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Validation of numerical and analytical methods of downburst wind load calculation through full-scale monitoring

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SUMMARY:

The response of structures under downburst winds has been studied by many researchers in the past two decades. The studies ranged from the simulation of downburst winds in wind tunnels and in the computational fluid dynamics framework to the proposal of numerical and analytical downburst wind load calculation methods. On the other hand, the collection of downburst wind speed data through a network of anemometers has also resulted in a richer dataset. Although it is currently rare in literature, full-scale monitoring of structural response during downbursts plays a major role in validating the proposed numerical and analytical downburst wind load calculation methods. This research introduces the full-scale wind-and-structural response monitoring of three slender structures. The response of one of the monitored structures under selected downburst wind events was calculated using the wind speed measurement at the top of the structure and applying numerical and analytical downburst wind load calculation methods. The calculated response is then compared with the registered response of the structure, to highlight important parameters in the downburst wind load calculation, and to validate the selected downburst wind load calculation methods.

Keywords: Downburst, Thunderstorm outflow, Full-scale monitoring

1. INTRODUCTION

Thunderstorm outflows/downbursts have been known to be one of the causes of failure in structures, contributing to the total economic and social loss due to extreme winds. However, guidelines for the design of structures against downburst winds have not been codified. This stems from the limited availability of thunderstorm wind data due to the small spatial and temporal scale of these events. The distance between meteorological stations and the frequency of wind speed measurement was not adequate for the registration of wind speed during these events. In recent years, the provision of a closely spaced network of anemometers by different research groups has enabled the acquisition of wind speed data during thunderstorm events. In addition, numerical and analytical methods of calculation for the response of structures under downburst winds have been proposed by researchers. Validation of the proposed methods with full-scale wind-and-structural response monitoring data plays a major role in the codification of the proposed numerical and analytical methods. However, this task is not easily attainable because it requires long-term monitoring of structures to have a probability of a downburst event occurring over the location of the full-scale monitored structure. The GS-WinDyn research group at the University of Genova has been working on the collection of wind speed data using a network of closely spaced anemometers through the projects "Wind and Ports", and "Wind, Ports and Sea" (Repetto et al., 2017). This has played a major role in the enrichment of the thunderstorm outflow winds database. This work has been extended to the full-scale monitoring of three slender structures under the ERC-funded project THUNDERR. (Solari, Burlando, et al., 2020).

2. THE MONITORING CAMPAIGN

The monitoring campaign started in February 2019 and it is focused on slender structures. Three structures were selected to be equipped with wind-and-structural response measurement sensors to register the simultaneous measurement of wind and structural response.

The first structure is located in the harbor of La Spezia, Italy (Fig. 1 (a)). It is a 16.6 m lighting pole founded on a concrete cube. The pole is made of 16 sided hollow steel shaft of thickness 4 mm. The cross-section of the shaft is non-prismatic, with a decreasing cross-section in height. The pole has a fundamental frequency of 0.75 Hz. The wind speed is measured by an anemometer installed on the top of the pole. The structural response is registered by strain gauges and accelerometers located at various structure heights. The monitoring system on this pole has been registering wind-and-structural response data since February 2019 except for periods of interruption.

The second structure is located in open, flat terrain, in Sannicolau Mare, Romania. It is a 50 m lattice communication tower made of a three-dimensional truss of triangular cross-section (Fig. 1 (b)). All of the three-dimensional truss components are hollow circular steel sections. The bottom part of the tower which ranges up to 40 meters forms a pyramid frustum with a convergence angle of 5% and the upper part is made of parallel legs. The structure has a fundamental frequency of 1.72 Hz. The wind and structural monitoring system comprises an anemometer installed at 50 m, and strain gauges and accelerometers at various structure heights. In addition, the tower is equipped with a temperature sensor and a video surveillance system documenting temperature variation and cloud movement respectively. This monitoring system has been registering wind-and-structural response data since January 2021.

The third structure is located in the harbor of Genova, Italy (Fig. 1 (c)). It is a 35 m lighting pole founded on a concrete cube. The pole is made of a 4 mm thick, 16-sided hollow steel shaft. The cross-section of the shaft is non-prismatic, decreasing its size with height. The pole has a fundamental frequency of 0.4 Hz. The wind speed is measured by an anemometer installed at the top of the pole. The structural response is registered by strain gauges and accelerometers located at various structure heights. The monitoring system on this pole has been registering wind-and-structural response data since November 2022.

3. VALIDATION OF NUMERICAL AND ANALYTIC METHODS

The monitoring campaign was started with the goal of long-term monitoring of simultaneous wind and structural response measurement. This aimed to capture wind speed and structural response time history during downburst events. Accordingly, it was possible to extract several downburst events from the long-term monitoring data of the two towers in La Spezia and Romania. The recently commenced monitoring system in the harbor of Genova is also expected to register such events.


(a) La spezia, Italy (b) Romania (c) Genova, Italy

Figure 1. The three monitored towers.

The time history of wind speed and structural response measurement by the monitoring system in La Spezia during the identified downburst events were extracted for a detailed study. Initially, the time history of strain and acceleration registered by the strain gauges and accelerometers during the two events were analyzed to obtain top displacement. Once the displacement time histories were obtained, wind speed parameters such as mean wind speed, mean wind direction, and standard deviation of the wind fluctuation were compared with structural response parameters such as mean response, response direction, and response fluctuation to investigate the correlation between the selected parameters. The square of the mean wind speed was found to be highly correlated with the mean top displacement and the standard deviation of top displacement fluctuation (Fig. 2). This correlation is close to perfect especially for response in the alongwind direction.

The time history of the aerodynamic force acting on the structure was calculated using the wind speed measurement time history at the top of the tower and adopting different assumptions for the wind field model. The dynamic response of the structure was calculated in the time domain by solving the equation of motion numerically. The calculated response of the structure was then compared with the registered response. The comparison showed that the mean response can be predicted with reasonable accuracy as long as appropriate aerodynamic coefficients are applied. The result also highlighted the importance of the wind field model and structural response in the determination of the fluctuating and peak response.

Validation of two analytical downburst wind load calculation techniques was also done using the wind and structural response data during two downburst events. The two analytical methods, namely, the thunderstorm response spectrum technique (Solari and De Gaetano, 2018) and the generalized gust factor method (Kwon and Kareem, 2009), were selected because of their suitability for codification. The peak response of the structure was calculated using the two analytical

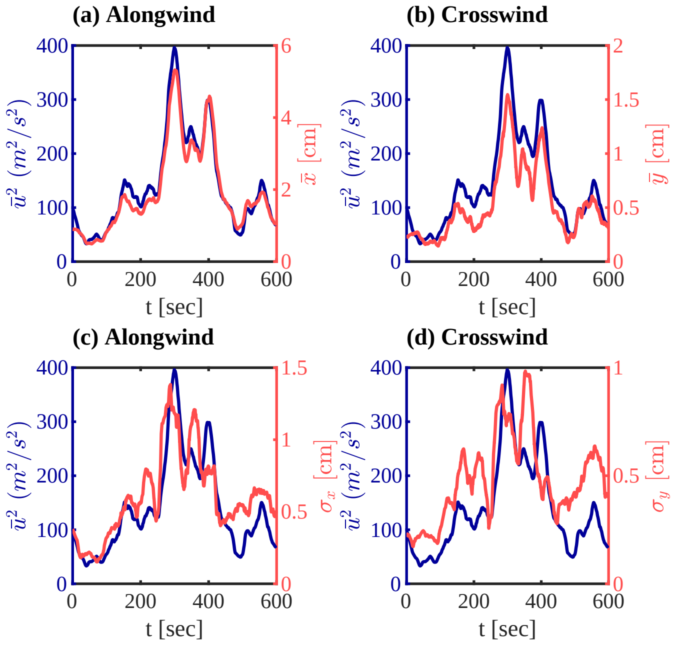

Figure 2. Relationship between mean wind speed, $\bar{u}$, and mean alongwind and crosswind displacements,$\bar{x}$ and $\bar{y}$ ((a) and (b)); relationship between mean wind speed and alongwind and crosswind standard deviation of top displacement fluctuation, σ_x and σ_y ((c) and (d))

downburst wind load calculation methods and the result was compared with the registered peak response. In general, the along wind response calculated using both methods is found to be higher than the registered response for both selected downburst events.

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