Engineering Structures 148 (2017) 1–10

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Equivalent Static Wind Loads: Recent developments and analysis of a suspended roof

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ARTICLE INFO

Article history:
Received 30 June 2016
Revised 29 May 2017
Accepted 31 May 2017

Keywords:
Equivalent Static Wind Loads
Structural response
Buffeting
Envelope reconstruction

ABSTRACT

Equivalent Static Wind Loads (ESWLs) represent an extremely useful tool for the characterization of the structural response to the wind action and provide a convenient way for structural engineers in order to include the results of a complete, rigorous, buffeting analysis in the design process. Recently, a novel approach to the determination of ESWLs has been proposed which is based on the adoption of Proper Skin Modes for the characterization of the static/quasi-static structural response. In that study, the reconstruction of the extreme internal forces over the structure for all structural members has been performed in a least square sense and a smoothed version of the maximum/minimum operators, typical of envelope calculations, has been adopted. By using such formulation, it is possible to use efficient, gradient-based, optimization techniques in the minimization procedure which leads to the identification of ESWLs. In this paper, two refinements of the original technique are proposed: the least square approach is modified in order to ensure a complete covering of the envelope and the original formulation is extended in order to take into consideration the contemporaneity between effects. Finally, the proposed approach is tested on a large span suspended roof derived from the structural model of the New Juventus Stadium showing extremely encouraging results.

1. Introduction

Wind effects on structures are often taken into account by structural engineers by following extremely simplified methods in which a series of statically applied load conditions, usually prescribed by building codes, are used in order to characterize the wind time-averaged and dynamic action. Such an approach, although greatly simplified, is well established and leads to results which are acceptable for the design of the majority of conventional buildings.

Nevertheless, when complex slender structures are considered, such a way of proceeding is no longer applicable and wind tunnel tests on scaled models are usually performed. The raw output of such tests is represented by time histories of the pressure coefficients at each monitored point. Dynamic analyses should be thus performed in order to obtain from the measured data the effects induced by the wind on the structure: each attack angle must be separately considered and envelopes containing the maximum/minimum internal forces for each structural member obtained. In the following, in order to highlight the generality of the proposed procedure, the term *internal forces* is often replaced by the term *effect* so indicating any component of the structural linear response.

It must be noticed that, for practical reasons, such work-flow is only rarely applied: due to the specific competencies needed to interpret wind tunnel tests results and the inefficiency of standard commercial finite elements softwares in processing the sizeable amount of data collected in the wind tunnel, such calculations are preferably performed by specialized users by means of *ad hoc* developed codes.

In such context, a first problem is represented by the characterization of the structural mechanical behaviour itself. In fact, aiming at performing numerous dynamic analyses, it is convenient to built reduced models of the structure in order to minimize the effort needed to perform the calculations. Such an approach has, indeed, also the advantage of reducing the amount of data needed to describe the structure mechanic behaviour, so facilitating the interaction between structural and wind engineers.

The construction of such reduced models is often based on a modal representation of the structure which might lead to strong inaccuracies if the number of considered modes is not adequate, especially in the static/quasi-static limit. Recently, in order to overcome such difficulties, a simple approach based on the well known method of static corrections has been proposed by Patruno et al.

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http://dx.doi.org/10.1016/j.engstruct.2017.05.071
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[21]. In that study, the modal base, due to its efficiency, is adopted for the description of the static, quasi-static and resonant part of the response without any distinction. In order to minimize the potential inaccuracies introduced by the unavoidable truncation of the modal base, static and quasi-static corrections [28,1,10,7] are developed based on the structural response to predefined pressure modes, statically applied, named Proper Skin Modes (PSMs). Such pressure modes, which depend only on the structure geometry, can be seen as a modal enhanced version of the influence coefficients, traditionally used in order to characterize the structural behaviour in the static and quasi-static regime. By adopting such kind of methodologies, it is possible to efficiently calculate the envelope of the extreme internal forces for all structural members by collecting the maximum and minimum values recorded in all the considered wind conditions or, alternatively, by performing appropriate statistical treatments of the obtained time series [23,24]. Such envelopes represent the design values which can be directly used in the design process.

On the other hand, Equivalent Static Wind Loads (ESWLs) represent an extremely convenient way to exchange data between wind and structural engineers (the last ones being usually familiar with statically applied pressure distributions in order to represent the wind action). The basic idea underlaying their definition is to search for a set of static load conditions which, once enveloped, provide the correct design value in each structural member.

Several approaches to the determination of ESWLs have been presented in the literature. Initially proposed by Davenport [8,9], the Gust Loading Factor approach, in its simplest version, assumes that the structural response to the time averaged wind profile can be appropriately amplified in order to synthetically take into account the structure dynamic response. Such an approach, although still widely used in practice due to its simplicity, is prone to numerous limitations, the principal one being the impossibility to describe effects which are null when the time averaged response is considered.

Aiming at overcoming such limitations, the Conditional Sampling Technique (CST) [11,27,13], assuming a quasi-static structural behaviour, individuates the most important load conditions as the average of the pressure distribution conditioned to the maximization of a preselected effect. By adopting such a strategy, a series of critical load cases are obtained which, enveloped together, are able to reproduce the observed average of the extreme values for each considered effect. A scaling coefficient can be introduced in order to amplify such value so recovering the extreme response associated to a predefined return period. Similarly to CST but with greater statistical insight, Load-Response Correlation method (LRC) [14,15] defines ESWLs as the most probable pressure distribution corresponding to the maximum expected value of the considered internal force by adopting a Gaussian framework.

It must be noticed that, when ESWLs are extracted by adopting such techniques, at least in their basic form, only one effect on the structure is considered at a time in order to drive the identification of the critical load condition and this is often assumed as the maximization of a global quantity (i.e. the total uplift on a roof structure).

Nevertheless, the obtained critical pressure distributions have a clear physical meaning and this is reflected by the fact that the contemporaneity between effects is respected. This means that if, for example, CST is used to identify the ESWL corresponding to the maximization of the bending moment at the footing of a tower in one direction, the bending moment in the other directions produced by the ESWL will be the expected ones in that condition. For the sake of clearness, in the following, the extreme effects measured on the structure and used to drive the ESWLs identification are named *primary effects* while the ones acting in contemporaneity with them are named *secondary effects*.

A number of extensions to the previously introduced techniques have been presented in the literature. Formulations able to take into account combinations of static, background and resonant responses have been proposed by Holmes [12] and Chen and Kareem [6]while Blaise and Denoël [4] and Blaise et al. [2]proposed the concept of CESWL which extends the LRC formulation in order to take into account the effects of non-Gaussianity by using an Hermite moment based translation procedure [29]. Lou et al. [18] proposed to use appropriate combinations of EWSLs obtained within the framework of the LRC approach in order to match multiple effects at the same time. Nevertheless, such techniques do not lead, properly speaking, to an envelope reconstruction procedure (as it would be desirable for design purposes).

Within the methods which attempt to provide a general envelope reconstruction procedure, for high-rise buildings, Repetto and Solari [25] proposed to use a polynomial expansion of the applied load distribution along the building height deduced in order to match multiple effects while [16,17,26] proposed the concept of Universal ESWL which allowed to derive a load condition able to reproduce the extreme response to wind loading in a number of considered structural elements at the same time. In the same spirit, in order to simplify the ESWLs calculation, Blaise et al. [5] and Blaise and Denoël [3]proposed the concept of Principal Static Wind Load (PSWLs) which, by Singular Value Decomposition (SVD) of the effects induced on the structure by preselected load cases, obtained a few pressure distributions which induce on the structure independent effects. In that case, the envelope reconstruction has been obtained by combining PSWLs by means of a Monte Carlo optimization.

More recently, an efficient methodology able to drive the envelope reconstruction procedure by means of efficient gradient-based optimization algorithms has been proposed by Patruno et al. [22]. By using such an approach, the envelope can be reconstructed globally, so taking into account at the same time the extreme effects measured in all the structural elements of interest. The procedure is extremely efficient and it is often able to condensate in a few, statically applied, load cases the results obtained by rigourous buffeting analyses. The drawback of such an approach is represented by the fact that the critical load cases might not have a direct physical meaning. More importantly, from the design point of view, there is no guarantee that the extreme *primary effects* are reproduced together with the expected corresponding *secondary* ones.

In this paper, two modifications to the approach proposed by Patruno et al. [22] for the extraction of the ESWLs are proposed. The first one aims at avoiding possible underestimations of the design values in the definition of the ESWLs while the second one aims at ensuring that *secondary effects* are properly reproduced, i.e. the contemporaneity between *primary* and *secondary effects* is correctly taken into account.

The paper is organized as follows: in Section 2 the original methodology for the extraction of ESWLs is briefly recalled. In Section 3 the original technique is modified in order to avoid underestimations in the reconstructed envelope and to take into account the presence of *secondary effects*. In Section 4 the proposed methodology is tested on the suspended roof of the New Juventus Stadium. Finally, in Section 5 some conclusions are drawn.

2. Extraction of ESWLs

In order to efficiently extract ESWLs, a first step is represented by the identification of the independent load cases which might effectively contribute to the envelope reconstruction. Such elementary load cases, named Principal Static Wind Loads (PSWLs), have been introduced by Blaise et al. [5] and represent an efficient