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.

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