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Experimental and computational aeroelastic studies of a curved deck arch bridge

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SUMMARY
Cable-supported bridges often have complex geometries designed for aesthetic appeal with original curved shapes. These structures present a structural challenge because they are highly flexible, yet their performance under extreme wind loads raises concerns. This paper presents aeroelastic studies of flutter, buffeting, and vortex excitation of a curved-deck arch bridge over the Duero River near Valladolid, Spain. Sectional wind tunnel tests were also performed to study the aerodynamics of the arch.

Keywords: Curved arch bridge, aeroelasticity, aerodynamics.

1. HYBRID METHOD FOR AEROELASTIC STUDIES

This paper analyzes a bow-string road bridge with two carriageways, one in each direction, with a slight curvature in plan (see Fig. 1). In order to obtain the necessary parameters for the aeroelastic analysis of flutter and buffeting phenomena, aerodynamic and aeroelastic tests must be performed in a wind tunnel on a sectional model of the bridge deck. These experiments determine the aerodynamic coefficients of drag, lift and moment C_D, C_L and C_M, and the flutter functions A^*_{1-6}, H^*_{1-6}, P^*_{1-6}. This is the experimental phase of the hybrid method, while the computational part works with structural models of the entire bridge to obtain the critical wind speed at which the flutter phenomenon appears and the nature of the displacements generated by turbulent wind in the buffeting study. Specifically, a finite element model with SAP2000 software has been used to obtain natural vibration modes and frequencies, and subsequently, programs developed by the Structural Mechanics group at the University of A Coruña were used to analyze flutter and buffeting.

Figure 1. View of the arch bridge and sectional model in the wind tunnel.

The sectional model is built to a 1:40 scale and represents a 37.2 m segment of the deck. Although the deck is curved, a straight sectional model was created because the bridge curvature layout is very small. However, the curvature will be taken into account during the computational phase. The dimensions of the model are 93.00 × 76.65 × 15.06 cm, with a weight of 7.550 kg. The model's components were manufactured using the "Raise Pro2 plus" 3D printer (see Fig. 1). The design of the barriers for the cross-sectional model followed the procedure outlined in Jones et al. (1995). The objective was to design a barrier model, easy to construct, that would produce the same aerodynamic effects as the actual bridge. To achieve this, two coefficients were estimated for the drag force and for the aerodynamic moment.

1.1. Aerodynamic coefficients and flutter derivatives of the deck

The aerodynamic tests were conducted for 13 different angles of attack (-6°, -5°, -4°, -3°, -2°, -1°, 0°, 1°, 2°, 3°, 4°, 5°, 6°) with the model fixed (see Fig. 2). To determine the wind speed for the test, preliminary tests were performed, observing at what wind tunnel speed the coefficient values became stable. The speed finally selected was 10 m/s.

The objective of the aeroelastic tests is to obtain the flutter derivatives of the spring-supported sectional model, studied under free vibration with permitted vertical and lateral displacement and rotation around the deck axis. The incident wind speed affects the response of the sectional model in terms of damping and frequency. The flutter functions are derived from the difference in behavior compared to vibration without wind (Jurado et al., 2011). In Fig. 2 is graphically represented the trend of the values of the main flutter derivatives in the case of angles of attack -6°, -3°, 0°, 3°, 6° used later for the computational analysis of the full bridge. The remaining flutter functions were also obtained, although they are not shown because they have very small values and little influence on the results.

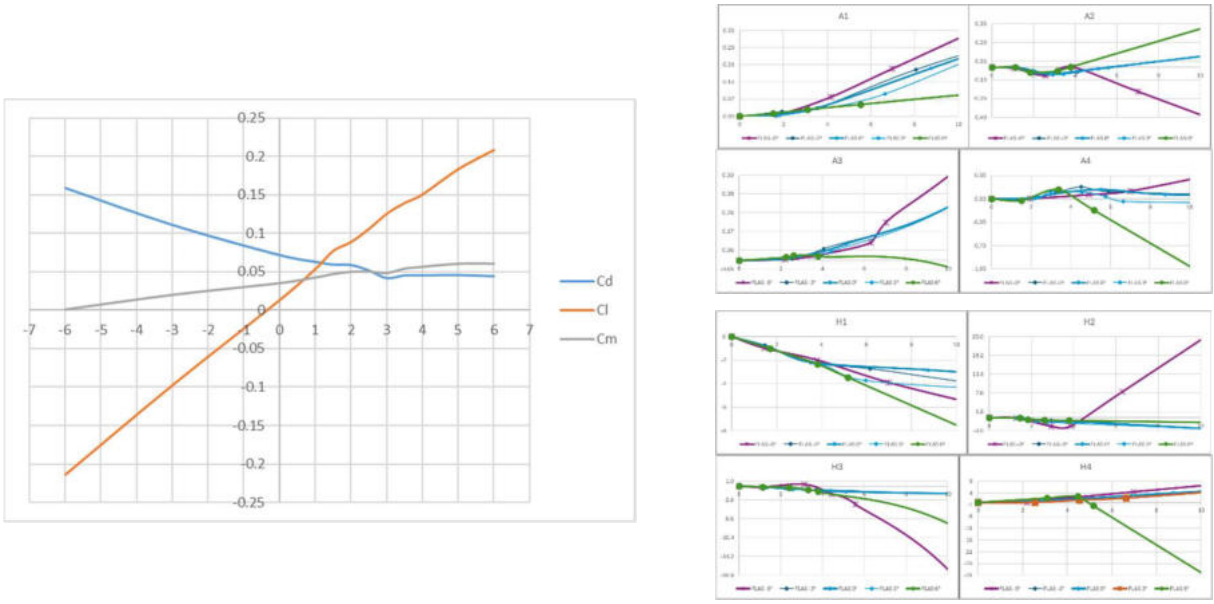
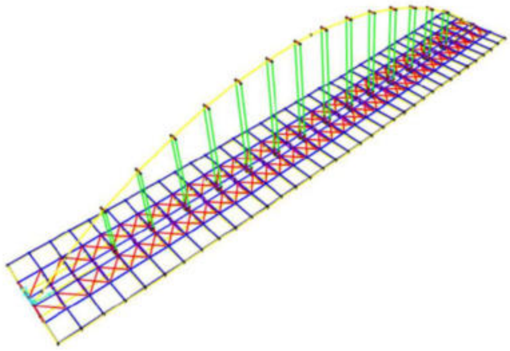


Figure 2. Aerodynamic coefficients (on the left) and main flutter derivatives (on the right).

1.2. Dynamic structural model

In parallel with the wind tunnel experimentation on the sectional model, a finite element numerical analysis of the viaduct has been carried out using the SAP2000 software. Through the dynamic analysis of the model, the vibration modes and natural frequencies of the structure are obtained, which are subsequently required by the aeroelastic analysis (see Fig. 3).



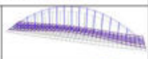
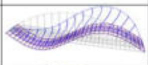
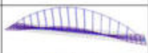
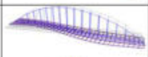
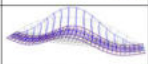
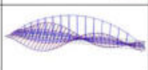
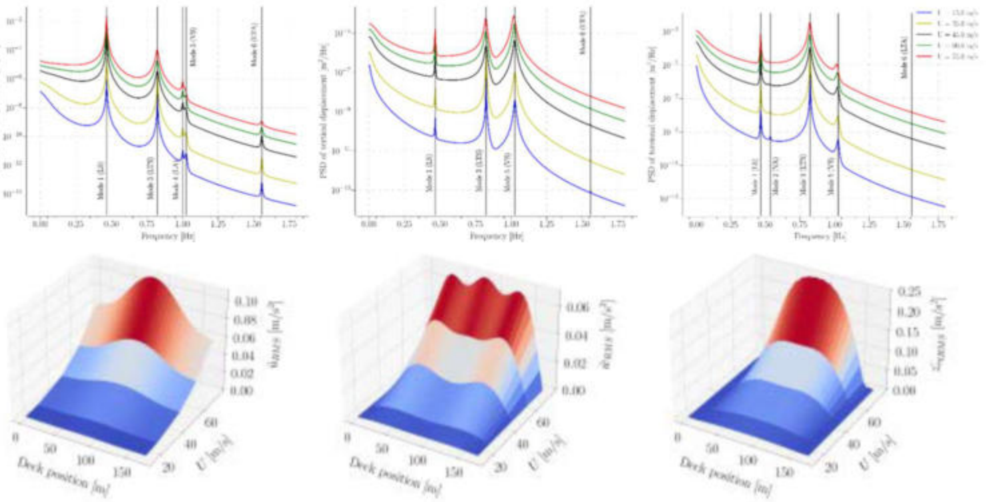
Mode Type		Frequency
1 LS		0.466 Hz
1 VA		0.535 Hz
1 TS		0.824 Hz
2 LA		1.002 Hz
2 VS		1.026 Hz
2 TA		1.558 Hz

Figure 3. Structural model and results of the dynamic analysis.

2. FLUTTER AND BUFFETING RESULTS

The critical wind speed at which flutter occurs is obtained from the dynamic equilibrium equation of the structure by applying multimodal analysis and solving a nonlinear eigenvalue problem that depends on the vibration frequency at which instability occurs. The critical condition corresponds to the lowest wind speed at which some complex eigenvalue indicates negative damping with oscillations of increasing amplitude. For this arch bridge, a structural damping ratio of 0.003 was considered, along with flutter functions for different angles of attack and various combinations of natural modes. The lowest critical velocity value corresponds to an angle of attack of -6° and is v=116 m/s.

Buffeting is an aeroelastic phenomenon in which turbulent wind exerts dynamic and repetitive forces on a structure caused by gusts or, in other words, by fluctuations in wind speed. In the case of bridges, these fluctuating dynamic forces can produce oscillations or vibrations that can become unacceptable. Using a frequency domain approach, the multimodal analysis of buffeting can be solved using the Fourier transform of the dynamic equilibrium equation, also considering the self-excited forces caused by the deck displacements, which are modeled with flutter derivatives. The bridge's buffeting responses are obtained by working with the power spectral density matrix of the displacements, which is obtained by taking into account the relationship from the spectra of the wind speed fluctuations with which the buffeting forces along the bridge deck are defined. This study adopts Kaimal spectra for wind speed fluctuations and the Davenport admittance function. Results were obtained for mean wind speeds of 15, 25, 45, 60, and 75 m/s and for angles of attack of 6°, 3°, 0°, -3°, and -6°. Spectra of displacements, velocities, and accelerations were obtained along the span, in the vertical, lateral directions, and equivalent torsional displacement $B/2\cdot\alpha$ (see Fig. 4). In bridge reliability studies against buffeting, Quintela et al. (2025) have established limits for equivalent vertical and torsional accelerations of 0.25 m/s², both evaluated at the center of the span. Similar thresholds are imposed in the design specifications of many bridges, such as in the design of the Messina Bridge (Stretto di Messina, 2004). In most of the cases the accelerations obtained are extremely low and far from the mentioned limit values. The maximum acceleration obtained is 0.247 m/s² for the case with an angle of attack of 6º, and this value was achieved with a wind speed of v=75 m/s, much higher than any wind speed in service, so the bridge is completely safe against buffeting.



(d) RMS of lateral accelerations $\ddot{u}_{RMS}$ $[m/s^2]$

(e) RMS of vertical accelerations $\ddot{w}_{RMS}$ $[m/s^2]$

(f) RMS of equivalent torsional accelerations $\ddot{z}_{eq\,RMS}$ $[m/s^2]$

Figure 4. Above, motion spectra for different wind speeds at the center of the span. Below, RMS accelerations for increasing speed along the entire span; both graphs for an angle of attack of 6°.

3. CONCLUSIONS AND FURTHER INVESTIGATIONS

The critical flutter velocity found is v=116 m/s, which is a very safe value for the area where the bridge is located.

The response of the arch bridge in buffeting is very safe and the accelerations along the span are extremely low for the wind speeds at which the structure is used.

Tests have also been conducted to study vortex excitation. These tests showed no lock-in phenomenon or high-amplitude displacements.

Wind tunnel tests were also conducted on two sections of the arch to accurately determine their aerodynamic coefficients. The values obtained are lower than those prescribed by the Spanish code IAP-11, therefore the bridge has been designed with a higher wind load than the actual load.

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