Determination of Wind Loading Patterns and Structural Response of Constructions in Coastal Area of Croatia – Field Full-Scale Experiment

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Abstract: Two prominent characteristic local winds, Bora and Sirocco, are worldwide recognized and researched winds. However, there has been modest research of their effects on structures in Croatia. The Bora wind is characterized as downslope wind and it is known for its gustiness and turbulent characteristics. Both local winds have the similar distribution of mean wind speeds at standard meteorological level (10 m above the ground level) averaged at 10 minutes interval. Key differences of these local winds have been presented in this research with respect to structural dynamics.

Dynamic features of winds are difficult to simulate by numerical or physical models without detailed field investigations. In the presented experimental study simultaneous measurements of wind speed profile and structural response were conducted for the first time in Croatia. The data obtained from meteorological measurements enabled us to perform statistical analysis of wind records, to describe underlying stochastic processes and to highlight differences between stated prominent local winds. The final results of described operations are extrapolated measurements in the spatial and temporal domain. Parallel to this research, the proprietary numerical model was developed which enables the input of enhanced wind series as an additional layer of validation via an independent data set.

Keywords: full scale field experiment, profile wind speed and direction measurements, structural response, numerical model

Introduction

Due to a specific geolocation and terrain morphology, the Croatian wind climate is very diverse and complex. Dominant local winds in Croatia are identified according to their genesis. Extensive research was done on meteorological aspects of local winds in Croatia (Stiperski et al., 2012, Horvath et al. 2009). However, their effects on constructions are not well investigated. The local wind Bora is worldwide known due to similarity with other downslope types of wind. The first international research campaign on the Bora was done by a delegation of Japanese scientists, which resulted in the publication Yoshino, 1976.

A full-scale field experiment was performed to gain insight into wind loading of constructions in Croatia. The location of the test was the hill Bobani, near the city of Split. The site was suitable for examining properties of winds Bora and Sirocco, as it was unobstructed in both directions. The experiment was conducted as a part of scientific projects "Dynamic wind loading of constructions" and "Reliability of structures and risk estimation under extreme loading" (lead researcher is the author, B. Peros) (Bajić, 2005, Barle et al., 2010, Peroš et al. 2011).

Truss antenna tower was used as the case study. The experiment included measurements of a vertical profile of wind speed and direction, and structural response, which was followed by an analysis of the obtained data and the development of the numerical model. All meteorological data was verified using the data from the nearby meteorological station, which is part of the National Hydrometeorological Service.

The described field experiment has been conducted since 2007 with occasional interrupts. This manuscript is based on the data acquired in the period 2007 – 2009 when the longest campaigns of structural response measurements were carried out.

The goals of the described experiment were:

- Development of the database of wind speeds and corresponding structural responses
- Differentiation in effects on constructions of the local Bora and Sirocco winds
- Comparison of the obtained data with the current norms regarding wind loading
- Development of the numerical model for case study construction, capable of introducing wind loading in the form of field-recorded time series
- Examination of the dynamic structural response of the investigated structure under realistic wind loading
- Validation of the numerical model based on structural response records

The behavior of the free-standing lattice tower under environmental wind loading was previously presented in the papers by Glanville and Kwok, 1997 and Holmes, 1996. Their primary interest was to define the structural behavior concerning displacements in the wind direction. A more modern approach to full-scale environmental wind loading experiments is found in papers concerning structural health monitoring – mainly wind turbines (Wei-Hua et al. 2016). Recent experimental studies have been tackling problems using air tunnels (Hermon, 2015). Several experimental studies are combating problem of fatigue in construction with dominant wind loading (Barle et al., 2011).

Materials and methods

The field experiment was conducted on location “Bobani”, municipality Klis, just near the city of Split. The testing site is a leased active communication antenna tower. The antenna tower is used both as the carrier of the meteorological equipment and as case study and the field laboratory was set in an adjoined shed, which was originally used as storage for communication equipment. The geographic location of the site is 43°35›40» N, 16°26›43» E with an absolute height of 520 meters above sea level (Picture 1). This location was chosen because of two main reasons. Firstly, the position comforts to World Meteorological Organization rules for meteorological measurement station, which states that the surrounding of the station should remain relatively unchanged during the duration of measurements. The data obtained from this kind of measurement stations are consistent in time and can be used in the stationary stochastic analysis.

Another reason for the selection of this location is similar terrain roughness for two dominant wind directions, usually connected to the prominent local Bora and Sirocco winds. There are also no significant differences in the terrain orography. The terrain surrounding antenna tower has low height vegetation, characterized by Davenport with surface roughness of 0.1 m. The stated classification is further verified from calculations done on measurements of wind speed profile. Using the recorded data, the surface roughness was estimated to 0.051m.

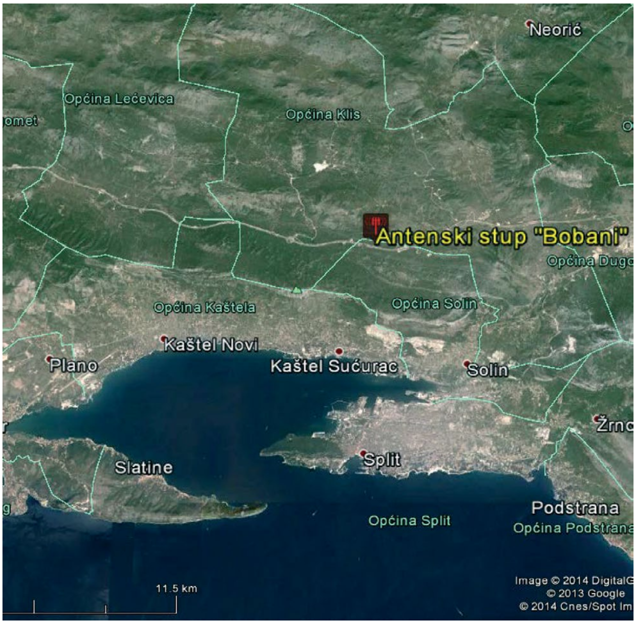


Fig. 1 – Location of field experiment

Fig. 2 – Antenna lattice tower with cantilever beams with meteorological instruments

The onsite antenna tower was a suitable case study for this type of experiment. High and slender spatial lattices are very susceptible to dynamic loading of wind. There were many documented cases of their collapse under strong winds over the world and in Croatia as well. The wind loading coefficients for inclined cylindrical shapes are well researched and documented. The construction is a triangular spatial lattice with a variable cross-section. The base width of the tower is 3.2 m and the top has a width of 1.2m. The total height of the construction is 39.2 m. The construction is mainly built from circular bars. The cross-section of the outer chords on lower levels are 114.3/4.5 mm, while the cross-sections of inner chords and outer chords upper level are 88.3/5.0 mm. The construction is built in segments (see Fig. 3) and fastened using endplates and bolts. The construction main material is steel S355.

The construction dynamics are calculated in numerical model SCIA Engineer. This preliminary calculation was used to determine the best position of accelerometers and strain sensors. The final locations of the sensors are shown in Fig. 3.

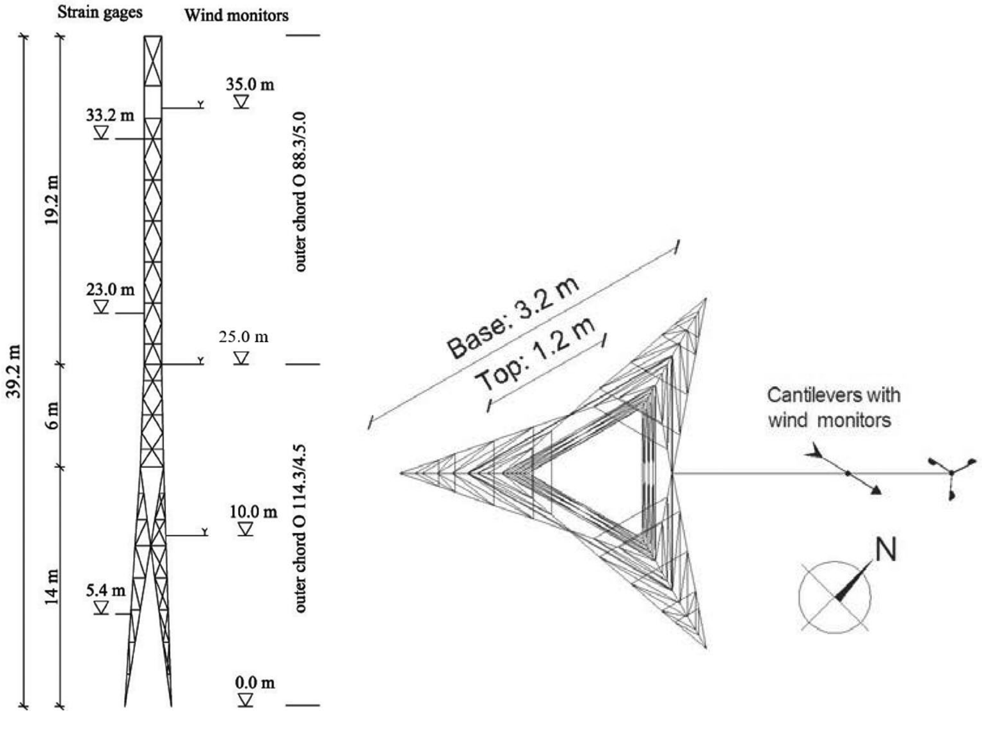


Fig. 3 – Antenna lattice tower plan

Measurement system

The meteorological measurement system was fitted on the target construction. The system consists of three cup anemometers and wind vanes, atmospheric pressure, humidity and temperature sensors and data loggers. Wind speed and direction sensors are positioned on three levels – 10, 25 and 35m above the ground. The data from these sensors are acquired with a sampling frequency of 1 Hz. The characteristics of the sensors are given in Table 1. The field laboratory is shown in Fig. 4.

Table 1 – Sensor characteristics

Type	Wind speed	Wind direction	Atmospheric temperature	Atmospheric humidity	Atmospheric pressure
	umSP 2.2	umDR 2.2	HIGROCLIP S,C,S3,C3	HIGROCLIP S,C,S3,C3	Vaisala PTB 220
Transducer	Cup anemoemter	Wind vane	PT100	ROTRONIC HYGROMER - C94	BAROCAP
Accuracy	0.2 m/s	5°	0.1°C	1%	0.1 hPa
Range	0.2…75 m/s	0°…360°	-40°C…+85°C	0…100%	500…1100hPa
Sampling rate	1 s	2.3 s	0.7s	0.7s	1s
Absolute working temperature	-40°C…+85°C	-40°C…+85°C	-40°C…+85°C	-40°C…+85°C	-40°C…+60°C

The structural response is measured as strains in all three outer chords of the lattice and as accelerations of characteristic points. The stress of the elements is measured on three levels – 5.4 m, 23.0 m and 33.2 m AGL. The accelerations are measured on three levels – 10m, 25m and 35.0m AGL. T-rosette strain gauges are positioned in the middle of the elements and configured in a full-bridge mode for the measurement of axial forces. The sample rate for the structural mesponse was 33 Hz, which was defined from the preliminary calculation of the construction dynamics. Two axial MEMS accelerometers were used, and they were aligned with the horizontal plane. The accelerometer range was 1.7 g. Measurements from both strain gauges and accelerometers were conditioned and digitalized in the field lab. The recording of the data was on the same PC used for meteorological data.

Antenna towers are very sensitive to lateral displacements, due to nature of mounted communication equipment. The analysis of movement under wind loads was also within the scope of this research.

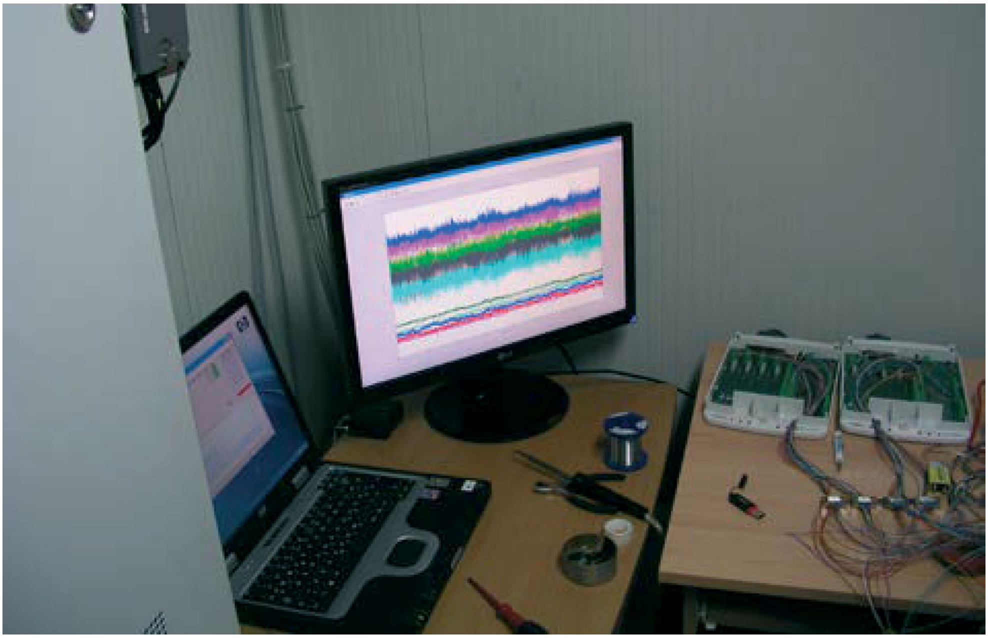


Fig. 4 – Analog to digital converters and PC for logging data

Nevertheless, it was hard to achieve a reliable long-term field measurement of the displacements of characteristic points. Using the spectral domain integration of acceleration data, we were able to estimate displacements, unburdened by drift errors in classical time domain integration (Divic, 2014).

Results and discussion

Wind speed and direction analysis were performed in 10-minute time intervals, by implementation of Reynolds decomposition into mean and fluctuating component. The 10-minute segments are continuous and non-overlapped to ensure the equal significance of every wind event. The described time segments were sorted considering the mean direction of wind speed. The sorted dataset consists of 1,248 records of the Bora wind and 1,053 records of the Sirocco wind.

A general overview of wind currents at the testing location is presented by wind rose graph of mean wind speed shown in Fig. 5. The dominant local winds are Bora (generally blowing from NE direction) and Sirocco (usually blowing from SE direction). Frequent, but not so intensive is Levante wind from E direction. From wind rose graph it is observable that Sirocco is a more frequent wind while Bora has higher peak values of speed.

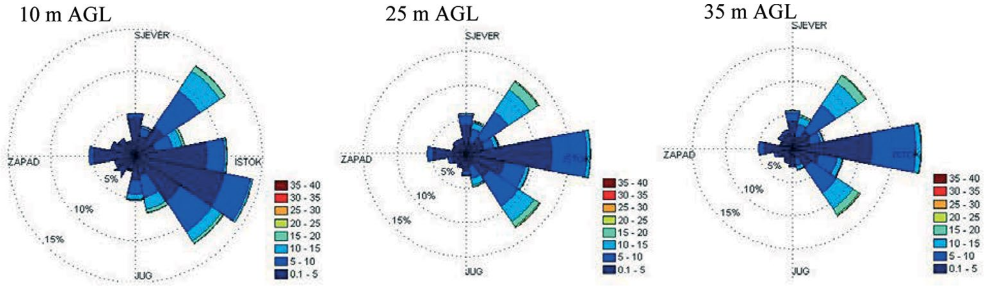


Fig. 5 – Wind roses

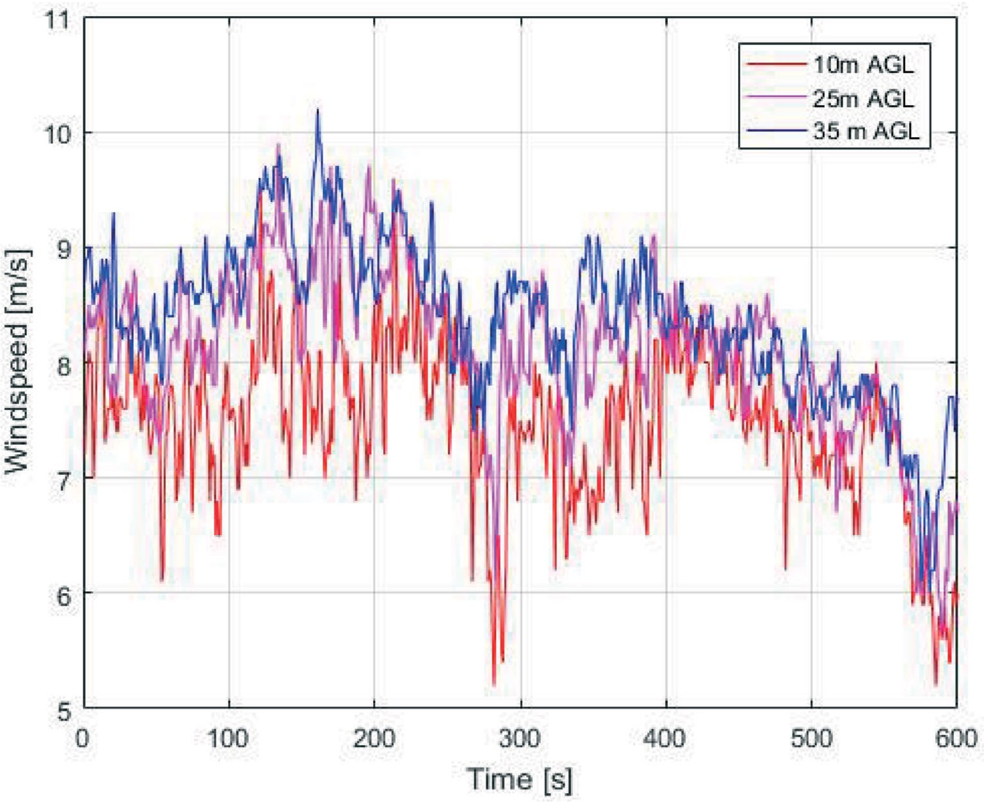


Fig. 6 – Time series of wind speed

The measured wind speed is decomposed into mean wind velocity U and wind speed fluctuation u by Reynolds decomposition.

To describe the mean vertical wind profile from measurements, the logarithmic law was used. It states that the distribution of mean wind speed is governed by Equation (1).

$$U(h) = U_{10}\left(\frac{h}{10}\right)^{\alpha}$$

where U(h) is mean wind speed at level h, U10 is mean wind speed at 10 m A.G.L. and α is the rate of change of wind speed over the height. To retrieve this parameter from measurements, a simple method of data fitting is used according to Equation (1). Equation (2) is obtained using the method of least squares.

$$\alpha = \frac{\sum_i \left[\log\left(\frac{U(h)}{U_{10}}\right)\cdot\log\left(\frac{h_i}{h_{10}}\right)\right]}{\sum_i \left[\log\left(\frac{h_i}{h_{10}}\right)\right]^2}$$

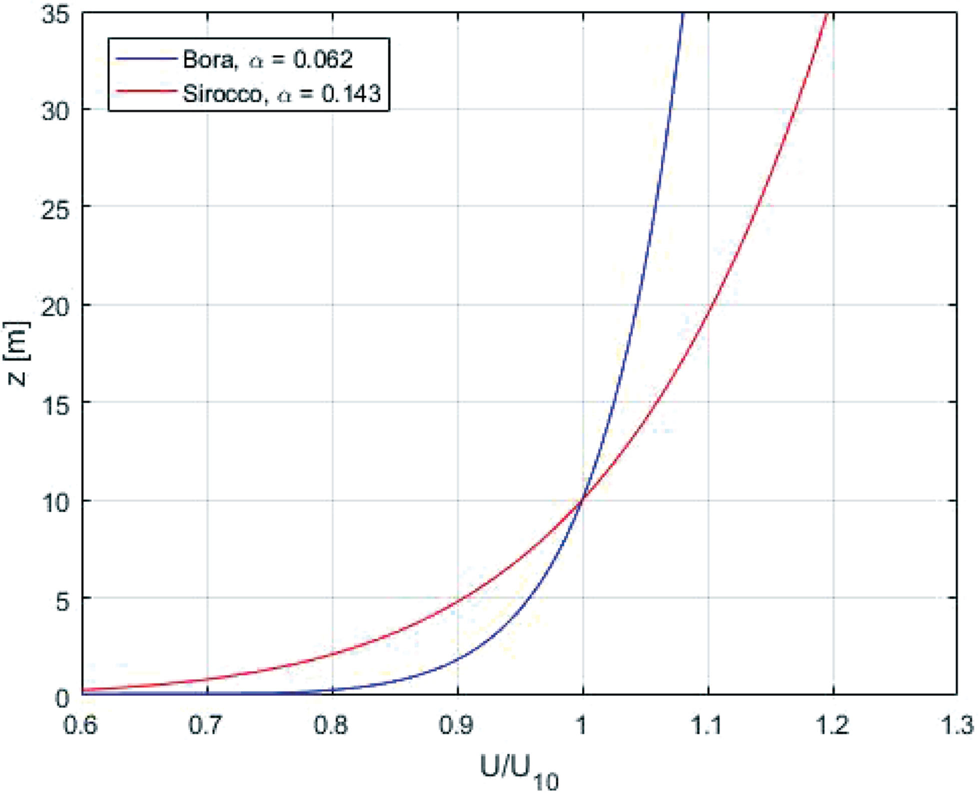


Fig. 7 – Distribution of mean wind speed over the height

The fluctuating component of wind speed obtained from Reynolds decomposition is intrinsically random. Every dataset consists of 600 data points (1 Hz sampling frequency multiplied by 600 seconds duration of the interval). Using statistical tests, the distribution of the fluctuating component is well matched with the normal distribution with null mean and variance obtained from an ensemble. The representative histograms and adjoining normal distributions are shown in Fig. 8.

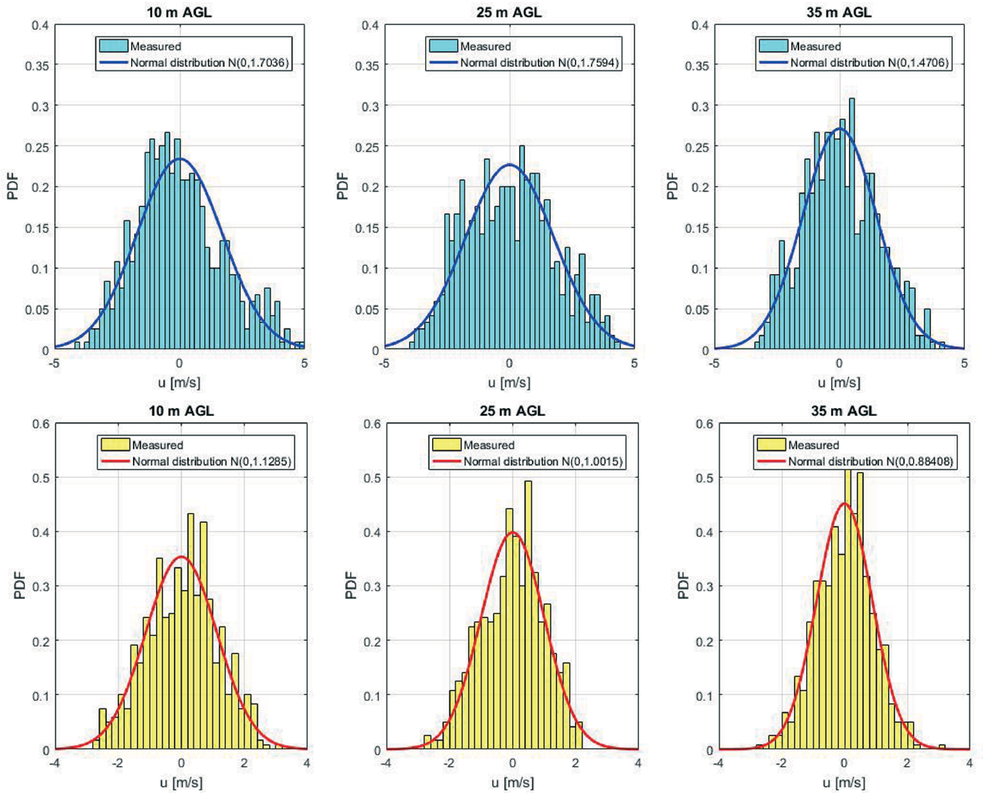


Fig. 8 – Histogram of fluctuating components and corresponding normal distribution

The longitudinal turbulence intensity coefficient is a measure of wind gustiness, and it is defined by Equation (3). The simple equation establishes a linear relationship between mean wind speed and standard deviation of fluctuating wind speed.

$$Iv = \frac{\sigma}{U}$$

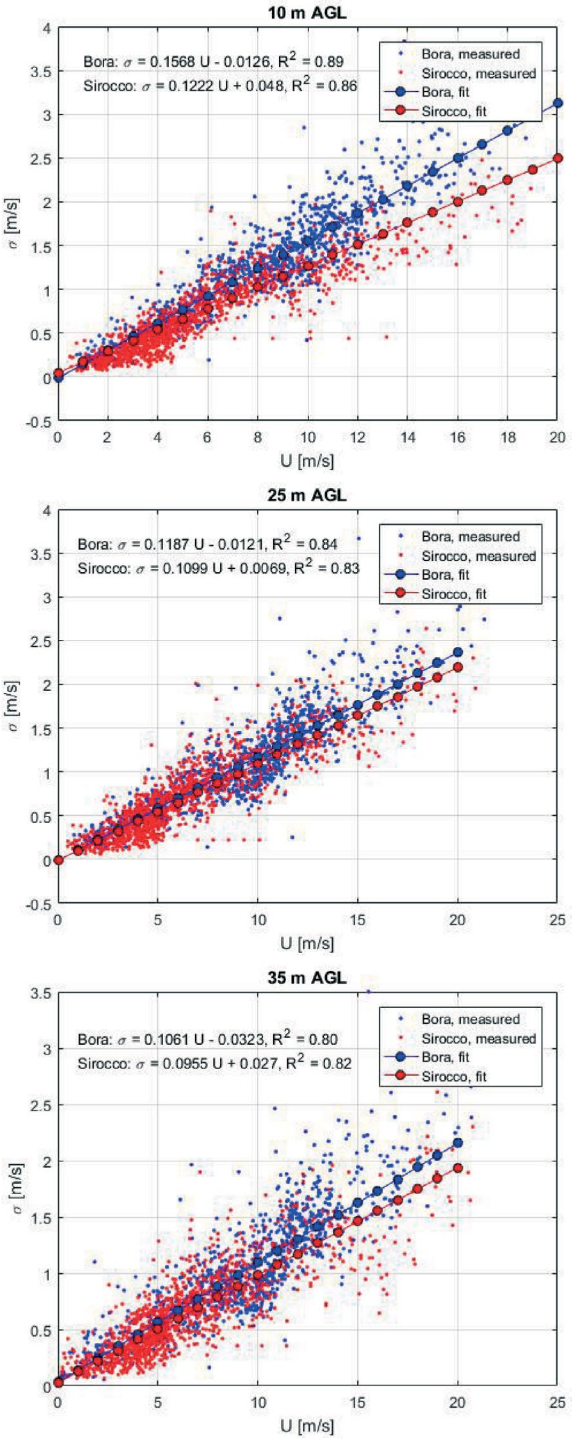


Fig. 9 – Relation on mean wind speed and standard deviation of fluctuating component of wind speed

In Fig. 9 along with graphs equations of the fits are given. The linear fit shows a good correlation between mean speed and standard deviation, with R^2 statistics form 0.80 up to 0.89. The additional component in fit is sufficiently small, which confirms the statement from Equation 3. The coefficient along with U member is the value of turbulence intensity.

The distribution of turbulence intensity over the height is calculated from every measured level (10m, 25m and 35m AGL). As an interpolant between data points, a logarithmic curve is used, which analogue to turbulence intensity approximation is given by Holmes, 2007. The parametric curve is given by Equation (4).

$$Iv(z) = \frac{a}{\ln(b \cdot z)}$$

In Fig. 10 along with the graphs, equation of fit and coefficient of determination R2 are given. Three points are a minimal set of data for two parametric curves to fit; therefore a high-value R2 is required to indicate the relationship. It is observable

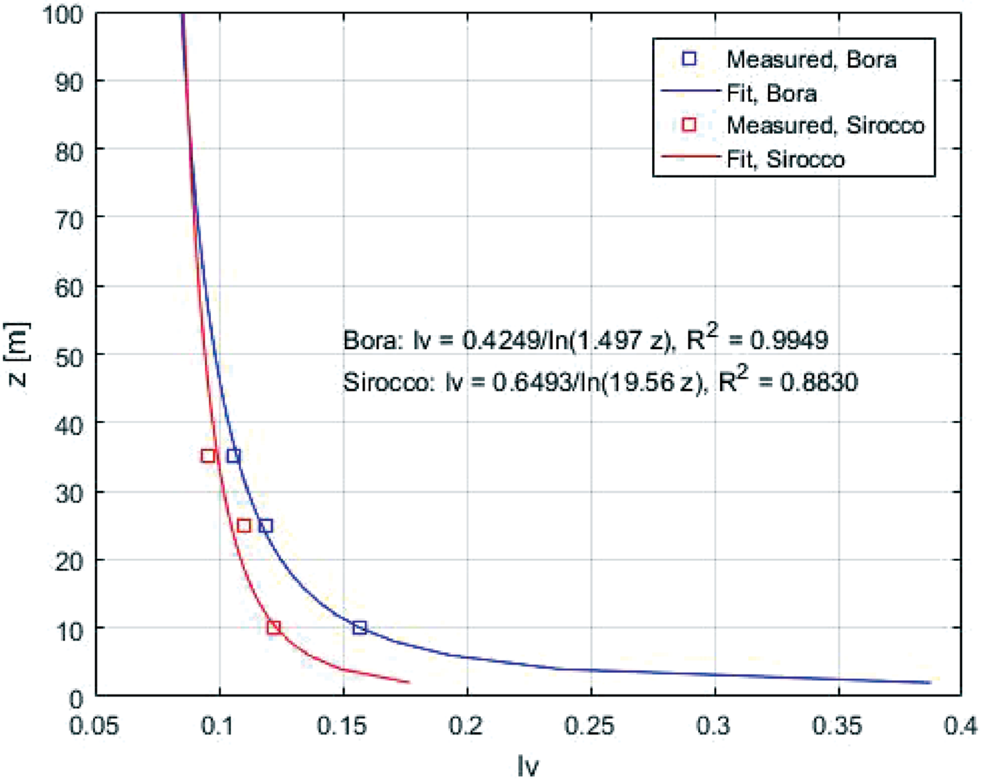


Fig. 10 – Distribution of turbulence intensity over the height

that the Bora wind is more variable than Sirocco, especially in an area below 10 m A.G.L.

Wind power spectra were obtained, and they represent the energy content of wind over frequency. The Fast Fourier Transform was used on the previously described datasets. For each set of data in one group, an analysis was performed, and the resulting power spectra were averaged over the frequency domain. This is shown in Fig. 11 for the Bora and Sirocco case, for three different measurement levels above the ground.

Our dataset was limited by the upper distinguishable frequency band, which was fixed at 0.5Hz defined by Nyquist frequency. To enhance the spectral description of data, a parametric von Karman – Harris spectrum was used. The dimensionless wind spectra by Harris (1990) is defined by Equation (5).

$$\frac{nS_u(n)}{\sigma_u^2}=\frac{4\left(\frac{nl_u}{U}\right)}{\left[1+70.8\left(\frac{nl_u}{U}\right)^2\right]^{5/6}}$$

Where f is frequency, $S_u(f)$ power spectra, l_u turbulence length scale and U mean wind speed.

Turbulence length scale is assessed from spectrum function fit. The parametric spectrum fits data sufficiently well, as shown in Fig. 12.

A detailed description of wind data at the location, both in the temporal and spatial domain, enables the generation of precise time series input for the numerical model. Fig. 13 shows an example of these time series. The original recording is denoted as a red line, and the rest of the field is generated using the procedure which was described above.

The structural response is measured as the acceleration of specific points and strain in chord elements. This data is mostly used as the validation of the numerical model for steel lattice constructions and as a method for fatigue assessment (Barle, 2011). Figs. 13 a and b show the acceleration spectra in two orthogonal directions and displacement and strain time-series caused by the typical Bora and Sirocco winds.

The limiting frequency for observing dynamic phenomena is, again, defined by the Nyquist rate, which is for this setup 16.5 Hz. The frequency range is sufficient for this type of construction, since the first natural frequency of the structure is 0.85Hz (observable in the spectra in Figures 13a and 13b) and following ten modes are under 10Hz.

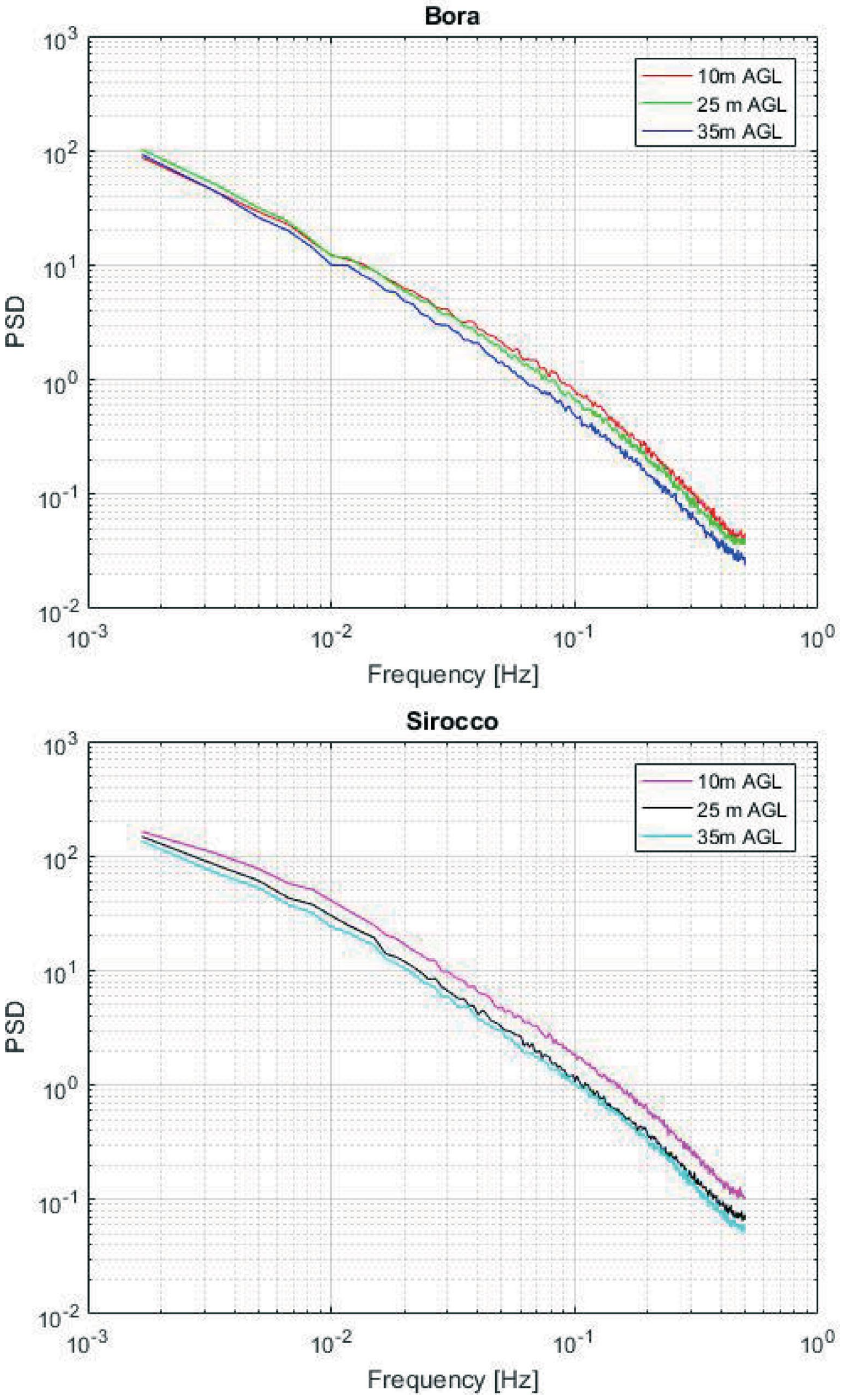


Fig. 11 – Mean spectra for measured wind speeds

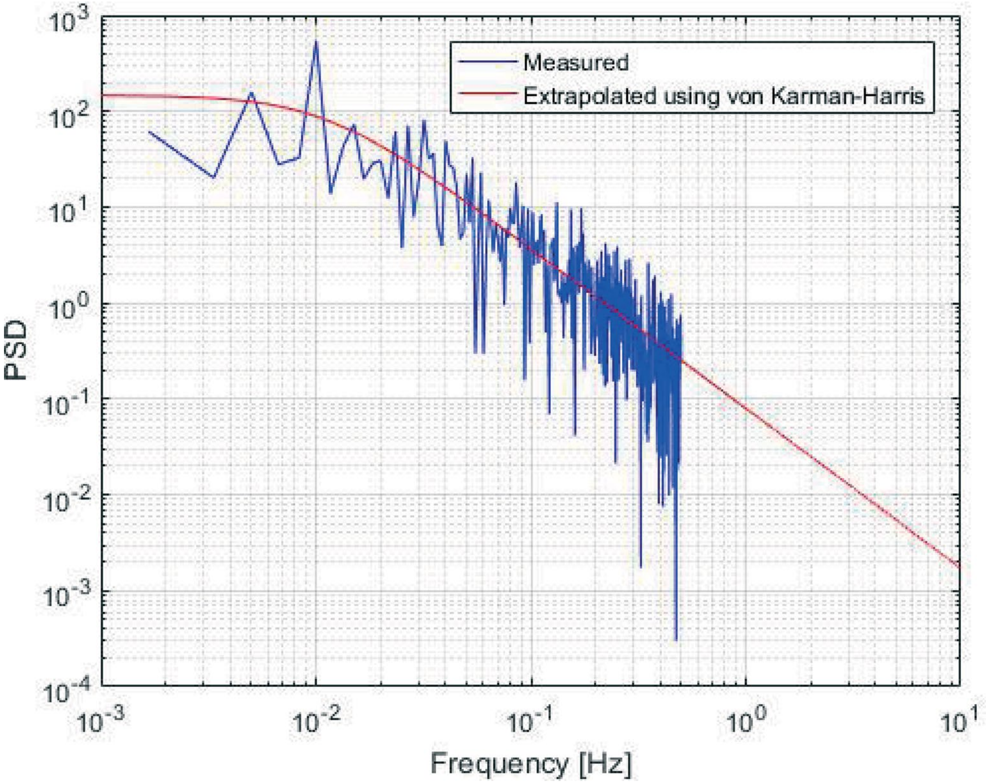


Fig. 12 – Power spectrum from measured data and fitted von Karman – Harris spectrum

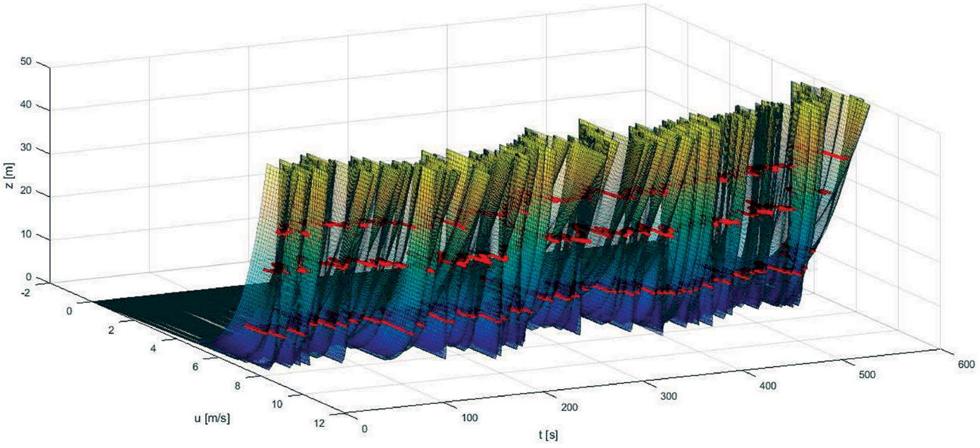


Fig. 13 – Enhanced wind series

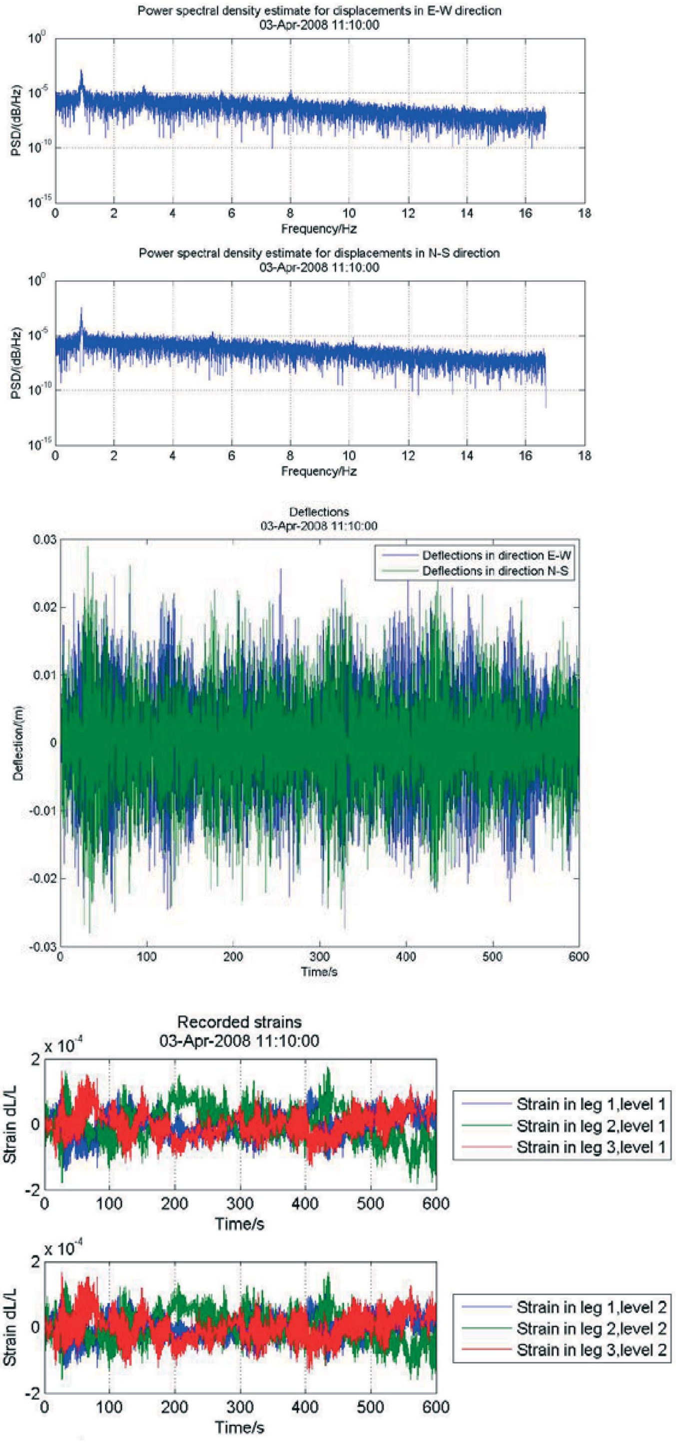
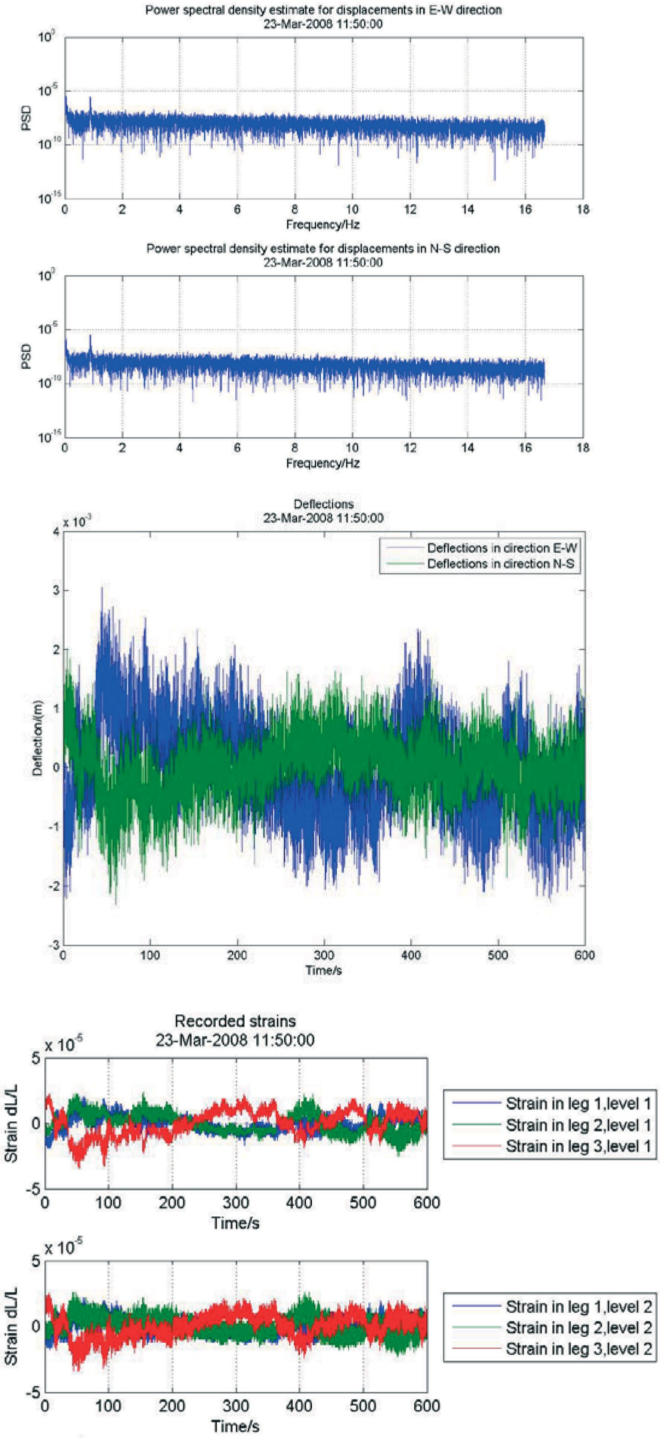


Fig. 13a – Structural response for the Bora



Power spectral density estimate for displacements in E-W direction 23-Mar-2008 11:50:00

Power spectral density estimate for displacements in N-S direction 23-Mar-2008 11:50:00

Deflections 23-Mar-2008 11:50:00

Recorded strains 23-Mar-2008 11:50:00

Fig. 13b – Structural response for the Sirocco

Conclusions

This paper presents the first experimental campaign with the aim of investigating differences between the local Bora and Sirocco winds in the context of construction loading. By inspecting wind roses, a similar distribution of wind speeds at 10 m AGL is observable. The distribution of the mean wind speed over the height creates a significantly higher parameter α for the Sirocco wind (0.143) than for the Bora wind (0.062). Due to the formulation of this vertical profile, both distributions have the same values at a height of 10m AGL. The higher coefficient for the Sirocco means a higher mean speed for heights above 10 m AGL, hence the Bora wind has a higher wind speed below 10m AGL.

The fluctuating component is also described over the height. The Bora wind has higher values of variability concerning the mean wind speed than the Sirocco, especially in the area below 10 m AGL. At a height of 10m ALG, the turbulence intensity for the Bora is 0.156 and for the Sirocco is 0.122. An added variability increases the chance of high wind speeds for the Bora in the height domain 0 – 10m.

Spectral analysis of data sets showed a finer structure in time-series patterns. It is usable for data interpolation in combination with parametric von Karman – Harris spectrum. The reconstruction into time domain is possible via inverse Fourier Transform. As Fig. 13 shows, all this information combined creates more detailed spatial and temporal data. This data can be used either to interpolate actual measurements or to generate synthetic quasi-random wind fields for use in reliability analysis of structures.

A proprietary numerical model was simultaneously developed to investigate structural behavior further. The results of the model were compared to the measurements of structural response. The overall mean difference in strain obtained from measurements and model is 8.2% and for displacements is 11.2%. The difference is mostly due to measurement errors, uncertainty in material and geometry, and long-term structural effects.

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