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Assessment of extreme value overestimations with equivalent static wind loads

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ABSTRACT

The wind-resistant design using equivalent static wind loads is convenient for structural engineers. This paper studies the reliability of such an approach in the case of non-Gaussianities in both aerodynamic pressures and responses. These non-Gaussianities are responsible for overestimations of envelope values and may result in uneconomical designs, if not appropriately understood, assessed and addressed. In this study, it is shown that the equivalent static wind loads defined with the Conditional Expected Load method, which extends the physical meaning of the Load-Response Correlation approach in a non-Gaussian framework, improves the issue of overestimations of envelope values. Several envelopes of structural responses are considered: the mean of extremes and the 86% quantiles of extremes, together with two reference periods (10 min and 1 h). Extensive wind tunnel measurements have been collected, which correspond to 371 h full scale. This study is undertaken for quasi-static analysis of structures and is illustrated with a low-rise building.

1. Introduction

The aerodynamics of unusual structures built in the atmospheric boundary layer is so complex that a case-by-case study needs to be specifically developed for every new project. Although standards and codification processes properly describe the main features of the atmospheric wind flows, as well as their statistical distributions, the determination of actions on buildings and other civil engineering structures is practically obtained by means of wind-tunnel experiments or computational fluid dynamics simulations. Whatever method is chosen, this huge quantity of information is usually too heavy and too detailed for the structural engineer who designs the bearing system of the building, or even for the façade engineer who designs the envelope. Some 50 years after the gust loading factor has been suggested by Davenport (1967), it is still very common to proceed with the structural design on the basis of equivalent static wind loads (ESWLs) rather than the time-dependent wind loads.

Although these detailed time series are too heavy for the design, especially for the combination of wind loads with other load cases, it is possible to determine structural displacement and internal forces at different places of the structure. The statistical treatment of the time series associated with these *structural responses* (e.g. a bending moment in a decisive element of the structure), also sometimes referred to as *effect*, provides design values that should be used for the final structural design. The set of design values associated with all structural responses defines the *envelope* of structural responses. In this paper —and in most works related to this subject—, it is assumed that this envelope is known and sufficiently accurate to serve as a reference.

Equivalent static wind loads are usually defined with respect to a single *structural response*. The equivalence is defined in such a way that the structural analysis under an equivalent static load provides the same structural response as the design response that would be obtained by extreme value analysis considering the time-dependent response. The determination of an equivalent static wind load is far from trivial because it should include not only the variability in time and space of the loading but also the possible dynamics of the structure, the possibly non-Gaussian nature of the loads, the possible nonlinear structural behavior, etc. Several methods are therefore available to define an equivalent static load. Among others, three families being respectively the Gust Loading Factor (GLF), the Conditional Sampling Technique (CST) and the Load-Response-Correlation (LRC) are well-documented. The GLF methods and the likes (Davenport, 1967; Vickery, 1970; Simiu, 1973; Solari, 1993a, b; Holmes, 1994; Simiu and Scanlan, 1996) consist in amplifying a profile of structural responses, e.g., the structural response under the average wind loads, by a scalar in order to estimate the envelope. Although this is not the original spirit of the method, this scalar might be adjusted, if required, from one structural response to another (Tamura

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et al., 1992; Huang and Chen, 2007). The CST (Holmes and Best, 1981; Stathopoulos, 1984; Holmes, 1988) suggests to process the long time-dependent series by retaining the patterns of pressure distributions that corresponds to the maximum (or design) value of the considered structural response. In case several occurrences are detected, averaging is conducted. There are as many CST-based equivalent static wind loads as the considered number of structural responses. In the LRC method (Kasperski and Niemann, 1992), the equivalent static wind load is defined as a function of the correlation coefficient between the considered structural response and the aerodynamic pressure field. The concept has been also extended to the resonant component of the response (Chen and Kareem, 2001), in which case the displacement field is the total, background plus resonant, displacement field of the structure under the buffeting wind load. In a Gaussian framework only, the LRC equivalent static wind load has the virtue to be interpreted as the most probable wind load pattern associated with the design structural response. In a non-Gaussian analysis, the LRC ESWL loses its probabilistic sense.

The Conditional Expected Static Wind Load (CESWL), defined as the average of the wind load patterns given the occurrence of the design value, generalizes this features of the LRC method to non-Gaussian pressures and responses fields (Blaise et al., 2016).

When a large number of responses are of interest, the envelope reconstruction problem arises (Blaise et al., 2016), which consists in finding a set of static loadings (minimum in number and satisfying some accuracy criteria) whose own envelope somehow covers the actual envelope of structural responses. Several advanced techniques (Repetto and Solari, 2004; Katsumura et al., 2007; Chen and Zhou, 2007; Li et al., 2009; Zhou et al., 2011; Blaise and Denoël, 2013; Lou et al., 2015; Patruno et al., 2017) are available to solve the envelope reconstruction problem, for instance multi-objective equivalent static wind load that targets the reconstruction of several envelope values at a time. These techniques rely on all sorts of approximations and overestimations of some envelope responses are unavoidable. Significant overestimations of the reconstructed envelope are typically undesired since they lead to uneconomical designs and one should make sure that the overestimation remains controlled (Blaise et al., 2016).

In some circumstances, the structural engineer may not want to use such advanced techniques because they are heavier and more tricky to exploit. To disentangle himself from the envelope reconstruction problem, the structural engineer can alternatively consider the sequential reconstruction of the envelope using equivalent static wind loads. This approach is viable to some degree, i.e., the number of responses must be manageable, or responses governing the design are easily identified. The sole disadvantage is that, for large structures, the number of load cases is likely to be much larger than with multi-objective techniques. This paper exclusively focuses on using equivalent static wind loads to reconstruct the envelope. In particular, an interesting feature of the LRC method is that it does not provide any overestimation of the envelope and the LRC based reconstructed envelope is, therefore, the actual one as long as a Gaussian context is used (Blaise et al., 2016). The merit and advantage in this approach is that the structural engineer does not have to address overestimations and is ensured to do an economical design. However as soon as a non-Gaussian context is considered, examples show that this non-overestimation property fails. It is no longer possible to ascertain that the envelope of structural responses is not overestimated. This is attributed to the distortion of probability density functions, in the non-Gaussian framework. To alleviate this issue, the CESWL was precisely imagined to cope with non-Gaussian loadings or structural responses. It is therefore expected to provide smaller overestimations of the envelope. This statement is studied by means of a large experimental campaign which is reported and summarized in this paper. From a practical standpoint, the implications of the present study might also be considered when developing multi-objective techniques in a non-Gaussian context.

Section 2 exposes the establishment of the envelope values of non-Gaussian structural responses. Section 3 introduces the conditional expected load method and discusses the bicubic model to estimate conditional expected static wind load. Section 4 illustrates the developments with the non-Gaussian quasi-static analysis of a low-rise gable-roof building.

2. Extreme values of non-Gaussian structural responses

Structures with linear quasi-static behavior under a stationary non-Gaussian aerodynamic pressure field are considered. Decisive structural responses, such as internal forces or stresses are studied. The mean $\boldsymbol{\mu}_{\mathbf{r}}$ and fluctuating parts $\mathbf{r}(t)$ of the structural responses (wind effects) are obtained by linear combinations of the aerodynamic pressures as

$$\boldsymbol{\mu}_{\mathbf{r}} = \mathbf{B}\,\boldsymbol{\mu}_{\mathbf{p}}, \qquad \mathbf{r} = \mathbf{B}\,\mathbf{p}, \tag{1}$$

where $\mathbf{B}$ is an $n_r \times n_l$ matrix of influence coefficients and $\boldsymbol{\mu}_{\mathbf{p}}$, $\mathbf{p}(t)$ are $n_l \times 1$ vectors gathering the mean and fluctuating part of the aerodynamic pressures measured at n_l pressure taps, respectively. For the purpose of design, statistics of extreme values of $\mathrm{r}_i(t)\ \forall i \in [1, n_r]$, are defined for the negative extreme $\check{\mathrm{r}}_i = \min\{\mathrm{r}_i(t), 0<t<T\}$ and the positive extreme $\hat{\mathrm{r}}_i = \max\{\mathrm{r}_i(t), 0<t<T\}$ for a reference period T, typically 10 min or 1 h. The mean of the extremes is usually considered for design when structural responses are Gaussian

$$\mathbf{r}^{(min)} = \mathbb{E}[\check{\mathbf{r}}];\ \mathbf{r}^{(max)} = \mathbb{E}[\hat{\mathbf{r}}]. \tag{2}$$

For non-Gaussian wind effects, p-quantiles are used such that

$$\overline{F}_{\check{\mathbf{r}}}\left(\mathbf{r}^{(min)}\right) = p;\ F_{\hat{\mathbf{r}}}\left(\mathbf{r}^{(max)}\right) = p, \tag{3}$$

where $\overline{F}_{\check{\mathbf{r}}}(\mathbf{r}) = \mathrm{Prob}(\check{\mathbf{r}} \geqslant \mathbf{r})$ is the complementary distribution of the negative extremes and $F_{\hat{\mathbf{r}}}(\mathbf{r}) = \mathrm{Prob}(\hat{\mathbf{r}} \leq \mathbf{r})$ is the distribution of the positive extremes. Assuming Gumbel distributions for the extreme values, the mean and mean plus standard deviation of the extremes are associated with the 57% and 86%-quantiles. For non-Gaussian responses, 78% or 86%-quantiles are usually considered (Ding and Chen, 2014).

The couple $(\mathbf{r}^{(min)}, \mathbf{r}^{(max)})$ defines the *envelope* which is considered in this work. Notice that the *total envelope* $(\mathbf{r}'^{(min)}, \mathbf{r}'^{(max)})$ is then obtained by adding the mean component $\boldsymbol{\mu}_{\mathbf{r}}$. This is not further discussed since the average wind load is typically accurately measured and well understood.

3. Structural responses under conditional expected static wind loads

An equivalent static wind load is a loading such that its application provides the same structural response as that resulting from the extreme value buffeting analysis. As introduced before, several techniques exist to compute an equivalent static wind load. Chen and Zhou (2007) stressed that "*The load distribution for a given peak response is not necessarily unique simply because multiple load distributions can result in an identical response*.".

Among others, the conditional expected static wind load (CESWL) is a new kind of equivalent static wind load that was specifically designed for non-Gaussian wind pressures and responses (Blaise et al., 2016). This static wind load corresponds to the LRC method in a Gaussian framework. For each wind effect, the CESWL is unique and manifests two important properties.

The conditional expected static wind load $\mathbf{p}^{(\mathscr{E},max)}$ (resp. $\mathbf{p}^{(\mathscr{E},min)}$) is defined as the average of the wind loads conditioned upon recovery of the envelope value $\mathrm{r}_i^{(max)}$ (resp. $\mathrm{r}_i^{(min)}$)

$$\mathbf{p}^{(\mathscr{E},max)} = \mathbb{E}\left[\mathbf{p}(t)\,\middle|\,\mathrm{r}_i = \mathrm{r}_i^{(max)}\right]. \tag{4}$$

The k-th component of the CESWL (4) associated with the envelope value $\mathrm{r}_i^{(max)}$ is therefore expressed as the first moment of the conditional distribution, as