

Reliability based design optimization of the deck suspension bridge considering buffeting constraints

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SUMMARY

A Reliability-Based Design Optimization (RBDO) method was applied to a suspension bridge, specifically the Great Belt Bridge, using a girder box section and incorporating probabilistic buffeting constraints. The girder box section was characterized by four design variables corresponding to the thicknesses of the upper, lower, and lateral plates of the deck. Regarding the buffeting constraints, uncertainty in the wind speed, structural damping, and both the vertical length scale and turbulence intensity was considered. In the RBDO analysis, a target reliability index was specified and required to be satisfied for the vertical and torsional accelerations at midspan, as well as for the maximum static displacement of the deck.

Keywords: *reliability-based design optimization, buffeting, suspension bridge*

1. INTRODUCTION

The design of long-span suspension bridges requires particular attention to structural reliability, especially regarding wind-induced vibrations such as buffeting. This aeroelastic phenomenon can lead to fatigue damage when the resulting accelerations are high, as well as discomfort for users crossing the bridge.

In addition, structural optimization plays a key role in improving the design of such bridges. Minimizing the amount of material used is crucial for reducing construction costs while maintaining a safe structural configuration. RBDO incorporates system uncertainties into the optimization process (Kusano et al., 2014, 2020), making it more robust than deterministic optimization approaches.

In this study, RBDO is applied to a box-girder deck section, with buffeting-induced responses considered as constraints. Several sources of uncertainty are introduced in the buffeting analysis to more accurately capture the variability inherent in the system.

2. RELIABILITY AND RBDO ANALYSIS OF SUSPENSION BRIDGES

Reliability analysis provides the probability of structural failure with respect to a defined limit state, while accounting for multiple sources of uncertainty. In the buffeting analysis, there are various parameters with associated uncertainties that significantly influence the structural response. In this work, we considered uncertainties in the wind velocity, the structural damping, the vertical length scale and the vertical turbulence intensity. The distribution and characterization of these random variables are shown in Table 1.

Table 1: Characterization of the random variables in the reliability analysis

Random variable	Distribution	Mean value	CoV
Wind speed U	Gumbel	25	6
Structural damping ξ	Log-Normal	0.003	0.4
Vertical turbulence intensity I_w	Log-Normal	0.05	0.1
Vertical integral length scale L_w	Log-Normal	20	0.1

The limit state function that defines the structural failure under buffeting constraints can be written as:

$$G(\mathbf{x}) = RMS_{max} - RMS_{buff}(x_i) \quad i = 1, \dots, n \quad (1)$$

In Eq.(1) RMS_{max} is the maximum buffeting response established in the project, RMS_{buff} is the buffeting response obtained in the analysis, and x_i are all the random variables considered in the buffeting analysis. After defining the random variables and establishing the limit state function, structural reliability can be determined using the First Order Reliability Method (FORM). This method defines the reliability index, denoted as β , as the minimum distance between the origin in the normalized random variable vector \mathbf{u} and the limit state function $G(\mathbf{u}) = 0$. This is solved as an optimization problem defined in Eq.(2)

$$\min \beta = \sqrt{\mathbf{u}^T \cdot \mathbf{u}} \quad \text{s.t.} \quad G(\mathbf{u}) = 0 \quad (2)$$

Once β is obtained, the probability of failure is computed as $\Phi(-\beta)$, where Φ denotes the cumulative distribution function of the standard normal distribution. The iterative procedure required to determine the reliability index demands the evaluation of the limit-state function and its gradients at each step. Consequently, a large number of buffeting analyses must be performed during every iteration. This results in a significant computational burden due to the high dimensionality of the random variables and the wide frequency range considered in each buffeting analysis.

To alleviate this cost, a parallelization strategy using a High-Performance Computing Cluster (HPCC) was implemented. In this method, the full frequency range is partitioned into smaller sub-intervals that can be analysed simultaneously. After all interval-specific analyses are completed, their results are combined to obtain the full structural response over the entire frequency range.

In RBDO analysis, the objective is to minimize the weight of the deck section while satisfying reliability constraints associated with buffeting and static displacement conditions. The RBDO problem can be formulated as follows:

Minimize: *Girder volume*(**d**)

subject to:

$$\begin{aligned}
 g_1: P[\ddot{w}_{max} - \ddot{w}_{buff} \leq 0] &\leq P_f & P_f &= \Phi(-\beta) \text{ where } \beta = 4.5 \\
 g_2: P[\ddot{Z}_{eq,max} - \ddot{Z}_{eq,buff} \leq 0] &\leq P_f & P_f &= \Phi(-\beta) \text{ where } \beta = 4.5 \\
 g_3: w_d/w_{max} - 1 &\leq 0 & \text{where } w_{max} &= L/500 \\
 g_4: 10 \text{ mm} \leq d_i &\leq 40\text{mm} & \text{where } i &= 1,2,3,4
 \end{aligned} \tag{3}$$

Where \ddot{w}_i refers to the maximum vertical accelerations, $\ddot{Z}_{eq,i}$ refers to the equivalent torsional accelerations and w_d is the static vertical displacement. In Eq.(3) g_1 is the probabilistic buffeting constraint for the vertical accelerations, where a minimum beta reliability index of 4.5 is established, g_2 is the same constraint but for the equivalent torsional accelerations, g_3 is the deterministic constraint for the maximum displacement and g_4 sets the design limits for the four design variables.

3. APPLICATION EXAMPLE: GREAT BELT BRIDGE

The method described in the previous section was applied to optimize the box girder section of the Great Belt Bridge considering buffeting constraints. Figure 1 illustrates the bridge's general layout. The structural model used for the modal analysis was developed in the open-source software OpenSees, with the deck and towers modelled as beam-column elements that account for large displacements.

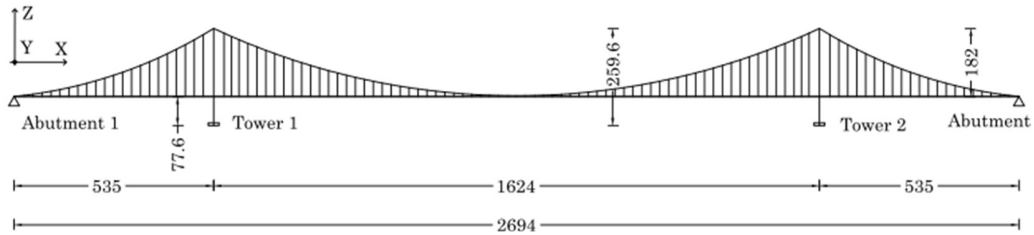


Figure 1: Great Belt bridge general layout

The steel bridge deck is a slender, aerodynamic box girder measuring 31 meters in width and 4 meters in depth. A box girder configuration was selected instead of plate or truss girders because it offers lower construction and maintenance costs. Its external form also provides favorable structural and aerodynamic performance (Larsen, 1993).

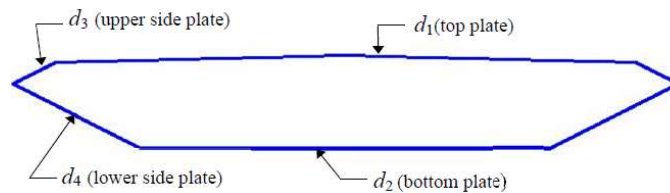


Figure 2: Design variable of the optimization problem

The four design variables considered in the thickness of the plates of the girder as shown in Figure 2. The RBDO algorithm varies the values of the thickness of each plate for each iteration until the optimum values is obtained. The variation of each variable can be seen in Figure 3.

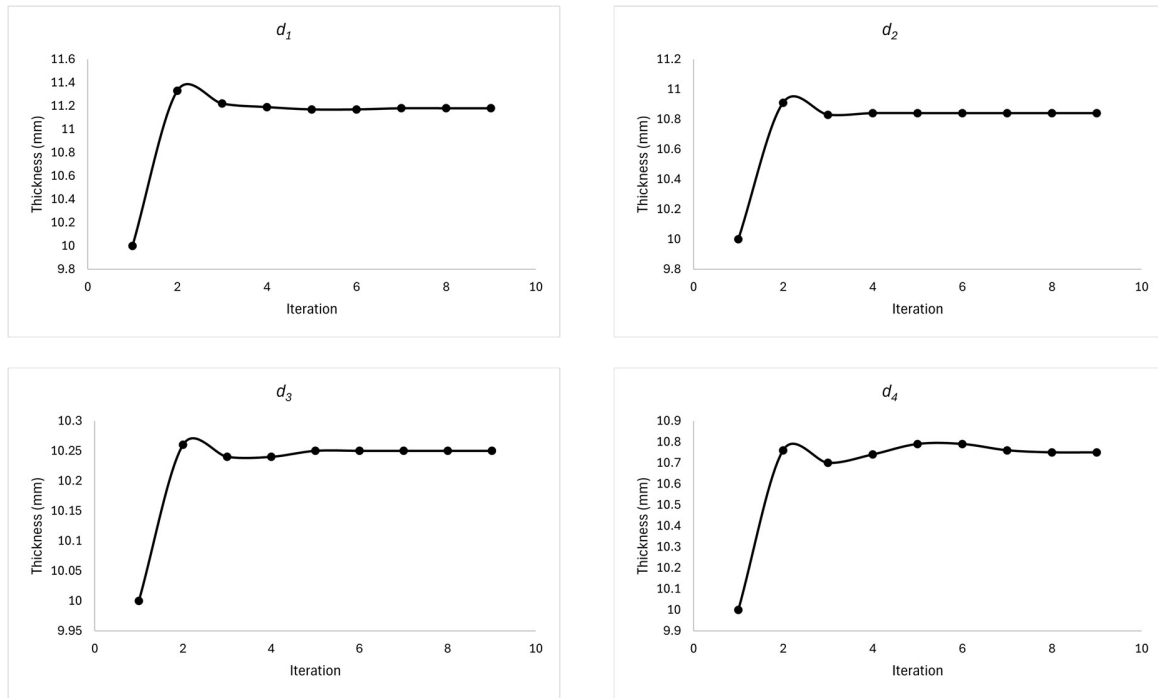


Figure 3: Design variables variation during the iterations of the algorithm

4. CONCLUSIONS

The RBDO was carried out for a girder-box deck section of a long-span suspension bridge. The buffeting constraints account for uncertainties in the extreme wind velocity, the structural damping, the vertical integral length scale and the vertical turbulence intensity. This approach yields an optimal design that incorporates the inherent uncertainties of wind-induced phenomena in suspension bridges, resulting in a solution that is more robust than traditional deterministic designs. This probabilistic optimization varies the thicknesses until achieving a minimum cross-sectional area and therefore a material saving, while ensuring that the established safety conditions are met with the defined beta.

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