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Aero-structural optimization of a twin-box bridge: Balancing structural, flutter and buffeting design requirements

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ABSTRACT

The design of long-span bridges is highly conditioned by their aeroelastic responses. Improving the aeroelastic characteristics of the deck by introducing shape modifications is the most efficient way to prevent undesired wind-induced phenomena. However, shape variations may compromise its structural responses, turning the deck geometry design into a trade-off problem whose optimum solution is defined by the particular requirements of each project.

In previous studies, a design framework combining CFD simulations, surrogate models, FEM analyses, optimization algorithms and parallel computing was developed and applied to a long-span cable-stayed bridge with a single-box deck cross-section and several aeroelastic phenomena were considered as design constraints. The present study expands the capabilities of the methodology by recasting the problem for long-span bridges considering twin-box decks with a relatively short gap. This deck typology provides a better aeroelastic performance in exchange for a poorer stiffness contribution, where the gap between boxes and the boxes' geometry play a key role.

The optimization problem is formulated seeking the minimization of the steel volume of the cable-supporting system and the deck. The problem is conditioned by 4817 design constraints of structural and aeroelastic nature. The structural design constrains control the performance of the bridge under the action of self-weight and 4 representative live load cases in terms of the displacements of deck and towers and the stress level of the deck and stays. On the other hand, the aeroelastic design constraints are the flutter critical wind velocity of the bridge and the buffeting-induced RMS of accelerations along the deck at four different reference wind velocities.

Results for this application case show that the geometry of each individual deck box is an important feature for the control of the buffeting response, particularly the vertical acceleration. Conversely, flutter and torsional buffeting constraints require designs with larger gap distance and different box geometries. Hence, depending on the considered wind load scenario and the specific requirements of each project, an optimum aero-structural bridge design with a particular deck shape can be identified.

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1. INTRODUCTION

Deck cross-section geometries of long-span bridges are designed aiming at minimizing the aerodynamic and aeroelastic loads and increasing its stiffness contribution to the bridge. The potential of introducing deck shape modification to improve the aeroelastic responses of a long-span bridge was highlighted in Larsen and Wall, 2012, particularly for vortex-induced vibrations. Other aeroelastic phenomena are also extremely sensitive to deck shape modifications, such as flutter (Mannini et al. 2016) and buffeting (Li et al. 2018). Furthermore, the deck configuration is also very influential in the bridge dynamic properties, which play a fundamental role in the aeroelastic responses (Larsen and Larose, 2015).

In the case of twin-box decks, the gap distance is an additional variable that deeply affects its aerodynamic performance. The influence of the gap distance in the self-excited forces was studied in Yang et al. 2015. The buffeting performance of decks with different shape and gap distance were compared in Wang et al. 2020. Furthermore, the relationship between the gap and vortex-indcued vibrations was analyzed in Kwok et al. 2012 and Laima and Li, 2015. Hence, it is important to consider all these factors in the design process in order to successfully achieve the reduction of wind-induced effects on the bridge.

In general, twin-box decks provide a better aeroelastic performance than single-box decks in exchange for a poorer stiffness contribution. In both cases, the definition of the deck geometry is key issue in the bridge design, and the most efficient way to find the balance between all design requirements is the use of optimization algorithms. The application of numerical design techniques in the aero-structural optimization of long-span bridges with single-box deck sections was previously introduced in Cid Montoya et al. 2018a, 2018b, 2020), including flutter and buffeting responses. Similar efforts have been done in other studies for the shape optimization of tall buildings (Bernardini et al. 2015, Elshaer et al 2017, Ding and Kareem 2018) and other structures (Horvat et al. 2020), and there is a growing interest in the optimization of bridges considering wind-induced responses (Santos et al. 2019).

The goal of this paper it to formulate the aero-structural optimization problem for long-span bridges with twin-box decks considering simultaneously flutter and buffeting design constraints. The deck shape design variables adopted are the deck depth, the width of each box and the gap distance between the boxes. The aeroelastic characteristics of every deck geometry within the shape domain are provided by an aerodynamic surrogate model reported in a previous work (Nieto et al. 2020) in combination with the use of the quasi-steady formulation (Scanlan, 1987). The optimum design obtained for a long-span cable-stayed bridge with a short gap twin-box deck is presented and discussed. Finally, the influence of the aeroelastic constraints on the final design is studied.

2. DESCRIPTION OF THE OPTIMIZATION FRAMEWORK

The methodology adopted in this study is described in Figure 1. The aerodynamic surrogate model (Forrester et al. 2008) used to emulate the aerodynamic force coefficients and their slopes has been reported in Nieto et al. 2020, where the model was validated and an approximation to estimate the aerodynamic centers of the twin-box deck was proposed. With this information, flutter derivatives and admittance functions can be estimated. The buffeting-induced accelerations are obtained using the frequency domain approach (Diana et al. 2019).

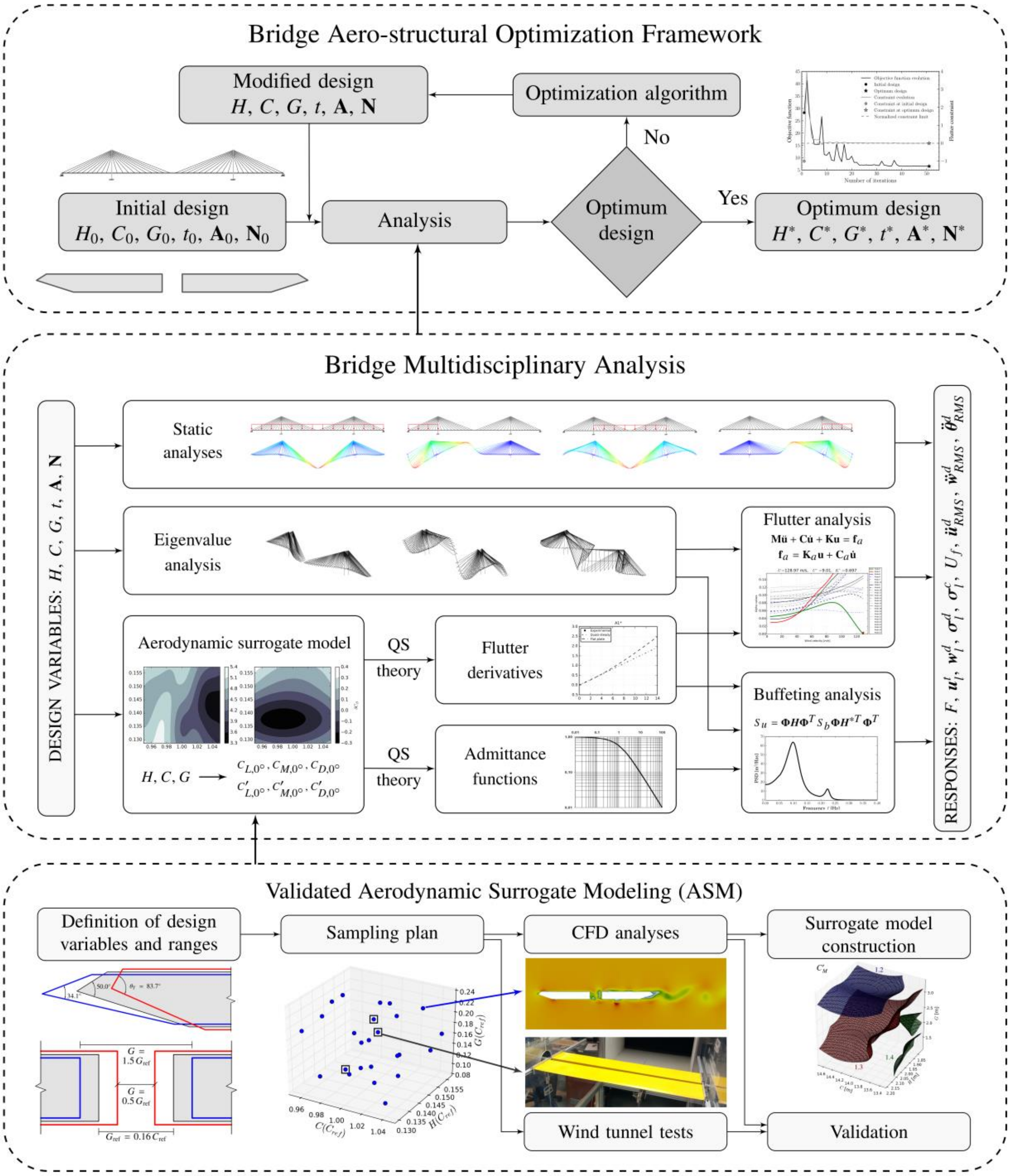


Fig. 1. Flowchart of the aero-structural optimization framework for twin-box bridges.

3. APPLICATION CASE

This methodology has been applied to a long-span cable-stayed bridge with the twin-box deck arrangement studied in Nieto et al. 2020, where box shape modifications and relatively short gap distances are considered as shown in Figure 2. The layout of the parametrized FEM of the long-span bridge is shown in Figure 3.

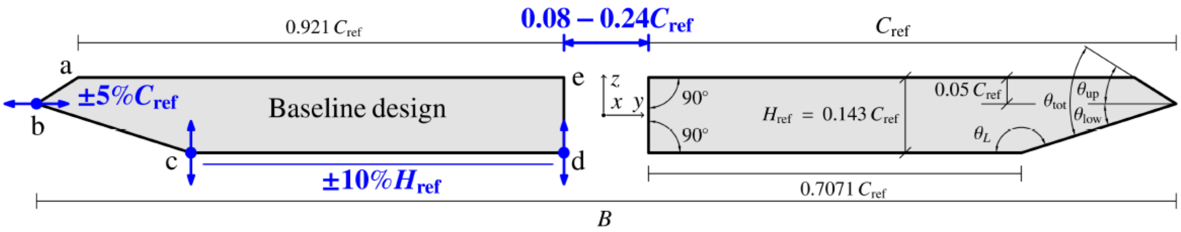


Fig. 2. Initial design of the twin-box deck cross-section and definition of the shape design variables.

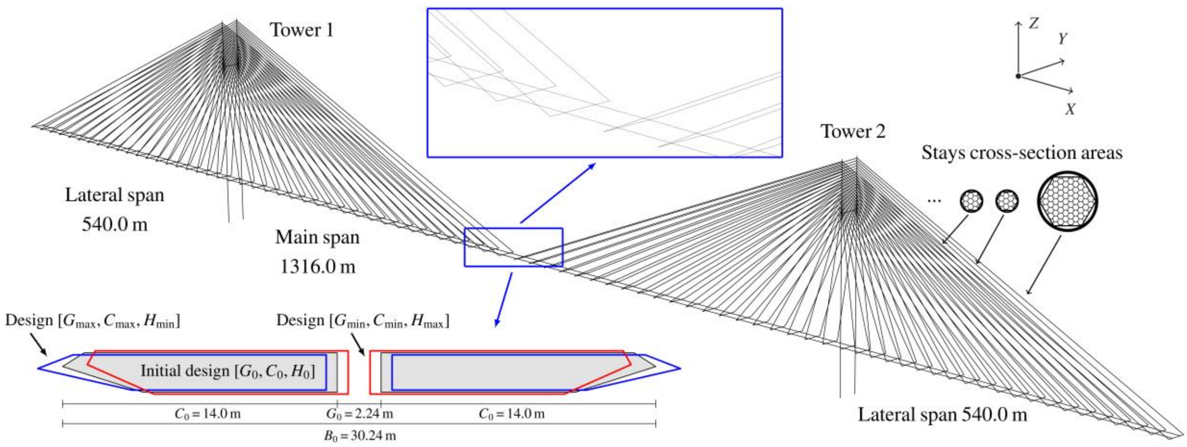


Fig. 3. Layout of the parametrized FEM of the long-span cable-stayed bridge

The objective function to be minimized is the sum of the steel volume of the cable-supporting system and the deck. The design variables are the three deck shape variables (*C*, *H*, and *G*), the deck plate thickness (*t*), and the cross-section area and prestressing forces of each stay in the cable supporting system (**A** and **N**). It is important to include in the optimization problem all the structural characteristics that may affect the aeroelastic responses of the bridge, such as the deck shape and size, and the design of the cable supporting system, aiming at combining in the aero-structural bridge optimization framework the capabilities of aerodynamic shape optimization (Bernardini et al. 2015) and structural optimization (Ferreira and Simoes, 2020). The design constraints of the problem are summarized in Table 1, where it can be seen that structural constraints involve kinematic and stress limitations, and aeroleastic constraints include the RMS of accelerations caused by the buffeting phenomenon along the deck for 4 different wind scenarios U=[15,30,45,60] m/s, as well as the critical flutter velocity of the bridge.

Table 1. Summary of the structural and aeroelastic constraints considered in the aero-structural optimization problem.

Type	Location	Limit constraint value	# RP [R]	Load cases [L]	# constraints
Displacement (SW)	Deck nodes	$w_{\max} = 0.05\,\mathrm{m}$	78	SW (1)	78
	Tower top nodes	$u_{\max} = 0.05\,\mathrm{m}$	2	SW (1)	2
Displacement (L_l)	Lateral spans	$w_{\max} = 540\,\mathrm{m} / 500 = 1.080\,\mathrm{m}$	38	L (4)	152
	Main span	$w_{\max} = 1316\,\mathrm{m} / 500 = 2.632\,\mathrm{m}$	40	L (4)	160
	Tower top nodes [T]	$u_{\max} = 314.4\,\mathrm{m} / 600 = 0.524\,\mathrm{m}$	2	L (4)	8
Stress (SW & L_l)	Deck top fiber	$\sigma_{\max} = 200\,\mathrm{MPa}$	244	L (4)	976
	Deck bottom fiber	$\sigma_{\max} = 200\,\mathrm{MPa}$	244	L (4)	976
	Stays	$\sigma_{\max} = 800\,\mathrm{MPa}$	80	SW & L (5)	400
Buffeting ($\ddot{r}_{RMS}$)	Deck lateral acc.	$\ddot{u}_{RMS}^{\max}(U) = [0.005, 0.05, 0.15, 0.30]\ \mathrm{m/s^2}$	172	B_U (4)	688
	Deck vertical acc.	$\ddot{w}_{RMS}^{\max}(U) = [0.0125, 0.10, 0.25, 0.50]\ \mathrm{m/s^2}$	172	B_U (4)	688
	Deck torsional acc.	$\ddot{Z}_{eq_{RMS}}^{\max}(U) = [0.005, 0.05, 0.15, 0.30]\ \mathrm{m/s^2}$	172	B_U (4)	688
Flutter	Bridge deck	$U_{f,min} = 100\,\mathrm{m/s}$	-	U_f (1)	1
Total number of design constraints				SW, L, B_U & U_f	4817

[R] RP = Response points where the response of the bridge is controled by a design contraint.
[L] SW = self weight, L = live loads, B_U = buffeting loads for each wind velocity value U, (#) = total number of load cases

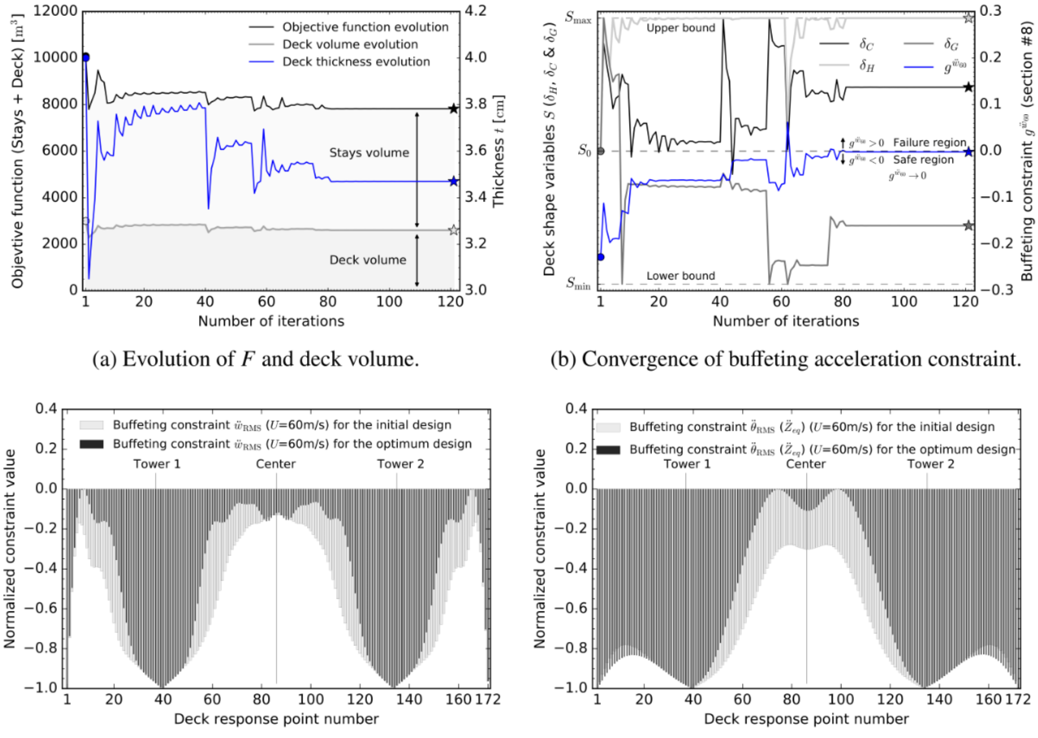
4. RESULTS AND DISCUSSION

A subset of the optimization results is presented in this section. Table 2 provides a summary of the optimum values for the design variables and the objective function, and indicates which aeroelastic constraints (see Table 1) are active when the optimization reaches convergence: the vertical and torsional RMS of accelerations at wind velocity of 60 m/s. Furthermore, the flutter constraint is close to the limit imposed. It should be noticed that the gap distance was reduced, the depth has been increased as well as the boxes' width. Figure 4 illustrates the convergence of the optimization problem, and the degree of fulfillment of buffeting constraints along the deck. The role played by the deck shape variables can be understood by examining Figure 4b), where the sensitivity of the buffeting constraint to deck shape variations is clear. Figures 4c) and 4d) shows that the maximum buffeting accelerations can be found in different locations along the deck.

Table 2. Summary of the results obtained in the aero-structural optimization.

Design	Iter.	F [m^3]	C [m]	H [m]	G [m]	t [cm]	$\overline{A^B}$ [m^2]	$\overline{A^s}$ [m^2]	$\overline{N}$ [MPa]	U_f	$\max(\ddot{w}_{RMS}^{60})$	$\max(\ddot{\theta}_{RMS}^{60})$
Initial	1	10 079.94	14.000	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	1.03	-57.46	59.11	-19.19	14.50	38.48

[*] The constraints active in the optmization process are indicated in bolt and underlined.



(a) Evolution of F and deck volume. (b) Convergence of buffeting acceleration constraint.

(c) Vertical buffeting constraint along the deck. (d) Torsional buffeting constraint along the deck.

Fig 4. Subset of results: Objective function, buffeting convergence and buffeting normalized design constraints.

The influence of the aeroelastic constraints on the optimum deck shape is shown in Figure 5. The optimum design obtained considering the design constraints reported in Table 1 is shown in Figure 5 as Set A, and it is plotted along with the geometry of the initial design to appreciate the deck changes introduced by the optimization algorithm. Set B stands for an alternative set of limit values for the design constraint consisting in the same values as Set A but increasing the minimum flutter velocity to 120 m/s. In this case, the optimization algorithm uses the gap distance to improve the bridge flutter performance to fulfill the more demanding flutter requirement of Set B.

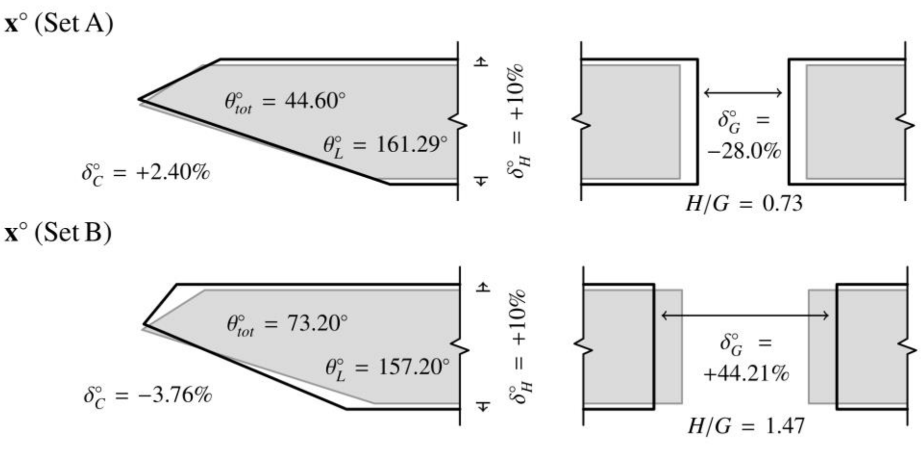


Fig 5. Optimum designs for the twin-box deck cross-section.

5. CONCLUSIONS

This paper reports the implementation of an aero-structural optimization framework for the design optimization of long-span bridges with short gap twin-box decks considering a high number of design constraints, which includes displacements and stress under gravitational loads, the critical flutter wind velocity, and buffeting-induced RMS of accelerations in three degrees of freedom. Results show that the optimization algorithm is able to reduce the material of the structure while keeping the required level of safety in the considered aeroelastic responses. The gap distance is an important design variable, particularly to improve the flutter response of the bridge. On the other hand, modifications in the box geometry are very useful to control the buffeting response, particularly through the box width *C*. Increasing *C* helps to decrease the vertical acceleration at the expense of higher torsional accelerations. The equilibrium between the deck shape variables and the aeroelastic constraints has been found through the aero-structural optimization process.

Hence, depending on the considered wind load scenario and the specific requirements of each project, an optimum aero-structural bridge design with a particular deck shape can be identified.

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