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Aeroelastic stability of two long-span arch structures: A collaborative experience in two wind tunnel facilities

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ABSTRACT

In this paper, a rare example of comparison between sectional and full-aeroelastic model tests is presented. Interestingly, the experiments were conducted in two very different wind tunnel facilities by different research teams. The study concerns two long-span steel arch structures recently built in Milan, Italy, for Expo 2015 World Fair. The structures have only aesthetic purposes and are therefore very flexible and light, which makes them sensitive to wind-induced excitation and prone to aeroelastic instabilities. In particular, in smooth flow an interesting phenomenon of interference between vortex-induced vibration and galloping was observed up to high values of the Scruton number. This aeroelastic instability is very dangerous as large-amplitude vibrations can occur in wind speed ranges where they are not expected, at least for what classical theories for vortex-induced vibration and quasi-steady galloping are concerned. Moreover, the provisions of Eurocode 1 resulted clearly unsuitable and non-conservative to address such a phenomenon. Despite the differences in the facilities and in the models, a good agreement was found between the results obtained in the two laboratories. The major discrepancies were observed in the transitional behavior for intermediate values of the Scruton number, the sectional model showing a more unstable behavior. The tests on the full-aeroelastic model also allowed considering the effect of the angle of wind exposure of the structures, both the in-plane and the out-of-plane vibrations of the arches and the dynamic response to turbulent wind. In particular, a set of tests in smooth flow was performed accounting for the presence of the other arch and of the surrounding buildings. A particular dynamic excitation of the in-plane flexural modes of the structures was observed in well defined ranges of flow speeds when one arch is in the wake of the other. Finally, both experimental campaigns highlighted the need for the installation of tuned mass dampers on the real structures to guarantee their safety. The effectiveness of these devices against the observed galloping-type instability was also verified through wind tunnel tests on the full-aeroelastic model.

1. Introduction

Two large arches were recently built in Milan, Italy, for Expo 2015 World Fair. These structures, visible in Fig. 1, have only an aesthetic function and therefore are very slender and light. Moreover, they present a rectangular cross section with a side ratio of 1.5 (short side parallel to the plane of the arch), which makes them prone to transverse galloping, vortex-induced vibration and to the interesting phenomenon of interference between the two types of dynamic excitation. These phenomena are crucial for the safety of the structures and hence are the main concern of this study.

This project gave the authors the great opportunity to compare the results obtained in two different wind tunnels using two types of models. In the CRIACIV[1] wind tunnel, a sectional model of the arches was tested in smooth flow, measuring static forces on the stationary model and dynamic excitation in the transverse degree of freedom on the model suspended by springs. By contrast, in the GVPM[2] laboratory, a full-aeroelastic model of the entire structure was tested and the measurements were carried out in smooth flow (both including and not including surrounding effects) and with the simulation of the atmospheric turbulent boundary layer. These

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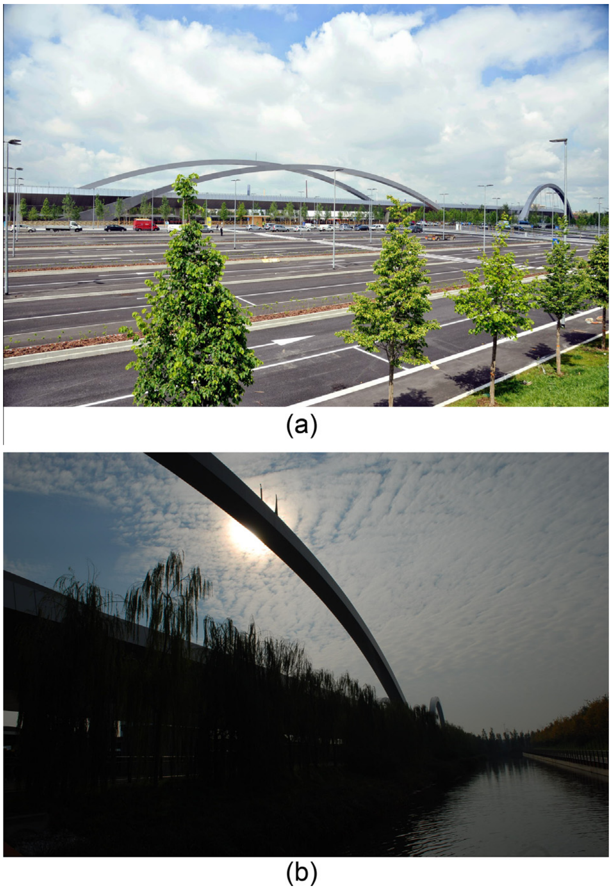

Fig. 1. View of the twin arches in the Expo 2015 area in Milan, Italy.

tests enabled considering three-dimensional features, both in-plane and out-of-plane vibrations of the arches and also various angles of exposure of the structure to the wind flow.

This is a rare occasion to compare two- and three-dimensional results from different scaled tests. Moreover, the whole measurement campaign is completed by a monitoring program that is currently running on the full-scale structure to verify the effectiveness of the damping system finally installed on the arches.

The paper starts with the description of the investigated arch structures (Section 2) and then it reports a brief overview of the aeroelastic phenomena involved in the study (Section 3). Sections 4 and 5 discuss respectively the static and dynamic experimental results obtained at CRIACIV with a sectional model and those obtained at GVPM with a full-aeroelastic model. Finally, the wind tunnel data are compared in Section 7 prior to drawing some concluding remarks.

2. Description of the structures

The structures under analysis are very long and light arches whose scope is only aesthetic. Basically, they are the main entrance gate to the Expo Milano 2015 Universal Exposition area, at the side of a highway viaduct (Fig. 1). The two arches, denoted as Arch 1 and Arch 2, are respectively 200 and 195 m long and their height is 30 and 25 m. Their planes are 32.2 m apart and their apices are misaligned by 10.8 m. The structural design is quite simple: each arch is basically a steel beam flanged to concrete foundations, the so called "noses", using stud bolts. Fig. 2 shows a picture of the structure where the concrete noses are clearly visible.

The cross section of the arches, *i.e.* their aerodynamic shape, is rectangular and it is characterized by a side ratio of 1.5. In particular, the length of the shorter side, parallel to the plane of the arch, is 2 m (D), while the other side is 3 m long (B). This shape is well known for its proneness to aerodynamic instability of galloping type [1,2].

Fig. 2. Detail of the connection between the steel arch and supporting concrete flange.

The arches have a low mass per unit length, m = 2091 kg/m and, being welded steel structures, they are expected to have also a low ratio-to-critical damping ζ. In fact, ζ = 0.3% was assumed in the calculations [3]. Low mass and low damping obviously imply a low dissipation capability of the structures, and it is known that the mass-damping factor, called Scruton number, is a driving parameter in wind-induced instability problems. Herein, the resulting Scruton number was $Sc = 4\pi m\zeta/\rho D^2 = 15.8$, with $\rho = 1.25$ kg/m^3 for the air density.

The two structures have very similar natural frequencies and Table 1 summarizes the characteristics of the first vibration modes of Arch 1, whose mode shapes are shown in Fig. 3. The frequency of the first out-of-plane vibration mode is low and therefore a significant response to turbulent wind is expected. Also the frequencies of the first antisymmetric vibration modes in the plane of the arches are low, enabling vortex-induced excitation and transverse galloping instability at wind velocities lower than the design one. Finally, it is worth noting that the frequency of the first torsional mode is much higher, so that torsional wind-excitation does not represent a problem.

3. Theoretical background

As previously said, the two aesthetic arches are slender shallow structures with a rectangular cross section with a side ratio $B/D = 1.5$. When the wind is perpendicular to the plane of the arches, which seems the most harmful exposure for aeroelastic excitation (see also [4]), D and B represent respectively the cross-flow and the streamwise section dimensions. It is known that this type of structures may be prone to galloping in the vertical bending modes [1]. This is a single-degree-of-freedom dynamic instability caused by the self-excited force component in phase with the velocity. For small vibrations, this corresponds to negative aerodynamic damping that overcomes the dissipation capability of the system. During galloping, a structure exhibits nearly harmonic limit-cycle oscillations whose amplitude steadily grows by increasing the flow velocity. The practical engineering importance of this phenomenon has been shown for many types of structures, such as lighting poles and antenna masts [5]. The critical wind speed is usually obtained by the quasi-steady force criterion [6,7]. It is proportional to the Scruton number and inversely proportional to the slope in the origin of the transverse force coefficient (galloping