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The Role and Capabilities of Aero-structural Optimization of Long-span Cable-Supported Bridges with Multi-box Deck

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SUMMARY

In recent years suspension bridges have reached main spans of more than 2000 m, and cable-stayed bridges have surpassed 1100 m. Moreover, more challenging project proposals are being studied, including decks composed of two or three streamlined boxes. They must be designed considering the aeroelastic phenomena produced by laminar and turbulent wind and providing safety and comfort to users during their service life. Given their significance, using the best technologies for their design is essential, and numerical optimization methods are powerful tools with great potential to advance contemporary designs. They have been applied in other engineering fields, but their implementation in the design of long-span bridges considering aeroelastic constraints is very recent. The optimization problem can be formulated as deterministic, meaning that all bridge properties and loads' values have fixed known values, or probabilistic, indicating that a level or uncertainty is included in the formulation due to the random nature of wind speed and possible inaccuracies in bridge properties. This abstract describes both approaches of aero-structural optimization applied to long-span bridges with multi-box decks considering flutter and buffeting. Results of the suspension bridge over the Messina strait and a long-span cable-stayed bridge are presented.

Keywords: Super long span bridges, Multi-box deck, aeroelastic phenomena, design optimization.

1. THE MOMENTUM OF LONG-SPAN BRIDGES

The past decades have been a period of realization of multiple long-span bridges. Some of them adopted multi-box decks, given their good aeroelastic performance. The Xihoumen and the Yavuz Sultan Selim are representative examples of suspension bridges fitted with twin-box decks. The Edong and Stonecutters bridges demonstrate the applicability of this deck configuration for cable-stayed bridges. Challenging designs as the Messina Strait bridge contain a deck composed of three boxes. Still, the design of efficient multi-box decks is a technical challenge. This study shows the capabilities of numerical optimization as a design tool for these structures under the wind.

2. NUMERICAL OPTIMIZATION

The modern formulation of structural optimization was defined by Schmit (1960), (see Hernandez (2010)) as a non-linear constrained optimization problem in which the purpose is to identify the values of a set of design variables **X** that produce the best value of a function $F(\mathbf{x})$, coined objective function, while accomplishing a number of conditions, also labeled constraints $g_j(\mathrm{X}) \le 0 \quad (j = 1,\ldots n)$. These constraints can be deterministic or probabilistic. In the latter case, some characteristics of the loads and bridge properties are considered of random nature. The first application of numerical optimization in long-span bridges with constraints related to aeroelastic phenomena, namely flutter, corresponds to Jurado et al., 2004, and Nieto et al., 2009. These studies optimized the thicknesses of the plates of the deck cross-section but maintained the same deck shape. Deck shape variables were included in the optimization problem by harnessing surrogates trained with CFD simulations in Cid Montoya et al., 2018. Optimization techniques are iterative processes in which the design variables change at each iteration, and each modification of deck geometry alters its aerodynamic properties. Thus, a fully numerical procedure avoiding wind tunnel testing is needed. Surrogate models can be generated using CFD simulations data for values of the design variables that map their range of variation (Forrester et al. 2008). This methodology is applied to long-span cable-stayed and suspension bridges in the next sections.

3. DETERMINISTIC OPTIMIZATION OF DECK SHAPE AND CABLE AREAS OF A LONG-SPAN CABLE-STAYED BRIDGE UNDER STRUCTURAL, FUTTER, AND BUFFETING CONSTRAINTS

This formulation has been applied to the bridge shown in Figure 1 (Cid Montoya et al. 2021). The objective function is defined as the sum of the volume of deck V_D and the stays V_S as

$$\min F(C,H,G,\mathbf{t},\mathbf{A},\mathbf{N}) = \quad \min\left(A_x(C,H,\mathbf{t})L_D + V_t(H,G) + P_d \sum_{i=1}^{n_s} A_i L_{s,i}\right) \tag{1}$$

where A_x stands for the deck cross-section area, L_D is the total deck length, V_t represents the volume of the transversal beams that link the two girders of the twin-box deck system, and n_t is the number of transversal beams. The volume of cables is obtained by summing the product of the cross-section area A_i of each stay by its length $L_{s,i}$, and P_s is the number of planes of stays. These quantities are a function of the set of design variables, which includes the cross-section area A_i and prestressing force N_i of the n_s stays, the deck plate thickness t, and the shape design variables that define the geometry of the twin-box deck.

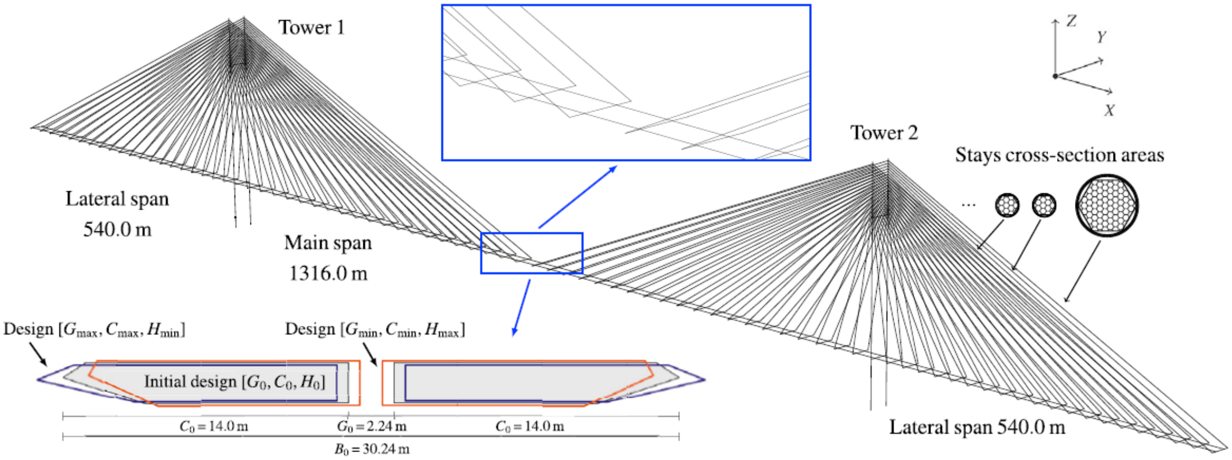

Figure 1. Cable stayed bridge and detail of deck

The optimization problem is subject to two kinds of design constraints:

- ***Structural constraints***: those related to the bridge's performance under the action of gravity.

The list of structural constraints reported by Cid Montoya et al. (2018) can be summarized as:

1. Displacements along the deck and towers under self-weight and live loads.
2. Normal stress at the top and bottom fibers of the deck under self-weight and live loads.
3. Tensile stress in the stays under self-weight and live loads.

- ***Aeroelastic constraints***: those related to the bridge performance under the action of wind:
  1. Minimum critical flutter velocity allowed for the bridge: where $U_{f,min}$ is the minimum value accepted for the critical flutter velocity U_f.
  2. Maximum values allowed for the RMS of lateral vertical and torsional accelerations, produced by buffeting forces checked for the set of n_h wind velocities considered U_h, at n_j control points uniformly distributed along the deck.

This selection generates a total number of 4817 design constraints. The wind velocity intervals considered in the buffeting constraints to establish limitations in the RMS of buffeting accelerations are U_1 = [0 -15] m/s, U_2 = [15 – 30] m/s, U_3 = [30-45] m/s and U_4 = [45 – 60] m/s. The maximum values adopted are based on the specifications established for the Messina Strait Bridge (Stretto di Messina, 2004) and the International Organization for Standardization (ISO) specifications, particularly the code ISO 2631, 2018. Table 1 summarizes the main results of the optimum design and the convergence process, and more details will be reported in the full paper.

Table 1. Summary of the results of the aero-structural optimization: design variables, objective function, flutter velocity, and RMS of accelerations. The absolute Δ and relative δ changes produced by the optimization are shown.

Design	Iter	$F[\mathrm{m}^3]$	C[m]	H[m]	G[m]	t[cm]	$\bar{A}^B[\mathrm{m}^2]$	$\bar{A}^s[\mathrm{m}^2]$	$\bar{N}[\mathrm{MPa}]$	$U_f[m/s]$	$max(\ddot{w}^{60}_{RMS})$	$max(\ddot{w}^{60}_{RMS})$
Initial	1	10079.94	14.00	2.0020	2.2400	4.000	0.5000	0.0500	325.0	124.62	0.4359	0.2164
Optimum	121	7819.04	14.336	2.2022	1.6125	3.470	0.5052	0.0213	517.1	100.71	**0.4992**	**0.2997**
Δ[-]	-	-2260.90	0.336	0.2002	-0.6275	-0.530	0.0052	-0.0287	192.1	-23.91	0.0632	0.0833
Δ[%]	-	-22.43	2.40	10.00	-28.01	-13.25	1.13	-57.46	59.11	-19.19	14.50	38.48

4. PROBABILISTIC OPTIMIZATION OF DECK THICKNESS OF THE MESSINA BRIDGE SUBJECT TO STRUCTURAL CONSTRAINTS AND FLUTTER SPEED

A formulation of probabilistic optimization of the deck of the Messina bridge was proposed by Kusano et al. (2014). Random variables are the wind speed and the flutter derivatives that were assumed to have a normal distribution with variable standard deviation. The deck of the bridge appears in figure 2 and the design variables of the thicknesses of the lateral boxes in figure 3.

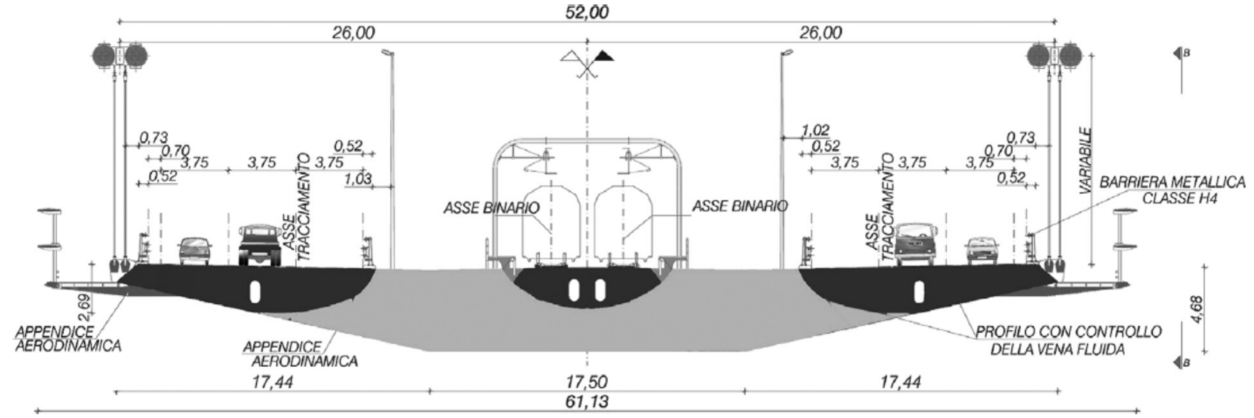

Figure 2. Cable stayed bridge and detail of deck

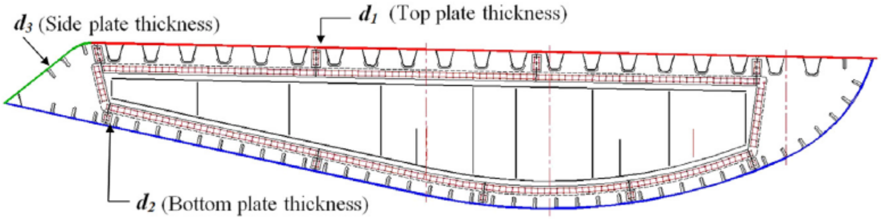

Figure 3. Cable stayed bridge and detail of deck

The probabilistic formulation is written as: Minimize the girder cross-sectional area (**d**) subject to

- ***Structural constraints***: those related to the bridge's performance under the action of gravity.
  1. Displacements along the deck under self-weight and live loads.
  2. Normal stress at the top and bottom fibers of the deck under self-weight and live loads.
- ***Aeroelastic constraints***: those related to the bridge performance under the action of wind:
  1. Probability of failure P_f with regards to the required flutter speed.

The results of the design variables and the objective function for the reliability index β^T =11, which is related to P_f as $P_f = \Phi\left(\beta^{\mathrm{T}}\right)$, will be presented in the full paper.

5. CONCLUSIONS

The capabilities of numerical optimization on the aero-structural design of long-span bridges have been demonstrated in two examples considering different aeroelastic phenomena, design variables, and, eventually, random variables. The multidisciplinary nature of the methodology presented involves several challenges related to the accuracy of the CFD simulations, the need to include more aeroelastic phenomena, and the addition of more details in deck geometry. Nevertheless, it is forecasted that this bridge design tool will be implemented more frequently in the future.

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REFERENCES

Cid Montoya, M., Hernandez, S., Nieto, F. 2018. Shape optimization of streamlined decks of cable-stayed bridges considering aeroelastic and structural constraints. J Wing Eng Ind Aerod, 177: 429–55.

Cid Montoya M, Nieto F, Hernandez S, Fontán A Jurado J, Kareem A 2021. Optimization of bridges with short gap streamlined twin-box decks considering structural, flutter, and buffeting performance. J Wing Eng Ind Aer; 208.

Forrester, A.I.J., Sobester, A., Keane, A.J., 2008. Engineering Design via Surrogate Modelling. Wiley.

Hernández, S. (2010). Structural optimization. 1960-2010 and beyond. Comput. Technol. Rev., 2, 177.

ISO 2631. (2018). Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration. ISO.

Jurado, J.A., Hernandez, S., 2004. Sensitivity analysis of bridge flutter with respect to mechanical parameters of the deck. Struct. Multidiscip. Optim. 27, 272–283.

Kusano, I., Baldomir, A., Jurado, J.A., Hernandez, S., 2014. Reliability based design optimization of long-span bridges considering flutter. J. Wind Eng. Ind. Aerod. 135, 149–162.

Stretto di Messina. (2004). Messina Strait Bridge: Basis of design and expected performance (Ponte sullo Stretto di Messina: Fondamenti progettuali e prestazioni attese per l'opera di attraversamento). Report GCG.F.04.01.

Nieto, F., Hernandez, S., Jurado, J.A., 2009. Optimum design of long-span suspension bridges considering aeroelastic and kinematic constraints. Struct. Multidiscip. Optim. 39, 133–151.

Schmit, L.A., 1960. Structural design by systematic synthesis. In: Proc. of the 2nd Conf. on Electronic Comp. ASCE.