ICWE 16
August 27-31, 2023
FLORENCE - ITALY
16th International
Conference on
Wind Engineering

Long-term extreme buffeting response in practical design of long-span bridges

Tor Martin Lystad [1,2], Aksel Fenerci [3], Ole Øiseth [2]

[1]*Norconsult AS, Sandvika, Norway, tor.martin.lystad@norconsult.com*
[2]*Norwegian University of Science and Technology, Trondheim, Norway*
[3]*Norwegian University of Science and Technology, Ålesund, Norway*

SUMMARY:
Recent studies have concluded that there is a need to revisit the design practice for the buffeting response of long-span bridges. Turbulence variability as well as short-term extreme response uncertainty needs to be accounted for to achieve the target annual return period load effect to be used in design considerations. It is found that simplified correction methods suggested in the Norwegian rules for offshore engineering, NORSOK, is also relevant for the design of long-span bridges. This implies that the short-term extreme response should be increased by 10-30 % to achieve the long-term response relevant for design in the ultimate limit state.

Keywords: Long-span bridge, Extreme response, Long-term response

1. INTRODUCTION

Bridges are usually designed based on the partial factor method, where the design value should be based on a load effect with a target annual return period (N) multiplied by a partial factor. A common way to estimate this load effect for long-span bridges is by using the short-term design storm approach:

1. Identify a short-term storm condition with the return period of interest. (This storm is usually identified by an N-year return period mean wind velocity, and its corresponding expected turbulence parameters.)
2. Identify the target return period load effect as the expected extreme value of the short-term buffeting response corresponding to this storm condition.

Recent studies on long-term extreme buffeting of long-span bridges (Lystad et al., 2020, 2021; Xu et al., 2017) indicate that this approach can severely underestimate the target annual return period load effect. The variability of the turbulent wind field parameters and the uncertainty of the short-term extreme response is found to be important when estimating the design load effects. Full long-term extreme response calculations can be used to estimate the target return period load effect directly, but such calculations can often be cumbersome and impractical for design of complex structures like large bridges. However, simplified methods to improve on the short-term design storm approach described above can be used without increasing the complexity of the calculation approach for the practicing engineer. Methods to improve the estimate of the short-term design storm, and to account for the uncertainty of the short-term response suitable for practical design purposes is discussed in this paper. The suggested approaches follow the healthy design principle of making sure simplifications yield conservative estimates. In todays practice, the simplifications in the methods tend to be unconservative, and can in some cases cause a significant reduction in the achieved structural reliability of long-span bridges.

2. EXTREME RESPONSE CALCULATIONS

2.1 Short-term extreme response

The short-term extreme response is the largest peak response during a short-term period, $\tilde{T}$. Since the wind load process is stochastic, the extreme peak will be realization dependent, and thus uncertain. Under the assumptions of a stationary and ergodic short-term process, the cumulative density function (CDF) of the extreme response can be calculated as:

$$F_{\tilde{R}|\mathbf{w}}(\tilde{r}\,|\,\mathbf{w}) = \exp\left\{-v^{+}(\tilde{r}\,|\,\mathbf{w})\tilde{T}\right\} \tag{1}$$

Where v^{+} is the upcrossing rate, $\tilde{r}$ is the short-term extreme response and **w** is the vector containing the environmental parameters.

2.2 Long-term extreme response

The long-term period, *T*, can be considered as a sequence of short-term periods. If the short-term periods can be considered as stationary and ergodic, the CDF for the long-term response can be described as follows (Borgman, 1967):

$$F_R(r) = \exp\left\{\int_{\mathbf{w}} \ln\left\{F_{\tilde{R}|\mathbf{w}}(\tilde{r}\,|\,\mathbf{w})\right\} f_{\mathbf{w}}(\mathbf{w})\,d\mathbf{w}\right\} \tag{2}$$

Where $f_{\mathbf{w}}$ is the joint probability density function (PDF) for the environmental parameters. From this formulation, the long-term extreme response with a target annual return period can be estimated directly, whereas for the short-term approach, it can only be estimated as a stochastic quantity.

The expression in Eq. (2) is computationally demanding to solve for complex systems, especially if the number of environmental variables in **w** is large. Further, the joint PDF of the environmental variables, $f_{\mathbf{w}}$, is often unavailable for most practical applications. This results in a need for simplified methods that account for the long-term effects, without resulting in significantly unconservative design responses.

The expression in Eq. (2) can be written in an approximate form, that enables the problem to be solved using reliability based methods, like the IFORM (Lystad et al., 2021; Winterstein & Haver, 1993). In this way, the long-term problem can be solved efficiently, but challenges remain with this method when considering large complex structures like long-span bridges. The IFORM efficiently iterates towards a solution for a single response quantity, but generally the same iteration must be repeated to find another response quantity in another position of the bridge.

In offshore engineering, the environmental contour method is often used to define the short-term storm by including the effect of environmental variable randomness. Then the effect of the short-term extreme response uncertainty is accounted for by inflated contours, multiplying the expected short-term extreme response by a correction factor, C_{corr}, or by choosing a higher fractile in the short-term extreme response CDF as the design value (Haver & Kleiven, 2004). According to the Norwegian offshore design code, NORSOK (Norwegian Technology Standards Institution, 2007), the correction factor C_{corr} should be picked within the interval 1.1-1.3 or the design value should be chosen as the fractile in the range 85% to 95 % in the short-term CDF to estimate the 100-year annual return period load effect.

3. SIMPLIFICATIONS FOR PRACTICAL DESIGN

3.1 Buffeting calculations

To investigate simplified correction methods to account for the long-term effects for a long-span bridge, the buffeting stresses in stress point 2 (see Figure 1) in the quarter-span of the Hardanger Bridge girder is considered. The Hardanger Bridge (HB) is a classical suspension bridge with a main span of 1310 m, with the first lateral eigen period at 20 seconds, and the first vertical period at 9.1 seconds.

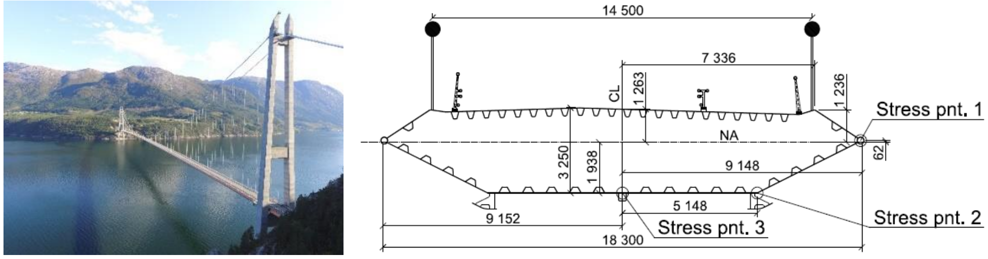

Figure 1. The Hardanger Bridge and the typical girder cross section (Picture and drawing by the authors)

3.2 Turbulence variability

The effect of turbulence variability needs to be taken into account either by using the environmental contour method (Lystad et al., 2020) or by a conservative estimate of the design storm condition (Fenerci & Øiseth, 2017). To establish the environmental contour, the joint PDF of the turbulence parameters are necessary, which is often not available information. The effect of the turbulence variability can be significant (Lystad et al., 2020), so if the contour cannot be established, a simplified approach could be to estimate the design storm conservatively by using the *N*-year return period mean wind velocity in combination of a higher percentile in the statistical distributions for the turbulence parameters as seen in (Fenerci & Øiseth, 2017).

3.3 Long-term correction of short-term response

The full long-term extreme girder stresses for the HB (Eq. (2)) is calculated for the combination of different turbulence parameters described as full stochastic variables (Lystad et al., 2020, 2021). Based on these analyses, the necessary correction factors, C_{corr}, and short-term extreme CDF fractiles, p_{corr}, to achieve the same load effect from a short-term analysis has been estimated and shown in Figure 2. It should be noted that in these figures the short-term response is estimated based on the environmental contour method.

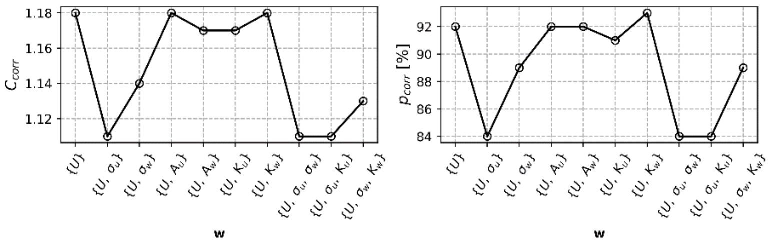

Figure 2. Long-term correction of the short-term response

It can be seen that the appropriate correction factor and fractile in the short-term CDF is dependent on the number of environmental variables described as stochastic variables. If the turbulence parameters that is most important for the considered response is included, the need for correction is reduced, which is also an observation made by (Haver & Winterstein, 2009). It can also be seen that the appropriate corrections needed to estimate the long-term response of the stresses in the HB girder is in line with the suggested intervals in the NORSOK rules.

4. CONCLUSIONS

In conclusion, the expected short-term extreme buffeting response should be corrected for the long-term effect as well as accounting for turbulence variability to achieve a reliable estimate for the target annual return period load effect that should be used in the design of long-span bridges. The corrections suggested in the NORSOK standard is in line with the necessary corrections when considering the girder stresses for the Hardanger Bridge.

REFERENCES

Borgman, L. E., 1967. Random Hydrodynamic Forces on Objects. The Annals of Mathematical Statistics, 38(1), 37–51.

Fenerci, A., & Øiseth, O. 2017. Measured buffeting response of a long-span suspension bridge compared with numerical predictions based on design wind spectra. Journal of Structural Engineering, 143(9). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001873

Haver, S., & Kleiven, G. 2004. Environmental Contour Lines for Design Purposes: Why and When? 23rd International Conference on Offshore Mechanics and Arctic Engineering, Volume 1, Parts A and B, 2, 337–345. https://doi.org/10.1115/OMAE2004-51157

Haver, S., & Winterstein, S. R. 2009. Environmental Contour Lines: A Method for Estimating Long Term Extremes by a Short Term Analysis. Transactions of the Society of Naval Architects and Marine Engineers, 116, 116–127.

Lystad, T. M., Fenerci, A., & Øiseth, O. 2020. Buffeting response of long-span bridges considering uncertain turbulence parameters using the environmental contour method. Engineering Structures, 213, 110575. https://doi.org/10.1016/J.ENGSTRUCT.2020.110575

Lystad, T. M., Fenerci, A., & Øiseth, O. 2021. Long-term extreme buffeting response of cable-supported bridges with uncertain turbulence parameters. Engineering Structures, 236, 112126. https://doi.org/10.1016/j.engstruct.2021.112126

Norwegian Technology Standards Institution. 2007. NORSOK N-003 Actions and Action Effects.

Winterstein, S. R., & Haver, S. 1993. Environmental Parameters For Extreme Response : Inverse FORM with Omission Factors. Proc 6th Int. Conf of Structural Safety and Reliability, March 2018.

Xu, Y., Øiseth, O., Naess, A., & Moan, T. 2017. Prediction of long-term extreme load effects due to wind for cable-supported bridges using time-domain simulations. Engineering Structures, 148, 239–253. https://doi.org/10.1016/J.ENGSTRUCT.2017.06.051