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Wind tunnel tests on Notre Dame Cathedral in Paris

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SUMMARY:
The paper concerns an experimental study on the wind pressures over the surface of a worldwide known Gothic Cathedral: Notre Dame of Paris. The experimental tests have been conducted in the CRIACIV wind tunnel on a model of the Cathedral at the scale 1:200, reproducing the atmospheric boundary layer. Two types of tests have been conducted: with and without the surrounding modeling the part of the city of Paris near the Cathedral. This has been done, on the one hand, for evaluating the effect of the surrounding buildings on the wind pressure distribution on the Cathedral, and, on the other hand, to estimate a wind pressure distribution plausible for any other Cathedral with a similar shape. Mean and peak pressure coefficients have been determined for all wind directions. The results emphasize that the complex geometry of this type of structures is responsible for a peculiar aerodynamic behavior that does not allow estimating correctly the wind loads on the various parts of the Cathedral based on codes and standards, which are tailored for ordinary regular buildings.

Keywords: Heritage, Pressure field, Wind tunnel testing

1. MOTIVATIONS

Scientific research on architectural heritage is more and more urgent due to environmental issues, such as the climate change, which represents an increasing threat for its preservation. Some recent, still ongoing, research projects demonstrate the importance of the relationship between architectural heritage and climate change and of the increasing interest of governments, supranational organizations, conscious that the conservation of heritage is linked to the fundamental values of the social and intellectual life of the nations.

Steenbergen et al., 2012, climate change implies an increase up to 2.3% in the hourly mean wind speed with a return period of 50 years. An adequate evaluation of the wind pressure on monumental structures is hence of paramount importance for their correct safety evaluation in the next future. This is particularly stringent for high-rise buildings, like Gothic cathedrals. An example of the increasing danger such monuments are exposed to, is the damage to the great rose of the Cathedral of Soissons (France), destroyed by the storm Egon on January 13_{th}, 2017.

In this work, the iconic Cathedral of Notre Dame of Paris was selected as a case study, and the detailed dynamic wind pressure field on the various parts of the structure was determined by means of wind tunnel tests. Particular attention was devoted to highlighting the effect of buildings surrounding the Cathedral.

2. EXPERIMENTAL CAMPAIGN

The tests were carried out in the open-circuit boundary layer wind tunnel of CRIACIV (Prato, Italy). The campaign of experimental tests has been done on a detailed physical model of the Cathedral, whose geometric scale (1:200) accounts for the dimensions of the Cathedral (130 m long, 45 m wide, 44 m high at the roof's top and 96 m at the spire's top) in order to satisfy a number of requirements. The model should be as large as possible to allow for a finer reproduction of the complex geometry of the structure and to facilitate the installation of a large number of pressure taps in all of its parts. However, the most cogent physical limitation is often represented by the scale at which it is possible to reproduce in the wind tunnel the target wind flow characteristics. Finally, the model used is 65 cm long, 22.5 cm wide, 22 cm high (top of the roof), and the spire is 48 cm high.

2.1. Model design and fabrication

The model of the Cathedral has been fabricated starting from an existing high-fidelity numerical mock-up. However, the numerical model has been thoroughly modified in order to comply with the specificity of the Fused Deposition Modeling (FDM) printing technology. Moreover, the physical model had to be equipped with many pressure captors, and it had to allow the different manipulations needed in the laboratory for the set up of the experiment. The model is composed of 15 parts separately fabricated and then assembled together (Fig. 1), and printing was performed at the ENSAM facilities in Bordeaux by means of a Lynxter S600D 3D printer. The spire, which is rich in extremely fine details, has been fabricated using a more precise numerical model, and a 3D printer based upon the Stereolithography (SLA) technology, that allows to obtain extremely precise objects, also when of very complicated shape. The model of the spire so obtained has then been assembled with the Cathedral.

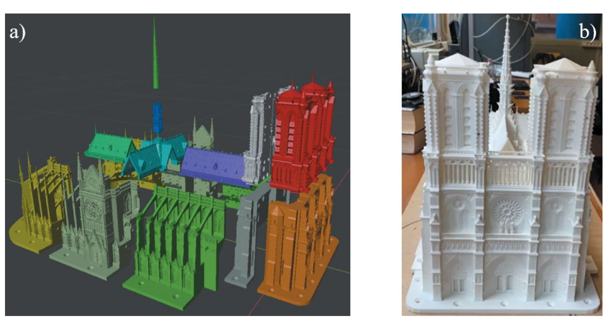

Figure 1. Scale model of the Cathedral: a) the 15 parts of the numerical model; b) the 3D-printed model.

2.2. Surroundings and model equipment

The external surface of the Cathedral model has been equipped with 1200 pressure gauges, whose distribution has been studied in order to obtain, by interpolation methods, detailed charts of the pressure coefficients. Due to the limited number of pressure sensors available, groups of 222 pressure taps were simultaneously recorded at a sampling rate of 500 Hz with the system PSI DTC Initium. For this reason, the groups of pressure taps have been chosen based on the structural macro-elements of the Cathedral. The study has been conducted without and with the model of the surrounding parts of the city of Paris (Fig. 2), for two reasons: to evaluate the influence of the surrounding buildings, and to obtain pressure coefficient distributions that can generally approximate the wind loading on similar buildings immersed in a generic urban wind profile (considering Notre Dame of Paris as a sort of Gothic cathedral archetype).
For the purposes of the wind tunnel tests, it was sufficient to realize buildings having simplified shapes but correct heights. It is also worth noting that the wind tunnel floor was lifted up of 4 cm, so to simulate the presence of the Seine River, being the distance between the base of the Cathedral and the average water level about 8 m at full scale.

Figure 2. Model of the Cathedral in the wind tunnel without (*left*) and with (*right*) surrounding.

3. RESULTS

The results of pressure measurements on the external surface of the Cathedral will be reported in the full paper in the form of pressure coefficients normalized with the mean flow velocity at the top of the roof ($z_{ref}H = 44$ m at full scale). The results are reported in terms of mean and peak pressure coefficient charts, obtained by linear interpolation and statistically controlled extrapolation of the measured values.

A small lateral portion of the Cathedral was equipped with a dense distribution of pressure taps, and the resulting pressure field was compared with that derivable from Eurocode 1 (EN 1991-1-4, 2010) for a standard building (Mannini et al., 2022). Finally, the global wind loads acting on specific parts of the Cathedral, nemely the roof and the great rose windows of the transept, was determined by pressure integration, and the results were compared with those that could be obtained based on codes and standards.

4. CONCLUSIONS

The complex geometry of a large Gothic cathedral and the important aerodynamic role played by some architectural elements imply specific phenomena in the wind-structure interaction process

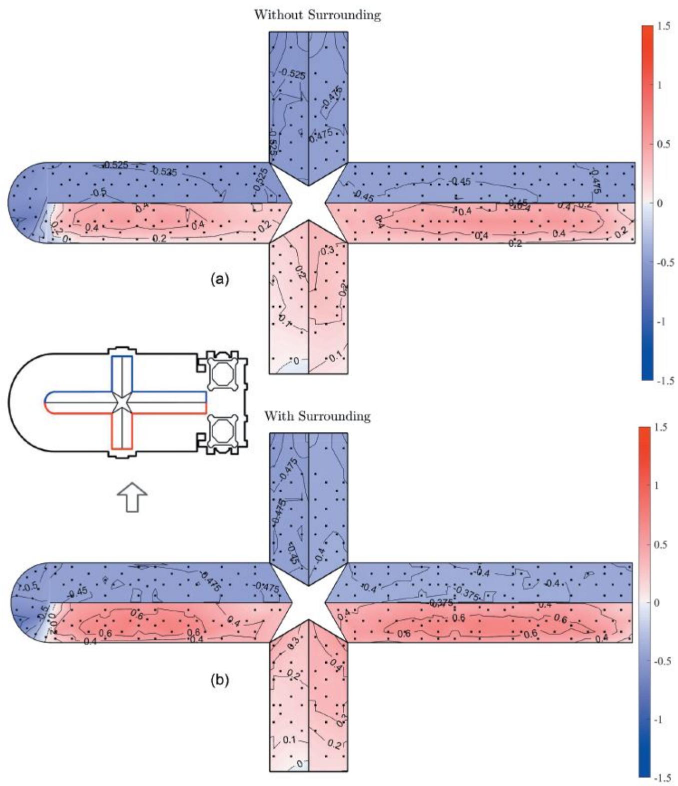

Figure 3. Plan view of the mean pressure coefficients on the roof of the Cathedral: results without (a) and with surrounding (b). The wind direction is also sketched in between the two maps. Small black spots indicate the taps where pressure was actually measured.

that do not allow the correct estimation of the wind loads based on the data available for standard buildings. In fact, depending on the structural element considered or the specific configuration examined, these loads can be either significantly higher or lower than the values that can be predicted based on codes and standards. In particular, the roof of the Cathedral may be subjected to drag and uplifting forces significantly larger than those calculated with the Eurocode 1 (EN 1991-1-4, 2010), which demonstrates the need for accurate wind tunnel tests to assess the safety of this type of structures. Secondly, the influence on the wind load of the neighboring portion of the city where the considered Cathedral stands is extremely important, and can vary on a case-bycase basis. The current analysis highlights that the presence of the surrounding buildings does not only affect the aerodynamics of the portions of the Cathedral at a comparable height but also of parts significantly above. For instance, the drag force on the roof of the Cathedral increases by nearly 10%, while the uplifting force reduces to about one third.

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