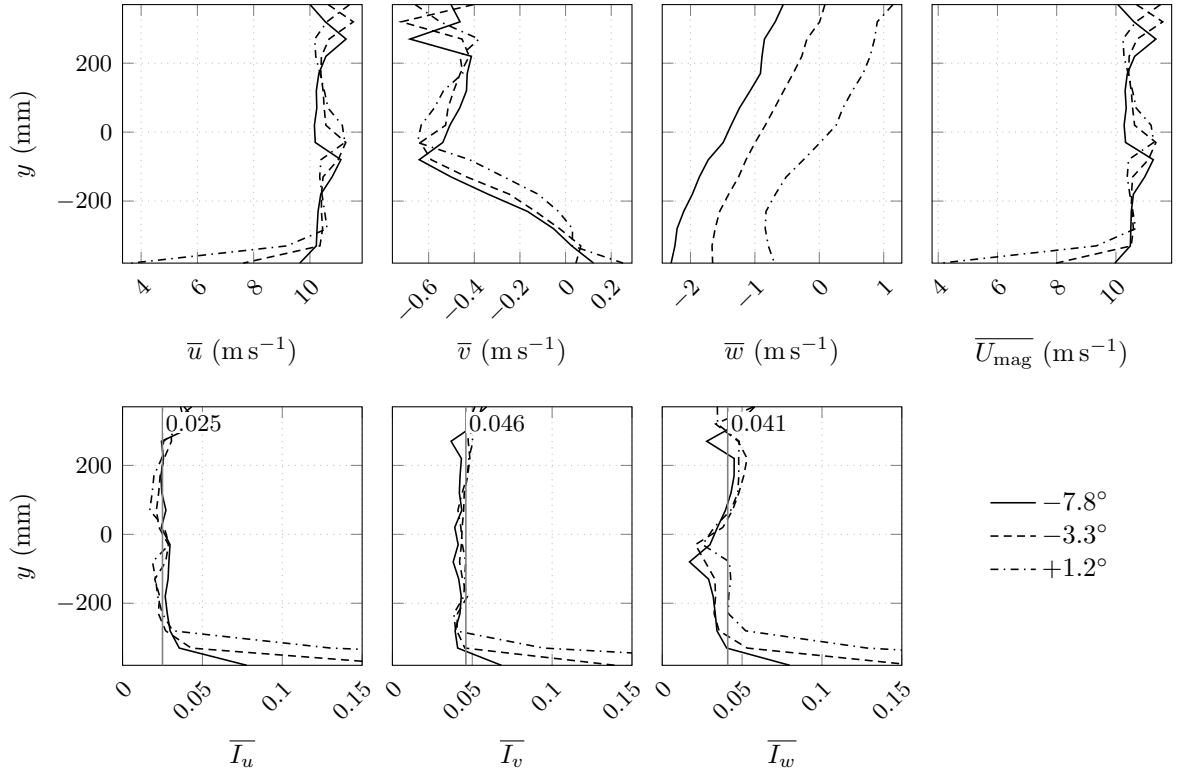


Figure 6. Vertical profiles at U_{Sweep} of the mean velocity components $\bar{u}$, $\bar{v}$, $\bar{w}$, the magnitude $\overline{U_{\text{mag}}}$ and the mean turbulence intensities $\overline{I_u}$, $\overline{I_v}$, $\overline{I_w}$ against traverse height y , for three of the seven flap settings (line style by setting; legend: effective AoA). Grey lines on the lower column mark the deck-band mean of the middle setting.

because the measurement was taken at 1.5 m from the left end of the open jet, rather than along the tunnel centreline. The vertical component w grows close to linearly with height, matching the vertical sweep presented in Figure 5.

The turbulence is low and anisotropic, with the along-wind component showing only about half the intensity of the others. This is likely linked to the flow expanding, both laterally and vertically, as it exits the tunnel section. The sharp rise towards the floor seen in Figure 6 follows naturally from the jet mixing with still air.

4.2 Velocity spectra

Figure 7 show the normalised spectra fS_i/σ_i^2 , with S_i the autospectrum computed by Welch's method and σ_i^2 the variance of the wind signal in direction $i = \{u, v, w\}$ at the fixed position U_{H08} .

The spectra are drawn against the reduced frequency $f L_i/\bar{U}$, where L_i is the streamwise integral length scale of the component i , found from the zero-crossing integral of the autocorrelation under Taylor's frozen-turbulence hypothesis. The Kaimal [12] and Simiu & Scanlan [13] model forms are overlaid for reference. The example shown is at -0.3° AoA and $U_{\text{ref}} = 11.3 \text{ m s}^{-1}$. The streamwise spectrum closely tracks the theoretical form, deviating only slightly at low normalised frequencies, where the peaks of the two coincide. The other two components follow the theoretical shape to a lesser degree.

The integral length scales all lie near 0.08 m and shift somewhat with the effective AoA, as Figure 8 shows. Normalised by the deck depth, $L_i/D_m \approx 0.3\text{--}0.5$, against roughly 25–55 at the Lysefjord Bridge for winds near 10 m s^{-1} [14], i.e. two orders of magnitude smaller. Above about 1° , L_u drops below L_v and L_w , most likely because larger flap settings smooth the large-scale streamwise fluctuations.

5 Deck pressure results

This section presents the measured surface-pressure distributions and the approximate sectional force coefficients derived from them. The mean pressures, their fluctuations, and their dependence on the angle of attack are examined first, after which the integrated coefficients are compared with the closed-section and full-scale references, and the influence of pressure-tap resolution is assessed.

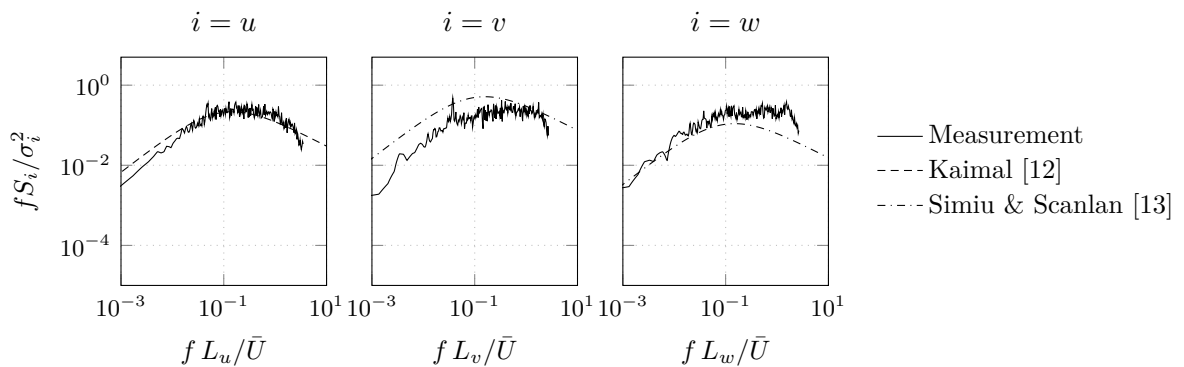


Figure 7. Normalised velocity spectra fS_i/σ_i^2 against $fL_i/\bar{U}$ from the five-hole probe at the fixed U_{H08} position, at an effective AoA of -0.3° .

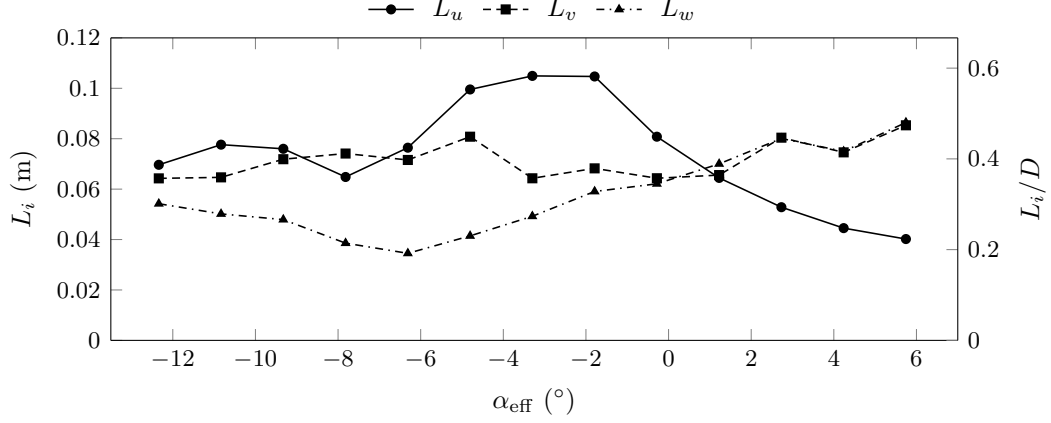


Figure 8. Streamwise integral length scales L_u , L_v , L_w at the fixed U_{H08} position against effective AoA, over the flap sweep at the reference wind speed (configuration with railings).

5.1 Surface pressure distributions

Figure 9 shows the mean pressure distribution for configuration (ii) at three different AoA and a wind speed near 10 m s^{-1} . The three panels cover the two most extreme AoA values tested and one case whose AoA value is close to that in a full-scale measurement.

The mean field shows the expected streamlined-box pattern: a stagnation region on the windward face, strong suction over the windward soffit chamfer and along the upper surface, and a weak, almost uniform base pressure on the leeward face. Raising α_{eff} primarily increases

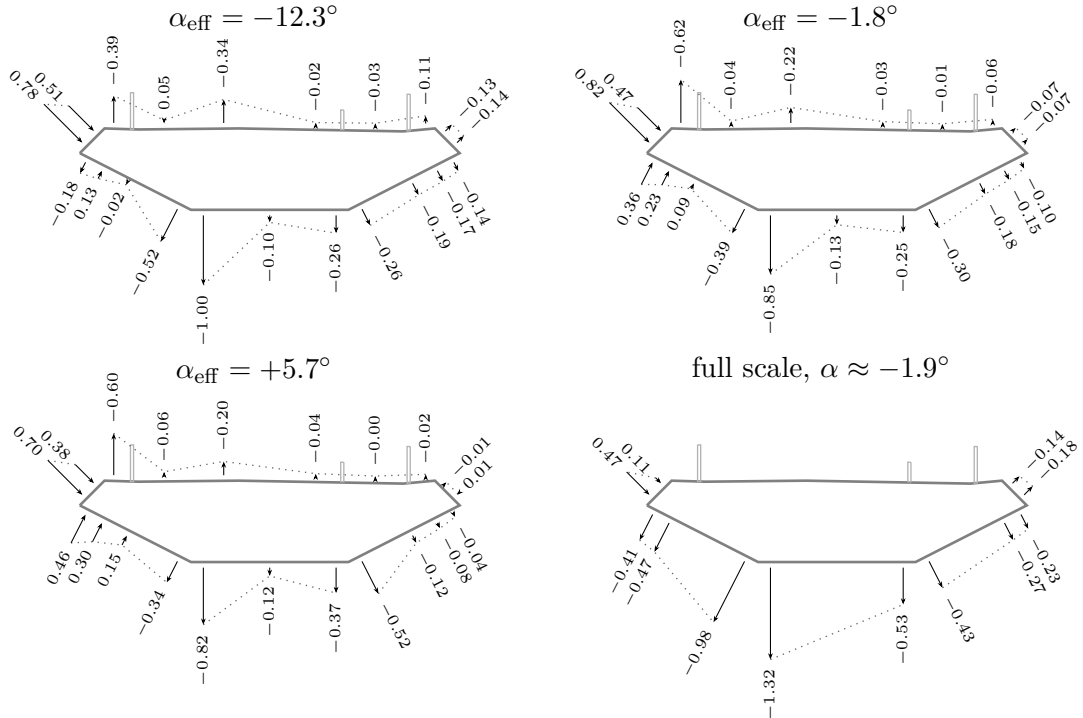


Figure 9. Mean surface pressure coefficient distribution, $\overline{C_p}$, shown at three AoA, together with a full-scale reference distribution measured on 6 August 2021.

the pressure on the lower chamfer, indicating that the drag is carried mainly by the pressure difference across the two inclined side plates rather than by the nearly horizontal top and bottom panels for these tests. On the upper side of the windward face, the model matches the full-scale mean distribution as expected; the agreement breaks down over the windward soffit chamfer, where the full-scale results show suction. The AoA noted in Figure 5, could account for this, since only the very steepest negative AoA gives suction in that area of the deck.

Figure 10 sets the bare girder (configuration (i)) next to the girder with railings and vehicle (configuration (iii)) at the same AoA $\alpha_{\text{eff}} = -1.8^\circ$, which Figure 9 shows for the girder with railings (configuration (ii)). On the leeward side of the girder, the mean pressures do not change much relative to configuration (ii), shown in Figure 9. The pressure on the top-surface falls steadily from windward to leeward, a smooth trend that the railings naturally disturb. The static vehicle results in a greater qualitative change, chiefly by diverting more flow beneath the deck, thereby increasing the suction on the soffit and the chamfered soffit. Across the truck, the upper surface shows a steep pressure gradient, positive on the windward side and suction on the leeward side, marking a recirculation zone in the flow.

Figure 11 contrasts the standard deviation of the pressure coefficients, σ_{C_p} , at full and model scale. At this AoA, the model-scale fluctuations are much the same all around the perimeter, increasing only a little downwind of the windward railing. By contrast, the full-scale values are an order of magnitude larger at most taps, reflecting the very different turbulence intensities. The full-scale distribution also follows the mean distribution more closely, with stronger fluctuations on the windward side that fall off towards the leeward and pick up again at sharp corners. At model scale, this is only faintly visible: sharp corners do raise the fluctuations, but the windward and leeward levels stay very close.

To see how AoA affects the pressure coefficients, the first four statistical moments are plotted for the four upstream taps in Figure 12. These taps were chosen because the windward side is least affected by the strong blockage, yet it is usually the face most responsive to changes in AoA. In the first panel, showing $\overline{C_p}$, the two upper taps respond only weakly to AoA and follow each other closely apart from a nearly constant offset. On the lower surface – as already seen in Figure 9 – the two lower taps are generally at positive pressure, which reduces for smaller AoA. Below $\sim 7^\circ$ the slope of pressure at tap 3 steepens, while tap 4 keeps an almost constant slope. Given that the full-scale result showed suction at these two lower taps, the effective AoA might seem in need of redefinition, but, judging from this panel, getting suction on the two would need

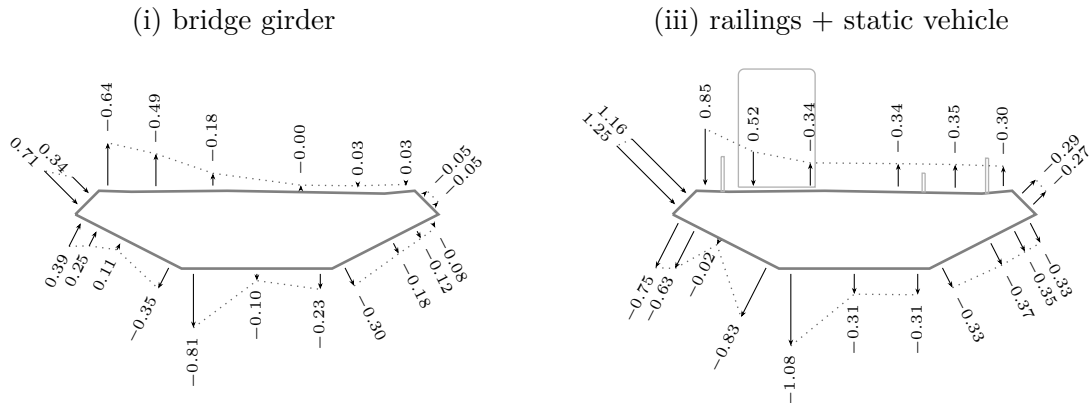


Figure 10. Mean pressure distribution $\overline{C_p}$ for configuration (i) and configuration (iii) at $\alpha_{\text{eff}} \approx -1.8^\circ$

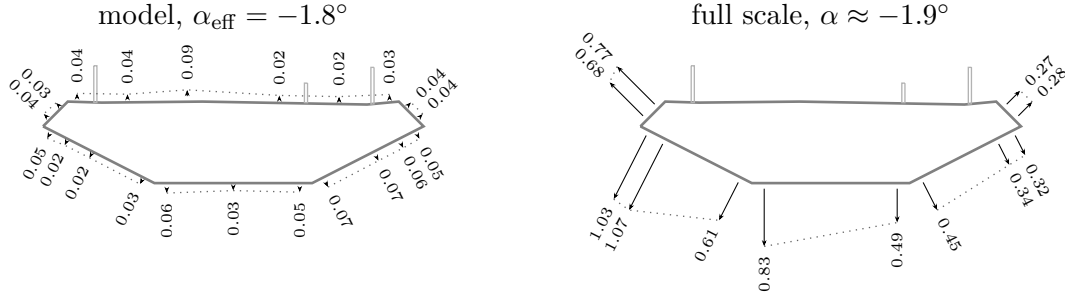


Figure 11. Distribution of fluctuating components, σ_{C_p} , for the model- and full-scale cases, with the full-scale measurement stemming from measurements conducted on 6 August 2021.

a much larger change, again pointing to a flow shape that is not constant along the test section. Tap 3 also stands out among the remaining three panels. In the standard deviation, the change in mean slope below $\sim 7^\circ$ also increases the fluctuations, suggesting flow separation when the flow is aimed steeply downward. Skewness and kurtosis are each near 0 and 3, as expected for a normal distribution, although tap 3 deviates with larger absolute skewness and higher peak values.

5.2 Aerodynamic coefficients

Figure 13 plots the mean sectional force coefficients against the effective AoA for configuration (ii), alongside results from the Burlington wind tunnel facility at SOH Wind Engineering [11]. Those were measured with a force balance, so the integrated forces – including those on the railings – were recorded directly. They come from a 1:50 model at $I_u \approx 10\%$ and $Re \approx 3.6 \times 10^4$, a flow with higher roughness but lower Reynolds number than in the present tests.

On the whole, the results bear little resemblance to the reference study; only the lift and

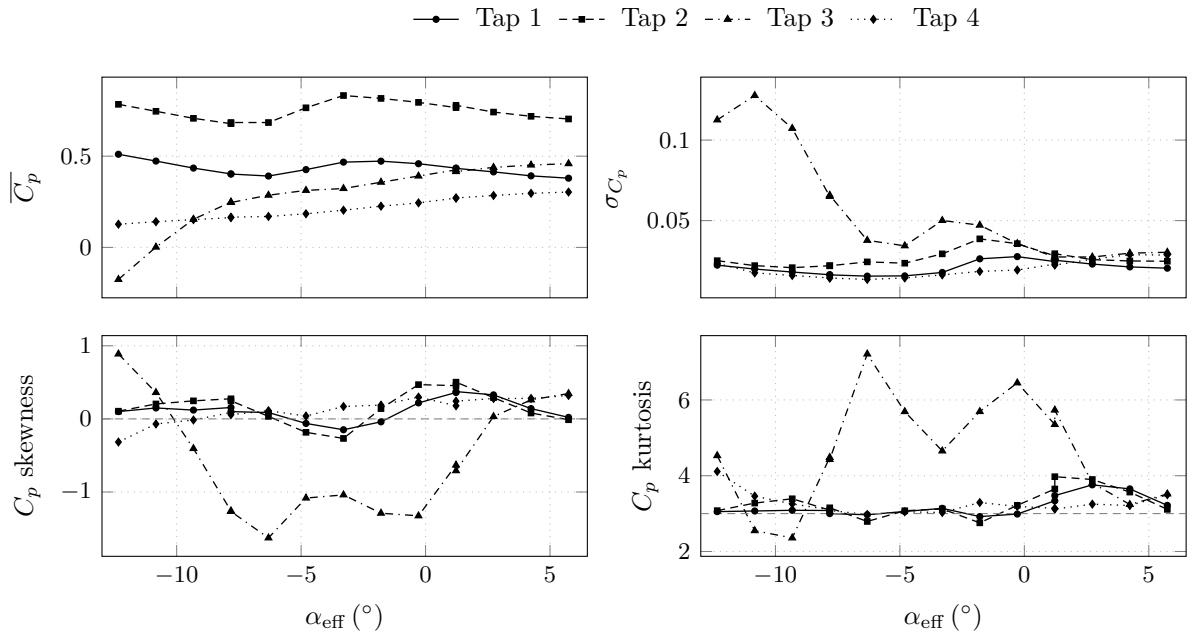


Figure 12. First four statistical moments of the tap C_p versus AoA for four leading-edge taps

moment curves cross it at $\text{AoA} = 0^\circ$. At $\alpha_{\text{eff}} \approx -1.9^\circ$ the 21-tap drag is $\overline{C_D} \approx 0.37$, against 0.71 in the reference, and the lift and moment slopes are about 0 and 0.17 rad^{-1} (0.003 per degree), against about 4.6 and 0.92 rad^{-1} in the reference, the lift slope of the latter being close to the 2π of a thin aerofoil. The railing pressures were not included in the force integration, but this omission is small against the full deck geometry and does not account for the large shortfall. The remaining, larger part of the drag deficit is therefore attributed to the open-jet blockage and jet-deflection effects described in Section 2.2 and to the roughness and Reynolds-number mismatch with the reference study noted above. The lower tunnel turbulence is unlikely to explain this, as turbulence usually shortens separation bubbles and smooths the coefficient curves [1]; smoother inflow should therefore give steeper, not flatter, lift and moment curves. Lift and moment, moreover, show almost no dependence on AoA and stay rather flat, again far from the reference behaviour. The aerodynamic coefficients for the other two configurations show the same trend, but since no reference study exists for them, those results are omitted here.

The full-scale sample is a one-hour-long record from the Lysefjord Bridge from 6 August 2021 (18:20–19:20), sampled at 25 Hz [7]. The H08E sonic anemometer logged a mean wind of $\bar{U} \approx 10.6 \text{ m s}^{-1}$ at deck level, some 25° yawed from the deck normal, with turbulence intensities around $I_u \approx 28\%$, $I_v \approx 24\%$ and $I_w \approx 19\%$, well above the tunnel inflow (Section 4). No stationarity considerations have been taken into account. The vertical inflow angle fluctuates strongly, spanning roughly 17° between its quartiles about a median of $\alpha \approx -1.9^\circ$. Sectional coefficients were integrated from the twelve chord-A surface-pressure taps with the same sign convention and reference dimensions as before; because of the strong yaw and angle fluctuations, the girder does not see the steady, quasi-two-dimensional flow of the sectional test, so only the central tendency of the two data sets is compared. Dividing the hour into six 10-minute segments yields the scatter in Figure 13, with segment means $\overline{C_D} = 0.06$, $\overline{C_L} = -0.27$ and $\overline{C_M} = -0.035$. The full 21-tap model integration results in a drag higher by a factor of about six, and more positive $\overline{C_L}$ and $\overline{C_M}$ values, which are plausible considering that the suctions on the upper deck surface are not captured in the full-scale.

The full-scale array contains only the 12 taps, with none on the top surface, while the model

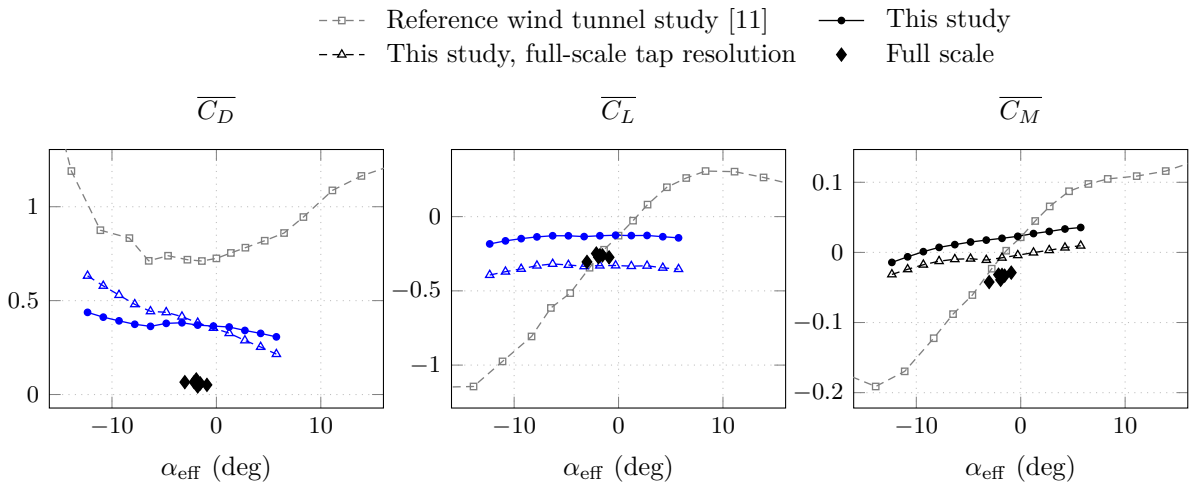


Figure 13. $\overline{C_D}$, $\overline{C_L}$ and $\overline{C_M}$ as a function of effective AoA for configuration (ii), integrated over the full 21-tap perimeter and over the 12-tap subset matching the full-scale monitoring array. Shown next to a reference study [11] and the full-scale segment means.

includes the full 21-tap perimeter. To distinguish the effect of this sparser coverage from a genuine model–prototype difference, the configuration (ii) pressures were re-integrated over the same twelve-tap subset, with the same tributary-area weighting, as the full-scale reduction. The resulting curve appears in Figure 13.

For lift and moment, the lower-resolution integration draws the model markedly towards the full-scale measurement. At the reference incidence, $\alpha_{\text{eff}} \approx -1.9^\circ$ the full 21-tap integration gives $\overline{C_L} \approx -0.13$ and $\overline{C_M} \approx +0.02$, while restricting to the twelve-tap layout gives $\overline{C_L} \approx -0.33$ and $\overline{C_M} \approx -0.01$. This reduces the offset from the full-scale values $\overline{C_L} = -0.27$, and $\overline{C_M} = -0.035$, and restores the correct negative sign of the pitching moment, producing residuals of 0.03–0.06. Much of the lift and moment discrepancy in Figure 13 is thus an artefact of the monitoring array, which misses the top-surface suction that carries a considerable share of both coefficients. The improved agreement, however, only shows that model and prototype pressures are consistent at the twelve shared taps, not that the full sectional forces are reproduced, since the full-scale top-surface loading is not measured.

Drag is another matter. Lowering the resolution introduces a bias that swings strongly with AoA: the twelve-tap set overpredicts $\overline{C_D}$ at the steepest negative angles and underpredicts at positive incidence, agrees with the 21-tap value only near the reference incidence, and never brings the model down to the full-scale level $\overline{C_D} = 0.06$. The drag offset cannot, therefore, be linked to the tap coverage, and it remains consistent with the blockage and Reynolds-number arguments above. Sectional drag read from the sparse array should thus be treated with low confidence, whereas the lift and moment comparison is clarified by this resolution test.

6 Conclusions

The static aerodynamic coefficients of the Lysefjord Bridge girder were measured in the TSG’s short open-jet side-wind module, on a 1:15 sectional model with 21 surface pressure taps in three configurations. Since model and jet alike cannot be inclined, the mean inflow angle was set with an array of adjustable flaps, and the effective angle of attack was recovered from five-hole-probe surveys rather than read off from the geometric flap setting. The inflow is nearly uniform above the deck and only weakly turbulent, so the mean inflow is well controlled while the fluctuating parts fall short of the full-scale bridge (Section 4).

The pressures on the windward face closely track the full-scale pressure distribution, and the streamlined-box character of the loading holds across the tested range of effective angles of attack, over which the mean coefficients are essentially independent of wind speed. Re-integrating the model pressures over the twelve-tap subset that mirrors the full-scale monitoring array pulls the lift and moment coefficients substantially towards the full-scale values: at $\alpha_{\text{eff}} \approx -1.9^\circ$ the lift offset is more than halved from 0.14 to 0.06 and the moment offset from 0.055 to 0.027. The sparser full-scale monitoring array therefore accounts for most of the lift and moment discrepancy, and the facility can hence reproduce these two coefficients to some extent (Section 5.2).

The drag, by contrast, is not well represented: the model gives $\overline{C_D} \approx 0.37$ against 0.71 in the closed-section reference, and the lift and moment slopes, about 0 and 0.17 rad^{-1} , fall far below the reference values of about 4.6 and 0.92 rad^{-1} . The cause is likely the open-jet blockage and collector-proximity effects of the short test section, which distort the wake and leeward pressures, rather than the instrumentation (Section 5.2). The windward-face loading, lift and moment are better reproduced. For the vehicle-safety study behind this work, the facility is well-suited to reproduce the upstream flow and windward-face loading of the bare deck and its railings, provided a good effective angle of attack is found; the same procedure carries over to the moving-vehicle configurations, for which the static loads reported here will serve as a reference.

Acknowledgements

The authors are grateful to the Department of Ground Vehicles, Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR), Göttingen, for hosting the measurement campaign at the TSG, and to its head, Claus Wagner, for enabling the staff time spent on the project. The visit was facilitated by James Bell, who also acted as principal contact and collaborator, and the adjustable flap system was designed and built by Felix Werner.

References

- [1] Dyrbye C and Hansen S O 1996 *Wind Loads on Structures* (Wiley)
- [2] Bell J R, Wilhelmi H, Heine D, Jessing C, Wagner A, Wiedemann J, Ehrenfried K and Wagner C 2020 Experimental investigation of automotive vehicle transient aerodynamics with a reduced-scale moving-model crosswind facility Tech. Rep. 2020-01-0671 SAE International
- [3] Bell J R, Meyer-Johansen C O H, Tolo I, Snæbjörnsson J T and Jakobsen J B 2026 A moving-model and side-wind-tunnel methodology with full-scale validation for investigating the crosswind-stability of vehicles on bridges *Proc. IN-VENTO 2026, 17th International Conference of the Italian Association for Wind Engineering* (Bari, Italy)
- [4] Tolo I 2025 *Wind Tunnel Testing of a Bridge with a Moving Vehicle: Safety of Road Vehicles on a Bridge* Master's thesis University of Stavanger
- [5] Cheynet E, Jakobsen J B and Snæbjörnsson J 2016 *Eng. Struct.* **128** 474–487
- [6] Cheynet E, Jakobsen J B and Snæbjörnsson J 2019 *J. Sound Vib.* **450** 214–230 ISSN 0022-460X URL <https://www.sciencedirect.com/science/article/pii/S0022460X19301737>
- [7] Daniotti N, Jakobsen J B, Cheynet E and Snæbjörnsson J T 2025 *Measurement* **254** 117747
- [8] Barlow J B, Rae W H and Pope A 1999 *Low-Speed Wind Tunnel Testing* 3rd ed (New York: John Wiley & Sons) ISBN 9780471557746
- [9] Mercker E and Wiedemann J 1996 On the correction of interference effects in open jet wind tunnels Tech. Rep. 960671 SAE International
- [10] Bergh H and Tijdeman H 1965 Theoretical and experimental results for the dynamic response of pressure measuring systems Tech. Rep. NLR-TR F.238 National Aerospace Laboratory NLR Amsterdam, The Netherlands
- [11] Daniotti N 2022 *Bridge deck aerodynamics: A case study in full-scale* Ph.D. thesis University of Stavanger
- [12] Kaimal J C, Wyngaard J C, Izumi Y and Coté O R 1972 *Q. J. R. Meteorol. Soc.* **98** 563–589
- [13] Simiu E and Scanlan R H 1996 *Wind Effects on Structures: Fundamentals and Applications to Design* 3rd ed (New York: John Wiley & Sons) ISBN 9780471121572
- [14] Cheynet E 2016 *Wind-induced vibrations of a suspension bridge: A case study in full-scale* Ph.D. thesis University of Stavanger