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Investigation of uncertainties in pressure coefficients for flat roofs of low-rise buildings

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SUMMARY

When assessing wind actions on structures, one of the main sources of uncertainty arises from the modelling of aerodynamic interaction, which is quantified in the wind action model through the aerodynamic coefficients. This paper brings some results from an investigation concerning the uncertainties contained in the pressure coefficients in use for flat roofs of low-rise buildings. In detail, with reference to the loading zones of Eurocode 1 Part 1-4 and based on available experimental data, the intra- and the inter-building variability of the pressure coefficients are first evaluated. Then, a comparison with the values proposed in Eurocode 1 is made and a model for uncertainty in pressure coefficient is proposed. Values of bias on average greater than one is found, suggesting that the pressure coefficients adopted by Eurocode 1 are largely on the unsafe side. On the other hand, values of the coefficient of variation between 7.4 and 40.7 affect calibration of the load partial factor.

Keywords: pressure coefficients; uncertainty; code calibration

1. INTRODUCTION

The design of structures to wind actions requires the assessment of a return wind pressure (or wind force), i.e. its maximum expected value in the reference period. According to the partial factor format adopted by structural codes, e.g. the Eurocodes, a load safety factor is applied to a representative (often characteristic) value of the wind action, which accounts for all the uncertainties associated with such value. Among these is the model uncertainty, accounting for all the deviations between the representative value w_{rep} of the action assessed with the Code model, and the corresponding reference value w, assumed to be the exact one, e.g. the value coming from measurements. If the wind action is made explicit, then the model uncertainty can be defined by the ratio (Davenport, 1983; JCSS, 2001):

$$\theta_w = \frac{w}{w_{rep}} = \frac{q_b}{q_{b,rep}} \cdot \frac{c_e}{c_{e,rep}} \cdot \frac{c_p}{c_{p,rep}} \cdot \frac{c_s c_d}{(c_s c_d)_{rep}} = \theta_{q_b} \cdot \theta_{c_e} \cdot \theta_{c_p} \cdot \theta_{c_s c_d} \quad (1)$$

where q_b is the basic value of the velocity pressure, defined as the T_a-averaged velocity pressure measured in standard conditions (T_a = 600 s in Eurocode 1); c_e is the exposure factor, accounting for all the deviations from standard conditions; c_p is the pressure coefficient, accounting for the (static) interaction between the wind flow and the construction; and $c_s c_d$ is the structural factor, accounting for the construction size effects (c_s) and for the dynamic interaction (c_d) between the wind flow and the construction. Current work aims at contributing to the issue of modelling uncertainty in wind action, focusing on the uncertainty θ_{c_p} in pressure coefficients for flat roofs of low-rise buildings. Explicit reference is made to Eurocode 1 Part 1-4 on wind actions, EN 1991-1-4:2005 (CEN, 2005).

2. METHODOLOGY

2.1. Pressure coefficients in the Eurocode

Within the gust factor approach, two sets of pressure coefficients are provided in EN 1991-1-4. Among these, the *detailed coefficients*, $c_{pe,10}$ are used for the design of structural elements having a tributary area of $10\ \mathrm{m}^2$ or more. The detailed coefficients are mainly derived from the work of Cook (1990), in turn obtained by applying the method of Cook and Mayne (1979).

In their pioneering work, Cook and Mayne (1979) attempted a statistical description of pressure coefficients as an alternative to the use of nominal values, at the time used in all codes of practice, e.g. the UK Code of Practice for the design of buildings (BSI, 1972). A design approach was proposed in which the definition of both velocity pressure and pressure coefficients was based on the gap existing in the spectrum of synoptic wind speeds (Van der Hoven, 1957). The velocity pressure and the pressure coefficients therefore become statistical variables, whose design value is assessed through Extreme Values (EV) analysis. A Type I EV distribution (Gumbel, 1958) is used for both variables and the 78% fractile is calibrated for the design pressure coefficients, giving rise to a design value for wind action having annual probability of non-exceedance equal to 98%, i.e. the value corresponding to a return period of 50 yrs.

2.2. Experimental data

In order to assess uncertainty in pressure coefficients, the Aerodynamic Database of the Tokyo Polytechnic University (TPU) (Tamura, 2012) is used. The database gathers the results of many boundary-layer wind tunnel tests, including tests on isolated low-rise buildings with flat roofs. Ten runs of 10 min length at full scale were made for each configuration of 1:100 scaled model buildings, at a frequency of 15 Hz. Original time series were moving averaged each 0.2 s, roughly corresponding to 1 m^2 if the TVL formula is applied (Lawson, 1980). However, to derive $c_{pe,10}$ a moving-average time equal to 0.9 s is required, corresponding to an equivalent area of about 10 m^2. For further details, see e.g. Picozzi et al. (2021).

EV analysis is then applied, requiring to extract one single maximum from each run, therefore making only ten extremes available for the analyses. In order to improve reliability, a different approach is followed; three sub-samples having length of 200 s full scale are extracted from each i-th run, bringing 30 extremes, $\hat{c}_{p,i}$ of the pressure coefficient. The use of N=30 extremes is possible after their statistical independence is checked. To this aim, it was checked that the time lag for which the Auto Correlation Function approaches zero is lower than 200 s.

From the sample of 30 maximum (minimum) pressure coefficients, the mean and standard deviation were calculated and used to derive the Gumbel distribution parameters through the Method of Moments. Finally, the 78% fractile was evaluated from the EV distribution, thus providing the requested $c_{p,78}$ coefficient.

2.3. Uncertainty modeling

The way pressures are measured, the randomness of the maximum (minimum) pressure coefficients in the averaging period T_a, and the probabilistic modelling of the measured values all represent sources of uncertainty (Kasperski and Geurts, 2005; Picozzi, 2023). These are not considered in this work, where the assessment of uncertainty is focused to the evaluation of design pressure coefficients and their comparison with the values suggested in EN1991-1-4 (CEN, 2005). According to Eq. (1), uncertainty θ_{c_p} in the pressure coefficients is assessed by adopting a multiplicative error model, i.e. by evaluating the ratios between the values $c_{p,78}$ obtained by analyses on TPU data and the values $c_{pe,10}$ contained in EN 1991-1-4. In detail, we can identify:

- Intra-building uncertainty, quantifying the variability of pressure coefficients within the same zone of a given building. It is evaluated as the coefficient of variation of the pressure coefficients evaluated for that particular zone of the given building.
- Inter-building uncertainty, quantifying the variability of pressure coefficients with varying building geometry. It is evaluated as the coefficient of variation of the pressure coefficient of a given zone with varying building geometry.

The above coefficients of variation are evaluated for each roof zone defined in EN1991-1-4, and they quantify the random uncertainty. On the other hand, when the experimental values of the pressure coefficient associated to each area are normalized with respect to the design pressure coefficients given in EN 1991-1-4, then the bias (i.e., the mean error) introduced by the code is evaluated.

3. RESULTS

Calculated design pressure coefficients for each of the roof zones given in EN 1991-1-4 depend on wind direction within a ±45° angle around the orthogonal to each building face. Consequently, both the intra- and inter-building uncertainty models shall be calibrated with varying wind direction. However, the set of pressure coefficients $c_{pe,10}$ of EN 1991-1-4 are already given as an envelope in the 90° sector, therefore for the purpose of comparison also the design pressure coefficients $c_{p,78}$ shall be enveloped.

In Table 1 the bias and the coefficient of variation of error in assessing pressure coefficients when using $c_{pe,10}$ are summarized for each roof zone, including both intra- and inter-building uncertainty. A bias greater than one is evaluated for all the zones loaded with negative pressure, suggesting that the negative pressure coefficients adopted by EN 1991-1-4 underestimate the load. Limited to positive pressures coefficients in Zone I, a bias equal to 0.45 is observed.

The variability of pressures within the same roof zone appears to be moderate for zones F, G and H, and much larger for Zone I, either when loaded with negative or positive pressures.

Table 1. Statistical models for pressure coefficient for low-rise buildings with flat-roof.

Roof Zone	bias	c.o.v. [%]
F	1.28	17.8
G	1.15	7.4
H	1.63	21.8
I (negative)	2.45	40.7
I (positive)	0.45	35.0

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