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Experimental Stress Analysis

Response of a building under wind loading

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Abstract: A real building response measuring is used for verification of the response calculations and of the model measuring reliability in a boundary layer wind tunnel. Measuring of the moment coefficients on a model in a wind tunnel and calculation of the model building equivalent loading derived from them is the alternative procedure in the stage of designing of a general shape buildings, Reliability of the procedures applied can be checked on very simple shapes of buildings by comparing the tests in the wind tunnel to the measurement results on a real building. This contribution describes such a procedure.

Keywords: Acceleration, Building, Displacement, Load, Measurement, Response, Wind

1. Introduction

In order to be able to specify the coefficients of pressures, forces and moments for buildings, tunnels with a modelled atmospheric boundary layer (BLWT) are used. The pressure coefficients, the so-called „pseudo-steady coefficients" are defined as a ratio of statistic estimates of maximum pressure values at the point of measurement and of the reference pressure [1]. The forces and moments coefficients concern the force effect of wind on an unyielding model of the whole modelled structure or its part. "Scales" with a high own frequency of forces sensors are used for measuring; they are identified as the „the high frequency base balance". The principal problem of the model measurements reliability is the selection and observance of model laws, especially the Reynolds´s number [2]. According to [3], deviation up to 15 % between the coefficients specified by measurements in the tunnel and on the building is considered to be acceptable. In [4], the authors enumerate a systematic list of the above specified procedures advantages and drawbacks. In [5], the authors demonstrate some future possibilities at evaluation of non-stationary processes at measuring wind effects on civil engineering structures. Paper [6] includes description of an electronically available service that offers data for wind loading specification on the basis of a model measurements and this methodology data basis. The model measurements can serve also for investigation of interference phenomena, caused by turbulences in the wake behind other structures [7, 8].

Measurements of wind effects on real structures are the most important knowledge source. They are used for reliability verification of the above-specified procedures of the loading and response calculations and model measurements in wind tunnels [9, 10]. They are absolutely un-substitutable at a structure response investigation in relation to wind velocity measurement in a system of meteorological stations. Measurements of real structures response are much simpler than direct measurements of their loading by wind. Compared to model measurements in the tunnel, occurrence of wind loading in nature is a random phenomenon from the viewpoint of its magnitude as well as from the viewpoint of its direction in relation to

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the structure orientation. Already the very analysis of frequency of wind loading occurrence of a specific magnitude and direction in a given location is the subject of research – c_f, for example, [11]. Buildings for long-term monitoring of wind effects must have suitable characteristics (dimensions, shape, dynamic characteristics), optimum location and they should be close to a meteorological station. The goal of the measurements realized is, in particular, recording of a building response under extreme meteorological situations, systematic response recording at increased velocities and various directions of wind, investigation of occurrence frequency of certain meteorological situations and connection between the closest meteorological station data and the structure response.

2. The measured building description

An older administration building has been selected for monitoring - the „Shiran Tower“ (former VÚMS) on the northwest outskirts of Prague. The building is 63.8 m high and it has a rectangular cross section, the dimensions of which are 31 m x 14 m. The carrying system consists of three walls and a prefabricated reinforced concrete frame structure with three rows of columns. The two shorter outside walls of the building are 12.4 m long and 0.35 m thick. The third wall is in the longitudinal axis of the building. It is 18 m long and 0.2 m thick. The carrying system drawing is on Fig. 1.

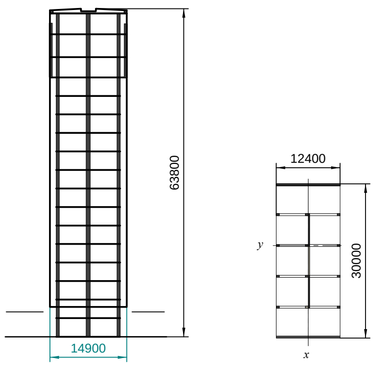


Fig. 1. Drawing of the building carrying system

At dynamic testing of the building after it was put into operation [12], the value of a logarithmic decrement of damping was 0.074 at the lowest own frequency of f_1 = 0.83 Hz. Now, the lowest own frequency of the building is 0.75 Hz, 1.0 Hz (torsional) and 1.312 Hz. The building characteristics and its response to the Kyrill hurricane are described in [13]. The first pieces of knowledge from a long-term monitoring of the building response were described in [14].

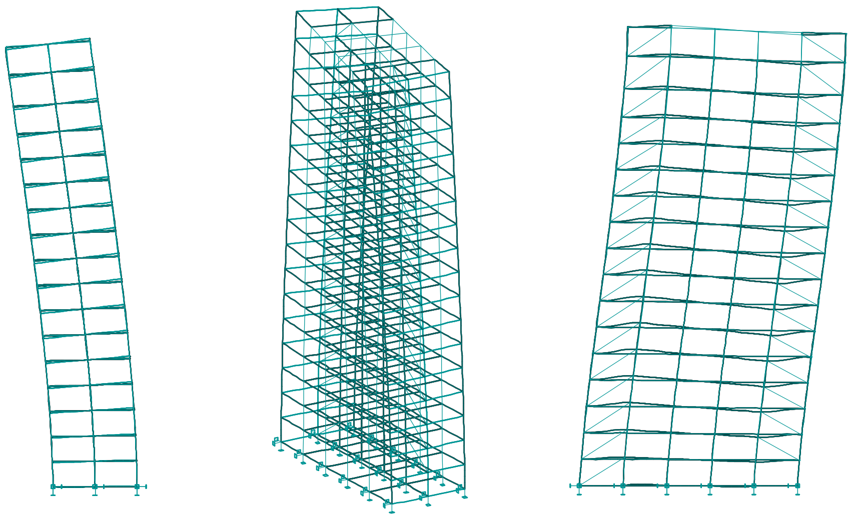
3. Calculation of the building response

We have carried out a simplified static and dynamic calculation for the measuring needs. The building documentation was not available, therefore we had to use the dimensions and information from other sources. However, we could use the published results of the dynamic test [12]. Gradually, we were able to create and verify the building functional model in the NEXIS program. Fig. 2 shows a developed computational model. For the six lowest own frequencies, a good congruence of the calculated and measured own frequencies for the corresponding oscillation shapes was established.

Fig. 2. Computational model

Fig. 3 shows three lowest oscillation shapes. We monitor the structure response on these shapes. The response magnitude was checked by calculation of response for loading by impulse rocket motors at a loading test [12] for the originally measured logarithmic decrement of damping. The congruence of the calculated and measured response was good when we did not take into consideration

The building was loaded by wind according to the valid standard [15]. The response characteristics, specified in a more detailed way in Table 1, were calculated for terrain category III and initial value of the basic wind velocity $v_b = 25$ m.s^{-1}.



Mode 1, $f_1 = 0.777$ Hz Mode 2, $f_2 = 1.073$ Hz Mode 3, $f_3 = 1.325$ Hz

Fig. 3. The lowest natural frequencies and mode shapes of the building

Table 1. Characteristic response values

Charakteristic response values	Calculation according [15]		Kyrill	
			calculation	measurement
Dispacement at the top of building [mm]	Wind load	25	22	
Acceleration at the top of the building for the damping ratio 1.27 % [mm.s^{-2}]	Standard deviation $\sigma_{a,ch}$	35	26	12.7
	Peak value $a_{max,ch}$	122	87	77.9
Corresponding displacement at the top of the building (f_1 = 0.075 Hz) [mm]	Standard deviation $\sigma_{y,ch}$	1.6	1.2	0.6
	Peak value $y_{max,ch}$	5.5	3.9	2.8

4. Measuring of the building response to wind effect

The building response recordings at a strong wind are the monitoring goal. Strong winds occurrence is very rare. At the anemometer installation we were obliged to observe certain conditions that limit the possibilities of the wind velocity measuring to certain wind directions only; they reduce the measurements accuracy. Therefore, the anemometer has, in particular, an auxiliary function in the measuring system; it reduces the recorded data volume. We store recordings when the wind velocity was higher than 10 m.s^{-1}. For recordings allocation to the wind velocity and direction we use data from the meteorological station Prague Ruzyně in the distance of 6 km. From the viewpoint of evaluation of effects on a specific building it is not quite ideal, from the viewpoint of its link-up to the maps of velocity and statistic information on the wind it is a very good solution.

Four sensitive acceleration sensors on the highest floor of the building monitor the dynamic component of the building response. Two relative deformation sensors are installed on the ground floor on one carrying wall and they monitor the total response of the building. The control computer activates periodically 10-minutes-long recordings of the measured variables time courses, it evaluates the records preliminarily and stores the results obtained. Providing the set criteria were fulfilled, it also stores the whole recording for later detailed evaluation. The equipment operation is controlled via internet. Internet connection is also used for downloading of the data measured, for periodical maintenance and for optimization of the whole system functioning.

4.1. Measurement results

4.1.1. Kyrill hurricane

Measuring equipment with one acceleration sensor was installed on the building just before the Kyrill hurricane arrival; within the course of 13 hours, 72 five-minutes-long recordings of oscillation in direction y (direction perpendicular to the wider wall of the cross-section) were stored in the control computer memory. Comparison to the wind velocity measuring in the Prague Ruzyně meteorological station has shown that recording of maximum wind effects on the building was achieved successfully. The maximum value of mean velocity 23.3 m.s^{-1} and the maximum wind impact 34.5 m.s^{-1} were measured in the Prague Ruzyně station. More information on wind velocity of the Kyrill hurricane can be found in [14], including comparison to statistical estimates [16]. Calculated acceleration values for relative damping of 1.27 %, corresponding amplitudes of dynamic deflections at own frequency f_1 = 0.075 Hz and maximum measured values of these quantities are specified in Table 1 for the measured mean velocity.

4.1.2. Response monitoring

Since the year 2007 we have been collecting recordings of a building dynamic response at higher wind velocities. The response recordings have two random parameters – the wind velocity and direction. The wind velocity is converted to dynamic wind pressure, which we consider to be independent. The building response depends then on the wind direction and, for the needs of comparison of the measured values to the measurement results on a building model in the wind tunnel by measurement, we are looking for a maximum values envelope. Should we limit ourselves to wind directions in the direction of 225°- 315°, it is possible to specify gradually in a more detailed way the dependence of the response fluctuation component efficient value on the mean value of the wind pressure on the top of the building – see Fig. 4.

Frequency analysis of the recordings stored is performed then. It is possible to ascertain easily own frequencies from the acceleration auto-spectra and to monitor changes of the auto-spectra individual frequency components in dependence on time within the recording course as well as on the wind pressure and direction.

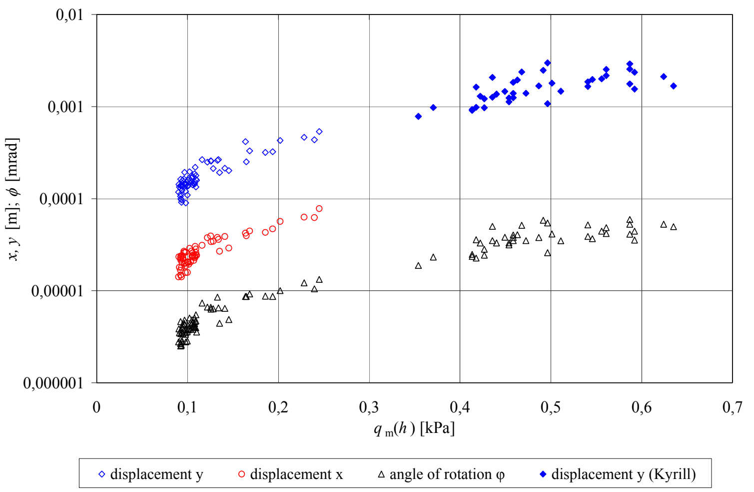


Fig. 4. Dependence of efficient value of the response fluctuation value on the mean value of the wind pressure on the top of the building

Recordings of a wall relative deformation are influenced significantly by changing temperatures on the inner and outer surfaces of the wall. Providing that such temperatures would be constant for the time of recording, it is possible to determine dependence between wind pressure and the quasi-static response component. Therefore, it is possible to estimate quite accurately the absolute value of the maximum relative deformation in the direction of axis y (direction perpendicular to the longer wall of the building). The estimate is loaded by error, resulting from wind direction changes within the recording course. Calibration of the relative deformation sensor data is performed using the known value of the deflection fluctuation component in the lowest own shape, obtained by integration of the acceleration records. Therefore, it is possible to determine maximum value of the top deflection and, from the numerical model, the equivalent moment to the footing bottom, or the moment coefficient $C_{M,x,rms}$. The measured values of the moment coefficient are shown on Fig. 5.

5. Measuring of the building response to wind effects

An unyielding model of the building has been constructed and, using elastic bearing, the lowest own frequencies of the building have been modeled. Fig. 6 shows an example of dependence of the $C_{M,x,rms}$ moment fluctuation component coefficient on the incidence angle β. Definition of the moment coefficient is specified in this Figure. Symbol $C_{M,x}$ means the efficient value of the moment around axis *x*. The frame shows the relation for the moment coefficient calculation, where M_x is the mean value of the moment around axis *x*, *H* is the model height, *B* and *D* are the lengths of the model cross section sides, U_H is the mean velocity on the model top and ρ is the specific weight of air.

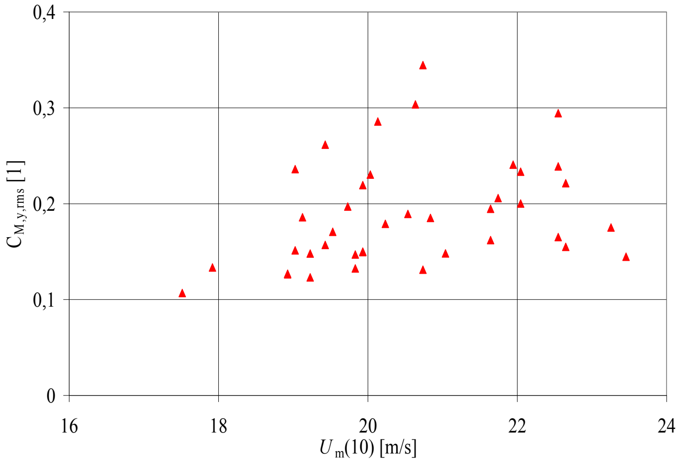


Fig. 5. Measured values of the moment coefficient on the building $C_{M,x,rms}$

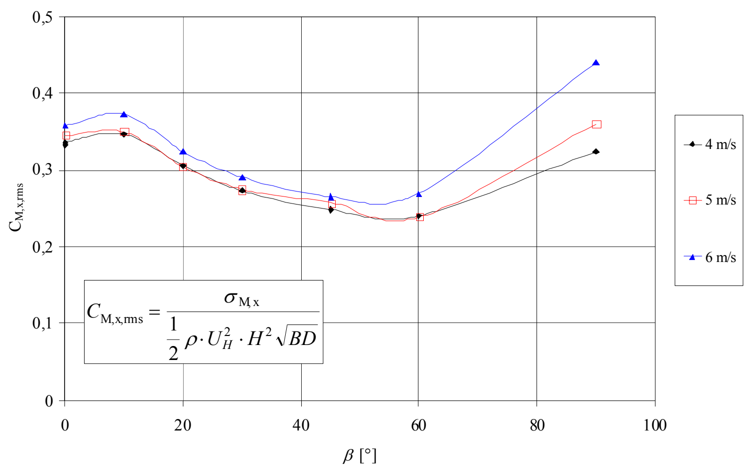


Fig. 6. Measured values of the moment coefficient on the building

6. Conclusions

A measuring system has been installed on a building with known characteristics; it allows monitoring of wind effects on the building. Results of the measuring performed show good congruence with the calculation results according to the Eurocode [15]. Within the results obtained, we have compared results from measuring the response fluctuation component on the building and on its model in the wind tunnel. Maximum values of the $C_{M,x}$ moment coefficient, measured on the building, are close to the maximum values of this coefficient in the wind tunnel with a modeled boundary layer. Therefore, it is possible to arrive to the conclusion that measuring in this tunnel is suitable for prediction of a real building or another shape response magnitude, while fulfilling the generally accepted principles for angular bodies modeling.

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References

[1] Cook, N. J., The designer's guide to wind loading of building structures, Part 2, BRE, London, Butterworths, 1990.

[2] Larose G.L., D'Auteuil A., On the Reynolds number sensitivity of the aerodynamics of bluff bodies with sharp edges, J. Wind Eng. and Ind. Aerodyn., Vol. 94 (2006) p.365–376.

[3] Dalgliesh W.A., Surry D., BLWT, CFD and HAM modelling vs. the real world: Bridging the gaps with full-scale measurements. J. Wind Eng. and Ind. Aerodyn., Vol. 91 (2003) 1651–1669.

[4] Lin, N., Letchford, Ch., Tamura, Y., Liang, B., Nakamura, O.: Characteristics of wind forces acting on tall buildings. J. Wind Eng. and Ind. Aerodyn., Vol. 93 (2005), p.217–242.

[5] Kareem, A., Kijewski, T., Time-frequency analysis of wind effects on Structures, J. Wind Eng. and Ind. Aerodyn., Vol.90 (2002), p.1435–1452.

[6] Kwon, D., Kijewski-Correa, T., Kareem, A., e-Analysis of High-Rise Buildings Subjected to Wind Loads, 50 p.

[7] Tang, U.F., Kwok, K.C.S., Interference excitation mechanisms on a 3DOF aeroelastic CAARC building model, J. Wind Eng. and Ind. Aerodyn., Vol. 92 (2004), p.1299–1314.

[8] Richards, P. J., Hoxey R. P., Quasi-steady theory and point pressures on a cubic building, J. Wind Eng. and Ind. Aerodyn., Vol. 92 (2004), p. 1173–1190.

[9] Kijewski-Correa, T., Kilpatrick, J., Kareem A., Kwon, D., Bashor R., Kochly, M., Young, B. S., Abdelrazaq, A., Galsworthy, J., Isyumov, N., Morrish, D., Sinn, R. C., F., Baker, W. F., Validating Wind-Induced Response of Tall Buildings: Synopsis of the Chicago Full-Scale Monitoring Program, Journal of Structural Engineering ASCE, October 2006, p.1509-1523.

[10] Lia, Q.S., Xiao,Y.Q., Fu, J.Y., Li, Z.N.: Full-scale measurements of wind effects on the Jin Mao building, J. Wind Eng. and Ind. Aerodyn., Vol. 95 (2007), p. 445–466.

[11] Marek, P., Pirner, M., Vlk, M., Fatigue life of tubular posts exposed to the wind, Proceedings of the 2nd EECWE, Praha, 1998.

[12] Pirner, M.: Dynamické charakteristiky vysokých budov při velmi malých buzeních. Stavebnícky časopis SAV, XXI 2; Bratislava, 1973.

[13] Král, J., Dynamic response of a high building in strong wind, IM 2007, Svratka, 12 p.

[14]] Král, J.: Ten-minute wind speeds and gusts in the Czech Republic, In: J. Wind Eng. and Ind. Aerodyn., Vol. 95, Issues 9-11, 2007, p. 1216-1228, ISSN 0167-6105.

[15] ČSN EN 1991-1-4:(2007) Zatížení konstrukcí - Část 1-4: Obecná zatížení - Zatížení větrem, ČNI, Praha.

[16] Král, J., Dynamic Response of a Building in Strong Winds, In: Environmental Effects on Buildings, Structures, Materials and People, Ed. by A. Flaga and T. Lipecki, p. 327