The 2016 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM16)
Jeju Island, Korea, August 28-September 1, 2016

Research advances in equivalent static wind load of large-span roofs

Wuyi Sun*

School of Engineering, China University of Geosciences, Wuhan, P.R. China

Abstract

Due to the sensitivity of the wind, the wind-resistant research of the large-span roofs is of importance, in which the equivalent static wind load (ESWL) is one of the focuses in structural wind engineering all the time. A comprehensive and detailed survey of the ESWL methods of the large-span roofs, which are related to wind-induced responses (WIRs) and structural stability, is presented in this paper. In the ESWL methods, the ESWL is linked with WIRs in general, it comprises the gust response factor (GRF) method, the ESWL methods based on the load-response-correlation (LRC) method, the ESWL methods based on POD modes of the wind and the ESWL method based on POD modes of the fluctuating wind and structural modes. The ESWL methods based on structural stability are relatively less, and lack a large number of fundamental researches. Finally, some conclusions and prospects are also put forward to give helpful suggestions for further researches shortly.

CE Database subject headings: research advances; large-span roofs; equivalent static wind load (ESWL); wind-induced response (WIR); stability

1. Introduction

The wind is usually a dominant kind of environmental load for these large-span roofs which have the characteristics of light mass, great flexibility, little damping and low natural frequencies (Chen and Zhou 2007; Holmes 2007; Uematsu *et al*. 1997a b; Zhou *et al*. 1999). The equivalent static wind load (ESWL) plays an essential role in the designs of the large-span roofs. Therefore, as one of topical issues in structural wind engineering, it has already been around for quite a while.

This paper intends to present the introductions of some representative advances in the ESWL methods of the large-span roofs. So far, the ESWL methods touch on two aspects which embody structural wind-induced responses (WIRs) and structural stability.

*Corresponding author, Ph.D., E-mail: sunwuyi@foxmail.com

2. ESWL methods based on WIRs

As a general rule, the ESWL methods are in correlated with structural WIRs. The modeling of the ESWL aims at seeking the static load distributions whose static effects on buildings are equal to actual peak dynamic effects, so that this load representation allows the designers to follow a relatively simple static analysis procedure for assessing building performance to wind (Chen and Zhou 2007).

2.1 Gust response factor methods

The original ESWL concept began with the emergence of wind-resistant studies on the high-rise buildings. Davenport (1961, 1967) initiated the gust response factor (GRF) method to express the ESWL on the high-rise buildings as the product of the mean wind and a specific GRF with the intention of evaluating the dynamic load, which gives rise to along-wind structural buffeting responses. The ratio of a maximum displacement to a mean displacement on the basis of the assumption that the displacement owns a Gaussian probability distribution is a definition of the GRF.

Due to its simplicity, this method had also been acclaimed and used in the large-span roofs. Marukawa *et al*. (1993), Uematsu *et al*. (1996, 1997a, b, 1999, 2002, 2008) and Uematsu and Yamada (2002) adopted the GRF method to investigate systematically the ESWL on some flat or dome roofs which possess the regular, symmetrical and simple geometries and closed forms without a consideration of the interior pressures. They set up a series of empirical equations which are related to geometrical and structural parameters, turbulence intensity of the approaching flows and wind direction.

The above works only take displacement WIRs into account in the calculation of the GRFs. As a matter of fact, the large-span roofs always have multiple kinds of WIRs in most cases. The GRF is originally defined for any WIR, if the GRF based on displacement is used indiscriminately for any WIR, this tacitly implies that the GRF for any WIR is the same as displacement GRF, which may yield inaccurate estimates (Zhou *et al*. 1999; Zhou and Kareem 2001; Kareem and Zhou 2003).

The ESWL of the beam supporting flat roofs should be changed depending upon the types of the maximum WIRs (Tamura *et al*. 1992). The authors derived the GRFs of the simply supported rigid and elastic beams based on the maximum bending moments, shear forces and displacements. The results clearly showed that the GRFs differ from the categories of WIRs. Lou *et al*. (2000) investigated WIRs of a flexible flat roof, and presented the nodal GRF that was the ratio of total wind-induced force to static wind force, in which total wind-induced force was the summation of static wind force and dynamic wind force, and dynamic wind force was equal to the product of the peak coefficient of acceleration, nodal mass and the RMS of nodal acceleration. The result indicated that the GRF distribution on the whole surface was a curved surface similar to the first structural mode shape.

It should be noted that WIRs in above large-span roofs are generally dominated by the first structural mode. Under this circumstance, every node vibrates almost synchronously, and the control object of displacement is explicit. Because only the fluctuating and mean displacements in the first structural mode are included in the derivation, the GRF is constant for a given whole structure (Zhou *et al*. 1999; Kareem and Zhou 2003). In effect, natural frequencies of some large-span roofs are closely spaced, structural WIRs are widely affected by the high-order structural modes (Uematsu *et al*. 1997c). At this point, the multi-mode participation in WIRs makes all nodes cannot keep completely synchronized during structural vibration, and the control objects of displacements are not clear. Correspondingly, the ESWL based on the control objects of displacements will be mutable and inconvenient for engineering application.

Also, the above works do not take into account structural nonlinearity at the time of calculating WIRs. For a nonlinear structure, the GRFs, which only consider the linear effects, will lead to structural unsafety (Kasperski 1992; Kasperski and Niemann 1992). Suzuki *et al*. (1997), Shen and Yang (1999) and Zhou *et al*. (2013) investigated the GRFs of multiple kinds of control WIRs at some particular positions of some cable-suspended and membrane roofs, and proposed some empirical equations or values, in which they considered geometrical nonlinearity.

As a universal method, there are other main limitations in the GRF method: (1) The method implies that the ESWL has the same shape as the mean wind, however, this is not true in some cases (Holmes 2002; Li and Tamura 2004, 2005); (2) The method falls short in the cases with zero mean load or WIR where the ESWL may not be appropriately defined, it is not valid at this point (Zhou *et al*. 1999, 2000; Kareem and Zhou 2003; Chen and Zhou 2007); (3) The method is unreliable in wind-induced stability analysis, a bigger GRF may lead to lower safety in some cases (Li and Tamura 2004, 2005; Gu and Huang 2015); and (4) The method obtains the ESWL according to a particular WIR of interest. The GRFs may vary widely for different WIRs and may have significantly different values for the structures with similar geometric configurations but different structural systems, which indicates that the ESWL given by a single GRF is incapable of providing adequate predictions of all peak WIRs (Chen and Zhou 2007). So the method has no extensive applicability in the large-span roofs, a need exists to explore more improved methods.

2.2 ESWL methods based on load-response-correlation method

In the ESWL research of the large-span roofs, the ESWL methods based on the load-response-correlation (LRC) method greatly promote its development progress.

2.2.1 LRC method

According to the characteristics of along-wind WIR spectrum of the structure, Davenport (1967, 1995) and Dyrbye and Hansen (1997) separated dynamic WIRs into the mean, background and resonant components. This separation first pointed out the opportunity of separating the ESWL into the static (i.e. mean), quasi-static (i.e. background) and resonant contributions (Repetto and Solari 2004).

Based on the WIR spectrum mentioned above, Kasperski (1992) and Kasperski and Niemann (1992) defined the ESWL of a special WIR as the sum of the mean wind and the weighted fluctuating wind with the modification by a peak factor, in which the weighted factor is the correlation between load and WIR. The method is commonly known as the load response correlation (LRC) method (hereafter referred to as the traditional LRC method).

The traditional LRC method is an important and eye-opening milestone in the ESWL developments; it enables the expected ESWL for the background fluctuating wind to be formulated on a sound theoretical basis (Holmes 2002). For a desired peak WIR, the traditional LRC method provides a most probable load distribution with a clear physical meaning (Kasperski and Niemann 1992; Chen and Kareem 2004).

When there are a large number of WIRs to consider, these computations of the LRC coefficients in the traditional LRC method can be time-consuming and challenging, it is not required to calculate directly the correlation between load and WIR (Holmes 1992; Fu *et al*. 2008). Consequently, some improved LRC methods are worth exploring.

In the rigid low-rise buildings, based on the proper orthogonal decomposition (POD) method by Holmes (1990), Holmes (1992) and Chen and Zhou (2007) extended the traditional LRC method to express the ESWL of the fluctuating wind as a linear combinations of some POD modes for a given WIR. In general, only a small number of dominant lower-order POD modes will result in sufficiently accurate ESWL and response prediction (Chen and Zhou 2007). Furthermore, the most attractive feature of this method is that the ESWL is dependent only on the aerodynamic characteristics (i.e. POD modes) of the approach flow and building. It is independent of structural behavior and system, and helps in understanding how the structure responds to spatial variation of the wind (Holmes 1992; Chen and Zhou 2007).

In the large-span bridges, WIRs of structural displacements based on the principle of modal decomposition can be viewed as the quasi-static WIRs under the spring restoring forces, which means that the WIRs are equivalent to the background displacements. Therefore, the ESWL can be accessed by the traditional LRC method and expressed in terms of the linear combination of a series of the equivalent modal inertial loads, in which each combination weighted factor is the LRC coefficient between a WIR of interest and each equivalent modal inertial load (Chen and Kareem 2001).

In the large-span roofs, Zhou et al. (2012) also came up with a modified LRC method to compute directly the dynamic component of the ESWL corresponding to a particular peak WIR, which was the product of the background component of the ESWL in the traditional LRC method and a modified coefficient.

2.2.2 ESWL methods associated with structural modes and based on LRC method

The traditional LRC method is developed by studying the wind tunnel tests of the low-rise buildings (Holmes 1992; Holmes *et al*. 1995; Ginger *et al*. 2000). It does not allow for the possibility of resonant amplification; therefore, it can be used to determine the ESWL from the mean component and especially the background component (Ginger 2000; Holmes 2002; Chen and Zhou 2007). In comparison with the low-rise buildings, the resonant effects of the wind on the large-span roofs, although not dominant, can be significant (Holmes 2007). Hence, there is a need to evaluate the resonant effects in WIRs and corresponding ESWL of the large-span roofs.

When considering dynamic WIRs of the fluctuating wind for any structure, it is necessary to distinguish between the resonant and background WIRs (Holmes 2007), because different WIR components have different ESWL distributions. If a total WIR is divided into the mean, background and resonant components, corresponding ESWL components can be calculated, and then the total ESWL is the linear combination of the three ESWL components with corresponding weighted factors, this is the so-called

Three-Component-Method (Sun *et al*. 2015).

Holmes (2002, 2007) and Chen *et al*. (2006) used the Three-Component-Method to compute the ESWL of the large-span roofs based on a total special maximum WIR of interest. In their methods, the background component of the ESWL was calculated by the POD method mentioned above just as Holmes (1990, 1992) and Chen and Zhou (2007) did, which implicitly includes the contributions of all structural modes and has no relation with structural dynamic characteristics. The resonant component of the ESWL could be obtained by a superposition of the equivalent inertial loads from more than one structural dominant mode.

The Three-Component-Method is physically meaningful. It is directly related to the fundament-al characteristics of the wind (the mean wind and POD modes of the fluctuating wind) and structural dynamic characteristics (structural modes or Ritz vectors) (Chen *et al*. 2006). However, they take advantage of the square root of the sum of squares (SRSS) method at the time of computing the resonant component of WIRs with an assumption of uncoupled structural modes; then they ignore the modal coupling effect for the resonant component of the ESWL. Unfortunately, such an assumption may not always be effective for some large-span roofs. It is essential that the effect of multi-mode coupling should be taken into account in computing the resonant components of WIRs and the ESWL for some flexible structures with low damping and concentrated modes (Gu and Zhou 2009; Zhou and Gu 2010).

Gu and Zhou (2009) and Zhou and Gu (2010) also employed the Three-Component-Method to compute WIR and corresponding ESWL of the large-span roof. On the basis of the modal coupling factor, a modified SRSS method for the computation of the resonant component of WIR by multi-modes and their coupling effects was first used. A new ESWL method was then proposed, in which the background component of the ESWL was computed by the traditional LRC method, and the resonant component of the ESWL was calculated regarding the equivalent inertial load method based on the above modified SRSS method.

These previous Three-Component-Methods assume that the background and resonant components of WIR are well separated. However, no conclusions have been reached on how to discriminate accurately the two components of WIR at present. Furthermore, it is noted that separating WIR mentioned above and associated ESWL of the fluctuating wind into the background and resonant components is not a necessary step (Chen and Kareem 2001; Fu *et al*. 2008).

A total peak WIR could be expresses as the linear combination of the mean WIR and dynamic fluctuating WIR, in which the latter was directly calculated by the complete quadratic combination method (Fu *et al*. 2008). Based on the traditional LRC method , the ESWL of the large-span roof was indicated by Fu *et al*. (2008) as the summation of the mean and dynamic fluctuating components, i.e. the so-called Two-Component-Method (Sun *et al*. 2015). The dynamic fluctuating component amounted to the sum of the background and resonant components of the ESWL in the Three-Component-Method; it was a linear combination of a series of the equivalent inertial loads contributed from each concerned structural mode, which completely agreed with the method presented by Chen and Kareem (2001).

The Two-Component-Method considers the contributions of multi-mode responses and the correlations of modal responses (i.e. the coupling effects) in the analyses of

WIR and the ESWL (Fu *et al*. 2008). Moreover, there is a calculation of the relatively simple correlation coefficient between modal displacements in the weighted factor instead of the direct calculation of the correlation of the load and WIR in the dynamic fluctuating component of the ESWL, which leads to a computational simplification.

Although the above Three-Component-Method and Two-Component-Method are simple, there are still some common defects: (1) The methods tend to concentrates on a special WIR which is not easy to select, a large-span roof usually has multiple WIRs. It is difficult to guarantee that all WIRs under the ESWL of a special WIR are consistent with accurate WIRs induced by the actual wind. For a given WIR, a variety of ESWLs may be defined based on different considerations. The ESWL distributions for a given WIR are not necessarily unique simply because multiple ESWL distributions can result in an identical WIR (Chen and Zhou 2007). (2) The methods rely on dominant structural modes, but how to select these modes is still in debate, and it is a crucial issue in the computations of WIRs and the ESWL for a complex large-span roof.

2.2.3 ESWL methods independent of structural modes but based on LRC method

To simplify the computation of WIRs, Zhou *et al*. (2012) also utilized the Two-Component-Method to calculate total peak WIRs and corresponding ESWL. For the sake of circumventing the cumbersome process of calculating the resonant component of the ESWL in the Three-Component-Method, the authors, based on the traditional LRC method, first presented a modified LRC method which is mentioned in section 2.2.1. The grouping response method was then proposed to construct the ESWL for a part of WIRs (i.e. the grouped WIRs) in the selected WIRs: According to the modified LRC method, the ESWL of each WIR in the selected WIRs could be easily obtained. Under these ESWLs, structural responses corresponding to the selected WIRs were reproduced, if some of these structural responses were relatively close, corresponding selected WIRs were classified into a group, that is to say the grouped WIRs. The ESWL of the grouped WIRs were the linear combination of the results of the modified LRC method for every grouped WIR, in which the combination factors were solved through the linear least-square method.

When the appropriate grouped WIRs are chosen, the range of the ESWL magnitude is similar to that of natural wind and is rational (Zhou *et al*. 2012). However, if the selection of the grouped WIRs is improper, some erratic and irrational ESWL distributions with extremely large values may result.

To obtain the ESWL with a reasonable value range, Zhou *et al*. (2014) thought up another form of the Two-Component-Method to compute the ESWL aiming at all peak WIRs in a certain group. In the method, the ESWL was regarded as a linear combination of two kinds of predefined basic wind load distributions, one of which can be obtained by the modified LRC method in Zhou *et al*. (2012). To avoid the occurrence of those above-mentioned erratic and irrational ESWL distributions, the value range of the ESWL was limited by controlling the bounds of the combination factors of the basic wind load distributions, and the solution of the combination factors was a constrained linear least-square problem. Meanwhile, a few focused WIRs rather than all WIRs in the certain group could be given more attention, the pre-established weighted factors were imported to improve the accuracy of these focused WIRs, the solution of the combination factors was turned into a weighted and constrained linear least-square problem.

These methods are not related to structural modes, which benefits the decrease of the ESWL calculation. Meanwhile, they consider simultaneously multiple WIRs. Furthermore, because of inheriting the characteristics of the traditional LRC method, the ESWL are analogous to those with the characteristics of the traditional LRC method, which demonstrates a certain physical meaning (Zhou *et al*. 2012, 2014).

However, these methods maybe have the following disadvantages: (1) Although the ESWL for the selected targeted WIR group has high accuracy, the accuracy is not ideal when it is used to other WIR groups. (2) The ESWL is in connection with the grouped patterns, the ESWL distributions are completely different from the grouped WIRs. Moreover, (3) The selected targeted WIRs are all peak WIRs, in reality, different WIRs can't reach peak values at the same time for the most part, it is necessary to take into consideration the correlations among WIRs. Otherwise, the value range of the ESWL is probably large.

2.3 ESWL methods based on POD modes of wind

The POD method is an effective means to analyze the complex random field; it can express the random field as a linear combination of a series of orthogonal basis functions (i.e. POD modes) whose combination factors are principal coordinates (Solari and Carassale 2000). When it is applied to the wind field, using significant physical distributions such as POD modes may express availably the ESWL (Katsumura *et al*. 2007).

2.3.1 ESWL method based on POD modes of total wind

Davenport and Surry (1984) also made use of the Two-Component-Method to calculate the maximum (minimum) ESWL of a saddle-shaped hyperbolic paraboloid roof that is nearly circular in the planform, in which the mean and fluctuating components of the ESWL were both expressed as the combinations of POD modes of the total wind (the mean wind + the fluctuating wind). In practical computation, POD modes were set as some simple mathematical shape functions-harmonic Fourier functions which coincide with the modes of a circular membrane and draw close to those for the hyperbolic paraboloid surface. Meanwhile, the shape functions were chosen to relate closely to the characteristics of structural WIRs. In the combination of POD modes, the combination coefficient of the mean component of the ESWL was the mean modal force coefficient, and the combination coefficient of the fluctuating component of the ESWL was the product of the RMS value, peak factor and resonant magnification factor of the modal force coefficient. The peak factor would be reduced by a load combination factor when more than one POD mode acts.

Differing from most methods, the authors didn't solve the ESWL based on WIRs, but first obtained the ESWL. Then corresponding WIRs could be obtained as long as POD modes were replaced by corresponding influence functions.

The method shuns the direct involvement of the influence function in the load description and leads directly to load cases representative of the highly complicated load patterns (Davenport and Surry 1984). Also, it calculates the ESWL directly from POD modes of the wind and is not involved in structural modes, which greatly simplifies the computation of the ESWL.

However, the above-mentioned WIRs for structural design are derived from the ESWL, so they are maybe not consistent with actual WIRs. What is more, the mean wind is included at the time of calculating POD modes. The inclusion of the mean wind distorts true POD modes, and it is obvious that such POD modes cannot help us to understand the fluctuating wind. The mean wind should be excluded from the POD analysis, and its contribution could be examined separately (Tamura *et al*.1999).

2.3.2 ESWL methods based on POD modes of fluctuating wind

It can be found from preceding most methods that it is necessary to determine initially a particular WIR or some suitable WIRs which have obvious impacts on the ESWL. However, it is not an easy thing to determine them especially for a complex structure (Li and Tamura 2005).

As WIRs vary both temporally and spatially, the largest WIRs for all structural members do not occur simultaneously. A universal ESWL would be of practical use especially in the early design stage even though it may have small changes in structural design. It could simultaneously reproduces these WIRs by using an inverse-analysis technique and was expressed as a linear combination of several arbitrary basic wind load distributions (Katsumura *et al*. 2004, 2005a,b, 2007; Tamura and Katsumura 2012).

For the fluctuating component in the universal ESWL, Katsumura *et al*. (2004, 2005a,b, 2007) and Tamura and Katsumura (2012) recommended the intrinsic POD modes of the fluctuating wind as an effective alternative for the basic wind load distributions, in case where the column vector of known WIRs could be formulated as the product of the known influence function matrix, the known POD mode matrix and the column of unknown combination factors of POD modes, and the combination factors could be solved by the least-square method.

The universal ESWL method also gains the ESWL directly by POD modes, which greatly simplifies the computation owing to the complete independence of structural modes. Meanwhile, the method can solve the ESWL not only by one kind of WIRs but also by different sorts of WIRs.

It is known from its derivation process that the method can be applicable to the simple structures with fewer WIRs in the case of fewer POD modes, however that it may not be suitable for the complex linear structures on condition that the number of POD modes is rather small but the number of WIRs is enormous, the method will yield greater errors in this context (Sun *et al*. 2015). Besides, such an ESWL is a pure mathematical operation which does not guarantee to give a physically meaning and realistic result (Chen and Zhou 2007). As well as Holmes (1992, 2002), Ginger *et al*. (2000), Chen *et al*. (2006, 2012, 2014) and Yang *et al*. (2013) only computed the background component of the ESWL by POD modes of the fluctuating wind.

As the existence of these defects in the universal ESWL method, Sun *et al*. (2015) theorized a modified ESWL method of the fluctuating wind on aforementioned complex linear large-span roofs by incorporating the above universal ESWL method with the POD compensation. In which the compensated POD mode and corresponding compensated factor, based on the response differences between accurate WIRs and approximate ESWL-induced responses in the universal ESWL method, were constructed. Then the product of the two compensated parameters is the compensated ESWL, the sum of the ESWL in the universal ESWL method and the compensated ESWL was the more accurate ESWL in the end.

Apart from previous advantages, the modified method reveals its clear physical meaning and high accuracy. Besides, it has widespread applicability which can hold for all linear complicated structures (Sun *et al*. 2015).

Whereas, it ought to be acknowledged that all above methods in this section also hypothesize that all WIRs reach simultaneously their maxima, which makes it possible to produce some erratic and irrational ESWL distributions (Sun et al. 2015). Actually, all WIRs cannot reach their maxima simultaneously (Katsumura *et al*. 2004, 2005a,b, 2007; Tamura and Katsumura 2012), it is still a must to consider their correlation in WIRs (Sun et al. 2015).

2.4 ESWL method based on POD modes of fluctuating wind and structural modes

Enlightened from Katsumura *et al*. (2004, 2005a,b, 2007), Chen and Yang (2009), Chen *et al*. (2012, 2014) and Yang *et al*. (2013) also studied the universal ESWL on the large-span roofs via the Two-Component-Method, in which the ESWL of the fluctuating wind was a linear combination of some dominant POD modes and inertial forces of structural modes, and the combination factors were still solved by the least-square method.

The method also enables multiple peak WIRs to be considered simultaneously. Meanwhile, it facilitates the ESWL computation without a discrimination of the background and resonant components for WIRs. Unfortunately, it seems that the method cannot prevent from the same shortcomings in Katsumura *et al*. (2004, 2005a,b, 2007) and Tamura and Katsumura (2012) from its computational process.

3. ESWL methods based on wind-induced stability

The ESWL methods in section 2 are in connection with WIRs; however, they are not suited to the stability analyses for some large-span roofs. For structural designs of some spatial roofs, the stability is of significance (Li and Tamura 2004, 2005).

Li and Tamura (2004, 2005) implemented the Two-Component-Method to calculate the most unfavorable ESWL of a single-layer reticulated shell. The mean component of the ESWL, based on the load code, was directly obtained from the reference wind pressure. To gain the fluctuating component of the ESWL, a stability analysis, under a linear combination of the dead load, live load and the mean wind, was conducted. Just before the instability point occurred in the equilibrium path, an eigenvalue analysis of the current tangent stiffness matrix of the structure in static nonlinear iteration was carried out to obtain the current possible instability mode, the first eigenvector was used as a rule. The instability mode was then pre-multiplied by the current tangent stiffness matrix and their product was further normalized. In the end, the fluctuating component of the ESWL could be obtained by way of multiplying the normalization result by the standard deviation of the wind.

Since the fluctuating wind has random characteristics, the possible instability mode is used as a most unfavorable estimation of its ESWL. Therefore, this method can provide a conservative estimation of the effects of the fluctuating wind on structural deformation and stability (Li and Tamura 2004, 2005). It can determine a suitable reference WIR for using the Holmes's (2002, 2007) method as well. The method, combined with Holmes's method, can be used efficiently to estimate the ESWL for structural deformation and stability analyses (Li and Tamura 2004, 2005). However, this method has no real consideration of the dynamic instability owing to its only involvement of the quasi-static stability under the mean wind in essence. Accordingly, the instability mode for the ESWL is not always the actual instability mode under the total wind, which illustrates that the method falls short of explicit physical meaning.

Inspired by the GRF method, Gu and Huang (2015) followed a similar pattern to investigate the ESWL of a spatial roof, which was equal to the mean wind multiplied by a dynamic instability factor. The mean wind was corresponding to the design wind velocity of the structure. The dynamic instability factor indicated the influence of the dynamic wind acted on structural stability, and it was quantitatively defined as the quotient of the critical wind load incremental factor in the statical nonlinear stability analysis divided by that in the dynamic nonlinear stability analysis.

The method is simple because of executing the same form as the GRF method. Furthermore, the static stability design under the ESWL can produce the real dynamic instability factor in the dynamic wind (Gu and Huang 2015), which validates its clear physical meaning. However, the two instability modes in the two nonlinear analyses may be totally dissimilar at the time of computing the critical wind load incremental factors. As a result, the dynamic instability factor from two different instability modes seems to make no sense.

4. Conclusions

This paper reviews the state of the art relevant to the ESWL methods in the large-span roofs. It can be concluded from above analyses that the methods will develop in a direction toward the simple computation, clear physical meaning, high accuracy and convenient engineering application. Although some achievements are acquired, there are a few pivotal questions which should be taken note of in the subsequent research:

(1) When the ESWL is in connection with WIRs, the determination of number and values of WIRs should be precise in advance. The existing methods do not work out well the question as of now. In addition, the existing methods often focus on those linear or weak nonlinear structures, how to calculate the ESWL of those strong nonlinear structures according to the characteristics of WIRs is worthy of further investigation.

(2) When the ESWL is relevant to structural stability, the instability mode under the ESWL should be consistent with the instability mode under the actual total wind. The issue is not efficiently disposed in the existing methods and need to be solved urgently in the near future.

Acknowledgments

This project is supported by the Fundamental Research Funds for the Central Universities (CUG2013059013), which is gratefully acknowledged.

References

Chen, B., Wu, Y. and Shen, S. Z. (2006). “Equivalent static wind loads on large span roofs”, *Proceedings of IASS-APCS Symposium*, Beijing.

Chen, B. and Yang, O. S. (2009). “Universal quivalent static wind loads of China national stadium”, *The Seventh Asia-Pacific Conference on Wind Engineering*, Taipei, Taiwan.

Chen, B., Yang, Q. S. and Wu, Y. (2012). “Wind-induced response and equivalent static wind loads of long span roofs”, *Adv. Struct. Eng.*, **15**(7), 1099-1114.

Chen, B., Yan, X. Y. and Yang, Q. S. (2014). “Wind-induced response and universal equivalent static wind loads of single layer reticular dome shells”, *Int. J. Struct. Stab. Dyn.*, **14**(4), 1450008.

Chen, X. Z. and Kareem, A. (2001). “Equivalent static wind loads for buffeting response of bridges”, *J. Struct. Eng.*, **127**(12), 1467-1475.

Chen, X. Z. and Kareem, A. (2004). “Equivalent static wind loads on buildings: new model”, *J. Struct. Eng.*, **130**(10), 1425-1435.

Chen, X. Z. and Zhou, N. (2007). “Equivalent static wind loads on low-rise buildings based on full-scale pressure measurements”, *Eng. Struct.*, **29**(10), 2563-2575.

Davenport, A. G. (1961). “The application of statistical concepts to the wind loading of structures”, *Proceedings of the Institution of Civil Engineering*, London.

Davenport, A. G. (1967). “Gust loading factor”, *J. Struct. Div.,* **93**(3), 11-34.

Davenport, A. G. (1995). “How can we simplify and generalize wind load?”, *J. Wind Eng. Ind. Aerod.,* **54-55**(3), 657-669.

Davenport, A. G. and Surry D. (1984). “Turbulent wind forces on a large span roof and their representation by equivalent static loads”, *Can. J. Civ. Eng.,* **11**(4), 955-966.

Dyrbye, C. and Hansen, S. O. (1997). *Wind Loads on Structures*, John Wiley & Sons Ltd, Chichester, England.

Fu, J. Y., Xie, Z. N. and Li, Q. S. (2008). “Equivalent static wind loads on long-span roof structures”, *J. Struct. Eng.*, **134**(7), 1115-1128.

Ginger, J. D., Reardon, G. F. and Whitbread, B. J. (2000). “Wind load effects and equivalent pressures on low-rise house roofs”, *Eng. Struct.*, **22**(6), 638-646.

Gu, M. and Huang, Y. Q. (2015). “Equivalent static wind loads for stability design of large span roof structures”, *Wind Struct.*, **20**(1), 95-115.

Gu, M. and Zhou, X. Y. (2009). “An approximation method for resonant response with coupling modes of structures under wind action”, *J. Wind Eng. Ind. Aerod.*, **97**(11-12), 573-580.

Holmes, J. D. (1990). “Analysis and synthesis of pressure fluctuations on bluff bodies using eigenvectors”, *J. Wind Eng. Ind. Aerod.*, **33**(1-2), 219-230.

Holmes, J. D. (1992). “Optimised peak load distribution”, *J. Wind Eng. Ind. Aerod.*, **41**(1), 267-276.

Holmes, J. D. (2002). “Effective static load distributions in wind engineering”, *J. Wind*

Eng. Ind. Aerod., **90**(2), 91-109.

Holmes, J. D. (2007). *Wind Loading of Structures*(*second edition*), Taylor and Francis Group, London, UK.

Holmes, J. D., Syme, M. J. and Kasperski, M. (1995). “Optimised design of a low-rise industrial building for wind loads”, *J. Wind Eng. Ind. Aerod.*, **57**(2-3), 391-401.

Kareem, A. and Zhou, Y. (2003). “Gust loading factor-past,present and future”, *J. Wind Eng. Ind. Aerod.*, **91**(12-15), 1301-1328.

Kasperski, M. (1992). “Extreme wind load distributions for linear and nonlinear design”, *Eng. Struct.*, **14**(1), 27-34.

Kasperski, M. and Niemann, H J. (1992). “The L.R.C.(load-response-correlation) - method a general method of estimating unfavourable wind load distributions for linear and non-linear structural behaviour”, *J. Wind Eng. Ind. Aerod.*, **43**(3), 1753-1763.

Katsumura, A., Tamura, Y. and Nakamura, O. (2004). “Universal equivalent wind load distribution reproducing maximum load effects on structural members”, *The 5th International Colloquium on Bluff Body Aerodynamics and Applications*, Ottawa, Canada, July.

Katsumura, A., Tamura, Y. and Nakamura, O. (2005a). “Maximum wind load effects on a large-span cantilevered roof”, *Struct. Eng. Int.*, *IABSE*, **15**(4), 248-251.

Katsumura, A., Tamura, Y. and Nakamura, O. (2005b). “Universal wind load distribution simultaneously reproducing maximum load effects in all subject members on large-span cantilevered roof”, *Proceedings of the 4th European and African Conference on Wind Engineering*, Prague, Czech.

Katsumura, A., Tamura, Y. and Nakamura, O. (2007). “Universal wind load distribution simultaneously reproducing largest load effects in all subject members on large-span cantilevered roof”, *J. Wind Eng. Ind. Aerod.*, **95**(9-11), 1145-1165.

Li, Y. Q. and Tamura, Y. (2004). “Wind-resistant analysis for large-span single-layer reticulated shells”, *Int. J. Space Struct.*, **19**(1), 47-59.

Li, Y. Q. and Tamura, Y. (2005). “Equivalent static wind load estimation in wind-resistant design of single-layer reticulated shells”, *Wind Struct.*, **8**(6), 443-454.

Lou, W. J., Lu, F. and Sun, B. N. (2000). “Study on buffeting response for flexible roof structures”, *Advances in Structural Dynamics*, Ko, J. M. and Xu, Y. L. ed., Oxford, UK, July.

Marukawa, H., Uematsu, Y., Tamura, Y., Nakamura, O. and Ueda, H. (1993). “Design wind load on flat long-span roofs”, *Proceedings of the 4th East Asia-Pacific Conference on Structural Engineering and Construction*, Seoul, Korea.

Repetto, M. P. and Solari, G. (2004). “Equivalent static wind actions on vertical structures”, *J. Wind Eng. Ind. Aerod.*, **92**(5), 335-357.

Shen, S. Z. and Yang, Q. S. (1999). “Wind-induced response analysis and wind-resistant design of hyperbolic paraboloid cable net structures”, *Int. J. Space Struct.*, **14**(1), 57-65.

Solari, G. and Carassale, L. (2000). “Modal transformation tools in structural dynamics and wind engineering”, *Wind Struct.*, **3**(4), 221-241.

Sun, W. Y., Gu, M. and Zhou, X. Y. (2015). “Universal equivalent static wind loads of fluctuating wind loads on large-span roofs based on POD compensation”, *Adv. Struct. Eng.*, **18**(9), 1443-1459.

Suzuki, M., Sanada, S., Hayami, Y. and Ban, S. (1997). “Prediction of wind-induced response of a semi-rigid hanging roof", *J. Wind Eng. Ind. Aerod.*, **72**(1-3), 357-366.

Tamura, Y., Fujii, K. and Ueda, H. (1992). "Design wind loads for beams supporting flat roofs", *J. Wind Eng. Ind. Aerod.*, **41-44**(1-3), 1841-1852.

Tamura, Y. and Katsumura, A. (2012). "Universal equivalent static wind load for structures", *The Seventh International Colloquium on Bluff Body Aerodynamics and Applications* (*BBAA7*), Shanghai, China.

Tamura, Y., Suganuma, S., Kikuchi, H. and Hibi, K. (1999). "Proper orthogonal decomposition of random wind pressure field", *J. Fluids Struct.*, **13**(7-8), 1069-1095.

Uematsu, Y., Yamada, M. and Sasaki, A. (1996). "Wind-induced dynamic response and resultant load estimation for a flat long-span roof", *J. Wind Eng. Ind. Aerod.*, **65**(1-3), 155-166.

Uematsu, Y., Yamada, M. and Karasu, A. (1997a). "Design wind loads for structural frames of flat long-span roofs: Gust loading factor for the beams supporting roofs", *J. Wind Eng. Ind. Aerod.*, **66**(1), 35-50.

Uematsu, Y., Yamada, M. and Karasu, A. (1997b). "Design wind loads for structural frames of flat long-span roofs: Gust loading factor for a structurally integrated type", *J. Wind Eng. Ind. Aerod.*, **66**(2), 155-168.

Uematsu, Y., Yamada, M., Inoue A. and Hongo, T. (1997c). "Wind loads and wind-induced dynamic behavior of a single-layer latticed dome", *J. Wind Eng. Ind. Aerod.*, **66**(3), 227-248.

Uematsu, Y., Watanabe, K., Sasaki, A., Yamada, M. and Hongo, H. (1999). "Wind-induced dynamic response and resultant load estimation of a circular flat roof", *J. Wind Eng. Ind. Aerod.*, **83**(1-3), 251-261.

Uematsu, Y. and Yamada, M. (2002). "Wind-induced dynamic response and its load estimation for structural frames of circular flat roofs with long spans", *Wind Struct.*, **5**(1), 49-60.

Uematsu, Y., Sone, T., Yamada, M. and Hongo, T. (2002). "Wind-induced dynamic response and its load estimation for structural frames of single-layer latticed domes with long spans", *Wind Struct.*, **5**(6), 543-562.

Uematsu, Y., Moteki, T. and Hongo, T. (2008). "Model of wind pressure field on circular flat roofs and its application to load estimation", *J. Wind Eng. Ind. Aerod.*, **96**(6), 1003-1014.

Yang, Q. S., Chen, B., Wu, Y. and Tamura, Y. (2013). "Wind-induced response and equivalent static wind load of long-span roof structures by combined Ritz-proper orthogonal decomposition method", *J. Struct. Eng.*, **139**(6), 997-1008.

Zhou, X. Y. and Gu, M. (2010). "An approximation method for computing the dynamic responses and equivalent static wind loads of large-span roof structures", *Int. J. Struct. Stab. Dyn.*, **10**(5), 1141-1165.

Zhou, X. Y., Gu, M. and Li, G. (2012). "Grouping response method for equivalent static wind loads based on a modified LRC method", *Earthq. Eng. Eng. Vib.*, **11**(1), 107-119.

Zhou, X. Y., Gu, M. and Li, G. (2014). "Constrained least-squares method for computing equivalent static wind loads of large-span roofs", *Adv. Struct. Eng.*, **17**(10), 1497-1515.

Zhou, X. Y., Han, Z. H., Gu, M., Zhang, A. A., Zhang, W. Y. and Fang, W. (2013). "Research on wind-induced responses of a large-scale membrane structure", *Earthq. Eng. Eng. Vib.*, **12**(2), 297-305.

Zhou, Y., Kareem, A. and Gu, M. (1999). “Gust loading factors for design applications”, *Proceedings of the 10th International Conference on Wind Engineering*, Copenhagen.

Zhou, Y. and Kareem, A. (2001). “Gust loading factor: new model”, *J. Struct. Eng.*, **127**(2), 168-175.

Zhou, Y., Kareem, A. and Gu, M. (2000). “Equivalent static buffeting loads on structures”, *J. Struct. Eng.*, **126**(8), 989-992.