Full-scale observation of the buffeting response of a suspension bridge and comparison with aeroelastic tests

Aksel Fenerci [1], Ole Øiseth [2]

[1]*Norwegian University of Science and Technology, Ålesund, Norway, aksel.fenerci@ntnu.no*
[2]*Norwegian University of Science and Technology, Trondheim, Norway, ole.oiseth@ntnu.no*

SUMMARY:
The Gjemnessund Suspension Bridge (GSB) in Norway was instrumented by the Norwegian University of Science and Technology (NTNU) with a minimalist monitoring system where accelerations (at quarter-span) and wind speed (at the midspan) were recorded for a period of approximately five years. The measured responses in full-scale were compared to the results of aeroelastic full bridge investigations that were carried out at the design stage by Alan Davenport's boundary layer wind tunnel. The comparisons concern the root-mean-square acceleration and displacements measured at the deck level as well as the peak responses. The correspondence between the full-scale and wind tunnel studies is presented and discussed. It is concluded that even though the wind environment at the site was modelled with good accuracy and detail, the aeroelastic tests gave lower response estimates, compared to what is measured in full-scale. The unique case study gives insight to both the potential and limitations of such investigations.

Keywords: suspension bridge, buffeting, aeroelastic model

1. FULL-SCALE MONITORING OF THE GJEMNESSUND BRIDGE

The Gjemnessund Suspension Bridge (GSB) is a 1257-meter-long suspension bridge (623 m main span) located on the mountain-rich and topographically complex west coast of Norway (Figure 1). The bridge was opened in 1992 after its construction. Meticulous investigations of the wind environment and wind-induced response of the bridge were carried out prior to and during the design stage of the bridge, including met mast measurements, wind tunnel terrain model tests, and aeroelastic full-bridge model tests. The wind-induced dynamics of the bridge have also been studied by others after its opening. The full-scale studies focused on different aspects of bridge performance (Andersen, 2021; Isaksen, 2008). Between 2013 and 2018, accelerations at the quarter span and wind speeds at the midspan (3 meters above the deck) were monitored by the Norwegian University of Science and Technology (NTNU) with a simple monitoring system (Figure 1).

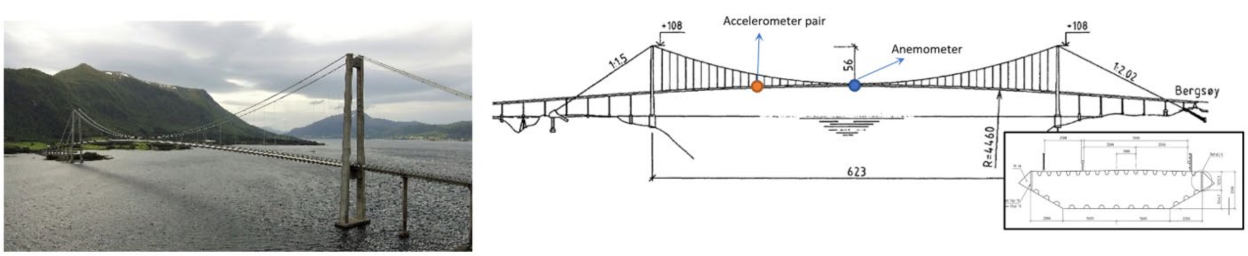

Figure 1. The Gjemnessund Bridge (GSB, left), the monitoring system (right)

2. FULL BRIDGE AEROELASTIC MODEL TESTS AT THE DESIGN STAGE

The wind environment at the bridge site as well as the wind-induced response, have been studied extensively in Alan G Davenport's Boundary Layer Wind Tunnel (BLWT) laboratory in Ontario, Canada, and the results of the investigations were reported (Davenport, 1987). An aeroelastic 1:135 scale full bridge model was constructed and tested in the wind tunnel (Figure 2). The resulting model had a 4.56 meters long span (corresponding to 615 meters, slightly different than the built bridge). The correspondence between the first few natural frequencies of the actual bridge and the model is given in Table 1. The time scaling factor between the model and the full-scale bridge was 0.086. It is seen that the modes are captured well by the model except for the anti-symmetric (first) vertical mode, which had a higher frequency than the symmetric vertical mode in the model scale. The model was tested under 15% and 30% turbulence intensities with a spectrum that matches the site spectrum rather well. Peak acceleration responses at the quarter span (where the accelerometers were located) and peak displacement responses at the midspan of the bridge in a time interval corresponding to approximately 10 minutes were measured and reported.

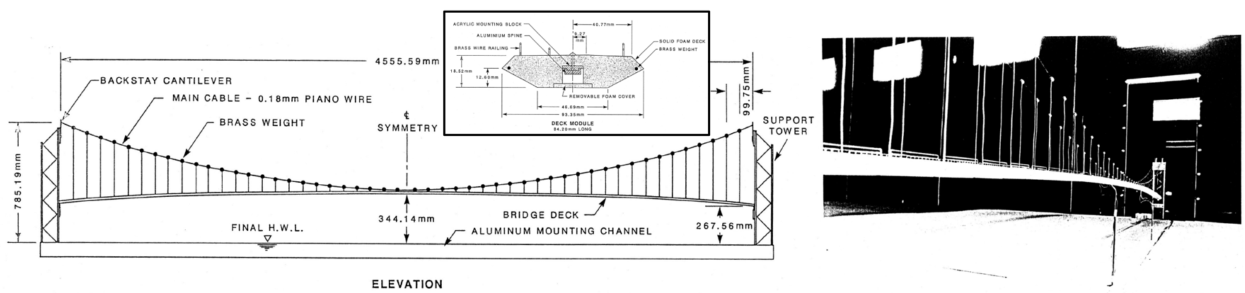

Figure 2. The aeroelastic full bridge model: drawings (left), shown in the wind tunnel (right)

Table 1. Full bridge and model natural frequencies (Hz)

	bridge	Prototype*	model
Lateral bending (symm.)	0.09	0.086	0.092
Lateral bending (anti-symm.)	0.26	0.24	0.25
Vertical bending (symm.)	0.22	0.22	0.238
Vertical bending (anti-symm.)	0.175	0.145	0.286
Torsion (symm.)	0.7	0.78	0.78
Torsion (anti-symm.)	-	1.39	1.41

*Proptotype bridge refers to the design considered by the wind tunnel team. The full-scale as-built bridge is slightly different (indicated as bridge)

3. MEASURED DYNAMIC RESPONSE AND COMPARISON WITH MODEL TESTS

The dynamic response of the deck was measured in full-scale with the help of an accelerometer couple installed at the quarter span of the bridge, inside the deck on both sides, with 13 meters between the two sensors. The monitoring effort spans a period of 5 years but was not continuous. Measurements were primarily taken during strong winds (when the mean speed was above 15 m/s) and, in some cases, also in moderate or calm conditions. The measured data were processed (Fenerci et al., 2017), and the root-mean-square (RMS) and peak acceleration responses were calculated for the lateral, vertical, and torsional motions. The signals were then double-integrated in the time domain to obtain the corresponding displacement responses. The measured RMS responses are shown in Figure 3, and the peak responses in Figure 5.

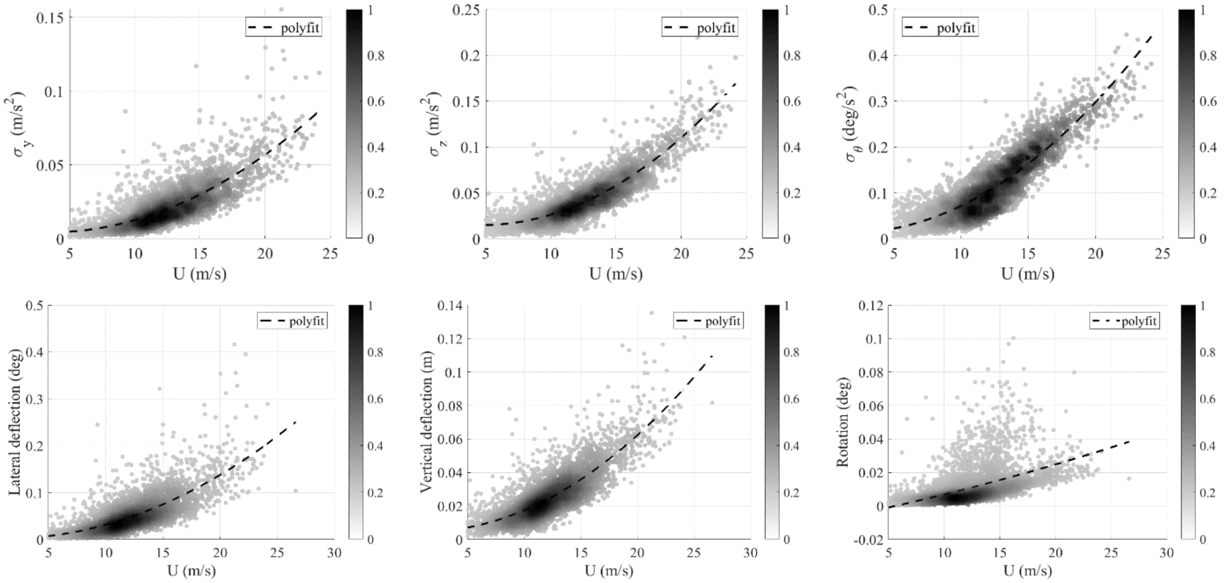

Figure 3. The measured full-scale RMS responses at the quarter-span. Top row: RMS acceleration response (from left to right: lateral, vertical, and torsional acceleration). Bottom row: RMS displacement response (from left to right: lateral and vertical deflection, rotation). Grayscale color coding used to indicate relative data density.

For each 10-minute interval that was studied, the expected peak value of the acceleration response was also calculated and compared (Figure 4) with the measured peak acceleration using:

$$E[p] \approx \sigma_a\sqrt{2\ln\left(\upsilon_a^+(0)T\right)} + \frac{0.5772}{\sqrt{2\ln\left(\upsilon_a^+(0)T\right)}}, \quad \upsilon_a^+(0) = \frac{1}{2\pi}\frac{\sigma_{\dot{a}}}{\sigma_a} \tag{1.1}$$

where T is the considered interval (10 minutes), $\upsilon_a^+(0)$ is the zero up-crossing rate of the acceleration process, σ_a and $\sigma_{\dot{a}}$ are the standard deviations of the acceleration process and its time derivative, respectively.

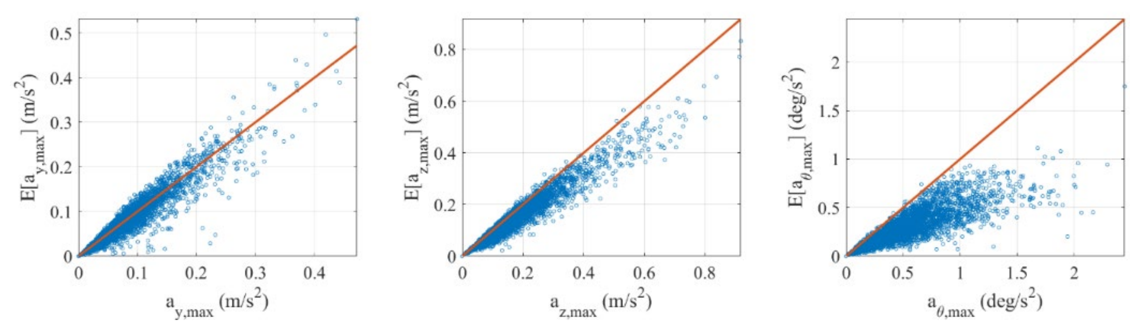

Figure 4. Comparison of the measured and the expected value of the peak accelerations (red lines indicate 1:1)

4. COMPARISONS WITH THE AEROELASTIC MODEL TESTS

The vertical and torsional peak accelerations that were measured in full-scale are plotted together with the measured peak values at the wind tunnel (Figure 5). The lateral acceleration was not measured in the wind tunnel and, therefore, not compared. The accelerations obtained from the aeroelastic tests were systematically lower, even for a high turbulence intensity of 30%, which represents the higher bound in full-scale. Comparisons of displacement were also plotted; however, a good correspondence there is not expected as the measurements were taken at the midspan in the case of the model. The deflections at the quarter span would be much smaller, perhaps, except for the vertical response.

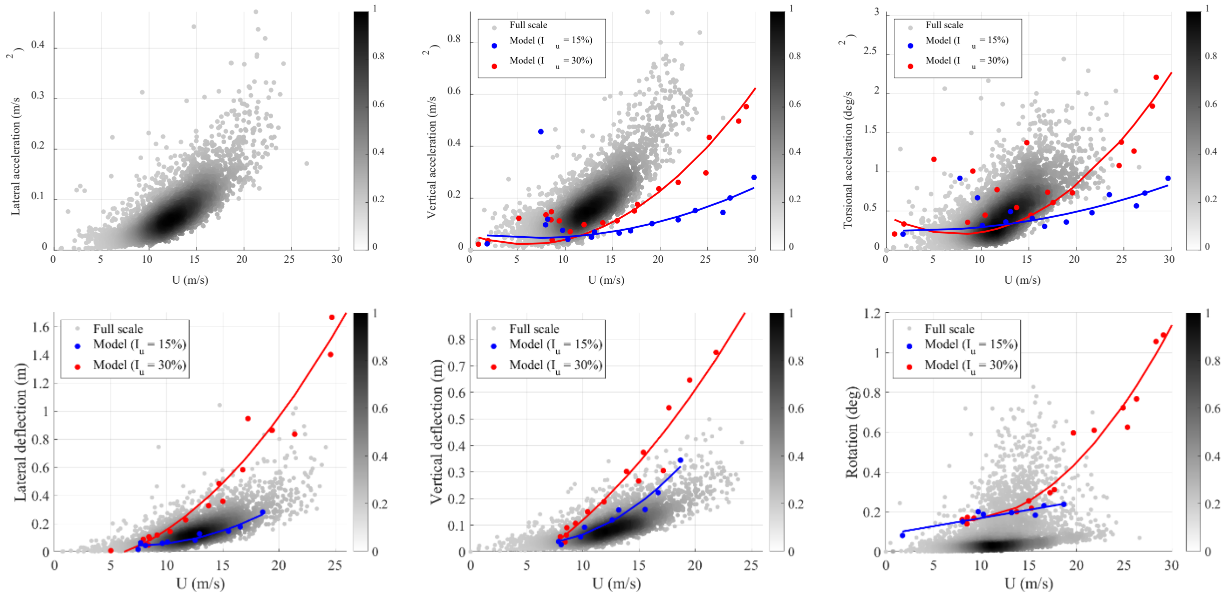

Figure 5. The measured full-scale peak responses compared with model tests. Top row: peak acceleration, quarter span (from left to right: lateral, vertical and torsional acceleration) Bottom row: peak displacement response, model results are at mid-span, full-scale at quarter-span (from left to right: lateral and vertical deflection, rotation). Trendlines are mere polynomial fits and used only to show trend of the scattered dots.

5. CONCLUSIONS

The peak acceleration responses at the quarter span of the GSB were measured in full-scale and compared with responses measured from aeroelastic full-bridge tests in the wind tunnel that were conducted at the design stage. It was observed that the response was underpredicted despite the consideration of high turbulence intensity.

ACKNOWLEDGEMENTS

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