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Wind tunnel study of global wind loads on a swing bridge

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SUMMARY:
A wind tunnel study on the global wind loads of two side-by-side swing bridges allowed for a comparison with provisions in NEN 6786-1 and NEN-EN 1991-1-4. Measurements were performed with a dynamic six-component balance in an ABL wind tunnel. A comparison of the results with code provisions shows that NEN-EN 1991-1-4 results in an overestimation of the coefficients c_{Fx}, c_{Fy}, c_{Fz} and c_{Mx}. The coefficients c_{Fz} and c_{Mz} obtained with NEN 6786-1 agree well with the measured result, but the moment coefficient c_{My} is underestimated.

Keywords: Swing bridge, wind tunnel measurements, global wind loads

1. INTRODUCTION

Wind loads are an important aspect in the design of movable bridges. In the Netherlands, movable bridges are designed according to NEN 6786-1 (NEN, 2021). This code gives provisions for wind loads, both outside and during the movement cycle. Outside the movement cycle and for some loads during the movement cycle, NEN 6786-1 also refers to provisions for fixed bridges specified in NEN-EN 1991-1-4 (NEN, 2020). In some cases, the provisions in these codes are different. For example, NEN 6786-1 gives a value of 0.4 for the vertical wind force coefficient for a closed bridge. NEN-EN 1991-1-4 recommends a coefficient of 0.9 or allows the use of a graph (Figure 8.6), in which this coefficient depends on the slenderness of the bridge deck and the angle of incidence of the wind with the deck. Another difference is observed for the torsion coefficient on swing bridges. These differences arise from the different origins of the provisions in these codes. The provisions for fixed bridges in NEN-EN 1991-1-4 are largely based on wind tunnel measurements of bridge deck sections in low-turbulent flows. Few studies have published results of global wind loads on movable bridges. Allaart (1949) and Bouma and Rem (1950) performed wind tunnel measurements on a bascule bridge in a simplified environment. The results of these measurements form the main basis for the set of coefficients in NEN 6786-1. The background of other provisions in NEN 6786-1, such as for the wind moments, are unknown to the authors.

A wind tunnel study was carried out to determine global wind loads for the reassessment and renewal of two existing side-by-side swing bridges in the Afsluitdijk (Netherlands). The results of this study provide a good opportunity to expand the literature on global wind loads on movable bridges and to make a comparison with current code provisions for swing bridges. This abstract describes the setup of these measurements, gives some of the results obtained in this study and compares them with values determined with NEN 6786-1 and NEN-EN 1991-1-4.

2. METHODS

This section gives some information about the swing bridges, the setup of the experiment and the analysis performed; a detailed description can be found in Akhnoukh (2022) and Bronkhorst (2022). Figure 1(a) shows a picture of the opened swing bridges. The bridges are located on the West end of the Afsluitdijk, near the village of Den Oever, and serve as a passage for ships between the IJsselmeer and the Waddenzee. Figure 1 shows that the near surroundings of the bridges consist of dikes on both inlets of the fairway with behind them elevated land masses with a traffic road; the more distant surroundings consist mainly of water. Both bridges are plate girder bridges with a length of 45.7 m, a width of 11 m and a deck height of 6.3 m.

The wind tunnel measurements were carried out in the closed circuit atmospheric boundary layer wind tunnel of Peutz (the Netherlands), which has a working section of 7 m, a test section width of 3.2 m and height of 1.8 m. The experiments were performed at a geometric scale of 80. The boundary layer had a roughness length $z_{0,wt}$ = 6.3·10^{-5} m. This value was chosen to represent a full scale roughness length $z_{0,fs}$ = 0.005 m (coastal area). The mean velocity and turbulence intensity in the wind tunnel were V_{ref} = 10.2 m/s and I_{ref} = 0.14 at a reference height h_{ref} = 6.3 m. The full scale wind velocity at this height is 34.1 m/s. The full-scale and wind tunnel Reynolds numbers were $Re_{fs} = \rho v_m d/\mu$ = 4.9·10^6 (with ρ = 1.25 kg/m^3, d = 2.1 m and μ = 1.81·10^{-5} kg/ms) and Re_{wt} = 1.9·10^4 (with d = 2.6 cm). A Reynolds sensitivity study showed that the influence on the peak coefficients is negligible.

Figure 2 shows the model of the swing bridges on the turn table in the wind tunnel. Dynamic balance (Kistler, type 927B) measurements were performed on the southern bridge. Both swing bridges have the same design and the modelled surroundings on the turn table are such that the measured loads also apply for the other swing bridge using symmetry. A total of six configurations were investigated with different opening angles and one configuration with a ship in front of the bridge (see Figure 2). For configurations 0°-0°, 30°-30°, 60°-60°, and 90°-90° measurements were performed for 24 wind directions.

Figure 1. Pictures of the Den Oever swing bridges (a) birds eye view of the opened bridges, (b) top view of the closed bridges (indicated with a circle) and the surroundings.

For configurations 90°-0° and 0°-0° (ship) only 12 wind directions were measured. The results for the other 12 wind directions were respectively obtained from the 90°-90° configuration for wind directions 60° to 210°, and from the 0°-0° configuration for wind directions 0° to 45° and 225° to 345°. The forces and moments were sampled with 400 Hz for a total of 120 s per wind direction. The measured signals were filtered with a 65 Hz low pass filter to remove the influence of the dynamic response of the bridge model.

Peak force coefficients were obtained through extreme value analysis of the measured time series following the procedure described in the Dutch wind tunnel guideline (CUR, 2005). To obtain code-compliant coefficients, these peak coefficients were recomputed using values for the reference area, moment arm, and peak velocity pressure, as explained in Bronkhorst (2022).

3. RESULTS AND DISCUSSION

Table 1 gives an overview of the largest peak force and moment coefficients over all wind directions. Also provided are the coefficients derived from the provisions in NEN 6786-1 and NEN-EN 1991-1-4. An explanation of the derivation and an in-depth discussion of the results can be found in Bronkhorst (2022). The following observations are provided here:

- The force coefficient $c_{Fx,max}$ determined with NEN-EN 1991-1-4 is a factor 1.7 greater than the largest $c_{Fx,max}$ value found in the measurements. The $c_{Fx,min}$ value is a factor 2.6 greater than the largest measured $c_{Fx,min}$ value.
- The force coefficients $c_{Fy,max}$ and $c_{Fy,min}$ derived with NEN-EN 1991-1-4 are a factor of 2 to 2.5 greater than the values from the measurements.
- The force coefficient $c_{Fz,max}$ specified in NEN 6786-1 corresponds well with the largest measured maximum value. The measured $c_{Fz,max}$ values of the other configurations are up to ~25% smaller. The measured $c_{Fz,min}$ values are 25-50% smaller than NEN 6786-1.
- The $c_{Fz,max}$ values derived with NEN-EN 1991-1-4 are a factor 1.8 to 2.1 greater than the largest measured $c_{Fz,max}$ value. The $c_{Fz,min}$ values according to NEN-EN 1991-1-4 are a factor of 2.8 to 3.5 greater than the largest measured $c_{Fz,min}$ value.

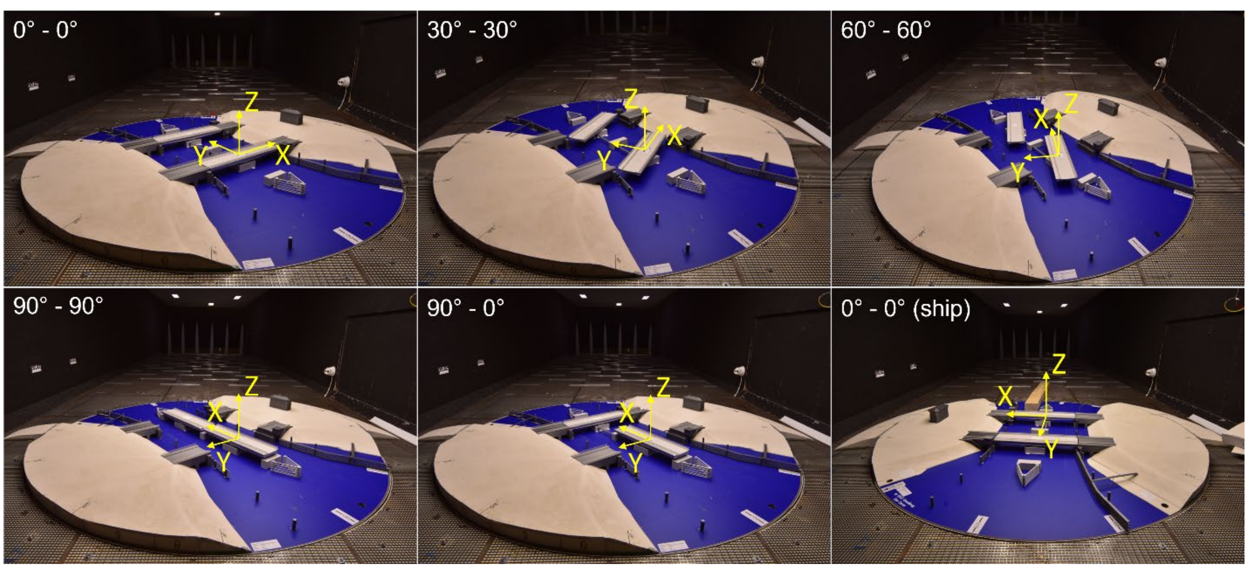

Figure 2. Investigated configurations with the opening angle of the two swing bridges specified. In the configuration 0°-0° (ship), the ship was modelled with a wooden block representing a scaled transport barge.

Table 1. Overview of the peak force and moment coefficients determined for the six investigated bridge configurations in the wind tunnel. Also provided are the coefficients derived from the provisions in NEN 6786-1 and NEN-EN 1991-1-4.

Conf.	$c_{Fx,max}$	$c_{Fx,min}$	$c_{Fy,max}$	$c_{Fy,min}$	$c_{Fz,max}$	$c_{Fz,min}$	$c_{Mx,max}$	$c_{Mx,min}$	$c_{My,max}$	$c_{My,min}$	$c_{Mz,max}$	$c_{Mz,min}$
0°-0°	0.21	-0.21	0.67	-0.54	0.42	-0.20	0.18	-0.23	0.18	-0.18	0.024	-0.022
30°-30°	0.31	-0.21	0.60	-0.52	0.33	-0.18	0.16	-0.17	0.18	-0.19	0.020	-0.032
60°-60°	0.28	-0.21	0.51	-0.53	0.31	-0.25	0.17	-0.18	0.15	-0.16	0.033	-0.024
90°-90°	0.24	-0.20	0.51	-0.55	0.33	-0.26	0.18	-0.19	0.17	-0.17	0.034	-0.026
90°-0°	0.24	-0.21	0.51	-0.59	0.33	-0.22	0.17	-0.20	0.17	-0.15	0.036	-0.026
0°-0° (ship)	0.19	-0.17	0.59	-0.54	0.36	-0.20	0.18	-0.18	0.18	-0.18	0.024	-0.029
NEN 6786-1	-	-	1.30	-1.30	0.40	-0.40	-	-	0.06	-0.06	0.032	-0.032
NEN-EN	0.52	-0.52	1.30	-1.30	0.74	-0.74	0.47	-0.47	-	-	0.026	-0.026
1991-1-4	-	-	-	-	0.90	-0.90	0.58	-0.58	-	-	0.064	-0.064

- The moment coefficients $c_{Mx,max}$ and $c_{Mx,min}$, determined from the provisions in NEN-EN 1991-1-4, are a factor of 2 - 2.5 greater than the largest values from the measurements.
- The moment coefficients $c_{My,max}$ and $c_{My,min}$ derived from the NEN 6786-1 provisions are a factor of 3 lower than the largest values determined in the measurements. NEN-EN 1991-1-4 does not give provisions for this coefficient.
- The moment coefficient $c_{Mz,max}$ determined with NEN 6786-1 is 10% lower than the largest value determined in the measurements. The $c_{Mz,min}$ values from the measurements are smaller or equal to the value determined with NEN 6786-1.
- NEN-EN 1991-1-4 gives two ways to determine the torsional moment. One way results in an underestimation of $c_{Mz,max}$ and $c_{Mz,min}$ for a number of configurations, the other in an overestimation for all configurations.

3. CONCLUSION

Measurements were performed in an ABL wind tunnel on the global wind loads of two side-by-side swing bridges. From the comparison made in this paper between measured results and code provisions shows that NEN-EN 1991-1-4 results in an overestimation of the coefficients c_{Fx}, c_{Fy}, c_{Fz} and c_{Mx}. The coefficients c_{Fz} and c_{Mz} obtained with NEN 6786-1 agree well with the measured result, but the moment coefficient c_{My} is underestimated.

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