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Estimation of extreme wind pressure coefficient in a zone by multivariate extreme value theory

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Abstract. Knowledge on the design value of extreme wind pressure coefficients (EWPC) of a specific zone of buildings is essential for the wind-resistant capacity of claddings. This paper presents a method to estimate the representative EWPC introducing the multivariate extreme value model. The spatial correlations of the extreme wind pressures at different locations can be consider through the multivariate extreme value. The moving average method is also adopted in this method, so that the measured point pressure can be converted to wind pressure of an area. The proposed method is applied to wind tunnel test results of a large flat roof building. Comparison with existing methods shows that it can give a good estimation for all target zones with different sizes.

Keywords: large zone; claddings; extreme wind pressure coefficient; multivariate extreme value theory; wind tunnel test

1. Introduction

It is well known that wind load on a building varies due to the spatial characteristics of wind on the building surface (Kareem and Cermak 1984, Dong and Ye 2012). The design extreme wind load for the wind-resistant design of building claddings is different for different zones. A study on estimating the extreme wind pressure coefficients (EWPC) in different zones become quite necessary.

Many studies have been carried out on the estimation of local extreme wind load, and they may be classified into two major categories. The first approach estimates the extreme wind load according to the parent distribution of the local wind load, such as the Peak Factor Method (Davenport 1967, Davenport *et al*. 1977a, 1977b), Hermit Polynomial Method (Kareem and Zhao 1994; Huang, *et al*. 2016) and Translation Method (Sadek and Simiu 2002, Ding and Chen 2014). Peak Factor Method assumes that the probability density distribution follows the Gassian distribution, and it gives a peak factor according to the zero-crossing theory of the Gaussian process. Hermit Polynomial Method expands the Peak Factor method by considering the non-Gaussian characteristics of wind pressure through higher order moments of samplings. The translation process approach (Grigoriu 1995) makes use of the extreme value of the measured wind pressure for the estimation. The other approach estimates the extreme wind load based on the extreme values samples with the extreme value distribution. The extreme value distribution includes the Generalized Extreme Value Distribution (GEVD) (Cook and Mayne 1979, Kasperski 2007, Hui *et al*. 2017) and the Generalized Pareto Distribution (GPD) (Holmes and Moriarty 1999, Ding and Chen 2014), and etc. It should be noted that when GPD model is adopted, the threshold needs to be high enough to achieve asymptotic convergence (Galambos and Macri 1999, Harris 2005). Although a lot of studies have been carried out (Simiu 1996, Holmes 1999, Harris 2005, Ding and Chen 2014), this problem has not been solved properly yet. The GEVD model is widely used to describe the extreme value distribution of wind pressure (Holmes 2003, Kasperski 2009).

It is known that the wind pressures within an area are not totally correlated, and this fact makes it challenging to estimate the extreme wind load of a target area based on the measured wind pressure at a few locations. A few estimation methods for the representative EWPC of an area have been proposed, such as the area average (AA) method in space domain (Gumley 1984, Alrawashdeh and Stathopoulos 2015) and the moving average (MA) method in time domain (Lawson 1976, Uematsu and Isyumov 1999). They have been widely adopted in wind load codes (Stathopoulos *et al*. 1981). These methods, however, are not proposed for the estimation of the representative extreme wind load of a zone with large area.

To sum up, the current calculation methods of EWPC are mainly divided into two categories, namely local EWPC calculation method and area EWPC calculation method. The local EWPC calculation method is used to calculate and determine the EWPC of a single measuring point; the area EWPC calculation method is mainly used to solve the area reduction effect of cladding EWPC. The net effect of wind loading on the single cladding decreases with an increase in the cladding area, because the wind pressure acting on the cladding fluctuates across its surface, there by cancelling out the pressures simultaneously acting on

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different regions, that's the area reduction effect of cladding EWPC.

This paper mainly aims to solve the problem of calculation method of design EWPC for large-scale zone with multiple cladding components (multiple measuring points). This paper proposes a calculation method with adopting the multivariate extreme value (MEV) theory and MA method, which can consider the correlation of EWPC of multiple cladding components, and calculate the zonal EWPC of arbitrary guarantee rate according to the needs of structural design. The composition, principle and steps of the method are deduced and introduced. At the same time, taking the large-scale roof cladding as an example, the effectiveness of the method is further illustrated and verified. The method proposed in this paper can be used not only for long-span roofs, but also for cladding of super high-rise buildings.

2. Proposed method in this study

As previously described, extreme wind pressure coefficient (EWPC) is an important basis for wind load calculation and risk assessment of claddings. Due to the gradient of wind load distribution on the building surface, in general, in order to facilitate the engineering design, construction and maintenance, the EWPC on the surface need to be zoned. After zoning, it is necessary to give reasonable representative values for each zone as the unified basic design wind load for each zone. When the area of the partition is small, the maximum value of the local extreme wind load in the zone can be taken as the representative value; when the area is large, the way of taking the maximum value may lead to the structure design being too conservative and causing certain waste. Therefore, it is necessary to give the calculation method of EWPC for a zone based on probability on the basis of considering the correlation of local extreme wind pressure. As to facilitate the engineers to calculate the wind load for a zone based on probability According to the requirements of structural design, the design value of wind load in different zones under any guarantee rate required by structural design is determined.

The MA method is used to obtain the wind pressure coefficient time history of a single cladding component considering the pressure area reduction effect. For the zone with multiple cladding components, the multivariate extreme value distribution theory is used to calculate the zonal EWPC.

2.1 Moving average method for the EWPC of each measuring points

MA method is adopted in this proposed method to estimate the EWPC for every measuring point. It can be known that by adopting MA method, the tributary area of each of every measuring point could be taken into account, and the measured point pressure can then be converted to be able to represent the area pressure. So that a more reasonable estimation for can be obtained.

This method considers the correlations between different points on a building surface via the coherence functions. Lawson (1976) proposed a theoretical expression of the coherence function as

$$\sqrt{\mathrm{Coh}} = exp\left[-K\frac{fL}{U}\right] \tag{1}$$

where, L denotes the geometrical distance between the two points, U is the mean incident wind speed, f is the frequency, fL/U denotes the dimensionless frequency and K is the coefficient on the decaying wind speed.

Lawson (1976) suggested K=4.5, and its validity was proved with measured data from windows of a building surface. Uematsu (1998) believed that K represents the attenuation coefficient of the fluctuating pressure coherence between two different measuring points in the target zone, and the value varies within a range between 5.0 to 20.0 according to the wind tunnel test results of low-rise buildings. Holmes (1997) believed that the coherence refers only to the measurement on pressure correlation between two measuring points. It cannot indicate any change of wind load along a line or across the surface. Therefore, a moving average filter was used to fit the aerodynamic admittance function curve to get K=1.0 approximately in his study. Other scholars, such as Greenway (1979), recommended a K value of 1.2 or 1.7.

In this study, the value of K is obtained by adopting Lawson's definition, as the integration of Eq. (1) gives

$$\int_0^{+\infty} exp^{-K\frac{fL}{U}} \quad d\left(\frac{fL}{U}\right) = \frac{1}{K} \tag{2}$$

To simplify the analysis, a step function was assumed to simulate the coherence function instead of the usually adopted exponential function, i.e., the pressure coherence is assumed to be unity when the dimensionless frequency fL/U is lower than a critical value f_cL/U, and it becomes null if otherwise. Assuming the step function also follows the rule of Eq. (2), we have

$$1 \cdot \frac{f_c L}{U} = \frac{1}{K} \tag{3}$$

Accordingly, the pressure is fully correlated when the period of pressure fluctuation is longer than the critical period T_c as,

$$T_c = \frac{1}{f_c} = \frac{KL}{U} \tag{4}$$

Eq. (4) is known as the moving average formula (Lawson 1976). Rewrite Eq. (4) as

$$\tau = \frac{KL_C}{V} \tag{5}$$

where, τ represents the averaging time, and L_C represents the characteristic dimension of the target area, which is usually represented by the diagonal of the area. V represents the hourly mean wind speed. This function is proposed for providing a tool for the conversion from a pressure of a point within an area to the wind load acting on the area. It means that, instead of measuring the wind load on the entire area, wind load acting on an area can be estimated from a point pressure measured within the area by adopting the averaging in the time domain.

Moving average method for the EWPC of each measuring points as following procedure:

1) Calculate the square root of coherence between the two neighboring points, the calculation function is

$$\sqrt{\mathrm{coh}(r,n)} = \frac{S_{u_1,u_2}(r,n)}{\sqrt{S_{u_1}(r,n)S_{u_2}(r,n)}} \tag{6}$$

where, $S_{u1,u2}(r,n)$ is the cross spectral density function of two points, $S_{u1}(r,n)$, $S_{u2}(r,n)$ are power spectral density functions of fluctuating wind speed at two points respectively.

2) Find K by Eq. (1) to the Scatter plot of coherence

3) Calculate L_C of tributary area of each measuring points

4) Calculate the averaging time with Eq. (5)

5) Use moving average technique to process the time series of every point.

2.2 Multivariate extreme value distribution of zone extreme value pressure coefficient

The representative EWPC of a zone is the design wind pressure value of the target zone of cladding. The estimation of this value needs to consider the EWPC of various positions within the zone. MEV distribution is capable of studying the characteristics of extreme values containing several correlated variates (Kotz and Nadarajah 2000). Applying MEV distribution model to the estimation of the representative EWPC of a zone may well consider both the extreme values of various positions and the correlations of them. In this section, the basic theory and application of MEV on extreme is introduced.

2.2.1 Limit laws for multivariate extremes

The multivariate extreme value is defined based on the maximum value model of each variate similar to the traditional univariate method. If $\{(X_{i,1}, \ldots, X_{i,p}), i = 1, \ldots, n\}$ is the p-variate random vectors with a joint distribution F, then

$$\boldsymbol{M}_n = \left(M_{n,1}, \ldots, M_{n,p}\right) = \left(\max_{1\le i\le n} X_{i,1}, \ldots, \max_{1\le i\le n} X_{i,p}\right) \tag{7}$$

where $\mathbf{M}_n$ is a vector of maxima of each component. When the normalizing parameters are such that $a_{n,j} > 0$, $b_{n,j} > 0$ ($j = 1, \ldots, p$), then the following equation can be obtained when n→+∞,

$$\begin{aligned} Pr\left\{\frac{(M_{n,1}-b_{n,1})}{a_{n,1}} \le x_1, \ldots, \frac{(M_{n,p}-b_{n,p})}{a_{n,p}} \le x_p\right\} \\ = F^n\left(a_{n,1}x_1 + b_{n,1}, \ldots, a_{n,p}x_p + b_{n,p}\right) \\ \to G\left(x_1, \ldots, x_p\right) \end{aligned} \tag{8}$$

where G is a p-variate distribution with a non-degenerate marginal distribution. If there are proper $\boldsymbol{a_n}=(a_{n,1},\ldots, a_{n,p})\in R^p$ and $\boldsymbol{b_n}=(b_{n,1},\ldots, b_{n,p}) \in R^p$ applicable to Eq.(8), then variable G is called themultivariate extreme value distribution, and matrix F is called the domain of attraction of G, written as $F\in D(G)$.

In case of G is a non-degenerate distribution, then there is an equivalent expression of

$$\begin{aligned} Pr\left\{\frac{(M_{n,1}-b_{n,1})}{a_{n,1}} \le x_1, \ldots, \frac{(M_{n,p}-b_{n,p})}{a_{n,p}} \le x_p\right\} \\ = \lim_{n\to\infty} F^n(a_n x + b_n) = G(x) \end{aligned} \tag{9}$$

All x_j in Eq. (9) have $F_j\in D(G_j)$, ($j = 1, \ldots, p$), such that

$$\lim_{n\to\infty} F_j^n(a_{n,j}x_j + b_{n,j}) = G_j(x_j), (j = 1, \ldots, p). \tag{10}$$

Then F_j and G_j are the jth marginal distributions of F and G, respectively. The univariate marginal distribution G_j of G must follow the generalized extreme value distribution (GEV) as

$$G_j(x_j, \mu_j, \sigma_j, \xi_j) = exp\left\{-\left(1 + \xi_j \cdot \frac{x_j-\mu_j}{\sigma_j}\right)^{-\frac{1}{\xi_j}}\right\}, \quad (j = 1, \ldots, p) \tag{11}$$

where μ_j is the location parameters, ξ_j is the shape parameter, $\sigma_j > 0$ is the scale parameter with $(1+\xi_j(x_j-\mu_j)/\sigma_j) > 0$.

When the marginal distribution G_j is a continuous function,

$$Y_j = -\frac{1}{\log G_j(x_j)} \quad (j = 1, \ldots, p). \tag{12}$$

The joint distribution function can be rewritten as follows with the above transformation,

$$\begin{aligned} G_*(y_1, \ldots, y_p) = \\ G(G_1^{-1}(exp\{-y_1^{-1}\}), \ldots, G_d^{-1}(exp\{-y_d^{-1}\})), \\ (y_1\ge 0, \ldots, y_p\ge 0) \end{aligned} \tag{13}$$

where the marginal distribution of G_* is the standard Fréchet distribution, and G is a multivariate extreme value distribution if and only if G_* is also a multivariate extreme value distribution. Defining pseudo-radial (r) and pseudo-angular (w) coordinates as

$$r_i = \sum_{j=1}^{p} \frac{x_{i,j}}{n}, \quad w_{i,j} = \frac{x_{i,j}}{nr}, \quad (i = 1, \ldots, n, \quad j = 1, \ldots, p). \tag{14}$$

The multivariate extreme distribution can be further written in the following form as

$$G_*(y_1, \ldots, y_p) = exp\left\{-\int_{S_p} \max_{1\le j\le p}\left(\frac{w_j}{y_j}\right) dH(w)\right\}, \quad (y_1\ge 0, \ldots, y_p\ge 0) \tag{15}$$

where $H(w)$ is an arbitrary finite positive measurement on the simplex of (p-1) dimension satisfying the following equation.

$$\int_{S_p} w_j dH(w) = 1 \quad (j = 1, \ldots, p), \tag{16}$$

with

$$S_p = \{(w_1, \dots, w_p): \sum_{j=1}^{p} w_j = 1, w_j \geq 0\} \qquad (j = 1, \dots, p) \tag{17}$$

The detailed derivation process is referred to Coles and Tawn (1991). They introduced a variety of parameter models for $H(w)$. In this paper, the widely used Logistic model is adopted. Let $h(w)=H(w)/dw$ be the density function of the Logistic model with

$$h(w) = \prod_{j=1}^{p-1}(j\alpha - 1)\left(\prod_{j=1}^{p} w_j\right)^{-(\alpha+1)}\left(\sum_{j=1}^{p}\frac{1}{w_j^{\alpha}}\right)^{\frac{1}{\alpha}-p}, \quad (j = 1, \dots, p) \tag{18}$$

where, α is the correlation parameter indicating the correlation level of each marginal distribution of G_*, with $\alpha > 1$. When α is close to unity, each marginal distribution is mutually independent. When α is ∞, it denotes that each marginal distribution is completely correlated. The Logistic distribution can be written as

$$G_*(y_1, \dots, y_p) = exp\left\{-(y_1^{-\alpha} + \dots + y_p^{-\alpha})^{\frac{1}{\alpha}}\right\} \quad (y_1 \geq 0, \dots, y_p \geq 0). \tag{19}$$

2.2.2 Distribution of zone extreme value pressure coefficient

Multivariate extreme value distribution is used to describe the zonal EWPC distribution, then the marginal distribution refers to the local EWPC distribution, and the correlation parameter refers to the extreme value correlation of local EWPC.

In general, the local EWPC obeys the type I distribution or the type III distribution. Some scholars suggested that local EWPC be described by type III distribution (Kasperski 2007, Chen 2009). However, the type III distribution has an upper bound, so for a given average return period, using the type III distribution may lead to a lower estimation of wind load action. (Kasperski 2009). Therefore, type I distribution is adopted in this paper to describe the marginal distribution (local EWPC distribution) of zonal EWPC distribution (Holmes 2003).

Assuming the correlation between the measuring points conforms to the logistic parameter model, the EWPC of the target zone would asymptotically follow the multi-variate extreme value distribution with the following form,

$$G(x_1, \dots, x_p) = exp\left\{-\left[\sum_{j=1}^{p} exp\left\{-\alpha \cdot \frac{x_j - \mu_j}{\sigma_j}\right\}\right]^{\frac{1}{\alpha}}\right\} \quad (j = 1, \dots, p). \tag{20}$$

The maximum likelihood method or moment method (Shi 1995a) can be adopted for the parameter estimation of the multivariate extreme value distribution. Eq. (20) contains ($2p$+1) parameters indicating a rapid increase in the computation complexity with an increase of the number of variates. The distribution estimation method is one of the simplified methods for parameter estimation, where the parameters of the marginal distribution are firstly estimated followed by the estimation of correlation parameters in the joint distribution. The studies by Shi (1995a, 1995b) demonstrated the feasibility of the distribution estimation method for practical application, and the maximum likelihood method is adopted for the estimation of marginal distribution parameter. The moment method is adopted in this paper for the estimation of the correlation parameters.

2.3 Procedure of the proposed method

The estimation procedure is as follows:

1) Carry out the moving average process on the wind pressure coefficient time history of each measuring point according to Eq. (6).

2) Estimate the marginal distribution parameters and the extreme wind pressure at each measuring point.

The marginal distribution of the EWPC of a zone is assumed asymptotically following the Gumbel distribution as described above, with the logarithm likelihood function as

$$\ell(\mu_j, \sigma_j) = -n \log \sigma_j - \sum_{i=1}^{n}\left(\frac{x_{ij} - \mu_j}{\sigma_j}\right) - \sum_{i=1}^{n} exp\left\{-\left(\frac{x_{ij} - \mu_j}{\sigma_j}\right)\right\} \tag{21}$$

$(j = 1, \dots, p)$.

In order to find the maximum likelihood estimates of μ_j and σ_j, the likelihood equation system is obtained by taking $\partial/\partial\mu_j=0$, $\partial/\partial\mu_j=0\sigma_j=0$ with

$$\begin{cases} \sum_{i=1}^{n} e^{-(x_{ij} - \hat{\mu}_j)/\hat{\sigma}_j} = n \\ \sum_{i=1}^{n} (x_{ij} - \hat{\mu}_j)(1 - e^{-(x_{ij} - \hat{\mu}_j)/\hat{\sigma}_j}) = n\hat{\sigma}_j \end{cases} \tag{22}$$

$(i = 1, \dots, n, \quad j = 1, \dots, p)$.

The likelihood equation system does not have an explicit expression and it can only be solved numerically.

3) Estimate the correlation parameter α as

$$\hat{\alpha} = \frac{p(p-1)}{2\sum_{i<j}\sqrt{1 - r_{ij}}} \quad (i, j = 1, \dots, p), \tag{23}$$

where $\hat{\alpha}$ =1.0 denotes uncorrelated and $\hat{\alpha} = \infty$ denotes fully correlated, p is the number of variates, and r_{ij} is the sample correlation coefficient with

$$r_{ij} = s_{ij} / (s_i s_j) \quad (i, j = 1, \dots, p), \tag{24}$$

$$s_{ij} = 1/n \sum_{l=1}^{n} (x_{li} - \bar{x}_i)(x_{lj} - \bar{x}_j), \quad (i, j = 1, \dots, p), \tag{25}$$

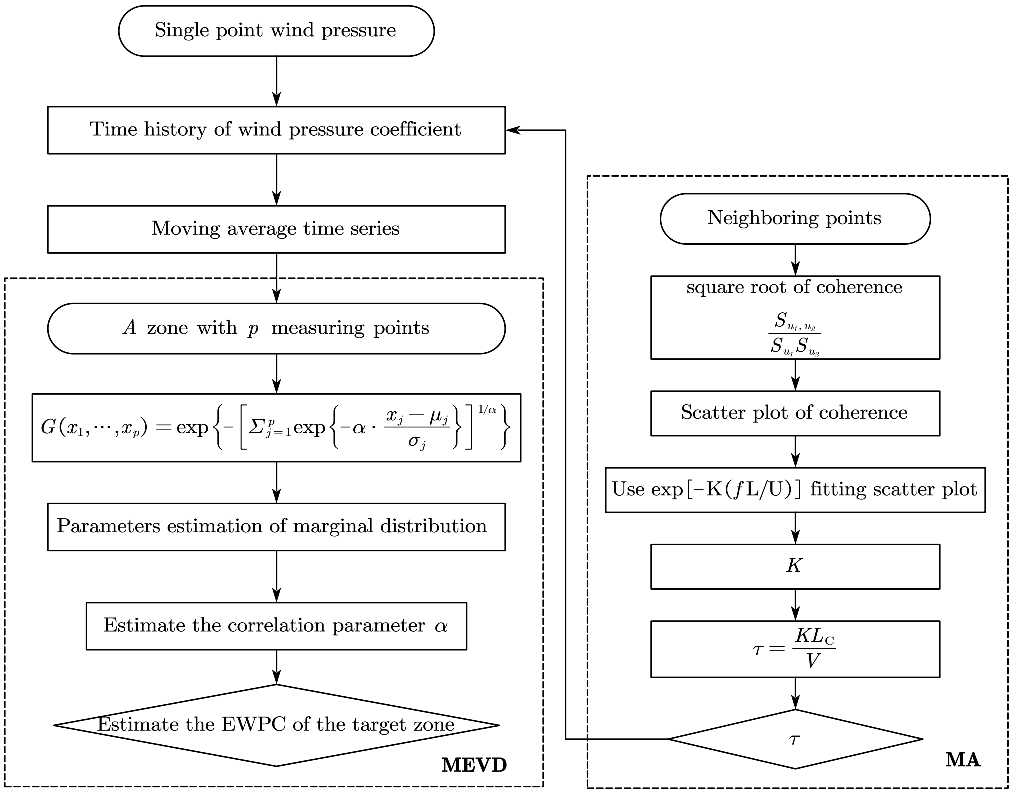


Fig. 1 Process of the proposed method

and variables $\overline{x}_i$ and s_i are the mean and variance of the extreme value of the ith measuring point respectively. n is the sample number.

4) Estimate the EWPC of the target zone.

Substitute the marginal distribution parameters at each measuring point obtained from Eq. (22) and the correlation parameters obtained from Eq. (23) into Eq. (20), the multivariate extreme value distribution can be obtained as

$$G(x_1,\ldots,x_p)=\exp\left\{-\left[\sum_{j=1}^{p}\exp\left\{-\hat{\alpha}\cdot\frac{x_j-\hat{\mu}_j}{\hat{\sigma}_j}\right\}\right]^{1/\hat{\alpha}}\right\} \quad (26)$$

$$(j=1,\ldots,p)$$

Further check on Eq. (26) shows that there are different solutions for multiple groups of x_j (j=1,…,p) with a given quantile value. Since our goal is to obtain the representative EWPC of each target zone, let $x_1=x_j\ldots=x_p=\boldsymbol{X}$ be the representative zone extreme value. Then the quantiles corresponding to different values of X will be evaluated according to Eq. (26), and they can also be treated as the guarantee ratio of the design zone extreme value. Designers can make decision on how to find the design zone extreme values based on their pre-determined guarantee ratio.

It is noted from above that the introduction of multivariate extreme value theory enables the estimation of extreme pressure coefficient of a region with any number of pressure taps, without making any assumptions on their correlations. The process of the proposed method is shown in Fig. 1.

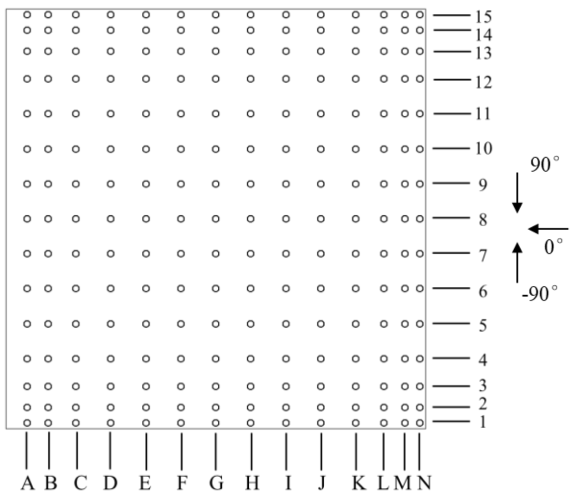


Fig. 2 Layout of pressure taps on flat roof

3. Experimental setup and basic data processing

In order to examine the efficiency of the proposed method, a building model with large flat roof is used for the wind tunnel test. The classical methods are noted not applicable to such large area even after partitions. The flat roof model under test has a square plan with dimensions 60 cm×60 cm, and the height of model is 20 cm. The geometric scale ratio is 1:200. The roof is furnished with 210 pressure measuring points with an arrangement as shown in Fig. 2.

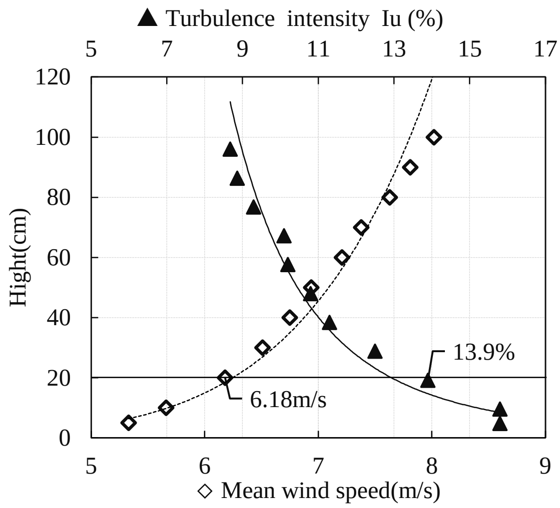


Fig. 3 Mean wind speed and turbulence intensity profiles

The wind tunnel test is conducted in the Atmospheric Boundary Layer Wind Tunnel Laboratory in Beijing Jiaotong University, China. Open land terrain is considered with the exponential exponent α=0.15. The mean wind speed profile and the turbulence intensity profile are shown in Fig. 3. The symbols refer to the measured value and the lines are fitting value. The reference height is set at the top of model, which is 20cm above the floor, and the mean wind speed at this reference height is set as 6.18m/s. The target means wind speed at the roof is 40m/s, that means the wind speed ratio is 1/6.4.

The time ratio of wind tunnel test is 1:31.25, and the sampling frequency is 312.5Hz. The sampling duration is 19.2s which corresponds to 10min in full scale. Ten samples are collected for each incident wind direction. The wind direction angle θ is 0° when it comes from the right side of the model (as shown in Fig. 2 and θ increases in anti-clock direction. A total of 13 directions ranging from −90° to 90° are tested with an interval of 15° considering the symmetric configuration.

The wind pressure coefficient at each measuring point on the roof surface is given as

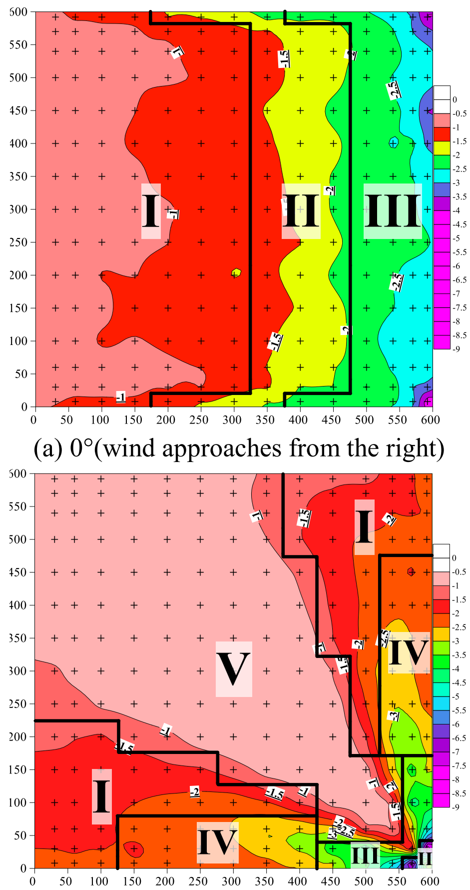
$$C_{pi}(t)=\left(P_i(t)-P_\infty\right)/0.5\rho\bar{v}_{zT}^2 \qquad (i=1,\ \ldots,\ n), \qquad (27)$$

where $P_i(t)$ is the wind pressure time history of the ith measuring point on the roof, the P_∞ is the static pressure at the reference height, ρ is the air density, and v_{zT} is the reference wind speed. Cook-Mayne method is adopted for the calculation of the EWPC, $\hat{C}_{pi}$, at a single measuring point. Assuming that the EWPC is asymptotically following the Gumbel distribution, the parameter estimation is conducted with the maximum likelihood method. The estimated extreme pressure coefficients take the 78% quantile according to the classical Cook-Mayne method.

4. Results and discussions

4.1 Partitions of roof surface

The most unfavorable negative pressure coefficient of the cases with θ=0° and −45° obtained from Sec. 4 are shown in Fig. 4. It can be checked that when the wind comes from right side of the model, large negative wind pressures are induced at the lead edge of roof, clearly indicates the conical vortex separated from the leading edge. Similarly, when wind comes from −45°, two strong conical vortexes can be formed at the two leading edges, with the largest value appearing at the leading corner. The method proposed by Yang and Li (2015) is adopted for the partition of roof basing on the K-means clustering technique. This method yields good results with different roof types and wind directions. The partitions of roof for two different wind directions are also shown in Fig. 4. It can be seen that although the roof is partitioned into several zones based on the distribution of extreme values on it, the extreme values within each zone still show strong variations. Such results indicate the difficulty in estimating the representative EWPC for each zone.



(a) 0°(wind approaches from the right)

(b) -45°

Fig. 4 Negative extreme pressure coefficients under different wind direction

4.2 Correlation of the fluctuating wind pressure on roof surface

Fig. 5 shows the correlation coefficients between every two adjacent measuring points (say A1 and B1, B2 and C2 etc. indicated in Fig. 2.) under two incident wind angles. For the case of θ=0°, the correlation coefficients can be

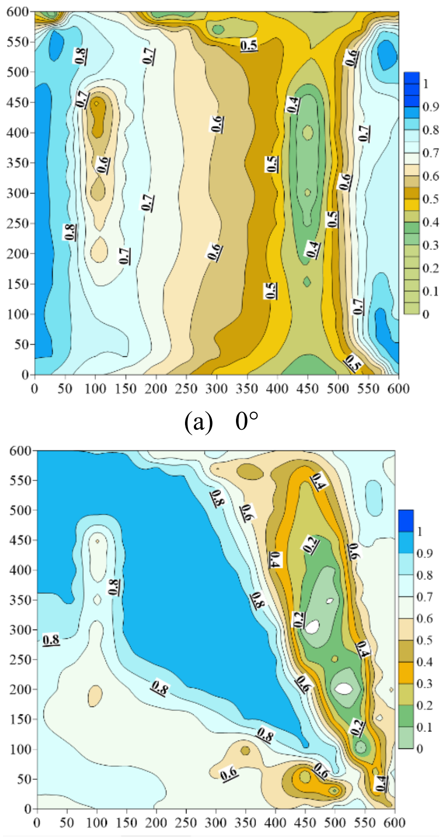


Fig. 5 Cross correlation coefficient of fluctuating wind pressure

close to unity in the leading and rear edge of roof (Zone I and Zone III in Fig. 5(a)). For the case of θ=-45°, correlation coefficients in Region V (indicated in Fig. 5(b)) can also be close to unity.

4.3 Results from different methods

The tributary area of the measuring points is assigned according to Fig. 6. The maximum plan dimension of each attributed area is used as the characteristic length. The computation procedure described in Section 3.2 is followed.

The 10 min. mean wind speed in wind tunnel test at reference height (10m high of the full scale structure) is 5.33m/s. A reduction coefficient of 0.938 is needed to get the average hourly wind speed according to Durst (1960) given the hourly mean wind speed at reference height $\bar{U}_{10}$ in wind tunnel test is 5.0m/s. The coherence function and K value of some measuring points (say G8, H5, N1 and N8. indicated in Fig. 2.) are shown in the Fig. 7. It should be noted that all the coherence functions between the target points and the points around it need to be calculated based on Eq. (6), and value K can be obtained by curving fitting using Eq. (1). The computation on the value of K is the same as that for the MA method as introduced in Sec. 2.1. The values of K at each measuring point are shown in Fig. 8. It can be found from Fig. 8 that, although the mean value of K for the adopting model in this study is about 3.0, the overall variation range is 0.0 to 10.0. That means the

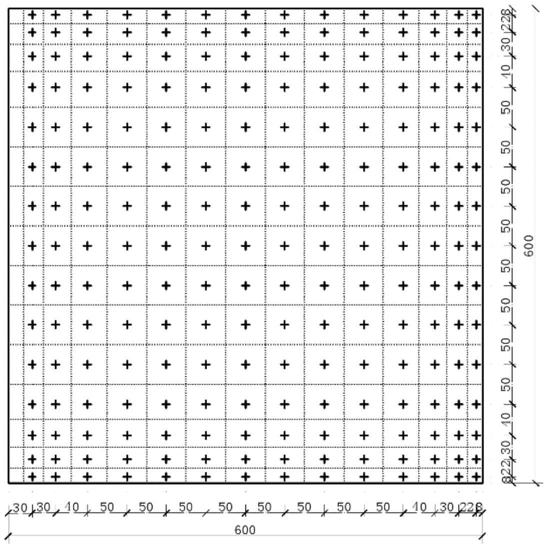


Fig. 6 Tributary area of each measuring point of roof model

Table 1 Estimated correlation parameter α

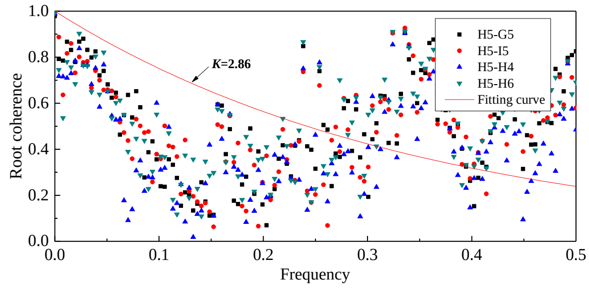
Zone	0°		-45°	
	Preprocessed by MA method	With no preprocess	Preprocessed by MA method	With no preprocess
I	1.080	1.034	1.060	1.045
II	1.154	1.062	1.689	1.053
III	1.204	1.061	1.240	1.074
IV	-		1.050	1.039
V	-		1.058	1.068

correlation between different positions can be quite different, adopting a uniform value of K for the entire roof is not appropriate. Considering the relations between moving average time τ and the tributary area (represented by L_c) defined in Eq. (5), the moving average time, τ, for each measuring point is calculated by substituting K, L and $\bar{U}_{10}$ into Eq. (5) as shown in Fig. 9. The time series of the wind pressure coefficient is processed by moving average according to the value of τ, and the EWPC of the measuring point can then be obtained.

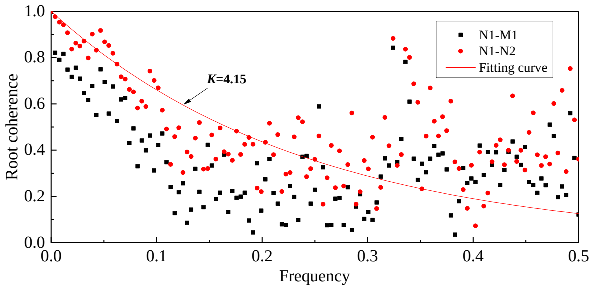
Some of the estimated correlation parameter α of the multivariate extreme distribution obtained from Eq. (23) are shown in Table 1. Table 1 shows the correlation parameters of different zones under different incident wind directions. The correlation parameters obtained through two approaches are compared. It can be checked that the correlation parameters increase when the MA method is adopted in priori. It is noted that when the area is smaller, the correlation parameter tends to be larger.

After all the preparation from Step 1 to 3, as discussed above, the cumulative probability of the EWPC for each zone can finally be estimated based the Step 4, and the results for different target zones in different cases are shown in Fig. 10. The results from direct MEV distribution (MEVD) is also shown. MEVD means the results are obtained with no preprocess of moving average.

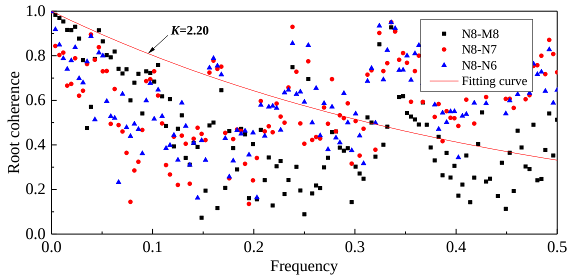
The results from univariate extreme value (UEV) method serving as reference for the comparison are also shown. The reference curves are obtained by ranking all the



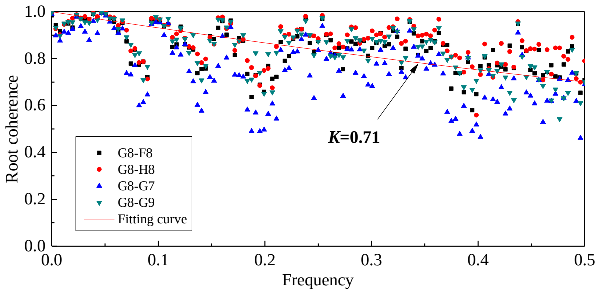
(a) 0° tap H5



(b) 0° tap N1



(c) 0° tap N8



(d) -45° tap G8

Fig. 7 Root coherence and K value of some taps

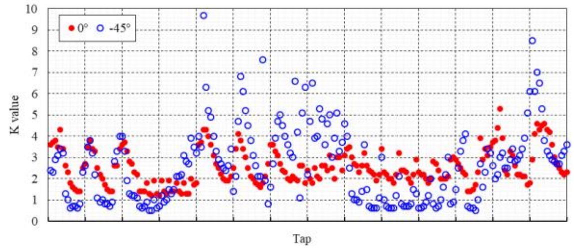


Fig. 8 K value in the TVL formula of each measuring point

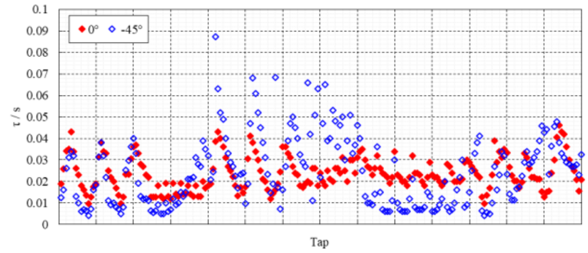


Fig. 9 Moving average time of each measuring point

estimated extreme values of each point in each zone. It can be checked that whatever the size of target zone, the results obtained from the direct MEV model method are larger than those from the proposed method (adopting MA method in priori) and the UEV method. Such results indicate that without considering the tributary area will leads to unreasonable larger estimations.

At the same time, the results from the proposed method agree well with those from UEV method, indicating a reliability of the proposed method. If there are only a few measuring points within the target zone, the estimated results shows relatively lager scatter as shown in Fig. 10(e). When the correlation parameter is large, the estimated results from the proposed method will be larger than those from the UEV method as shown in Fig. 10(c) and (h).

Such results indicate that the proposed method can well estimate the extreme wind pressure distribution within the target zone, and the estimated representative EWPC is much reliable than the direct MEV method.

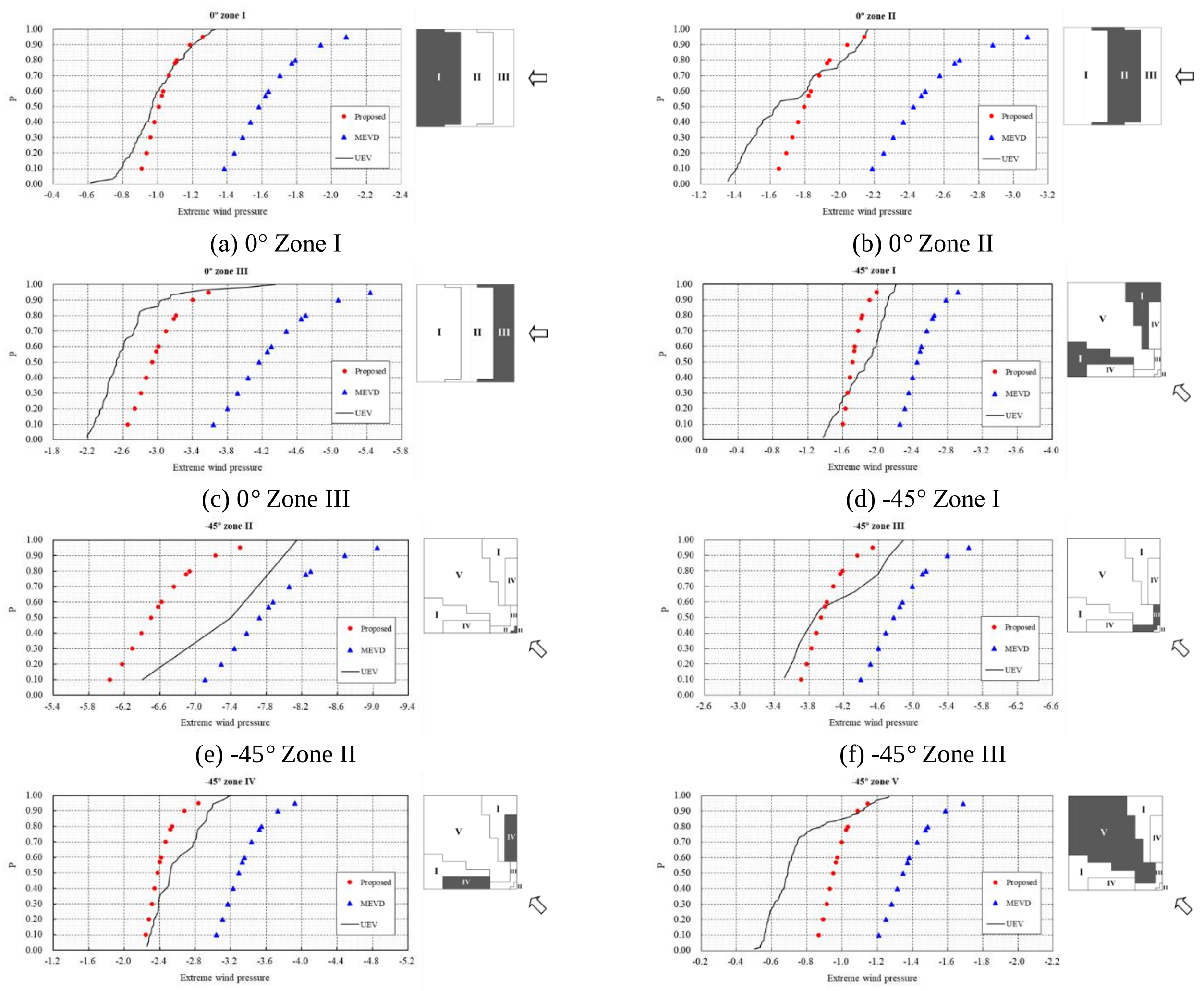
4.4 Effect of Size of zone on the correlation

It has been shown in Table 1 that the correlation parameters α are close to unity when the area of target zone is large enough, which means that the EWPC of the measuring points belonging to the same zone are nearly independent. The distribution of the joint EWPC of the zone can be approximately expressed by the product of the marginal extreme distribution of the wind pressure coefficients of each measuring point.

Fig. 11 shows the extreme wind pressure coefficients of a zone at different quantiles with values obtained based on the correlated (calculated α) and uncorrelated (α=1.0) models. It is noted that when α=1.0 is used, the estimated EWPC are always close to but larger than the values obtained from the calculated α as shown in Fig. 11(a). The differences increase when α increases as shown in Fig. 11(b) with α=1.204. That means correlation parameter is a critical parameter for the estimation of representative EWPC, with the increase of α, the EWPCs decrease accordingly. When the EWPC of different positions are fully correlated, the MEV distribution will then degenerate into UEV distribution.

5. Conclusions

This paper proposes a method for the estimation of EWPC in a zone. The method can more reasonably estimate the representative extreme wind load acting on a large area such as large roofs and facades. The method is



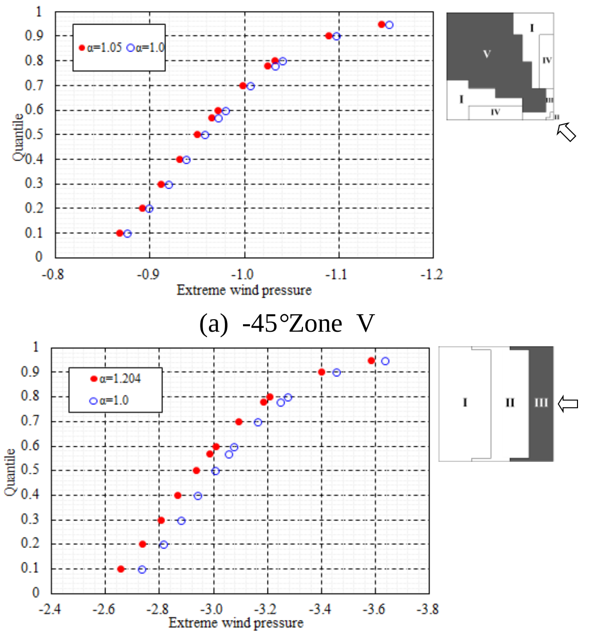
(a) 0° Zone I (b) 0° Zone II

(c) 0° Zone III (d) -45° Zone I

(e) -45° Zone II (f) -45° Zone III

(g) -45° Zone IV (h) -45° Zone V

Fig. 10 Cumulative probability of the extreme pressure coefficient of a zone by different methods



(a) -45°Zone V

(b) 0°Zone III

Fig. 11 Extreme wind pressure in each zone

demonstrated with application to estimate the extreme negative wind pressure of a large flat roof building based on wind tunnel experiment, and results from 0° and -45° wind direction are selected for discussions with the following conclusions:

- Multi-variate extreme value distribution is adopted in the proposed method to handle the correlations of extreme values at different positions in the same zone.
- Results show that when the correlation parameter of the target zone is greater than 1.2, the correlation of extreme values at different measuring points within the same zone needs to be considered in the estimation process.
- The proposed method combined the MA method and multi variate extreme value distribution. MA method is used to estimate the EWPC of every single measuring point, making the estimated result be more reasonable with considering its tributary area. And the multi-variate extreme theory can take into account the correlation effects between different measuring points. Thus, the representative EWPC at any quantile of a zone with any size can be properly estimated.

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References

Alrawashdeh, H. and Stathopoulos, T. (2015), "Wind pressures on large roofs of low buildings and wind codes and standards", *J. Wind Eng. Ind. Aerod*., **147**, 212-225. https://doi.org/10.1016/j.jweia.2015.09.014.

Chen, X.Z. and Huang, G.Q. (2009), "Estimation of probabilistic extreme wind load effects: Combination of aerodynamic and wind climate data", *J. Eng. Mech*., **136**(6), 747-760. https://doi:10.1061/(asce)em.1943-7889.0000118.

clustering", *The 14th International Conference on Wind Engineering*, Porto Alegre, Brazil, June.

Coles, S.G. and Tawn, J.A. (1991), "Modelling extreme multivariate events", *J. Royal Statistical Soc*., **53**(2), 377-392. https://doi.org/10.1111/j.2517-6161.1991.tb01830.x.

Cook, N.J. (1990), *The Designer's Guide to Wind Loading of Building Structures*. Vol. 2: Static Structures.

Cook, N.J. and Mayne, J.R. (1979), "A novel working approach to the assessment of wind loads for equivalent static design", *J. Ind. Aerod*., **4**(2), 149-164. https://doi.org/10.1016/0167-6105(79)90043-6.

Davenport, A.G. (1967), "Gust loading factors", *J. Struct. Div., ASCE*, **93**(ST3), 11-34.

Davenport, A.G., Surry, D. and Stathopoulos, T. (1977a), "Wind loads on low rise buildings: Final report of phases I and II BLWT-SS8-1977", *Univ. of Western Ontario*, London, Canada.

Davenport, A.G., Surry, D. and Stathopoulos, T. (1977b), "Wind loads on low rise buildings: Final report of phases III BLWT-SS8-1977", *Univ. of Western Ontario*, Ontario, Canada.

Ding, J. and Chen, X. (2014), "Assessment of methods for extreme value analysis of non-gaussian wind effects with short-term time history samples", *Eng. Struct*., **80**, 75-88. https://doi.org/10.1016/j.engstruct.2014.08.041.

Dong, X. and Ye, J. (2012), "The point and area-averaged wind pressure influenced by conical vortices on saddle roofs", *J. Wind Eng. Ind. Aerod*., **101**, 67-84. https://doi.org/10.1016/j.jweia.2011.12.001.

Durst, C.S. (1960), "Wind speeds over short periods of time", *Meteorol. Mag*., **89**(1056), 181-187.

Galambos, J. and Macri, N. (1999), "Classical extreme value model and prediction of extreme winds", *J. Struct. Eng*., **125**(7), 792-794. https://doi.org/10.1061/(asce)0733-9445(1999)125:7(792).

Greenway, M.E. (1979), "An analytical approach to wind velocity gust factors", *J. Wind Eng. Ind. Aerod*., **5**(1), 61-91. https://doi.org/10.1016/0167-6105(79)90025-4.

Grigoriu, M. (1995), *Applied Non-Gaussian Processes*, Prentice-Hall.

Gumley, S.J. (1984), "A parametric study of extreme pressures for the static design of canopy structures", *J. Wind Eng. Ind. Aerod*., **16**(1), 43-56. https://doi.org/10.1016/0167-6105(84)90048-5.

Harris, R.I. (2005), "A new direct version of the Cook-Mayne method for wind pressure probabilities in temperate storms", *J. Wind Eng. Ind. Aerod*., **93**(7), 581-600. https://doi.org/10.1016/j.jweia.2005.05.004.

Harris, R.I. (2005), "Generalised Pareto methods for wind extremes. Useful tool or mathematical mirage", *J. Wind Eng. Ind. Aerod*., **93**(5), 341-360. https://doi.org/10.1016/j.jweia.2005.02.004.

Holmes, J.D. (1997), "Equivalent time averaging in wind engineering", *J. Wind Eng. Ind. Aerod*., **72**, 411-419. https://doi.org/10.1016/s0167-6105(97)00266-3.

Holmes, J.D. and Cochran, L.S. (2003), "Probability distributions of extreme pressure coefficients", *J. Wind Eng. Ind. Aerod*., **91**(7), 893-901. https://doi.org/10.1016/s0167-6105(03)00019-9.

Holmes, J.D. and Moriarty, W. (1999), "Application of the generalized pareto distribution to extreme value analysis in wind engineering", *J. Wind Eng. Ind. Aerod*., **83**(1-3), 1-10. https://doi.org/10.1016/s0167-6105(99)00056-2.

Huang, G., Luo, Y., Gurley, K.R. and Ding, J. (2016), "Revisiting moment-based characterization for wind pressures", *J. Wind Eng. Ind. Aerod*., **151**, 158-168. https://doi.org/10.1016/j.jweia.2016.02.006.

Hui, Y., Tamura, Y. and Yang, Q. (2017), "Estimation of extreme wind load on structures and claddings", *J. Eng. Mech*., **143**(9), 04017081. https://doi.org/10.1061/(asce)em.1943-7889.0001304.

Kareem, A. and Cermak, J.E. (1984), "Pressure fluctuations on a square building model in boundary-layer flows", *J. Wind Eng. Ind. Aerod*., **16**(1), 17-41. https://doi.org/10.1016/0167-6105(84)90047-3.

Kareem, A. and Zhao, J. (1994), "Analysis of non-gaussian surge response of tension leg platforms under wind loads", *J. Offshore Mech. Arctic Eng*., **116**(3), 137-144 https://doi.org/10.1115/1.2920142.

Kasperski, M. (2007), "Design wind loads for a low-rise building taking into account directional effects", *J. Wind Eng. Ind. Aerod*., **95**(9-11), 1125-1144. https://doi.org/10.1016/j.jweia.2007.01.019.

Kasperski, M. (2009), "Specification of the design wind load-a critical review of code concepts", *J. Wind Eng. Ind. Aerod*., **97**(7-8), 335-357. https://doi.org/10.1016/j.jweia.2009.05.002.

Kotz, S. and Nadarajah, S. (2000), *Extreme Value Distributions. Theory and Applications. Price theory and applications*. Prentice Hall.

Lawson, T.V. (1976), "The design of cladding", *Build. Environ*., **11**(1), 37-38.

Lin, J.X. and Surry, D. (1998), "The variation of peak loads with tributary area near corners on flat low building roofs", *J. Wind Eng. Ind. Aerod*., **77-78**(5), 185-196. https://doi.org/10.1016/s0167-6105(98)00142-1.

Peterka, J.A., Hosoya, N., Dodge, S., Cochran, L. and Cermak, J. E. (1998), "Area-average peak pressures in a gable roof vortex region", *J. Wind Eng. Ind. Aerod*., **77-78**(98), 205-215. https://doi.org/10.1016/s0167-6105(98)00144-5.

Sadek, F. and Simiu, E. (2002), "Peak non-gaussian wind effects for database-assisted low-rise building design", *J. Eng. Mech*., **128**(5), 530-539 https://doi.org/10.1061/(asce)0733-9399(2002)128:5(530).

Shi, D.J. (1995a), "Moment estimation for multivariate extreme value distribution", Appl. Mathem., **10**(1), 61-68. https://doi.org/10.1007/bf02663895.

Shi, D.J. (1995b), "Multivariate extreme value distribution and its fisher information matrix", *Acta Mathematicae Applicatae Sinica*, **11**(4), 421-428. https://doi.org/10.1007/bf02007180.

Simiu, E. and Heckert, N.A. (1996), "Extreme wind distribution tails: a peaks over threshold approach", *J. Struct. Eng*., **122**(5), 539-547. https://doi.org/10.1061/(asce)0733-9445(1996)122:5(539).

Stathopoulos, T., Surry, D. and Davenport, A.G. (1981), "Effective wind loads on flat roofs", *J. Struct. Div*., **107**(2), 281-298.

Stathopoulos, T., Wang, K. and Wu, H. (2001), "Wind pressure provisions for gable roofs of intermediate roof slope", *Wind Struct*., **4**(2), 119-130. https://doi.org/10.12989/was.2001.4.2.119.

Uematsu, Y. and Isyumov, N. (1998), "Peak gust pressures acting on the roof and wall edges of a low-rise building", *J. Wind Eng. Ind. Aerod*., **77-78**(5), 217-231. https://doi.org/10.1016/s0167-6105(98)00145-7.

Uematsu, Y. and Isyumov, N. (1999), "Wind pressures acting on low-rise buildings", *J. Wind Eng. Ind. Aerod*., **82**(1-3), 1-25. https://doi.org/10.1016/s0167-6105(99)00036-7.

Yang, Q.S. and Li, D.Y. (2015), "A zoning method for wind pressures distribution on roofs based on K-means clustering", *The 14th International Conference on Wind Engineering*, Porto Alegre, Brazil, June.

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