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Role of Wind Pressure Data Probabilistic Interpretation in Wind Tunnel Tests on Tall Buildings

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Abstract

Implanting tall buildings, the present and future solution for the development of many big cities in the urban environment, is a design process marked by the effects of alteration of the local wind flow pattern, affecting the sustainable concepts of the investments. Many of these effects have being put in evidence up to now through studies in atmospheric boundary layer tunnels and the research in the buildings aerodynamics' domain is enlarging the directions and refining the methods of modelling and measurements.

A research program was developed during 2007-2008 in the laboratory of Buildings Aerodynamics of the Faculty of Constructions and Building Services and along refining the modelling of atmospheric boundary layer in wind tunnel, local pressure measurements on the walls of rigid models of high buildings were done. In order to validate the results one must use modern methods of calibration of the gathered data.

The paper presents the statistic analysis of aerodynamic pressure coefficients data and the results of this analysis. The conclusions drawn are very important for the future tests in the tunnel and also for the design of high rise buildings in our country.

Keywords

Atmospheric boundary layer tunnel, Laboratory modelling, Wind pressure coefficients, Statistic interpretation of extreme values, Peak factor

1. Introduction

Tall buildings became a frequent solution whenever a speedy urban development is imposing itself and their efficiency is most obvious in the public domain necessities: banks, corporation's headquarters, hotels and also residency. They share in common the centre of very big cities, they tend to become slender and slender, and they influence the local wind speed profile, interfering with other structures, higher or lower than themselves.

Both Romanian codes for design and the national experience in building and wrapping the tall buildings in light envelopes are facing new trials due to the economic expansion and the modern trends for higher and higher level of the constructions in central urban areas. New materials used for structural and non-structural elements exhibit increased strength-to -weight ratios and the major consequence is a surprising diminishing of the weight and massiveness of big buildings, this way increasing the translations and rotations of the structure itself under wind loading. More than that, the behaviour of the envelope of these buildings subjected to an increased local turbulence of wind action combined with dynamic effects may dramatically affect the comfort and safety of the inhabitants during the service life. More accurate safety design criteria needs specific rules and in the preliminary stages of designing important urban complex shapes, the tests on models in the wind tunnel are extremely relevant.

The design of the wall claddings of tall buildings, already takes into account important increasing of the stresses due to wind local instantaneous effects, because of the violent sudden bursts and repeated vibrations that caused many accidents by tearing out the wall panels (Cook, 1989).

The atmospheric boundary layer (ABL) tunnel SECO2 situated in the Laboratory of Aerodynamics of the Faculty of Construction in Iasi is used in the present for tests on rigid models of buildings. A part from a research program developed in 2008 was particularly dedicated for the acquisition of local wind pressures on the walls of buildings with a higher level than the usual urban environment of the cities in Romania. The study was directed towards the analysis of the risk level involved in the design and also in the service life of the structural elements and glass pains of light envelopes, like curtain walls.

A vast part of the scientific work had been directed to this subject, new criteria and design conditions being set up for the so called "second order structure" and also for the glazing panes for which basically, the effect of the turbulence of wind dynamic action is the dominant design action.

In the present, the scientific research is concerned in the calibration of speed and pressure data obtained in ABL tunnels with the measurements at natural scale and in the same time to solve the problem of credibility of the values of peak coefficients of pressure obtained in the tunnel through analysis and filter by using statistic methods.

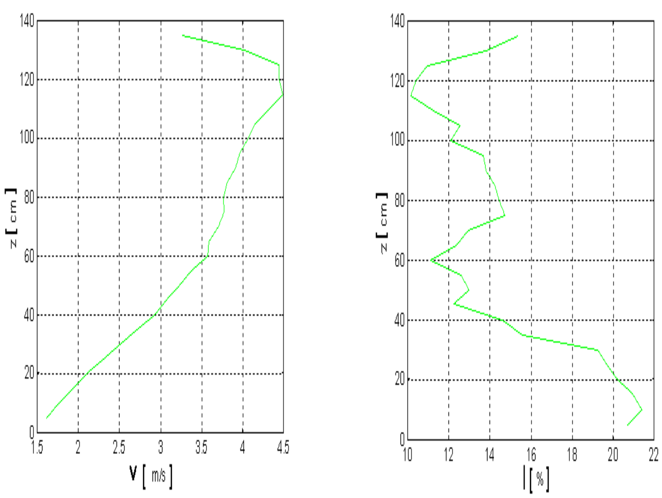
2. Experiments in Atmospheric Boundary Layer Wind Tunnels (A.B.L. Wind Tunnels)

2.1 Conditions and Criteria Imposed for the Experiments in A. B. L. Wind Tunnels

The ABL tunnel from the Laboratory of Aerodynamics of Structures is an open circuit tunnel with a working section of 1.4 m x 1.4 m and a length of aprox. 10 m, the speeds of the flow used for the usual experiments being of 4-6 m/s, the maximum speeds reached being 10-14 m/s. The tunnel is equipped with the complete chain of modern techniques of modelling the atmospheric turbulence and measurements of wind speeds and pressures on different models of buildings.

Modelling the interaction between the building and its environment to a specific scale is a rather complex process, which is developed in several successive stages the first one being the modelling of the boundary layer. The model of the atmospheric boundary layer is specific to the one of big cities where, due to the height of the buildings, the turbulence is increased and the pattern of the wind flow tends to become chaotic, with bursts and rapid fluctuations of the instantaneous values of speeds. The model of the flow must adjust the spatial turbulence scales to the geometric dimensions of the building in order to obtain realistic results. A thorough analysis of the results after processing the data with the help of specific software and special programs elaborated show a convenient modelling scale of 1/200...1/300 considering the numerous modelling criteria applied to the physical characteristics of the SECO 2 tunnel in order to obtain the expected parameters of the turbulent flow around the building.

Figure 1: Laboratory of Aerodynamics of Buildings from the Civil Engineering Faculty in Iaşi:
a) View along the Tunnel in the Experimental Zone
b) Model of a Tall and Slender Building Equipped with Pressure Taps



a **b**

Figure 2: Simulation of the Urban Atmospheric Boundary Layer in the Context of the Experiment:
a) Mean Wind Speed Longitudinal Profile; b) Turbulence Intensity

2.2 The Model of the Tall Building Used for the Measurement of Local Instantaneous Pressures

The proportions of the rigid model of the tall building were chosen in accordance with the studies and experience of the specialists from the team working in the Laboratory of Aerodynamics (Teleman, 2000); a prismatic model with the aspect ratio of 1:1.5:7 would fit to modelling domain of 1/250...1/400 scale, in accordance with a scale that match the dimensions of higher buildings designed in our country. The exposed surface in transversal section of the tunnel being of 1.9% much under 3%, there is no fear for blockage phenomenon. The model is placed in the centre of the experimental area, where the wind speed flow was verified to be symmetric to the axis of the tunnel. The model is equipped with pressure taps and flexible tubes.

2.3 Measurement Techniques and Stages Developed for the Experiment

The method for the measurements of local pressures is using in the present the pressure module ZOC 17, produced by SCANIVALVE-U.S.A. The pressure module is equipped with analogue equipment that samples data simultaneously from 16 taps, the frequency of acquisition being of 1000Hz/sample/tap. The advantages of this system consist especially in the accuracy of the measured signal. A very modern great capacity acquisition board is stocking all these data.

Experimental analogue-numerical data are processed with programs specific for aerodynamics laboratory, LABVIEWS and LABWINDOWS and afterwards transferred to the programs of processing-visualization and statistic interpretation. The processing of data is following the correction of instantaneous signals (pressure/suction).

The number of pressure taps depends on the afferent area fit to obtain local instantaneous pressure values (in the design process a minimum surface is taken, 10 m^2). The pressure taps are placed particularly in the areas localised on the surface of the model where an important increase of the instantaneous local pressures is expected. In placing these taps on the surface of the model, previous experience gathered from numerous studies on buildings with different levels of height was prevailing, in particular the areas subjected to high values of instantaneous negative pressure signals. The building studied herein was placed in built surrounding environment and two wind attack angles were considered, 0^0 , normal to the faced F1 and 90^0 , normal to the face F2, the pressure taps changing the number and the position from the first to the second case studied.

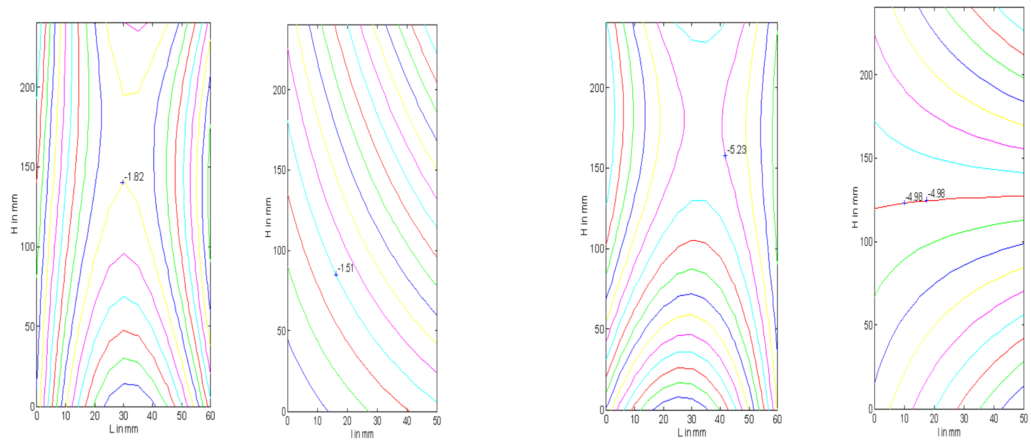
The local instantaneous pressure coefficients were statistically processed in order to obtain mean, r.m.s. and peak positive and negative values. Based on these values of mean and peak values, the peak factor values may be obtained, according to the following relationships: $\hat{g} = \dfrac{\hat{c}_p - \bar{c}_p}{c_p^{'}}$; $\breve{g} = \dfrac{\breve{c}_p - \bar{c}_p}{c_p^{'}}$.

3. Results and Statistic Processing the Data Based on the Local Pressure Measurements

The isopleths drawn on the faces of the model lighten the values of the aerodynamic coefficients studied in particular in areas where the shear layers detach and re-attach to the surface of the building. Increased peak negative values are always expected here, mostly because of the dispersion. Studies published in 1970-1980 showed that in these regions due to the rapid changes of sign and intensity of the signal, the peak factor " g ", although limited as values between 3,5…4,5 in the design recommendations, may currently reach values of 7….8.

The statistic analysis of the peak factor "g "is defying basically the level of accuracy of tests in laboratory, because as a result of finding realistic local values on specific areas of the buildings, they would further on directly be used in the design of the wall panels, steel, aluminium or glass, an extremely important aspect for the curtain walls producers.

An important number of studies were dedicated to the cumulated distribution functions (CDF) of the aerodynamic coefficients of pressure/suction and they all are emphasizing the factors that influence the extension of the scattering values of these coefficients to credible dimensions, which are: the importance of the sampling rate in choosing the extreme value data, the optimum sampling period during the observations in natural scale along with other aspects involved.



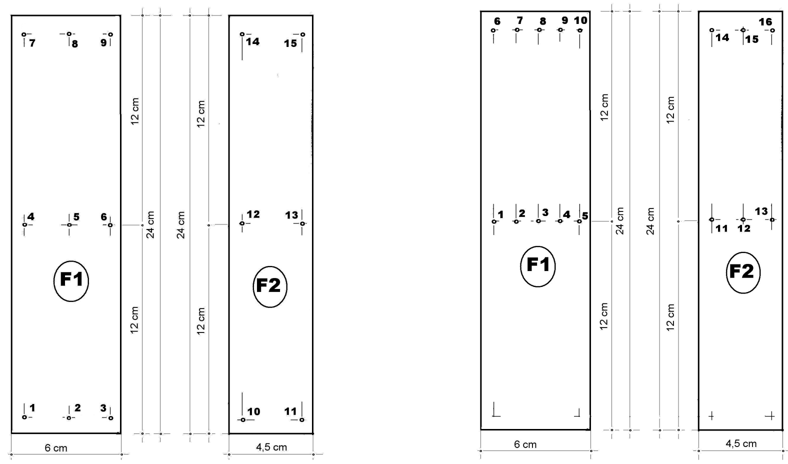
a b

Figure 3: Distribution of the Aerodynamic Suction Coefficients (Mean and Maximum Negative) on the Faces F1 and F2 of the Model (The Direction of Action of the Wind Parallel to the Face F1, F2 Respectively)

The results presented in this paper are based on 2 minutes sampling records/tap, the sampling rate of maxima values being of 5 samples/minute. In choosing this sampling rate the following factors were considered:

- the accuracy of the measurement and transferring of the analogue signal;
- previous studies that put into evidence the characteristics of the flow inside the ABL tunnel SECO2 and according to which the integral longitudinal scale of time of the turbulence is about 0,28 sec, in this period of time being possible to sample the instantaneous values of pressure during relevant vortices of the turbulent flow (Teleman, 2007).

The extreme values analysis of the suctions on the faces F1 and F2 was developed, on the taps placed exactly in the areas of detaching of the flows considering the wind action and the effect of neighbouring of other lower buildings.



(a) (b)

Figure 4: Position of the Taps 1...16 on the Faces F1 and F2 of the Model; a) Wind Acting Normally to the Face F1; b) Wind Acting Normally to the Face F2

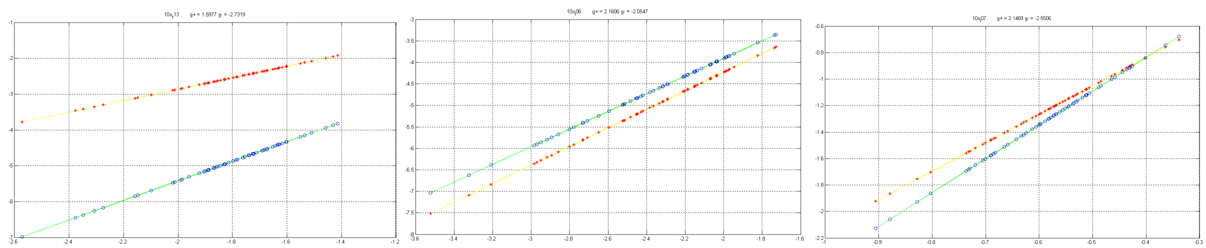


Figure 5: Statistic Values of the Peak Factor “g” from the Taps Placed on the Faces F1 and F2 Placed Parallel to the Wind Action

A huge amount of studies on the distribution functions of maxima values of wind pressure/suction showed that they may be described by Fisher-Tippet I (Gumbel) distributions (Holmes, 2007), (Tieleman *et al*., 2008), considering that the data obtained during the observation period are independent. In the course of the study presented in this paper, there was no particular method of sampling in order to obtain independent values, the scale of time being one of the preoccupations of the researchers in the Aerodynamics Laboratory that will be the object of further investigations. In order to evaluate the cumulative distribution function (CDF) of the extreme values of suction, respectively the calibration of these values, the Gumbel plot was traced, based on the following successive stages:

- The CDF called P is defined, as being the distribution of the extreme negative values of suction on the faces of the model; generally accepted expression of this repartition corresponds to the tails of parental distribution $P_X=1-e^{-g\{x\}}$, where g{x} is supposed to be a monotonic increasing function on x;
- The extreme values $\breve{c}_{p,\min}\{t\}$ are distributed in order by their “rank”, sampled at every 12 seconds/tap; according to this distribution, for the rank “m”=1 corresponds the probability: $P_{\breve{X}}\{m=1\} = 1/(N+1)$ and for the rank “m” in general, corresponds: $P_{\breve{X}}\{m=m\} = m/(N+1)$;
- $P_{\breve{X}}$ is transformed into the reduced variable: $y=-\ln(-\ln P_{\breve{X}})$;

- The Gumbel plot is traced, on the ordinate being the extremes $\breve{X}\{n\}$ and on the abscise the function: $y = -\ln\left[-\ln\left(\frac{m}{N+1}\right)\right]$;
- The intersection of the coordinates $\breve{X}\{n\}, y$ for $y = 0$ corresponds for the mode of the function, U;
- The angle between the regression line and the horizontal will give the value of the standard deviation of the function, 1/a.

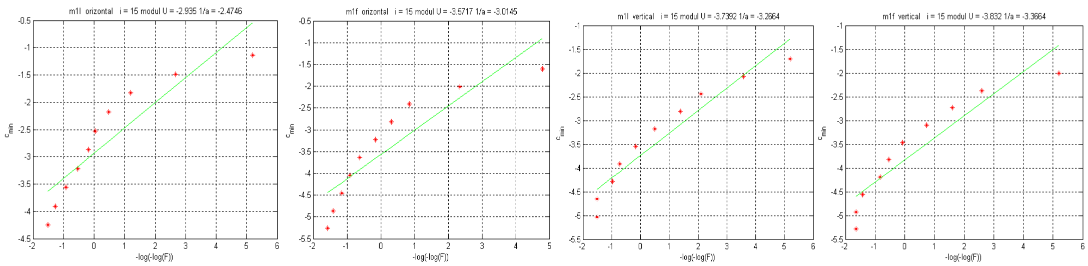


Figure 6: Gumbel Plot for the Maxima Values of Suction Registered on the Taps Placed on Horizontal and Vertical Lines Parallel to the Edges of the Faces F1 and F2

4. Observations and Discussions

The tests on models run in ABL tunnel proved to be very appropriate for studying a number of buildings for which, due to their uncommon dimensions or architectural shape, it is difficult to make a realistic evaluation of the dynamic effects of wind fluctuating action. The thorough the modelling of the environment of the studied building and its geometric proportions, the more reliable data are obtained, although the results are sometimes unpleasant surprises and use to worry both the specialists in aerodynamics and the designers of the building themselves.

High and somehow slender buildings are subjected to accelerated flow patterns on the faces parallel to the wind and in these regions not only that the suctions values increase dramatically but they move all the time on the façade, changing the position of maxima from corners to the middle and vice-versa. Isopleths traced in figure 3 exhibit several aspects:

- The width of the face parallel to wind action and also the ratio between the height and the width are crucial for the distribution of the pressure coefficients; for a wider surface, maxima values (suctions) move toward the centre of the face, in total disagreement with the code for practice for wind action and even the common knowledge also. As numerous studies in our laboratory pointed out this aspect (Teleman, 2000), there is no doubt that there is no mistake in this interpretation. Further studies will satisfy the scientific rigour;
- The pattern of maxima values shows but a poor similarity with those of the mean values; the interpretation depends on the accuracy of modelling the flow in this region, and in this respect a Computer Fluid Dynamics (CFD) simulation would give the possibility to illustrate this difference;
- The values of maxima suction are most important in the case of a statistic interpretation; it may be relevant if the position of these recorded values on the faces of the model are punctually specified, as precious scientific work done in this field had already begun to put it in evidence (Tieleman *et al*.,, 2008); we do already know that the regions of separated flow lines show several specific patterns, but it would be more important to control all the features of the flow in terms of design values of the aerodynamic coefficients.

The diagrams in figure 5 represent the plot of the values of peak factor "g" that links the statistic data of the distribution function of local pressure values (local and scale values): instantaneous, mean and standard deviation values. As a result, two lines regression are drawn, corresponding to the extremes of suction values, and the following conclusions may be drawn:

- The tap 13 placed in the region of separation of the tangent flow, show a clear tendency of asymmetry of the peak values, the minimum extreme values being over the values determined with the help of the standard recommendation (factor "g" is supposed to find limit values up to 3.5 for more than 10-15x10^3 sampling determinations);
- Taps placed in wind as 06 and 07 show quasi-parallel plots of the two lines of regression showing that for these regions only, the factor "g" is universally linking the extreme values of both pressure and suction with the statistic parameters which are the mean and standard deviation values;
- The characteristic of monotony of the "g" function is indirectly put in evidence by the constant value of the slope of the regression line;
- As one may observe the numerous extreme local pressure values exceeding the "common knowledge"; nevertheless, they are obtained through accurate methods of modelling and therefore they should be taken in evidence and only power spectral analyses will be able to clearly identify their importance on the wind load evaluations on the building.

The statistic analysis of negative extreme values of wind pressure through the means of Gumbel plot is run on 2 minutes acquisition data by sampling 10 peaks/tap; a re-sampling process was run afterwards for all the data originating from the taps placed either vertical along the corner of the wall parallel with the wind direction, in the separation region, or horizontal, close to the edge at the top of the model.

One may easily observe that all the plots show a great degree of similarity, regardless of the width of the face parallel to wind action and regardless the specific position of the tap, since this tap is placed in the separation region where the shear layers of the flow act. Specifically on the values of the function "y" we may also observe that the mode, U is placing itself under almost constant values of -3.0…-4.0 and the scale parameter, 1/a is fluctuating from -2.5 to -3.5 and of course that would give a general acknowledge of a mean value of the extremes suction coefficients, according to Gumbel law defined with: $\overline{X} = U + 0.577 \cdot 1/a$, situated between -4.5…-5.5.

Still, the function is underestimating the tail (the most extreme values) of the pattern distribution and is overestimating the values of lower ranks and it seems that a more abrupt regression line would be appropriate; further studies in this respect might give more detailed information.

5. Concluding Remarks

The experiments developed in the ABL tunnel on rigid prismatic models have proved to be a rich source of experience of the specialists involved in this domain. This experience is very important for the future simulations of high, important buildings in the preliminary stages of design but mostly, they may be considered as a bench of data accessed by the producers of building materials and systems, in particular of curtain walls. The Romanian standards and codes for practice impose specific criteria in the design of curtain walling to wind loading; according to the code NP 102-04, the evaluation of wind pressure/suction coefficients must take into account the unfavourable positions on the faces of the building and the recurrence values adopted for the reference pressure must be carefully selected in accordance with the meteorological data recommended by the national and local authorities.

A statistic processing of the maxima values of local minimum negative and maximum positive coefficients of the wind pressure is very important because it gives direct information about the possible situation that would influence the design to wind loading in the case of buildings with unusual dimensions or irregular shapes. In the same time, knowing that it is not a common procedure to model maxima speeds of the wind flow in the tunnel, the most important being to reproduce the wind profile and its turbulence, it would be more important to know from these statistic distributions the values that the peak factor "g" may reach, these values linking the mean with the maxima values.

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