Full-scale measurement of the response of a CPV tracker structure prototype under wind load

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Abstract

The response of concentrated photovoltaic (CPV) structures under wind loading has to be carefully predicted to optimize the design of these structures. Designers normally rely on wind tunnel tests and equivalent static approaches as recommended by codes for the design of this type of nonconventional structures. This paper aims to evaluate the full scale wind response of a concentrated photovoltaic (CPV) prototype with mirror surface of $8 \times 16 \text{ m}^2$ and correlate it with wind measurements made near the solar structure. The full-scale wind response of the structure was evaluated with continuous 10 minute measurements of deformations on tower leg members during moderate wind events. The utility of this work derives from enriching field measurement data in order to understand the behaviour of this type of structure and to validate the previous wind tunnel testing works. Standard wind design process based on the analytical method, which is adopted by ASCE 7, is also revisited in the light of the full scale observations.

Keywords: Parabolic solar concentrator, Full scale measurement, Wind force coefficients, Equivalent static wind load, Gust effect factor

1. Introduction

Parabolic dish collectors are used to generate concentrated photovoltaic (CPV) solar energy as a new economical alternative to flat photovoltaic (PV) structures. CPV structure is usually designed as a tracking system that follows the sun position and reflects solar energy to high performance receivers. The tracking accuracy may be sensitive to deformation and vibration during operation mode when the structure is subject to wind load. Furthermore,

tracking solar structures can be optimized such that the position of the structure under extreme wind events minimizes the ultimate wind loads. A proper understanding of wind load and its effects could avoid conservative design and pave the way to provide cost effective design needed by the solar industry to fully reach its potential.

Wind tunnel test is a common method used in evaluating wind load on parabolic trough solar collectors (Peterka and Cermak, 1980; Hosoya et al., 2008; Gani et al., 2011) . The study of Gong et al. (2012), is among the rare contribution for full-scale wind load study on this type of structure. The measurement was taken for only two days, but it included a large number of geometric configurations to evaluate simultaneously wind characteristics and the differential pressure over collector reflectors which is essential to assess the reflector deflection in its operating phase.

In accordance with the research elaborated in the National Laboratory of Renewable Energy in the U.S. Department of Energy Office (NREL) (Murphy, 1980; Murphy, 1981; Hosoya et al., 2008), ASCE standards and American National Building codes can be used to calculate wind loads on solar structures. Eurocode-1 (2005) could also be used to calculate wind load for this type of structure according to Giannuzzi et al. (2007). The equivalent static approach, also called Gust Factor Method, was first developed by Davenport and Vickery in the 1960s (Davenport, 1967; Vickery, 1970; Vellozzi and Cohen, 1968). It is the conventional method used in most codes and standards. The equivalent static wind force is considered equal to the mean wind force, as defined in section 4, multiplied by gust loading factor (GLF). As a consequence of employing the 3s peak gust as the basic wind speed in ASCE7-95 (1995), the concept of Gust Effect Factor was introduced and its derivation was thoroughly investigated in the case of building structure by Solari and Kareem (1998) and Zhou et al. (1999). Although ASCE 7 standard does not provide specific guidance for this type of non-conventional structure, Maffei et al. (2013) and the SEAOC (2012) wind design guideline, showed that the design of flat solar arrays, for example, could be inspired from the existing static equivalent approach already approved specifically for building structures. It is also important to note that according to ASCE 7 and recent review of Holmes (2015), for dynamic sensitive structure and for complex structures, it is necessary to consider wind load as a dynamic load in order to evaluate accurately the maximum response and identify resonance

problem using more advanced analysis such as stochastic spectral and time domain dynamic analysis. In order to confidently use the equivalent static method for design of CPV structure, there is a need to further study how and when the static equivalent approach proposed in codes can be used for the evaluation of wind load on CPV structures.

The objective of this study is to use a full-scale prototype exposed to natural wind and compare the effect of wind measured to the one predicted with the equivalent static method. The present work was preceded by the sectional wind tunnel test study of Gani et al. (2011) at Université de Sherbrooke which evaluated the aerodynamic force coefficients of a 1:22 reduced model of the studied CPV prototype. Therefore, the transition between model/full scale prototype could be reviewed properly in the light of the present work that consists in evaluating correlation between real wind characteristics and the structural response of the studied CPV structure in full scale. An experimental program was initiated to collect data representing both the response of the structure at varied position of the tracker and the wind characteristics. All results were analyzed in order to reproduce the process of evaluating wind force and structural response by following the equivalent static method. Although the average measured forces on the CPV prototype cannot be directly used in general for design of parabolic solar structure in extreme conditions, they could be used to evaluate how equivalent static methods proposed in design codes can be adapted for this type of structure.

In this paper, the methodology of instrumentation and data analysis is first presented, which leads to evaluate the static and dynamic wind load on the CPV structure. The results are presented in three parts in coherence with the design approach adopted in ASCE 7. First, wind characteristics are studied for the specific site and compared to existing ASCE 7 standard and literature. Second, full-scale mean wind load values and mean force coefficients are analyzed and discussed in the light of the previous wind tunnel test results. Finally, the equivalent static approach is evaluated in the case of the studied prototype and compared to the experimental results.

2. Methodology: Test program

2.1. CPV structure prototype description

The parabolic structure for solar tracker system studied here is a prototype structure designed for utility-scale solar farms. The parabolic structure comprises a double parabolic dish frame supported by a truss back-up structure linked to the support tower by a central beam. The 35 kW tracker uses 128 identical reflective solar panels. The parabolic frame is mounted on a 2-axis tracker base that points the solar concentrator precisely towards the sun throughout the day. Two-axis movement allow the CPV system to rotate at its tower base with azimuth tracking and to pivot, at its attachment point to the tower, to achieve the required elevation with rotative gear drive. This structure has 400 mm gaps between rows of mirrors on the two dish part which can reduce its frontal horizontal load coefficient. The height, from the ground to the top of the solar collector, is approximately 13.5 m. The dish aperture is approximately 8 m. Technical details are shown in **Fig. 1**. Hot-rolled steel was used for most of the parts of the structure except for the mirrors. It is typically A36 steel with a yield strength of 250 MPa. The experimental program was conducted in the Solar Park in the Interdisciplinary Institute of Technological Innovation (3IT) at the Université de Sherbrooke. The studied CPV structure, as shown in **Fig. 2**, is surrounded by hay field limited by forest and low rise building depending on the direction it is facing. The deciduous forest, in the South and West direction, and the building, in the North-West direction, are respectively distant by approximately 150 and 50 m from the CPV system.

2.2. Instrumentation and acquisition

The wind measurement system (see **Fig. 3 (a)**), which is based on four WindMaster anemometers, was installed in 2013 and has been used previously to study wind spatial correlation. WindMaster is a sound anemometer of Gill Instruments, which can measure wind speed up to 45 m/s with a sampling frequency of 20 Hz along the three axis. Anemometers 1 to 3 were installed at the top of three meteorological towers at a 10 m height. Anemometer 1 is installed in the reference tower which is located at approximately 28 m from the center point of the prototype in the South-West direction. Anemometers 2 and 3 are located in distinct towers located at 10 m from the reference tower in the North and East directions respectively. Anemometer 4 was attached to the reference tower at a 7.5 m height. Anemometer 4 was

Figure 1: Technical drawing for main details of CPV system

selected to be a reference representing the wind load applied to the central beam level of the CPV prototype. The wind measurement system was used to measure the wind speed and direction as a function of time.

Twelve Linear Variable Differential Transformer sensors (LVDT) were installed on the structure. They were attached by pairs to each of the six main tower members as shown in **Fig. 3(b)**. Four tower members are part of two rectangular plane trusses of width 1560 mm inclined at an angle of 45° with the ground. At the base, the distance between these two plane trusses is 1670 mm. The two additional members are part of a triangular vertical plane truss. This truss is 730 mm wide at its base and 5800 mm high. It is located at 560 mm from the base tower center. The LVDT sensors were installed at 1 m above the ground. They measure the relative displacement on L203*102*13 sections, at the neutral principal axis. In this specific experiment, LVDT sensors were extended by a steel bar of 750 mm length in order

Figure 2: Site view surrounding the solar concentrator prototype in the 3it

to evaluate the strain developed in the L section element. The LVDT instruments have a relative uncertainty of $\pm 0.1\%$ in measuring displacement. The anemometers have a relative uncertainty of $\pm 1\%$ in measuring mean wind speed. Assuming a $\pm 1^\circ$ of error in measuring temperature and a relative uncertainty of $\pm 5\%$ in evaluating elasticity modulus E, the total accumulated uncertainty in measuring force coefficient values could reach approximately $\pm 5.4\%$ for the measured wind scenarios range.

All sensors were connected to a data acquisition system with different connection type: analogical for LVDTs and RS connection for anemometers. A LabVIEW program was developed, allowing a simultaneous acquisition between the anemometers wind data and the structural response data recorded by LVDT sensors. The acquisition frequency was controlled by a trigger which can adjust time step sampling according to wind speed. Data are continuously collected with a frequency of 1 Hz until the instantaneous wind speed exceeds 10 m/s. Then, acquisition speed moves to 20 Hz during the following 10 min. In accordance with the acquisition concept, recorded data were analyzed in 10 min time series. The sample duration could be easily compared to previous literature studies and reference documents.

(a) Anemometer's set up for wind measurement

(b) LVDT's instrumentation for deformation measurement

Figure 3: Photographic description for the instrumentation dispositive in the field

2.3. Test configurations

Measurements were taken in different geometric configurations and different wind characteristics. The specificity that the studied structure could change position when tracking the sun requires a specific parametric study of wind load according to different configurations. A test configuration is then characterized by its pitch angle γ that controls elevation of the collector dish and its yaw angle θ which defines the deviation of along wind direction from the axis X normal to the dish collector. This axis changes according to the azimuth position calculated from the North and controlled by the drive mechanism. A schematic view of the convention used to define axis and angles is shown in **Fig. 4**. The current convention is harmonized to NREL (Hosoya et al., 2008) as well as the IEC-62787 specification for solar trackers (IEC-62817, 2014).

2.4. Data treatment

Recorded data were split in 10 min blocks. Theoretically, measured data could be analyzed for longer periods. However, the correlation between wind

Figure 4: Test configurations including definition of pitch and yaw angle

speed and induced force measured on the tower base supports could be distorted by secondary effects due the varying weather conditions. Preliminary observations showed that temperature fluctuation detected by LVDT sensors could lead to important errors in the calculation of wind forces. It was observed that the correction for temperature effect did not improve the correlation between wind speed and deformation measured on the structure. The best strategy identified was to restrict sample length to 10 min and eliminate samples where temperature variation is above 1 °C. The strain is calculated using the following equation:

$$\Delta\varepsilon = \Delta L/L = (V - V_0)C_{lvd\text{t}} \quad (1)$$

Where ΔL is the elongation measured by the LVDT sensor, L is the bar length, V is the recorded voltage, V_0 is the reference voltage, and $C_{lvd\text{t}}$ is the calibration factor between differential voltage in mV and elongation in mm. Because of the evolution of LVDT sensors due to temperature fluctuation with time and even within different parts of the structure, a global reference voltage could not be defined for all tests. Therefore, the reference

voltage V_0 has to be adjusted for each tower member and each test sample. The reference value selected, for a given LVDT, corresponds to the minimum (compression members) and maximum (tension members) voltage measured by the sensor. To avoid non-representative response peaks, the selection of the reference voltage was restricted to a 60 s period within the 10 min sample where the average wind speed is minimum. Therefore, in this study it is always measured a relative variation of wind force associated to a relative wind speed ΔV .

The wind forces and the pitching moment applied to the dish collector would induce moment around different axes at the structure base. In this study, it was only possible to evaluate the moment around the Y axis, which is the most important loading direction for this type of structure. This moment is distributed to the main tower members in tensile/compression forces because the support tower is a truss structure. There is certainly also a moment around the Z axis (global torsion of the structure). This moment creates also some axial loads in the leg members which was not possible to evaluate accurately in this study, and a small torsion in the leg members which could not be measured by the 1D LVDT sensors. In addition to that, flexibility in rotation around the Z axis due to the tracker bearing could provide damping that reduces the dynamic response of the structure along different axes. In this study, this effect was limited because additional rotational stiffness was provided by fixing the bearing during the tests. However, the global torsion of the structure (moment around Z axis) at various yaw angles could be important in some cases and might need to be considered in design.

Regarding the adopted measurement configuration, the main tower member forces, measured in a specific position are used to calculate a global moment applied on the structure as shown in equation (2). It represents the structure response induced by a wind force applied to an equivalent height H .

$$\Delta M = \sum_{n=0}^6 d_n \Delta F_n = \Delta F H \quad (2)$$

where d_n is the distance between the measuring points and the base cen-

ter, ΔF_n is the axial force measured on the tower member n , and ΔF is the effective lateral force applied at the height H to present the same moment ΔM . In this paper, because the exposed area from the dish collector is much higher than the area for the other components and because the altitude rotation axis of the dish coincides with the central beam axis and to be coherent with the wind tunnel standard for this type of structure, the mean forces and the pitching moment are evaluated at the pivot axis height H , which is constant for all pitch angles. H was assumed to be equal to 6 m. This height is slightly different from the 7.5 m height of the reference anemometer. However, the wind speed from the reference anemometer was used directly, without wind profile correction, due to the uncertainty on the wind profile. The relative axial force ΔF_n induced at the structure base, for the main member n , is calculated from displacement measurement using the following equation:

$$\Delta F_n = \Delta \varepsilon_1 + \Delta \varepsilon_2 / 2EA \quad (3)$$

where E is the modulus of elasticity of steel support members of 200 GPa, A is the L section area and $\Delta \varepsilon_1, \Delta \varepsilon_2$ is the couple of strain measured in the sensor pair installed in the identified L section.

3. Wind and terrain characteristics

3.1. Wind parameters

Statistical analysis of the static and dynamic characteristics of wind was carried out to obtain mean wind speed, wind direction, turbulence, gust parameters and its standard deviation values for 10 min test samples. The resultant fluctuating wind speed and wind direction angle ψ were calculated from the recorded velocity in the three orthogonal directions. A typical test sample, from data recorded between 14:20 to 16:20 on the 14th April 2015, when structure elevation (pitch angle) was at 45° , was selected as an example. **Fig. 5** shows the variation of mean wind speed recorded by different anemometers, and then averaged over 60s using mobile average. **Fig. 6** shows the variation of mean direction averaged over 60s and mean wind speed averaged over 3s, 60s, 10 min, recorded only by the reference anemometer (An. 4).

Figure 5: Mean averaged wind speed over 60s during a 10 min test sample recorded from the four anemometers

As expected, in **Fig. 5**, the wind speed is lower for the reference anemometer and a small variation is observed between the three anemometers placed at 10 m height due to spatial correlation. **Fig. 6** is shown also to highlight the transition between the dynamic and static characteristics of wind using the mobile average. It is observed that the wind direction variation is relatively small when using a mobile average over 60s on a 10 min time period. This was true in general for most samples and it further justified the use of 60s mobile average and 10 min record samples for the static analysis of the wind loading on the CPV prototype.

Turbulence intensity and gust factors are important parameters to characterize wind dynamic aspect and identify the maximum structural response. The ratio of maximum wind averaged over 3s, 30s and 60s, to the 10 min mean wind speed were defined and calculated in Table 1. These ratios were selected to analyze the gustiness of wind. The horizontal turbulence intensity, $I_u(z)$ is calculated using Equation 4. The 3s peak gust speed g_v at height z is computed using Durst statistical model (Durst, 1960) with Equation 5:

Figure 6: Measured fluctuations of averaged wind speed over 3s, 60s and 10 min and wind direction over 60s during a typical 10 min test sample recorded from 7.5 m height anemometer

$$I_u(z) = \sigma(z)/\bar{V}(z)\hat{V}_{3s}(z) = \bar{V}(z) + g_v\sigma(z) \quad (4)$$

$$\hat{V}_{3s}(z) = \bar{V}(z) + g_v\sigma(z) \quad (5)$$

Where σ is the standard deviation of wind speed, $\bar{V}(z)$ is the mean wind speed at the height z and $\hat{V}_{3s}(z)$ is the maximum 3s averaged wind speed as used in ASCE 7–10.

A total of 263 data sets samples were selected from the data recorded by the reference anemometer, when 10 min mean wind speed exceeded 4 m/s and wind direction ranged between 250–300, to show the statistical distribution of turbulence intensity as a function of mean wind speed as presented in **Fig. 7**. From these recorded wind samples, 42 were related to specific CPV structure response tests where the structure configuration was controlled.

Figure 7: Turbulence intensity as function of mean wind speed recorded by the reference anemometer

These specific tests are highlighted with triangles in **Fig. 7**.

Fig. 7 shows that the mean value for turbulence intensity measured at the height of 7.5 m is approximately 32%. The surface roughness length z_0 and the power law coefficient α allowing to define respectively the logarithmic law and the power law in ASCE 7, were evaluated using two recording point at 7.5 m and 10 m height. An average value of 0.62 and 0.29 was found for z_0 and α respectively. The site category in ASCE 7 best matching these parameters is Suburban-Urban type B which is characterized by turbulence intensity of $\sim 38\%$, z_0 between 0.5 and 1.3 and α equals to 0.25. This is consistent with the general characteristics of the site which is an open area with an interference of deciduous forest and some low rise building especially in the N-W and S-W direction.

Wind characteristics, for the selected test configurations, are summarized in Table 1 based on data recorded only by the 7.5 m height anemometer. Test samples are selected when mean wind are higher than 3 m/s in order to give rise to meaningful base moment values of the structure. Selected tests are

also classified in category according to its pitch angle γ . Here, the yaw angle is less controlled because it depends on wind direction and to facilitate the analysis, the yaw angle for the samples shown in Table 1 was only for 0° with a tolerance of 10° in mean value. From Table 1, the mean wind speed range between 3.13 and 8.87 and corresponds to moderate winds. Recorded values match the actual operational conditions of the system which moves to the stow position (security position) if gust wind speed exceeds 10 m/s. Higher wind speed values are permitted only at pitch angle $\gamma = 90^\circ$ and $\gamma = 80^\circ$. The ratios, calculated in Table 1, show the dependence of wind speed on averaging time as reported in Durst (1960). The mean value of $\hat{V}_{60s}/\bar{V}$, which is equal to 1.38, is slightly higher than the values of 1.30, adjusted for 10 min period, reported in Durst (1960). The mean value of $\hat{V}_{3s}/\bar{V}$, which is 2.00, is also higher than the 3s gust factor value of 1.53 recommended in the ASCE7-10 (2010) for design purpose. The 3s peak factor values are scattered from 2.34 to 4.38 and the highest values are associated to the important mean wind speed events. Generally, for conservative design purposes, the value is assumed to be between 3.5 and 4.1 as mentioned in Solari and Kareem (1998). The difference may be explained by the assumed site category hypothesis, the measurement point height and the range of mean wind speed which is considered weak compared to design wind speed values.

4. Mean Wind Load Evaluation

Design forces applied to this structure are presented in the equations below using the schema already defined in **Fig. 4**.

$$F_x = q_0 C_x A \quad (6)$$

$$F_z = q_0 C_z A \quad (7)$$

$$Mp = q_0 C_M AD \quad (8)$$

where F_x is the drag force, F_z is the lift force and M_p is the local pitch moment around the Y axis defined in **Fig. 4**. The coefficients C_x , C_z and C_M depends on the shape and the surface of the global exposed area of the structure. A and D are respectively the exposed area and the height of the structure dish. q_0 is the reference dynamic pressure calculated at the height H from the ground and defined in equation (8):

$$q_0 = 1/2\tau\rho_0(KV_r)^2 \quad (9)$$

where τ is the air density correction factor, ρ_0 is the reference air density, K is a roughness factor deduced using the design mean wind speed profile and V_r is the reference wind speed. In the experimental context, K=1 and V_r is equal to the measured wind speed.

Wind forces can exist in both flow direction when the structure is static. This study treats the normal force applied in the X direction and normal to the dish surface, and induced by the along wind. The force in the Y direction, which corresponds to weak exposed area, is not considered. The test sample already used in **Fig. 6**, was selected to show the correlation between averaged wind speeds and both the averaged forces measured on the main tower members (**Fig. 8 (a)**), and the averaged global moment (**Fig. 8 (b)**).

Intermediate results, shown in **Fig. 8**, are important to validate the adopted methodology from a structural point of view. The frontal tower member pair are stretched, the back member pair are compressed and the leg members of triangular plane truss are less sensitive to horizontal forces. This force distribution is in agreement with the design concept in which the triangular plane truss takes mainly the vertical load. Correlation is clear between the averaged moment presenting the static response and the averaged wind speed. This paved the way to investigate experimental wind force coefficients.

Wind force coefficients

Mean wind force coefficients were evaluated at six pitch angles γ and at two yaw angles θ for the upwind side. The elevation $\gamma = 90^\circ$ represents the assumed stow position, in which the structure is placed during strong wind

(a) 60s averaged force measured in the tower members Vs the 60s averaged wind speed (b) Instantaneous and 60s averaged moment Vs the 60s averaged wind speed

Figure 8: Structural response Vs wind speed for a typical test at $\gamma = 45^\circ$

to avoid damage and $\gamma = 0^\circ$ is considered as a critical position, in which the maximum dish surface is exposed to wind. Test samples were classified in two categories representing the yaw angle $\theta = 0^\circ$ and $\gamma = 45^\circ$, with a tolerance of 10° on the mean value. For both the yaw angle, wind force coefficients were evaluated for wind on the concave surface only. Considering that the total moment measured at the tower base is the sum of the moment induced by thrust wind force applied at the central beam height H and the reference pitching moment ΔM_p and assuming that the lift wind force is applied with small eccentricity from the rigidity center of the tower and could add an additional moment ΔM_l around Y axis, the moment induced by the drag forces only in the X direction could be evaluated from the total moment. Introducing Equation (8) and (7) in Equation (6) the horizontal force coefficient in the principal direction X can be defined as:

$$C_{fx} = 2(\Delta M - \Delta M_p - \Delta M_l)/(\rho A H \Delta V^2) \quad (10)$$

ΔM_p and ΔM_l are calculated based on wind tunnel test coefficients respectively C_M and C_{fz} . It was shown that the maximum contribution of the pitching moment and the eccentric lift force in the total moment around Y

axis were respectively +27% and -12% for the worst case, respectively. The values of C_M and C_{fz} are maximized for $\gamma = 60^\circ$ and $\gamma = 90^\circ$.

For each 10 minute sample, the relationship between moment ΔM and the square of wind speed ΔV^2 , both averaged over 60s, was plotted as shown in **Fig. 9**. By assuming a linear correlation, the average slope was extracted for each test and used to calculate the wind force coefficient C_{fx} . For each test, the air density ρ was adjusted using the recorded average temperature over the 10 min period. A mean force coefficient $\bar{C}_{fxj}$ was finally defined for each combination of pitch and yaw angle by averaging all test samples associated to a same configuration. **Fig. 10** shows the mean experimental

Figure 9: Correlation between mean moment M and mean wind speed square for the typical example of at $\gamma = 45^\circ$

wind load coefficients and its for varied pitch angle at yaw angle $\gamma = 0^\circ$ along with their standard deviation. Results are compared with previous wind tunnel test results of Gani et al. (2011). This figure shows also the drag force coefficients for standard CPV trough shape studied by Hosoya et al. (2008) as well as the Standard Ground Mounted Photovoltaic Tracker studied by Swagat (2011) for yaw angle $\theta = 0^\circ$. In order to investigate on the wind directionality effect, Fig. 10 shows also the variation of measured force coef-

ficient as a function of pitch angle when the recorded yaw angle was equal on average to 45° . It can be observed in **Fig. 10** that the maximum and mini-

Figure 10: Force coefficient as a function of pitch angle for full scale and reduced scale experimental studies at yaw angle $\theta = 0^\circ$ and $\theta = 45^\circ$

imum wind drag coefficients would occur at pitch angle $\gamma = 0^\circ$ and $\gamma = 90^\circ$ respectively, which is in agreement with wind tunnel results. It is also noted that by changing the position from $\gamma = 0^\circ$ to $\gamma = 90^\circ$, we could decrease the total force by more than 80%. This confirms that the moving characteristics of structure give more flexibility to engineer for design in ultimate state. By comparing with the results of Hosoya et al. (2008) and Swagat (2011), the difference could simply be explained by distinctive shape and geometry. It is obvious that the Cylindrical Trough studied by Hosoya et al. (2008), which has a smaller focal distance compared to the studied CPV prototype, give rise to more important force coefficients. However, it is important to note that the studied CPV prototype still has a lower force coefficient values even compared to Flat Reflective Surface Tracker. This could confirm the special aerodynamic shape of the parabolic dish used which is enhanced by the special disposition of mirror columns and the gap between them.

Fig. 10 shows also that the average measured full-scale force coefficients

are lower than wind tunnel test coefficients of Gani et al. (2011) for all positions. The standard deviation values of the experimental coefficients at yaw angle $\theta = 0^\circ$ are scattered between 0.09 and 0.28. The difference between the full and the reduced model scale could be attributed to several reasons. The first reason is related to small differences in geometry. For the wind tunnel tests, the model was reduced to only one dish part fixed on a cylindrical aluminum bar Gani et al. (2011). Then, the gap between the two dishes in the full scale model is not included and the porosity percentage is not accurately modeled. This porosity effect, which is detailed in Swagat (2011) could explain part of the difference. According to Swagat (2011), 5% porosity could reduce the drag force coefficient between $\sim 2\%$ and $\sim 9\%$ depending on the pitch angle, the higher reduction percentage occurring for pitch angle $\gamma = 45^\circ$ and $\gamma = 30^\circ$. This could explain part of the gap in **Fig. 10** where the maximum differences between full scale and wind tunnel tests occurs for $\gamma = 30^\circ$ ($\sim 16\%$) and $\gamma = 45^\circ$ ($\sim 12\%$). The second reason could be related to distinction in boundary layer conditions between wind tunnel and outdoor full scale experiment. In contrary to wind tunnel tests, full scale wind characteristics are unsteady in time and space. Turbulence intensity, Reynolds number and wind spatial correlation effect, could influence slightly mean force coefficient values and unsteady aerodynamic coefficients could differ from those in steady flow (Davenport, 1964). Generally, turbulence intensity and Reynolds number effect are not considered important for most usual solar structure shape. However incertitude remains for particular curved collectors pitches and Reynolds number variation accompanied with high distinction in turbulence intensity could lead to difference between full scale and model results as mentioned in Murphy (1980).

It is shown also in **Fig. 10** that force coefficients calculated for different pitch angles are sensitive to yaw angle. The deviation of wind direction from the normal axis changes the pressure distribution over the collector surface and reduces the drag force. The wind directionality becomes an important factor to optimize the operational conditions of the whole system if we consider that wind force could decrease between 10% and 30% depending on pitch angle by only changing the tracker azimuth by 45° away from the wind direction.

From this global study of wind load, it is mainly concluded that the methodology adopted to extract full-scale aerodynamic coefficients is ade-

quate. The results are in concordance with the need of most important studies in this field such as Hosoya et al. (2008) which recommended to validate the acceptability of the wind tunnel test data by comparing with field full-scale results for parabolic collectors with curved surfaces. In this study, wind tunnel testing gives values slightly higher to average full scale coefficients and the acceptance of wind tunnel results could be confirmed, even though important geometrical simplifications were made for the construction of the reduced scale model and a uniform steady flow was used. However, it is always recommended to consider the standard deviation of the force coefficients values and to use peak values rather than average values for a design of similar structure.

5. Gust Effect Factors

The GEF could be simply defined by the ratio between the maximum response including resonant and correlation effects and the maximum response including only wind gustiness. Therefore, it is the ratio between G_{GLF} and the gust pressure factor G_Q detailed in Solari (1993). The recent fundamental formulation introduced in the ASCE 7-10 is presented in the equation (13).

$$GEF = G_{GLF}/G_Q = 0.925(1 + 2I_z\sqrt{P_0}\sqrt{g_Q^2Q^2 + g_R^2R^2})/(1 + 2g_vI_z\sqrt{P_0}) \quad (11)$$

Where g_v and I_z are respectively the 3s peak velocity factor and the turbulence intensity already defined in Section 3. Q is a parameter which represents the background response factor, which depends on the distribution of the maximum pressure field on the exposed surface, R is the resonant response factor, which depends on the natural frequency, and g_Q, g_R are the peak factor for the background and the resonance response respectively. The constant 0.925 has been introduced for additional size reduction effects as well as to adjust loads closer to ASCE7-93 (1993) values as reported in Kwon and Kareem (2014). P_0 is the term that controls the effect of the gust averaging time (Solari and Kareem, 1998).

This paper includes an examination of the application of the GEF, using base moment formulation, in the particular context of a CPV prototype.

Many parameters influencing the calculation of the GEF are revisited such as geometrical parameters and wind spatial correlation hypothesis.

5.1. Design GEF (ASCE7-10 standard)

Based on the 3s gust wind speed map, the term $2\sqrt{P_0}$ is adjusted to 1.7 in the ASCE 7-10 (2010). Usually g_Q is considered equal to g_v for conservative design (Solari and Kareem, 1998). In order to adapt the calculation of GEF for this particular structure of solar concentrator, GEF is calculated in a design context departing from ASCE 7-10 (2010) hypothesis. The background response Q^2 is calculated using the actual geometric parameters of the CPV prototype. Dimensions b , h and d are respectively the dish width, the projected length over the orthogonal plan to wind direction X and the structure depth d (**Fig. 4**). Structure height h and depth d are adjusted with dish elevation γ . The depth d is assumed to be the distance along the X axis (along the wind direction) between the two furthest points on the dish collector. The tower support structure surface contribution in the background response is also neglected. The equivalent height H , where mean wind force is evaluated, is always assumed to be at the pivot axis. It is important to note that in ASCE 7-10, wind speed is assumed to be constant for elevation less than 10 m (33 ft), which corresponds to this case ($H=6$ m). At low stress level, corresponding to low and medium wind speed values, the structure is lightly damped even by considering the aerodynamic damping. The value of 0.0025 as damping ratio was selected based on the recommendation of Davenport (1964) for a similar geometry parabolic antenna structure. It is also appears realistic corresponding to the experimental study of Griffith et al. (2014). Table 2 presents the parameters calculated using ASCE 7-10 approach for the CPV prototype configuration at $\gamma = 90^\circ$. For this calculation, the hypothesis for wind characteristics and structural parameters are as follows:

- Basic wind speed at reference height in exposure C=40 m/s;
- Type of exposure= B (see Section 3);
- CPV structure height $h=1.49$ m;
- CPV structure width $b=14.63$ m;

Figure 11: Power spectral density of 10 min sample measured moment at pitch angle $\gamma = 90^\circ$

- CPV structure depth $d=8.38$ m;
- CPV natural frequency $n_1=1$ Hz ;
- Damping ratio $\beta = 0.0025$;
- Along wind force coefficient $Cf_x = 0.20$;
- Height of central beam axis above the ground $H=6$ m.

It is important to note that all wind parameters are calculated using Table 6.2 titled as Terrain Exposure Constant in ASCE 7-10. The CPV prototype natural frequency is assumed based on the power density spectrum representation of the instantaneous base moment over many test samples (for example, see Fig. 11). The GEF of Building 1 (used as an example in ASCE 7) is evaluated in Solari and Kareem (1998) for a site type of exposure A, using the same models. By referring to the Building 1, it is expected that the value of $Q^2(0.828)$ for the CPV structure would be higher than Building 1 (0.588) because of its smaller exposed surface to wind especially in its stow position. However, it is observed that the dynamic response factor $R^2(2.038)$

reflects a relatively important contribution of the resonant component in the maximum response despite the higher value of natural frequency ($n_1=1$ Hz) comparing to Building 1 ($n_1 = 0.2\text{Hz}, R^2 = 0.535$). It is clear that the specific geometry (especially small thickness of structural components and small exposed area) could increase the dynamic contribution. However, according to ASCE 7-10, structures with natural frequency above 1 Hz can be considered as rigid structures. For these structures, the resonant response normally can be neglected. For the studied CPV prototype a difference of 42% in the design GEF (Table 2) could be induced by using this assumption. This issue is further studied with the results for experimental GEF.

At this level, it could be concluded that applying the GEF concept by adapting geometrical parameters for the studied structure within the adoption of the existing theoretical models could give rise to coherent results by comparing to the ASCE 7 Building example. The geometric specificity of the CPV structure has an important impact on the calculation of the two component Q^2 and R^2 . This concept is also revisited by evaluating experimental GEF and compare it to analytical GEF, which could be calculated using theoretical models but departing from real statistical wind characteristics measured in the site.

5.2. Experimental GEF

The evaluation of experimental GEF for each test sample in the study is based on the definition of Solari and Kareem (1998) in which GEF is considered as the ratio of the gust response factor G_{GLF} to the Gust Pressure Factor G_v^2 using the following equation:

$$G_{GLF} = \Delta M_{max} + M_{ref} / \Delta M_{mean} + M_{ref} \quad (12)$$

$$G_v = \widehat{V}_{3s} / \overline{V}(600s) \quad (13)$$

Where ΔM_{max} and ΔM_{mean} are the measured maximum and mean base moment. V_{3s} and $\overline{V}(600s)$ are the 3s peak wind speed and the 10 min mean wind speed, which are already calculated in Table 1 for each test sample

using the reference anemometer. It is important to remember that the variation of moment was measured from a reference state and we have to adjust values by adding M_{ref} , which corresponds to the moment response calculated from the minimum reference wind speed and the experimental mean force coefficient for a given sample. The minimum reference wind speed for a sample is defined as the minimum instantaneous wind speed included in a 60 s period within the 10 min sample where the average wind speed is minimum.

5.3. Analytical GEF

For the evaluation of analytical GEF, most wind parameters (mean wind speed, turbulence intensity, peak factor, wind spatial correlation) involved in the calculation of GEF are adjusted to measured values instead of values calculated from theoretical models adopted by ASCE 7. The gust time duration, $\tau = 3s$, is taken similarly to ASCE 7-10. However, the time period T , over which the wind is averaged, is reduced to 600s instead of 3600s. Theoretically, this change would influence the g_v parameter but it would change slightly the GEF in the given wind conditions. g_Q is still taken equal to g_v , as a conservative assumption for the background component.

The term Q^2 is related to wind spatial correlation and geometric parameters. In order to evaluate Q^2 accurately within real serviceability wind conditions, Q_0 detailed in Solari and Kareem (1998) was modified by introducing the measured horizontal exponential decay coefficient C_y and C_z .

$$Q_0 = 1/(1 + 0.29\tilde{L}_{0.63} + 0.56\tilde{\tau}_{0.74}) \quad (14)$$

$$L_0 = 0.5(\tilde{H} + \tilde{B}) \quad (15)$$

$$\tilde{\tau} = \tau \bar{z}_{\bar{z}} / L_{\bar{z}} \quad (16)$$

$$\tilde{H} = C_z h / L_{\bar{z}} \quad (17)$$

$$\tilde{B} = C_y b / L_{\bar{z}} \quad (18)$$

Here, the existing wind measurement dispositive, detailed in section 2, allows evaluating the exponential decay coefficient depending on wind direction. The horizontal distances between the reference anemometer tower and the others are representative to the dish collector width. The evaluation of the coefficients is elaborated using the procedure reported in Parent (2015). The wind correlation in the Y direction, represented by C_y is calculated using the anemometers 1-2 and 1-3 depending on wind direction. The vertical wind correlation, represented by C_z , is calculated using anemometer 1-4. Resulting values for the test samples scatter between 1.5 and 4 for C_y and 7 and 9 for C_z . This result shows that wind is more correlated in the specific wind conditions and the hypothesis of $C_y=C_z=11.5$ would yield smaller background response. These low exponential decay coefficients were used for the calculations of the analytical GEF in Table 3. However, they were evaluated for relatively low wind speeds and therefore they are not necessarily representative of higher wind speeds. The coefficient C_x , for the along wind direction, is still assumed to be 15.4 (Solari and Kareem, 1998).

5.3.1. GEF results

Table 3 presents the results for experimental, analytical and design GEF for the test samples already presented in Table 1. The calculation of design values is extended to all pitch angle configurations for comparison purposes.

Overall, both experimental and analytical coefficients are under design values. By comparing the mean values associated to each pitch angle, the analytical and the experimental results are relatively close and mean experimental values are slightly higher than analytical values for most configurations. GEF values are more important for the security positions $\gamma = 90^\circ$ and $\gamma = 80^\circ$, where the structure is supposed to be exposed to higher wind speed and experimental values are under analytical estimations. In these particular positions, it seems that the dynamic response is slightly underestimated. The dynamic effect caused by the overturning moment (represented by the first frequency) is clearly more important in these configurations and its contribution to the resonant part increases the GEF values especially in the

higher wind speed range. An advanced structural dynamic analysis would be needed to confirm the resonant component contribution and its different components contributions, especially in the ultimate conditions with strong wind speed ranges for this specific type of structure.

It is noted also that analytical GEF increases as the exposed surface (pitch angle) decreases. Indeed, for the service positions ($\gamma = 0^\circ$, $\gamma = 30^\circ$, $\gamma = 45^\circ$), the dynamic contribution of the structure represented by R^2 is small because of the low wind speed and the background response factor Q^2 may dominate in most of the test samples. However, by increasing pitch angle ($\gamma = 90^\circ$, $\gamma = 80^\circ$), Q^2 becomes higher and R^2 contribution becomes significant especially when considering higher wind speed in those positions. This could also be observed with the experimental test results.

Moreover, a relatively high statistical data dispersion is observed in the experimental results comparing to the analytical ones. This can be explained in part by the fact that the wind speed is measured at only one point in space (reference anemometer). This uncertainty, is studied through the existing wind measurement dispositive. On one hand, the effect of reference height is studied by comparing GEF calculated using wind parameters from anemometers 1 and 4. On the other hand, the effect of horizontal spatial correlation, mentioned above, is studied by observing the effect of change between the three anemometers fixed at the same height. Table 4 shows the measured GEF using the wind data from the four different anemometers. In this table, the percentage of change indicated for anemometer 1 is calculated with respect to the reference anemometer 4, whereas the percentage of change indicated for anemometers 2 and 3 is calculated with respect to anemometer 1, which is located at the same height.

It is observed that the highest change percentage could occur due to the vertical wind correlation especially for weak wind speed configurations. Therefore, it could be concluded that identifying the optimal equivalent height for this type of structure is important to avoid conservative design. Applying literally ASCE 7 standard, where wind velocity is constant for elevation less than 10 m (33 ft), is a conservative assumption. This result has to be verified for high wind scenarios to be more conclusive in the design conditions. The horizontal wind spatial correlation is also a parameter which could influence the experimental assessment of the GEF and could explain the high disper-

sion of experimental results in Table 3.

In summary, applying the concept of GEF to evaluate the maximum equivalent static wind load and then the maximum along wind response is also validated for the given special structure. Regardless, of some observed difference between the theoretical model and measured values in predicting global wind characteristics, especially in the low and moderate wind speed range context, GEF as defined in ASCE 7 provides acceptable results for evaluating the maximum induced wind response.

6. Conclusions and Perspectives

Evaluating wind load on solar structures, more specifically parabolic solar concentrator, is an important component to optimize its design, therefore increase its financial flexibility. In this study, a methodology was used to correlate the global structural response of a full scale CPV prototype to measured wind characteristics. Analyzed data validated the acceptability of wind tunnels results and revised the application of the equivalent static approach for this specific type of structure. The main conclusions are as follows:

- (a) Wind characteristics including mean wind, turbulence intensity, gust factor, roughness parameters were evaluated and values were coherent with ASCE 7 standard and the site category;
- (b) Full scale wind force coefficients were evaluated at varied pitch angles and their sensitivity to wind direction were studied. Thus, the acceptability of wind tunnel method, using a simplified model and steady flow hypothesis, was confirmed and discrepancies with experimental coefficients were discussed;
- (c) The Gust Effect Factor concept and the equivalent static approach were also revisited in the light of experimental results. The existing GEF model could be adapted to this type of structure and experimental values were coherent with analytical prediction. Depending on structure configuration and wind speed range, the resonant part of the response can be important. Advanced dynamic analysis would allow studying accurately the importance of the dynamic contribution in evaluating the maximum force for this type of structure.

All experiments were conducted with operational conditions for the structure. Security recommendations limited the ability to test strong wind speed scenarios. Thus, the average measured forces on the CPV prototype can not be directly used in general for design of parabolic solar structure in extreme conditions. However, the existing data were sufficient to evaluate globally the structural static response within the service limit state and it were useful to evaluate the coherence of applying the equivalent static approach in the studied case. The need to test the structure within stronger wind events, is recommended. Numerical simulations are needed to further study the static and dynamic response of CPV structures under various wind conditions. These simulations could allow developing practical tools for the design of these structures to optimize its behavior in both serviceability and survivability conditions.

Acknowledgements

The authors would like to thank SpaceWatts division of Gestion TechnoCap for the technical contributions and financial support for the research, along with NSERC, PROMPT and Hydro-Sherbrooke. We are also grateful for the financial contributions of the Canadian Foundation for Innovation (FCI), the Ministère de l'Économie, Science et Innovation of Québec and the Université de Sherbrooke for the unique CPV infrastructures. Finally, the important technical contribution of Richard Norman to the project is warmly acknowledged.

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Table 1: Wind characteristics over selected test samples

γ	V	I_u	$\bar{V}/V$	$\bar{V}_{3s}/V$	$\bar{V}_{60s}/V$	g_v	ψ
0	3.81	0.42	2.74	2.15	1.49	3.00	213
	3.55	0.48	3.69	2.51	1.59	3.31	212
	4.05	0.36	2.67	2.19	1.25	3.88	205
	4.05	0.33	2.41	1.95	1.38	3.15	213
	3.58	0.33	2.24	1.98	1.39	3.20	215
	3.13	0.32	2.33	1.87	1.30	2.91	213
	4.27	0.36	2.37	2.13	1.31	3.63	197
30	4.92	0.41	2.47	2.26	1.79	3.16	299
	4.72	0.35	2.26	1.82	1.33	2.62	211
	4.56	0.32	2.29	2.03	1.37	3.58	292
	4.93	0.27	1.94	1.69	1.30	2.76	275
	5.39	0.35	2.13	1.88	1.39	2.73	228
	5.14	0.32	2.45	1.80	1.26	2.82	218
	4.71	0.35	2.46	2.02	1.34	3.91	215
45	5.09	0.35	2.37	1.91	1.40	2.88	218
	4.25	0.35	2.81	2.12	1.57	3.58	207
	6.85	0.38	2.62	2.43	1.48	4.05	288
	4.07	0.38	2.32	1.99	1.39	2.85	210
	6.81	0.29	2.22	1.99	1.32	3.63	301
	4.48	0.38	2.77	2.13	1.37	3.33	144
	4.87	0.37	2.54	2.07	1.32	3.30	125
60	5.09	0.26	2.20	1.94	1.29	4.01	294
	4.08	0.39	2.62	2.25	1.51	3.50	209
	7.03	0.29	2.47	1.84	1.30	3.32	281
	7.11	0.34	2.42	2.03	1.47	3.24	293
80	7.34	0.34	2.72	2.08	1.45	3.49	286
	8.52	0.32	2.30	1.82	1.30	2.83	293
	8.87	0.29	2.35	1.85	1.33	3.30	285
	7.54	0.34	2.57	2.15	1.42	3.75	278
	6.55	0.37	2.69	2.14	1.43	3.45	263
	6.77	0.32	2.52	2.18	1.27	4.23	272
	6.11	0.33	2.76	2.25	1.40	4.08	271
90	8.03	0.30	2.16	1.73	1.27	2.84	287
	6.37	0.29	2.80	2.12	1.46	4.38	281
	6.76	0.26	1.95	1.62	1.35	2.78	276
	7.32	0.35	2.47	2.11	1.52	3.45	283
	5.41	0.27	2.06	1.87	1.34	3.71	272
	5.63	0.34	2.48	2.12	1.43	3.61	278
	5.55	0.30	1.97	1.64	1.33	2.34	279
	6.62	0.31	2.19	1.82	1.44	2.89	290
	7.10	0.31	2.45	1.92	1.33	3.52	290
	6.59	0.27	2.29	1.79	1.27	3.94	289
Mean	5.65	0.33	2.44	2.00	1.38	3.35	252
Min	3.13	0.26	1.94	1.62	1.25	2.34	125
Max	8.87	0.48	3.69	2.51	1.79	4.38	301

Table 2: Wind characteristics over selected test samples

$\hat{V}_{ref}$	40 m/s	$\bar{V}_z$	33.33 m/s	g_v	3.40
$\bar{z}$	10 m	$\hat{V}_{\bar{z}}$	17.67m/s	g_Q	3.40
I_z	0.30	N_1	5.34	g_r	4.18
L_z	95 m	R_n	0.048	GEF	1.507
Q^2	0.828	R_b	0.228	GEF($R^2=0$)	0.872
		R_h	0.784		
		R_d	0.127		
		R^2	2.053		

Table 3: Experiment, analytical, design GEF values over different test samples at different pitch angles

Pitch angle γ	Δ Mean	Δ Mmax	G_{GLF}	Cy	Cz	Experimental GEF	Analytical GEF	Design GEF
0	6.09	35.219	5.784	3.20	4.45	1.246	0.871	1.382
	8.70	46.44	5.186	3.24	4.60	0.822	0.861	
	8.98	31.91	3.550	2.25	6.20	0.665	0.861	
	7.68	28.91	3.762	3.66	4.29	0.985	0.875	
	6.58	25.92	3.935	1.22	4.79	1.002	0.873	
	6.24	18.21	2.864	1.90	5.22	0.823	0.867	
	7.31	30.82	3.977	2.33	4.92	0.875	0.868	
					mean	0.916	0.868	
30					σ	0.184	0.005	1.266
	8.18	42.83	4.792	5.236	8.25	1.029	0.875	
	5.79	24.18	4.172	2.42	5.68	1.266	0.885	
	11.47	30.05	3.085	3.21	3.89	0.751	0.871	
	11.04	32.79	3.186	3.88	4.77	1.118	0.889	
	15.25	49.09	3.212	2.58	7.50	0.907	0.869	
	19.48	47.23	2.425	3.92	11.32	0.796	0.891	
	14.85	45.46	2.933	3.69	5.62	0.720	0.887	
45	12.98	36.78	2.832	3.62	9.22	0.778	0.867	1.295
					mean	0.920	0.879	
					σ	0.198	0.009	
	7.44	29.73	4.121	4.01	5.89	0.916	0.871	
	13.62	58.83	4.318	2.03	4.84	0.918	0.887	
	4.04	18.55	4.593	2.63	7.99	1.157	0.878	
	10.84	32.79	3.024	3.26	3.25	0.798	0.902	
	6.75	21.94	4.123	2.07	3.50	0.908	0.880	
80	5.81	26.40	4.262	3.53	8.57	0.998	0.879	1.499
					mean	0.949	0.883	
					σ	0.120	0.010	
	9.56	44.83	4.58	1.92	8.22	1.058	0.969	
	19.13	67.90	3.500	3.22	6.87	1.059	1.050	
	24.80	64.00	2.836	3.52	8.32	0.830	1.022	
	21.50	79.98	3.645	2.50	6.58	0.792	0.963	
	14.50	76.90	5.159	1.66	6.89	1.127	0.955	
90	23.55	119.95	4.965	2.35	7.52	1.045	0.931	1.507
	11.16	60.29	5.187	2.40	5.88	1.026	0.922	
					mean	0.991	0.973	
					σ	0.127	0.046	
	21.30	76.71	3.556	3.09	8.75	1.182	1.033	
	18.20	58.52	3.149	3.70	7.27	0.920	0.920	
	10.02	34.16	3.710	2.17	9.20	1.260	0.990	
	14.00	58.97	4.167	3.67	8.75	0.939	0.974	
	7.76	23.15	2.932	3.11	9.35	0.836	0.919	
	15.05	52.40	3.436	2.44	5.85	0.764	0.925	
	10.75	28.99	2.681	3.62	9.88	0.996	0.980	
	10.80	39.46	3.575	3.36	8.36	1.074	0.983	
	13.32	42.74	3.329	3.56	8.88	0.907	0.977	
	15.06	47.75	2.998	4.03	8.65	0.939	0.956	
					mean	0.982	0.966	
				σ		0.152	0.036	

Table 4: Comparison between the calculated GEF using different anemometers as a reference point to measure wind characteristics

Test sample	Anemometer 4		Anemometer 1		Anemometer 2		Anemometer 3		
	G_v	GEF	G_v	GEF	G_v	GEF	G_v	GEF	G_v
$\gamma = 0^\circ$	2.15	0.816	1.95	0.992	2.08	1.108	1.96	0.973	
$\gamma = 30^\circ$	1.90	0.865	1.71	21% 1.249	1.72	11% 1.263	1.69	-1.9% 1.274	
$\gamma = 45^\circ$	2.12	0.869	1.94	44.3% 1.059	1.88	1.1% 1.134	2.00	2% 1.008	
$\gamma = 80^\circ$	2.06	0.941	1.88	21% 0.976	1.89	4.7% 1.077	1.86	-4.8% 1.073	
$\gamma = 90^\circ$	1.87	1.013	1.88	3.7% 1.030 1.6%	1.85	10.3% 1.022 -0.7%	1.82	9.9% 1.052 2.1%	

Highlights (for review)

- Full-scale measurement of wind characteristics and force response of solar concentrator prototype is conducted and results could be exploited for design applications.
- Force coefficients calculated from full-scale measurement were successfully compared to wind tunnel results.
- The gust effect factor concept in ASCE7 could be adapted and applied to calculate peak dynamic wind response for this structure. The current results contribute to the efforts of standardisation for this category of special structure.

AUTHOR DECLARATION TEMPLATE

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from (bassem.kaabia@usherbrooke.ca)

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Full-scale measurement of the response of a CPV tracker structure prototype under wind load

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Abstract

The response of concentrated photovoltaic (CPV) structures under wind loading has to be carefully predicted to optimize the design of these structures. Designers normally rely on wind tunnel tests and equivalent static approaches as recommended by codes for the design of this type of nonconventional structures. This paper aims to evaluate the full scale wind response of a concentrated photovoltaic (CPV) prototype with mirror surface of $8 \times 16 \text{ m}^2$ and correlate it with wind measurements made near the solar structure. The full-scale wind response of the structure was evaluated with continuous 10 minute measurements of deformations on tower leg members during moderate wind events. The utility of this work derives from enriching field measurement data in order to understand the behaviour of this type of structure and to validate the previous wind tunnel testing works. Standard wind design process based on the analytical method, which is adopted by ASCE 7, is also revisited in the light of the full scale observations.

Keywords: Parabolic solar concentrator, Full scale measurement, Wind force coefficients, Equivalent static wind load, Gust effect factor

1. Introduction

Parabolic dish collectors are used to generate concentrated photovoltaic (CPV) solar energy as a new economical alternative to flat photovoltaic (PV) structures. CPV structure is usually designed as a tracking system that follows the sun position and reflects solar energy to high performance receivers. The tracking accuracy may be sensitive to deformation and vibration during operation mode when the structure is subject to wind load. Furthermore,

tracking solar structures can be optimized such that the position of the structure under extreme wind events minimizes the ultimate wind loads. A proper understanding of wind load and its effects could avoid conservative design and pave the way to provide cost effective design needed by the solar industry to fully reach its potential.

Wind tunnel test is a common method used in evaluating wind load on parabolic trough solar collectors (Peterka and Cermak, 1980; Hosoya et al., 2008; Gani et al., 2011) . The study of Gong et al. (2012), is among the rare contribution for full-scale wind load study on this type of structure. The measurement was taken for only two days, but it included a large number of geometric configurations to evaluate simultaneously wind characteristics and the differential pressure over collector reflectors which is essential to assess the reflector deflection in its operating phase.

In accordance with the research elaborated in the National Laboratory of Renewable Energy in the U.S. Department of Energy Office (NREL) (Murphy, 1980; Murphy, 1981; Hosoya et al., 2008), ASCE standards and American National Building codes can be used to calculate wind loads on solar structures. Eurocode-1 (2005) could also be used to calculate wind load for this type of structure according to Giannuzzi et al. (2007). The equivalent static approach, also called Gust Factor Method, was first developed by Davenport and Vickery in the 1960s (Davenport, 1967; Vickery, 1970; Vellozzi and Cohen, 1968). It is the conventional method used in most codes and standards. The equivalent static wind force is considered equal to the mean wind force, as defined in section 4, multiplied by gust loading factor (GLF). As a consequence of employing the 3s peak gust as the basic wind speed in ASCE7-95 (1995), the concept of Gust Effect Factor was introduced and its derivation was thoroughly investigated in the case of building structure by Solari and Kareem (1998) and Zhou et al. (1999). Although ASCE 7 standard does not provide specific guidance for this type of non-conventional structure, Maffei et al. (2013) and the SEAOC (2012) wind design guideline, showed that the design of flat solar arrays, for example, could be inspired from the existing static equivalent approach already approved specifically for building structures. It is also important to note that according to ASCE 7 and recent review of Holmes (2015), for dynamic sensitive structure and for complex structures, it is necessary to consider wind load as a dynamic load in order to evaluate accurately the maximum response and identify resonance

problem using more advanced analysis such as stochastic spectral and time domain dynamic analysis. In order to confidently use the equivalent static method for design of CPV structure, there is a need to further study how and when the static equivalent approach proposed in codes can be used for the evaluation of wind load on CPV structures.

The objective of this study is to use a full-scale prototype exposed to natural wind and compare the effect of wind measured to the one predicted with the equivalent static method. The present work was preceded by the sectional wind tunnel test study of Gani et al. (2011) at Université de Sherbrooke which evaluated the aerodynamic force coefficients of a 1:22 reduced model of the studied CPV prototype. Therefore, the transition between model/full scale prototype could be reviewed properly in the light of the present work that consists in evaluating correlation between real wind characteristics and the structural response of the studied CPV structure in full scale. An experimental program was initiated to collect data representing both the response of the structure at varied position of the tracker and the wind characteristics. All results were analyzed in order to reproduce the process of evaluating wind force and structural response by following the equivalent static method. Although the average measured forces on the CPV prototype cannot be directly used in general for design of parabolic solar structure in extreme conditions, they could be used to evaluate how equivalent static methods proposed in design codes can be adapted for this type of structure.

In this paper, the methodology of instrumentation and data analysis is first presented, which leads to evaluate the static and dynamic wind load on the CPV structure. The results are presented in three parts in coherence with the design approach adopted in ASCE 7. First, wind characteristics are studied for the specific site and compared to existing ASCE 7 standard and literature. Second, full-scale mean wind load values and mean force coefficients are analyzed and discussed in the light of the previous wind tunnel test results. Finally, the equivalent static approach is evaluated in the case of the studied prototype and compared to the experimental results.

2. Methodology: Test program

2.1. CPV structure prototype description

The parabolic structure for solar tracker system studied here is a prototype structure designed for utility-scale solar farms. The parabolic structure comprises a double parabolic dish frame supported by a truss back-up structure linked to the support tower by a central beam. The 35 kW tracker uses 128 identical reflective solar panels. The parabolic frame is mounted on a 2-axis tracker base that points the solar concentrator precisely towards the sun throughout the day. Two-axis movement allow the CPV system to rotate at its tower base with azimuth tracking and to pivot, at its attachment point to the tower, to achieve the required elevation with rotative gear drive. This structure has 400 mm gaps between rows of mirrors on the two dish part which can reduce its frontal horizontal load coefficient. The height, from the ground to the top of the solar collector, is approximately 13.5 m. The dish aperture is approximately 8 m. Technical details are shown in **Fig. 1**. Hot-rolled steel was used for most of the parts of the structure except for the mirrors. It is typically A36 steel with a yield strength of 250 MPa. The experimental program was conducted in the Solar Park in the Interdisciplinary Institute of Technological Innovation (3IT) at the Université de Sherbrooke. The studied CPV structure, as shown in **Fig. 2**, is surrounded by hay field limited by forest and low rise building depending on the direction it is facing. The deciduous forest, in the South and West direction, and the building, in the North-West direction, are respectively distant by approximately 150 and 50 m from the CPV system.

2.2. Instrumentation and acquisition

The wind measurement system (see **Fig. 3 (a)**), which is based on four WindMaster anemometers, was installed in 2013 and has been used previously to study wind spatial correlation. WindMaster is a sound anemometer of Gill Instruments, which can measure wind speed up to 45 m/s with a sampling frequency of 20 Hz along the three axis. Anemometers 1 to 3 were installed at the top of three meteorological towers at a 10 m height. Anemometer 1 is installed in the reference tower which is located at approximately 28 m from the center point of the prototype in the South-West direction. Anemometers 2 and 3 are located in distinct towers located at 10 m from the reference tower in the North and East directions respectively. Anemometer 4 was attached to the reference tower at a 7.5 m height. Anemometer 4 was

Figure 1: Technical drawing for main details of CPV system

selected to be a reference representing the wind load applied to the central beam level of the CPV prototype. The wind measurement system was used to measure the wind speed and direction as a function of time.

Twelve Linear Variable Differential Transformer sensors (LVDT) were installed on the structure. They were attached by pairs to each of the six main tower members as shown in **Fig. 3(b)**. Four tower members are part of two rectangular plane trusses of width 1560 mm inclined at an angle of 45° with the ground. At the base, the distance between these two plane trusses is 1670 mm. The two additional members are part of a triangular vertical plane truss. This truss is 730 mm wide at its base and 5800 mm high. It is located at 560 mm from the base tower center. The LVDT sensors were installed at 1 m above the ground. They measure the relative displacement on L203*102*13 sections, at the neutral principal axis. In this specific experiment, LVDT sensors were extended by a steel bar of 750 mm length in order

Figure 2: Site view surrounding the solar concentrator prototype in the 3it

to evaluate the strain developed in the L section element. The LVDT instruments have a relative uncertainty of $\pm 0.1\%$ in measuring displacement. The anemometers have a relative uncertainty of $\pm 1\%$ in measuring mean wind speed. Assuming a $\pm 1^\circ$ of error in measuring temperature and a relative uncertainty of $\pm 5\%$ in evaluating elasticity modulus E , the total accumulated uncertainty in measuring force coefficient values could reach approximately $\pm 5.4\%$ for the measured wind scenarios range.

All sensors were connected to a data acquisition system with different connection type: analogical for LVDTs and RS connection for anemometers. A LabVIEW program was developed, allowing a simultaneous acquisition between the anemometers wind data and the structural response data recorded by LVDT sensors. The acquisition frequency was controlled by a trigger which can adjust time step sampling according to wind speed. Data are continuously collected with a frequency of 1 Hz until the instantaneous wind speed exceeds 10 m/s. Then, acquisition speed moves to 20 Hz during the following 10 min. In accordance with the acquisition concept, recorded data were analyzed in 10 min time series. The sample duration could be easily compared to previous literature studies and reference documents.

(a) Anemometer's set up for wind measurement

(b) LVDT's instrumentation for deformation measurement

Figure 3: Photographic description for the instrumentation dispositive in the field

2.3. Test configurations

Measurements were taken in different geometric configurations and different wind characteristics. The specificity that the studied structure could change position when tracking the sun requires a specific parametric study of wind load according to different configurations. A test configuration is then characterized by its pitch angle γ that controls elevation of the collector dish and its yaw angle θ which defines the deviation of along wind direction from the axis X normal to the dish collector. This axis changes according to the azimuth position calculated from the North and controlled by the drive mechanism. A schematic view of the convention used to define axis and angles is shown in **Fig. 4**. The current convention is harmonized to NREL (Hosoya et al., 2008) as well as the IEC-62787 specification for solar trackers (IEC-62817, 2014).

2.4. Data treatment

Recorded data were split in 10 min blocks. Theoretically, measured data could be analyzed for longer periods. However, the correlation between wind

Figure 4: Test configurations including definition of pitch and yaw angle

speed and induced force measured on the tower base supports could be distorted by secondary effects due the varying weather conditions. Preliminary observations showed that temperature fluctuation detected by LVDT sensors could lead to important errors in the calculation of wind forces. It was observed that the correction for temperature effect did not improve the correlation between wind speed and deformation measured on the structure. The best strategy identified was to restrict sample length to 10 min and eliminate samples where temperature variation is above 1 °C. The strain is calculated using the following equation:

$$\Delta\varepsilon = \Delta L/L = (V - V_0)C_{lvd\text{t}} \quad (1)$$

Where ΔL is the elongation measured by the LVDT sensor, L is the bar length, V is the recorded voltage, V_0 is the reference voltage, and $C_{lvd\text{t}}$ is the calibration factor between differential voltage in mV and elongation in mm. Because of the evolution of LVDT sensors due to temperature fluctuation with time and even within different parts of the structure, a global reference voltage could not be defined for all tests. Therefore, the reference

voltage V_0 has to be adjusted for each tower member and each test sample. The reference value selected, for a given LVDT, corresponds to the minimum (compression members) and maximum (tension members) voltage measured by the sensor. To avoid non-representative response peaks, the selection of the reference voltage was restricted to a 60 s period within the 10 min sample where the average wind speed is minimum. Therefore, in this study it is always measured a relative variation of wind force associated to a relative wind speed ΔV .

The wind forces and the pitching moment applied to the dish collector would induce moment around different axes at the structure base. In this study, it was only possible to evaluate the moment around the Y axis, which is the most important loading direction for this type of structure. This moment is distributed to the main tower members in tensile/compression forces because the support tower is a truss structure. There is certainly also a moment around the Z axis (global torsion of the structure). This moment creates also some axial loads in the leg members which was not possible to evaluate accurately in this study, and a small torsion in the leg members which could not be measured by the 1D LVDT sensors. In addition to that, flexibility in rotation around the Z axis due to the tracker bearing could provide damping that reduces the dynamic response of the structure along different axes. In this study, this effect was limited because additional rotational stiffness was provided by fixing the bearing during the tests. However, the global torsion of the structure (moment around Z axis) at various yaw angles could be important in some cases and might need to be considered in design.

Regarding the adopted measurement configuration, the main tower member forces, measured in a specific position are used to calculate a global moment applied on the structure as shown in equation (2). It represents the structure response induced by a wind force applied to an equivalent height H .

$$\Delta M = \sum_{n=0}^6 d_n \Delta F_n = \Delta F H \quad (2)$$

where d_n is the distance between the measuring points and the base cen-

ter, ΔF_n is the axial force measured on the tower member n , and ΔF is the effective lateral force applied at the height H to present the same moment ΔM . In this paper, because the exposed area from the dish collector is much higher than the area for the other components and because the altitude rotation axis of the dish coincides with the central beam axis and to be coherent with the wind tunnel standard for this type of structure, the mean forces and the pitching moment are evaluated at the pivot axis height H , which is constant for all pitch angles. H was assumed to be equal to 6 m. This height is slightly different from the 7.5 m height of the reference anemometer. However, the wind speed from the reference anemometer was used directly, without wind profile correction, due to the uncertainty on the wind profile. The relative axial force ΔF_n induced at the structure base, for the main member n , is calculated from displacement measurement using the following equation:

$$\Delta F_n = \Delta \varepsilon_1 + \Delta \varepsilon_2 / 2EA \quad (3)$$

where E is the modulus of elasticity of steel support members of 200 GPa, A is the L section area and $\Delta \varepsilon_1, \Delta \varepsilon_2$ is the couple of strain measured in the sensor pair installed in the identified L section.

3. Wind and terrain characteristics

3.1. Wind parameters

Statistical analysis of the static and dynamic characteristics of wind was carried out to obtain mean wind speed, wind direction, turbulence, gust parameters and its standard deviation values for 10 min test samples. The resultant fluctuating wind speed and wind direction angle ψ were calculated from the recorded velocity in the three orthogonal directions. A typical test sample, from data recorded between 14:20 to 16:20 on the 14th April 2015, when structure elevation (pitch angle) was at 45° , was selected as an example. **Fig. 5** shows the variation of mean wind speed recorded by different anemometers, and then averaged over 60s using mobile average. **Fig. 6** shows the variation of mean direction averaged over 60s and mean wind speed averaged over 3s, 60s, 10 min, recorded only by the reference anemometer (An. 4).

Figure 5: Mean averaged wind speed over 60s during a 10 min test sample recorded from the four anemometers

As expected, in **Fig. 5**, the wind speed is lower for the reference anemometer and a small variation is observed between the three anemometers placed at 10 m height due to spatial correlation. **Fig. 6** is shown also to highlight the transition between the dynamic and static characteristics of wind using the mobile average. It is observed that the wind direction variation is relatively small when using a mobile average over 60s on a 10 min time period. This was true in general for most samples and it further justified the use of 60s mobile average and 10 min record samples for the static analysis of the wind loading on the CPV prototype.

Turbulence intensity and gust factors are important parameters to characterize wind dynamic aspect and identify the maximum structural response. The ratio of maximum wind averaged over 3s, 30s and 60s, to the 10 min mean wind speed were defined and calculated in Table 1. These ratios were selected to analyze the gustiness of wind. The horizontal turbulence intensity, $I_u(z)$ is calculated using Equation 4. The 3s peak gust speed g_v at height z is computed using Durst statistical model (Durst, 1960) with Equation 5:

Figure 6: Measured fluctuations of averaged wind speed over 3s, 60s and 10 min and wind direction over 60s during a typical 10 min test sample recorded from 7.5 m height anemometer

$$I_u(z) = \sigma(z)/\bar{V}(z)\hat{V}_{3s}(z) = \bar{V}(z) + g_v\sigma(z) \quad (4)$$

$$\hat{V}_{3s}(z) = \bar{V}(z) + g_v\sigma(z) \quad (5)$$

Where σ is the standard deviation of wind speed, $\bar{V}(z)$ is the mean wind speed at the height z and $\hat{V}_{3s}(z)$ is the maximum 3s averaged wind speed as used in ASCE 7–10.

A total of 263 data sets samples were selected from the data recorded by the reference anemometer, when 10 min mean wind speed exceeded 4 m/s and wind direction ranged between 250–300, to show the statistical distribution of turbulence intensity as a function of mean wind speed as presented in **Fig. 7**. From these recorded wind samples, 42 were related to specific CPV structure response tests where the structure configuration was controlled.

Figure 7: Turbulence intensity as function of mean wind speed recorded by the reference anemometer

These specific tests are highlighted with triangles in **Fig. 7**.

Fig. 7 shows that the mean value for turbulence intensity measured at the height of 7.5 m is approximately 32%. The surface roughness length z_0 and the power law coefficient α allowing to define respectively the logarithmic law and the power law in ASCE 7, were evaluated using two recording point at 7.5 m and 10 m height. An average value of 0.62 and 0.29 was found for z_0 and α respectively. The site category in ASCE 7 best matching these parameters is Suburban-Urban type B which is characterized by turbulence intensity of $\sim 38\%$, z_0 between 0.5 and 1.3 and α equals to 0.25. This is consistent with the general characteristics of the site which is an open area with an interference of deciduous forest and some low rise building especially in the N-W and S-W direction.

Wind characteristics, for the selected test configurations, are summarized in Table 1 based on data recorded only by the 7.5 m height anemometer. Test samples are selected when mean wind are higher than 3 m/s in order to give rise to meaningful base moment values of the structure. Selected tests are

also classified in category according to its pitch angle γ . Here, the yaw angle is less controlled because it depends on wind direction and to facilitate the analysis, the yaw angle for the samples shown in Table 1 was only for 0° with a tolerance of 10° in mean value. From Table 1, the mean wind speed range between 3.13 and 8.87 and corresponds to moderate winds. Recorded values match the actual operational conditions of the system which moves to the stow position (security position) if gust wind speed exceeds 10 m/s. Higher wind speed values are permitted only at pitch angle $\gamma = 90^\circ$ and $\gamma = 80^\circ$. The ratios, calculated in Table 1, show the dependence of wind speed on averaging time as reported in Durst (1960). The mean value of $\hat{V}_{60s}/\bar{V}$, which is equal to 1.38, is slightly higher than the values of 1.30, adjusted for 10 min period, reported in Durst (1960). The mean value of $\hat{V}_{3s}/\bar{V}$, which is 2.00, is also higher than the 3s gust factor value of 1.53 recommended in the ASCE7-10 (2010) for design purpose. The 3s peak factor values are scattered from 2.34 to 4.38 and the highest values are associated to the important mean wind speed events. Generally, for conservative design purposes, the value is assumed to be between 3.5 and 4.1 as mentioned in Solari and Kareem (1998). The difference may be explained by the assumed site category hypothesis, the measurement point height and the range of mean wind speed which is considered weak compared to design wind speed values.

4. Mean Wind Load Evaluation

Design forces applied to this structure are presented in the equations below using the schema already defined in **Fig. 4**.

$$F_x = q_0 C_x A \quad (6)$$

$$F_z = q_0 C_z A \quad (7)$$

$$Mp = q_0 C_M AD \quad (8)$$

where F_x is the drag force, F_z is the lift force and M_p is the local pitch moment around the Y axis defined in **Fig. 4**. The coefficients C_x , C_z and C_M depends on the shape and the surface of the global exposed area of the structure. A and D are respectively the exposed area and the height of the structure dish. q_0 is the reference dynamic pressure calculated at the height H from the ground and defined in equation (8):

$$q_0 = 1/2\tau\rho_0(KV_r)^2 \quad (9)$$

where τ is the air density correction factor, ρ_0 is the reference air density, K is a roughness factor deduced using the design mean wind speed profile and V_r is the reference wind speed. In the experimental context, K=1 and V_r is equal to the measured wind speed.

Wind forces can exist in both flow direction when the structure is static. This study treats the normal force applied in the X direction and normal to the dish surface, and induced by the along wind. The force in the Y direction, which corresponds to weak exposed area, is not considered. The test sample already used in **Fig. 6**, was selected to show the correlation between averaged wind speeds and both the averaged forces measured on the main tower members (**Fig. 8 (a)**), and the averaged global moment (**Fig. 8 (b)**).

Intermediate results, shown in **Fig. 8**, are important to validate the adopted methodology from a structural point of view. The frontal tower member pair are stretched, the back member pair are compressed and the leg members of triangular plane truss are less sensitive to horizontal forces. This force distribution is in agreement with the design concept in which the triangular plane truss takes mainly the vertical load. Correlation is clear between the averaged moment presenting the static response and the averaged wind speed. This paved the way to investigate experimental wind force coefficients.

Wind force coefficients

Mean wind force coefficients were evaluated at six pitch angles γ and at two yaw angles θ for the upwind side. The elevation $\gamma = 90^\circ$ represents the assumed stow position, in which the structure is placed during strong wind

(a) 60s averaged force measured in the tower members Vs the 60s averaged wind speed (b) Instantaneous and 60s averaged moment Vs the 60s averaged wind speed

Figure 8: Structural response Vs wind speed for a typical test at $\gamma = 45^\circ$

to avoid damage and $\gamma = 0^\circ$ is considered as a critical position, in which the maximum dish surface is exposed to wind. Test samples were classified in two categories representing the yaw angle $\theta = 0^\circ$ and $\gamma = 45^\circ$, with a tolerance of 10° on the mean value. For both the yaw angle, wind force coefficients were evaluated for wind on the concave surface only. Considering that the total moment measured at the tower base is the sum of the moment induced by thrust wind force applied at the central beam height H and the reference pitching moment ΔM_p and assuming that the lift wind force is applied with small eccentricity from the rigidity center of the tower and could add an additional moment ΔM_l around Y axis, the moment induced by the drag forces only in the X direction could be evaluated from the total moment. Introducing Equation (8) and (7) in Equation (6) the horizontal force coefficient in the principal direction X can be defined as:

$$C_{fx} = 2(\Delta M - \Delta M_p - \Delta M_l)/(\rho A H \Delta V^2) \quad (10)$$

ΔM_p and ΔM_l are calculated based on wind tunnel test coefficients respectively C_M and C_{fz} . It was shown that the maximum contribution of the pitching moment and the eccentric lift force in the total moment around Y

axis were respectively +27% and -12% for the worst case, respectively. The values of C_M and C_{fz} are maximized for $\gamma = 60^\circ$ and $\gamma = 90^\circ$.

For each 10 minute sample, the relationship between moment ΔM and the square of wind speed ΔV^2 , both averaged over 60s, was plotted as shown in **Fig. 9**. By assuming a linear correlation, the average slope was extracted for each test and used to calculate the wind force coefficient C_{fx} . For each test, the air density ρ was adjusted using the recorded average temperature over the 10 min period. A mean force coefficient $\bar{C}_{fxj}$ was finally defined for each combination of pitch and yaw angle by averaging all test samples associated to a same configuration. **Fig. 10** shows the mean experimental

Figure 9: Correlation between mean moment M and mean wind speed square for the typical example of at $\gamma = 45^\circ$

wind load coefficients and its for varied pitch angle at yaw angle $\gamma = 0^\circ$ along with their standard deviation. Results are compared with previous wind tunnel test results of Gani et al. (2011). This figure shows also the drag force coefficients for standard CPV trough shape studied by Hosoya et al. (2008) as well as the Standard Ground Mounted Photovoltaic Tracker studied by Swagat (2011) for yaw angle $\theta = 0^\circ$. In order to investigate on the wind directionality effect, Fig. 10 shows also the variation of measured force coef-

ficient as a function of pitch angle when the recorded yaw angle was equal on average to 45° . It can be observed in **Fig. 10** that the maximum and mini-

Figure 10: Force coefficient as a function of pitch angle for full scale and reduced scale experimental studies at yaw angle $\theta = 0^\circ$ and $\theta = 45^\circ$

imum wind drag coefficients would occur at pitch angle $\gamma = 0^\circ$ and $\gamma = 90^\circ$ respectively, which is in agreement with wind tunnel results. It is also noted that by changing the position from $\gamma = 0^\circ$ to $\gamma = 90^\circ$, we could decrease the total force by more than 80%. This confirms that the moving characteristics of structure give more flexibility to engineer for design in ultimate state. By comparing with the results of Hosoya et al. (2008) and Swagat (2011), the difference could simply be explained by distinctive shape and geometry. It is obvious that the Cylindrical Trough studied by Hosoya et al. (2008), which has a smaller focal distance compared to the studied CPV prototype, give rise to more important force coefficients. However, it is important to note that the studied CPV prototype still has a lower force coefficient values even compared to Flat Reflective Surface Tracker. This could confirm the special aerodynamic shape of the parabolic dish used which is enhanced by the special disposition of mirror columns and the gap between them.

Fig. 10 shows also that the average measured full-scale force coefficients

are lower than wind tunnel test coefficients of Gani et al. (2011) for all positions. The standard deviation values of the experimental coefficients at yaw angle $\theta = 0^\circ$ are scattered between 0.09 and 0.28. The difference between the full and the reduced model scale could be attributed to several reasons. The first reason is related to small differences in geometry. For the wind tunnel tests, the model was reduced to only one dish part fixed on a cylindrical aluminum bar Gani et al. (2011). Then, the gap between the two dishes in the full scale model is not included and the porosity percentage is not accurately modeled. This porosity effect, which is detailed in Swagat (2011) could explain part of the difference. According to Swagat (2011), 5% porosity could reduce the drag force coefficient between $\sim 2\%$ and $\sim 9\%$ depending on the pitch angle, the higher reduction percentage occurring for pitch angle $\gamma = 45^\circ$ and $\gamma = 30^\circ$. This could explain part of the gap in **Fig. 10** where the maximum differences between full scale and wind tunnel tests occurs for $\gamma = 30^\circ$ ($\sim 16\%$) and $\gamma = 45^\circ$ ($\sim 12\%$). The second reason could be related to distinction in boundary layer conditions between wind tunnel and outdoor full scale experiment. In contrary to wind tunnel tests, full scale wind characteristics are unsteady in time and space. Turbulence intensity, Reynolds number and wind spatial correlation effect, could influence slightly mean force coefficient values and unsteady aerodynamic coefficients could differ from those in steady flow (Davenport, 1964). Generally, turbulence intensity and Reynolds number effect are not considered important for most usual solar structure shape. However incertitude remains for particular curved collectors pitches and Reynolds number variation accompanied with high distinction in turbulence intensity could lead to difference between full scale and model results as mentioned in Murphy (1980).

It is shown also in **Fig. 10** that force coefficients calculated for different pitch angles are sensitive to yaw angle. The deviation of wind direction from the normal axis changes the pressure distribution over the collector surface and reduces the drag force. The wind directionality becomes an important factor to optimize the operational conditions of the whole system if we consider that wind force could decrease between 10% and 30% depending on pitch angle by only changing the tracker azimuth by 45° away from the wind direction.

From this global study of wind load, it is mainly concluded that the methodology adopted to extract full-scale aerodynamic coefficients is ade-

quate. The results are in concordance with the need of most important studies in this field such as Hosoya et al. (2008) which recommended to validate the acceptability of the wind tunnel test data by comparing with field full-scale results for parabolic collectors with curved surfaces. In this study, wind tunnel testing gives values slightly higher to average full scale coefficients and the acceptance of wind tunnel results could be confirmed, even though important geometrical simplifications were made for the construction of the reduced scale model and a uniform steady flow was used. However, it is always recommended to consider the standard deviation of the force coefficients values and to use peak values rather than average values for a design of similar structure.

5. Gust Effect Factors

The GEF could be simply defined by the ratio between the maximum response including resonant and correlation effects and the maximum response including only wind gustiness. Therefore, it is the ratio between G_{GLF} and the gust pressure factor G_Q detailed in Solari (1993). The recent fundamental formulation introduced in the ASCE 7-10 is presented in the equation (13).

$$GEF = G_{GLF}/G_Q = 0.925(1 + 2I_z\sqrt{P_0}\sqrt{g_Q^2Q^2 + g_R^2R^2})/(1 + 2g_vI_z\sqrt{P_0}) \quad (11)$$

Where g_v and I_z are respectively the 3s peak velocity factor and the turbulence intensity already defined in Section 3. Q is a parameter which represents the background response factor, which depends on the distribution of the maximum pressure field on the exposed surface, R is the resonant response factor, which depends on the natural frequency, and g_Q, g_R are the peak factor for the background and the resonance response respectively. The constant 0.925 has been introduced for additional size reduction effects as well as to adjust loads closer to ASCE7-93 (1993) values as reported in Kwon and Kareem (2014). P_0 is the term that controls the effect of the gust averaging time (Solari and Kareem, 1998).

This paper includes an examination of the application of the GEF, using base moment formulation, in the particular context of a CPV prototype.

Many parameters influencing the calculation of the GEF are revisited such as geometrical parameters and wind spatial correlation hypothesis.

5.1. Design GEF (ASCE7-10 standard)

Based on the 3s gust wind speed map, the term $2\sqrt{P_0}$ is adjusted to 1.7 in the ASCE 7-10 (2010). Usually g_Q is considered equal to g_v for conservative design (Solari and Kareem, 1998). In order to adapt the calculation of GEF for this particular structure of solar concentrator, GEF is calculated in a design context departing from ASCE 7-10 (2010) hypothesis. The background response Q^2 is calculated using the actual geometric parameters of the CPV prototype. Dimensions b , h and d are respectively the dish width, the projected length over the orthogonal plan to wind direction X and the structure depth d (**Fig. 4**). Structure height h and depth d are adjusted with dish elevation γ . The depth d is assumed to be the distance along the X axis (along the wind direction) between the two furthest points on the dish collector. The tower support structure surface contribution in the background response is also neglected. The equivalent height H , where mean wind force is evaluated, is always assumed to be at the pivot axis. It is important to note that in ASCE 7-10, wind speed is assumed to be constant for elevation less than 10 m (33 ft), which corresponds to this case ($H=6$ m). At low stress level, corresponding to low and medium wind speed values, the structure is lightly damped even by considering the aerodynamic damping. The value of 0.0025 as damping ratio was selected based on the recommendation of Davenport (1964) for a similar geometry parabolic antenna structure. It is also appears realistic corresponding to the experimental study of Griffith et al. (2014). Table 2 presents the parameters calculated using ASCE 7-10 approach for the CPV prototype configuration at $\gamma = 90^\circ$. For this calculation, the hypothesis for wind characteristics and structural parameters are as follows:

- Basic wind speed at reference height in exposure C=40 m/s;
- Type of exposure= B (see Section 3);
- CPV structure height $h=1.49$ m;
- CPV structure width $b=14.63$ m;

Figure 11: Power spectral density of 10 min sample measured moment at pitch angle $\gamma = 90^\circ$

- CPV structure depth $d=8.38$ m;
- CPV natural frequency $n_1=1$ Hz ;
- Damping ratio $\beta = 0.0025$;
- Along wind force coefficient $Cf_x = 0.20$;
- Height of central beam axis above the ground $H=6$ m.

It is important to note that all wind parameters are calculated using Table 6.2 titled as Terrain Exposure Constant in ASCE 7-10. The CPV prototype natural frequency is assumed based on the power density spectrum representation of the instantaneous base moment over many test samples (for example, see Fig. 11). The GEF of Building 1 (used as an example in ASCE 7) is evaluated in Solari and Kareem (1998) for a site type of exposure A, using the same models. By referring to the Building 1, it is expected that the value of $Q^2(0.828)$ for the CPV structure would be higher than Building 1 (0.588) because of its smaller exposed surface to wind especially in its stow position. However, it is observed that the dynamic response factor $R^2(2.038)$

reflects a relatively important contribution of the resonant component in the maximum response despite the higher value of natural frequency ($n_1=1$ Hz) comparing to Building 1 ($n_1 = 0.2\text{Hz}, R^2 = 0.535$). It is clear that the specific geometry (especially small thickness of structural components and small exposed area) could increase the dynamic contribution. However, according to ASCE 7-10, structures with natural frequency above 1 Hz can be considered as rigid structures. For these structures, the resonant response normally can be neglected. For the studied CPV prototype a difference of 42% in the design GEF (Table 2) could be induced by using this assumption. This issue is further studied with the results for experimental GEF.

At this level, it could be concluded that applying the GEF concept by adapting geometrical parameters for the studied structure within the adoption of the existing theoretical models could give rise to coherent results by comparing to the ASCE 7 Building example. The geometric specificity of the CPV structure has an important impact on the calculation of the two component Q^2 and R^2 . This concept is also revisited by evaluating experimental GEF and compare it to analytical GEF, which could be calculated using theoretical models but departing from real statistical wind characteristics measured in the site.

5.2. Experimental GEF

The evaluation of experimental GEF for each test sample in the study is based on the definition of Solari and Kareem (1998) in which GEF is considered as the ratio of the gust response factor G_{GLF} to the Gust Pressure Factor G_v^2 using the following equation:

$$G_{GLF} = \Delta M_{max} + M_{ref} / \Delta M_{mean} + M_{ref} \quad (12)$$

$$G_v = \widehat{V}_{3s} / \overline{V}(600s) \quad (13)$$

Where ΔM_{max} and ΔM_{mean} are the measured maximum and mean base moment. V_{3s} and $\overline{V}(600s)$ are the 3s peak wind speed and the 10 min mean wind speed, which are already calculated in Table 1 for each test sample

using the reference anemometer. It is important to remember that the variation of moment was measured from a reference state and we have to adjust values by adding M_{ref} , which corresponds to the moment response calculated from the minimum reference wind speed and the experimental mean force coefficient for a given sample. The minimum reference wind speed for a sample is defined as the minimum instantaneous wind speed included in a 60 s period within the 10 min sample where the average wind speed is minimum.

5.3. Analytical GEF

For the evaluation of analytical GEF, most wind parameters (mean wind speed, turbulence intensity, peak factor, wind spatial correlation) involved in the calculation of GEF are adjusted to measured values instead of values calculated from theoretical models adopted by ASCE 7. The gust time duration, $\tau = 3s$, is taken similarly to ASCE 7-10. However, the time period T , over which the wind is averaged, is reduced to 600s instead of 3600s. Theoretically, this change would influence the g_v parameter but it would change slightly the GEF in the given wind conditions. g_Q is still taken equal to g_v , as a conservative assumption for the background component.

The term Q^2 is related to wind spatial correlation and geometric parameters. In order to evaluate Q^2 accurately within real serviceability wind conditions, Q_0 detailed in Solari and Kareem (1998) was modified by introducing the measured horizontal exponential decay coefficient C_y and C_z .

$$Q_0 = 1/(1 + 0.29\tilde{L}_{0.63} + 0.56\tilde{\tau}_{0.74}) \quad (14)$$

$$L_0 = 0.5(\tilde{H} + \tilde{B}) \quad (15)$$

$$\tilde{\tau} = \tau \bar{z}_{\bar{z}} / L_{\bar{z}} \quad (16)$$

$$\tilde{H} = C_z h / L_{\bar{z}} \quad (17)$$

$$\tilde{B} = C_y b / L_{\bar{z}} \quad (18)$$

Here, the existing wind measurement dispositive, detailed in section 2, allows evaluating the exponential decay coefficient depending on wind direction. The horizontal distances between the reference anemometer tower and the others are representative to the dish collector width. The evaluation of the coefficients is elaborated using the procedure reported in Parent (2015). The wind correlation in the Y direction, represented by C_y is calculated using the anemometers 1-2 and 1-3 depending on wind direction. The vertical wind correlation, represented by C_z , is calculated using anemometer 1-4. Resulting values for the test samples scatter between 1.5 and 4 for C_y and 7 and 9 for C_z . This result shows that wind is more correlated in the specific wind conditions and the hypothesis of $C_y=C_z=11.5$ would yield smaller background response. These low exponential decay coefficients were used for the calculations of the analytical GEF in Table 3. However, they were evaluated for relatively low wind speeds and therefore they are not necessarily representative of higher wind speeds. The coefficient C_x , for the along wind direction, is still assumed to be 15.4 (Solari and Kareem, 1998).

5.3.1. GEF results

Table 3 presents the results for experimental, analytical and design GEF for the test samples already presented in Table 1. The calculation of design values is extended to all pitch angle configurations for comparison purposes.

Overall, both experimental and analytical coefficients are under design values. By comparing the mean values associated to each pitch angle, the analytical and the experimental results are relatively close and mean experimental values are slightly higher than analytical values for most configurations. GEF values are more important for the security positions $\gamma = 90^\circ$ and $\gamma = 80^\circ$, where the structure is supposed to be exposed to higher wind speed and experimental values are under analytical estimations. In these particular positions, it seems that the dynamic response is slightly underestimated. The dynamic effect caused by the overturning moment (represented by the first frequency) is clearly more important in these configurations and its contribution to the resonant part increases the GEF values especially in the

higher wind speed range. An advanced structural dynamic analysis would be needed to confirm the resonant component contribution and its different components contributions, especially in the ultimate conditions with strong wind speed ranges for this specific type of structure.

It is noted also that analytical GEF increases as the exposed surface (pitch angle) decreases. Indeed, for the service positions ($\gamma = 0^\circ$, $\gamma = 30^\circ$, $\gamma = 45^\circ$), the dynamic contribution of the structure represented by R^2 is small because of the low wind speed and the background response factor Q^2 may dominate in most of the test samples. However, by increasing pitch angle ($\gamma = 90^\circ$, $\gamma = 80^\circ$), Q^2 becomes higher and R^2 contribution becomes significant especially when considering higher wind speed in those positions. This could also be observed with the experimental test results.

Moreover, a relatively high statistical data dispersion is observed in the experimental results comparing to the analytical ones. This can be explained in part by the fact that the wind speed is measured at only one point in space (reference anemometer). This uncertainty, is studied through the existing wind measurement dispositive. On one hand, the effect of reference height is studied by comparing GEF calculated using wind parameters from anemometers 1 and 4. On the other hand, the effect of horizontal spatial correlation, mentioned above, is studied by observing the effect of change between the three anemometers fixed at the same height. Table 4 shows the measured GEF using the wind data from the four different anemometers. In this table, the percentage of change indicated for anemometer 1 is calculated with respect to the reference anemometer 4, whereas the percentage of change indicated for anemometers 2 and 3 is calculated with respect to anemometer 1, which is located at the same height.

It is observed that the highest change percentage could occur due to the vertical wind correlation especially for weak wind speed configurations. Therefore, it could be concluded that identifying the optimal equivalent height for this type of structure is important to avoid conservative design. Applying literally ASCE 7 standard, where wind velocity is constant for elevation less than 10 m (33 ft), is a conservative assumption. This result has to be verified for high wind scenarios to be more conclusive in the design conditions. The horizontal wind spatial correlation is also a parameter which could influence the experimental assessment of the GEF and could explain the high disper-

sion of experimental results in Table 3.

In summary, applying the concept of GEF to evaluate the maximum equivalent static wind load and then the maximum along wind response is also validated for the given special structure. Regardless, of some observed difference between the theoretical model and measured values in predicting global wind characteristics, especially in the low and moderate wind speed range context, GEF as defined in ASCE 7 provides acceptable results for evaluating the maximum induced wind response.

6. Conclusions and Perspectives

Evaluating wind load on solar structures, more specifically parabolic solar concentrator, is an important component to optimize its design, therefore increase its financial flexibility. In this study, a methodology was used to correlate the global structural response of a full scale CPV prototype to measured wind characteristics. Analyzed data validated the acceptability of wind tunnels results and revised the application of the equivalent static approach for this specific type of structure. The main conclusions are as follows:

- (a) Wind characteristics including mean wind, turbulence intensity, gust factor, roughness parameters were evaluated and values were coherent with ASCE 7 standard and the site category;
- (b) Full scale wind force coefficients were evaluated at varied pitch angles and their sensitivity to wind direction were studied. Thus, the acceptability of wind tunnel method, using a simplified model and steady flow hypothesis, was confirmed and discrepancies with experimental coefficients were discussed;
- (c) The Gust Effect Factor concept and the equivalent static approach were also revisited in the light of experimental results. The existing GEF model could be adapted to this type of structure and experimental values were coherent with analytical prediction. Depending on structure configuration and wind speed range, the resonant part of the response can be important. Advanced dynamic analysis would allow studying accurately the importance of the dynamic contribution in evaluating the maximum force for this type of structure.

All experiments were conducted with operational conditions for the structure. Security recommendations limited the ability to test strong wind speed scenarios. Thus, the average measured forces on the CPV prototype can not be directly used in general for design of parabolic solar structure in extreme conditions. However, the existing data were sufficient to evaluate globally the structural static response within the service limit state and it were useful to evaluate the coherence of applying the equivalent static approach in the studied case. The need to test the structure within stronger wind events, is recommended. Numerical simulations are needed to further study the static and dynamic response of CPV structures under various wind conditions. These simulations could allow developing practical tools for the design of these structures to optimize its behavior in both serviceability and survivability conditions.

Acknowledgements

The authors would like to thank SpaceWatts division of Gestion TechnoCap for the technical contributions and financial support for the research, along with NSERC, PROMPT and Hydro-Sherbrooke. We are also grateful for the financial contributions of the Canadian Foundation for Innovation (FCI), the Ministère de l'Économie, Science et Innovation of Québec and the Université de Sherbrooke for the unique CPV infrastructures. Finally, the important technical contribution of Richard Norman to the project is warmly acknowledged.

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Table 1: Wind characteristics over selected test samples

γ	V	I_u	$\bar{V}/V$	$\bar{V}_{3s}/V$	$\bar{V}_{60s}/V$	g_v	ψ
0	3.81	0.42	2.74	2.15	1.49	3.00	213
	3.55	0.48	3.69	2.51	1.59	3.31	212
	4.05	0.36	2.67	2.19	1.25	3.88	205
	4.05	0.33	2.41	1.95	1.38	3.15	213
	3.58	0.33	2.24	1.98	1.39	3.20	215
	3.13	0.32	2.33	1.87	1.30	2.91	213
	4.27	0.36	2.37	2.13	1.31	3.63	197
30	4.92	0.41	2.47	2.26	1.79	3.16	299
	4.72	0.35	2.26	1.82	1.33	2.62	211
	4.56	0.32	2.29	2.03	1.37	3.58	292
	4.93	0.27	1.94	1.69	1.30	2.76	275
	5.39	0.35	2.13	1.88	1.39	2.73	228
	5.14	0.32	2.45	1.80	1.26	2.82	218
	4.71	0.35	2.46	2.02	1.34	3.91	215
45	5.09	0.35	2.37	1.91	1.40	2.88	218
	4.25	0.35	2.81	2.12	1.57	3.58	207
	6.85	0.38	2.62	2.43	1.48	4.05	288
	4.07	0.38	2.32	1.99	1.39	2.85	210
	6.81	0.29	2.22	1.99	1.32	3.63	301
	4.48	0.38	2.77	2.13	1.37	3.33	144
	4.87	0.37	2.54	2.07	1.32	3.30	125
60	5.09	0.26	2.20	1.94	1.29	4.01	294
	4.08	0.39	2.62	2.25	1.51	3.50	209
	7.03	0.29	2.47	1.84	1.30	3.32	281
	7.11	0.34	2.42	2.03	1.47	3.24	293
80	7.34	0.34	2.72	2.08	1.45	3.49	286
	8.52	0.32	2.30	1.82	1.30	2.83	293
	8.87	0.29	2.35	1.85	1.33	3.30	285
	7.54	0.34	2.57	2.15	1.42	3.75	278
	6.55	0.37	2.69	2.14	1.43	3.45	263
	6.77	0.32	2.52	2.18	1.27	4.23	272
	6.11	0.33	2.76	2.25	1.40	4.08	271
90	8.03	0.30	2.16	1.73	1.27	2.84	287
	6.37	0.29	2.80	2.12	1.46	4.38	281
	6.76	0.26	1.95	1.62	1.35	2.78	276
	7.32	0.35	2.47	2.11	1.52	3.45	283
	5.41	0.27	2.06	1.87	1.34	3.71	272
	5.63	0.34	2.48	2.12	1.43	3.61	278
	5.55	0.30	1.97	1.64	1.33	2.34	279
	6.62	0.31	2.19	1.82	1.44	2.89	290
	7.10	0.31	2.45	1.92	1.33	3.52	290
	6.59	0.27	2.29	1.79	1.27	3.94	289
Mean	5.65	0.33	2.44	2.00	1.38	3.35	252
Min	3.13	0.26	1.94	1.62	1.25	2.34	125
Max	8.87	0.48	3.69	2.51	1.79	4.38	301

Table 2: Wind characteristics over selected test samples

$\hat{V}_{ref}$	40 m/s	$\bar{V}_z$	33.33 m/s	g_v	3.40
$\bar{z}$	10 m	$\hat{V}_{\bar{z}}$	17.67m/s	g_Q	3.40
I_z	0.30	N_1	5.34	g_r	4.18
L_z	95 m	R_n	0.048	GEF	1.507
Q^2	0.828	R_b	0.228	GEF($R^2=0$)	0.872
		R_h	0.784		
		R_d	0.127		
		R^2	2.053		

Table 3: Experiment, analytical, design GEF values over different test samples at different pitch angles

Pitch angle γ	Δ Mean	Δ Mmax	G_{GLF}	Cy	Cz	Experimental GEF	Analytical GEF	Design GEF
0	6.09	35.219	5.784	3.20	4.45	1.246	0.871	1.382
	8.70	46.44	5.186	3.24	4.60	0.822	0.861	
	8.98	31.91	3.550	2.25	6.20	0.665	0.861	
	7.68	28.91	3.762	3.66	4.29	0.985	0.875	
	6.58	25.92	3.935	1.22	4.79	1.002	0.873	
	6.24	18.21	2.864	1.90	5.22	0.823	0.867	
	7.31	30.82	3.977	2.33	4.92	0.875	0.868	
					mean	0.916	0.868	
					σ	0.184	0.005	
30	8.18	42.83	4.792	5.236	8.25	1.029	0.875	1.266
	5.79	24.18	4.172	2.42	5.68	1.266	0.885	
	11.47	30.05	3.085	3.21	3.89	0.751	0.871	
	11.04	32.79	3.186	3.88	4.77	1.118	0.889	
	15.25	49.09	3.212	2.58	7.50	0.907	0.869	
	19.48	47.23	2.425	3.92	11.32	0.796	0.891	
	14.85	45.46	2.933	3.69	5.62	0.720	0.887	
	12.98	36.78	2.832	3.62	9.22	0.778	0.867	
					mean	0.920	0.879	
					σ	0.198	0.009	
45	7.44	29.73	4.121	4.01	5.89	0.916	0.871	1.295
	13.62	58.83	4.318	2.03	4.84	0.918	0.887	
	4.04	18.55	4.593	2.63	7.99	1.157	0.878	
	10.84	32.79	3.024	3.26	3.25	0.798	0.902	
	6.75	21.94	4.123	2.07	3.50	0.908	0.880	
	5.81	26.40	4.262	3.53	8.57	0.998	0.879	
					mean	0.949	0.883	
					σ	0.120	0.010	
80	9.56	44.83	4.58	1.92	8.22	1.058	0.969	1.499
	19.13	67.90	3.500	3.22	6.87	1.059	1.050	
	24.80	64.00	2.836	3.52	8.32	0.830	1.022	
	21.50	79.98	3.645	2.50	6.58	0.792	0.963	
	14.50	76.90	5.159	1.66	6.89	1.127	0.955	
	23.55	119.95	4.965	2.35	7.52	1.045	0.931	
	11.16	60.29	5.187	2.40	5.88	1.026	0.922	
					mean	0.991	0.973	
					σ	0.127	0.046	
90	21.30	76.71	3.556	3.09	8.75	1.182	1.033	1.507
	18.20	58.52	3.149	3.70	7.27	0.920	0.920	
	10.02	34.16	3.710	2.17	9.20	1.260	0.990	
	14.00	58.97	4.167	3.67	8.75	0.939	0.974	
	7.76	23.15	2.932	3.11	9.35	0.836	0.919	
	15.05	52.40	3.436	2.44	5.85	0.764	0.925	
	10.75	28.99	2.681	3.62	9.88	0.996	0.980	
	10.80	39.46	3.575	3.36	8.36	1.074	0.983	
	13.32	42.74	3.329	3.56	8.88	0.907	0.977	
	15.06	47.75	2.998	4.03	8.65	0.939	0.956	
					mean	0.982	0.966	
				σ		0.152	0.036	

Table 4: Comparison between the calculated GEF using different anemometers as a reference point to measure wind characteristics

Test sample	Anemometer 4		Anemometer 1		Anemometer 2		Anemometer 3		
	G_v	GEF	G_v	GEF	G_v	GEF	G_v	GEF	G_v
$\gamma = 0^\circ$	2.15	0.816	1.95	0.992	2.08	1.108	1.96	0.973	
$\gamma = 30^\circ$	1.90	0.865	1.71	21% 1.249	1.72	11% 1.263	1.69	-1.9% 1.274	
$\gamma = 45^\circ$	2.12	0.869	1.94	44.3% 1.059	1.88	1.1% 1.134	2.00	2% 1.008	
$\gamma = 80^\circ$	2.06	0.941	1.88	21% 0.976	1.89	4.7% 1.077	1.86	-4.8% 1.073	
$\gamma = 90^\circ$	1.87	1.013	1.88	3.7% 1.030 1.6%	1.85	10.3% 1.022 -0.7%	1.82	9.9% 1.052 2.1%	