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Problematic in formulation of wind loads on buildings

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Abstract. This paper describes problematic in precise modelling of wind loads on buildings. Recent tall-building projects and plans in Finland, including wind-exposed buildings of order 100 m in height, have arose interest in usage of expert advice and boundary-layer wind-tunnel technologies. Such technologies have been developed since the 1960’s for the needs of skyscrapers. With wind-tunnel testing and their improved measurement instrumentation, results tend to go in more detail in the actual physical phenomenon. This progress is basically related to increased precisions and usable frequency band of the wind-tunnel instrumentation and wind anemometers; as well as practical issues including automated manufacturing of scale models from 3D CAD models and computational capabilities to process big amounts of data. With improved techniques, smaller and smaller eddies of turbulence and rapid pressure fluctuations can be measured. Wind-tunnel findings have doubted some older believes of proper assessment of structural wind actions. In this paper, this problematic is dealt by using actual wind-tunnel-test projects as examples.

Keywords: wind, wind load, buildings, wind tunnel, wind-tunnel testing, boundary layer wind tunnels, vibration

Introduction

Structural engineers have a well established tradition of using design standards for wind actions on structures. These standards contain aerodynamic parameters of usual-shape buildings, which have been gathered in number of wind-tunnel testing projects and wind measurements done in the past. These standards tend to become more and more comprehensive to cover more design situations. Nevertheless, tall buildings have been problematic for standardizations due to various reasons, including importance of dynamic behaviour due to low fundamental natural frequencies; size reduction effects; complex architecturally driven shapes; and effect of nearby other buildings and city outskirts on wind turbulence and wind loads. Wind-tunnel testing contributing the standards before roughly the 1960’s has been conducted in aeronautical wind tunnels, mainly in non-turbulent flows. While boundary-layer wind tunnels became in use, the implications of wind turbulence have been understood better. This tunnel type contains a long floor to generate turbulence to cope with wind velocity height profiles as well as proper turbulence characteristics, which are aimed to be similar with the wind turbulence at the building site.

Wind-tunnel testing has revealed that it is not only the tall buildings which need special attentions and expert advice. Any low-rise structure near a wind exposed tall building may be possessed to increased and highly localized peak wind loads. Here, some design standards define a building as ‘wind exposed’ if being twice the height of the average roof level of the site.

Despite the recent increase of computing power and the progress in the development of computational fluid dynamics (CFD) software, wind tunnel-testing has among wind engineers retained its position as the only trusted method of extracting wind actions of non-existing tall buildings in the city terrain. Basic problem in application of CFD is the huge amount of detail and the model size needed to model the building, terrain and the local turbulence with various size eddies that contribute the vibration response of the building. CFD may, however, have useful applications like optimizing shape of the building and visualizing the general fluid properties; and it is under continuous research and development that evidently widens its application possibilities in the future.

In course of time, tall buildings have been designed with stiffening systems, which minimize the material consumption and costs, as well as maximizing the usable floor area. This has result in modern tall buildings to be vulnerable to wind-induced vibration. To characterise this chance, two recognized skyscrapers in the City of New York, the US, are referred. Situated close to each other and having a height of order 400 m, the Empire-State Building (completed 1931) and the former World Trade Centre Twin Towers (completed 1970) had peak wind-induced displacement of order 0.04 m and 0.9 m, respectively (actual numbers vary depending on the source). The displacement response, known as swaying or drift of the tower, does not harm occupants if the acceleration related to swaying is small enough. Therefore, like in the former World Trade Centre Twin Towers, dampers are used to reduce wind-induced accelerations. In shorter buildings, of around 30 stories, there is a substantial difference in stiffening options as well. Fundamental natural frequencies of such towers lie typically in the range f_i = 0.3…0.5 Hz, meaning that a more slender tower sways with an amplitude about 4 times the amplitude of another one. Here, the vibration amplitude (A) is roughly proportional to the reduced wind velocity in power of three, i.e.

$$A \propto \left(\frac{V}{f_i d} \right)^k ;(k = 2.8...3.0)\,, \tag{1}$$

where V = wind speed; f_i = natural frequency and d = characteristic geometric dimension of the building. Note that without aerodynamic admittance (size correction) effects, turbulence frequency-content characteristics, etc. special issues, k = 2.0. The mass of the building affects dynamic stiffness, but in many cases the mass of the lateral stiffening system is small compared to the mass of the floor slabs and other structures retaining Eq. (1) to be valid. By using dampers, acceleration responses of skyscrapers have been reported to be halved. These have, however, their own drawbacks.

Improvements in wind-tunnel testing techniques and a number of case studies conducted have not only given a comprehensive database of typical behaviour of buildings, but have also raised new issues to be solved by the wind engineers. This problematic is pursued further in this paper using actual wind-tunnel test projects as examples.

Wind tunnel vs. analytical procedures

For a successful design of modern tall buildings, new type of wind tunnels, named boundary-layer wind tunnels have been built and started to be used in wind engineering since the 1960’s. This tunnel type contains a long floor to generate a boundary layer (Fig. 1). In the boundary layer friction with ground retards the flow velocity and the flow is turbulent. The depth of the boundary layer increases with distance causing the need of the long floor (see Fig. 1), and implying that the scale model of the actual test object is relatively small. Furthermore, the standard boundary-layer technology includes the so called proximity model, where the surrounding buildings and topography is precisely modelled. The needed coverage of the proximity model is usually of order 10 times the height of the building, which also constraints the geometric scale of the scale model. In leading tunnels worldwide, the typical geometric scale used for tall building testing is 1:300…1:500.

Bases of the boundary-layer testing technique and its challenges have not substantially changed in a half-decade. A comprehensively catalogue of the technique and discussion can be found e.g. in [1]. Instrumentation and computing capabilities used in testing have experienced a notable progress. This progress is basically related to an increased precision and usable frequency band available for the wind-tunnel instrumentation and to atmospheric wind anemometers. With improved techniques, smaller and smaller eddies of turbulence and rapid pressure fluctuations can be measured.

In the wind-tunnel testing procedure, multiple different testing techniques and testing types are usually needed. These have been formed as a standard in tall building projects, and include:

- pedestrian level environmental wind study (wind mapping) for wind comfort and risk issues
- cladding pressure study with miniature pressure transducers named as pressure taps
- dynamic base shear and moment extraction with HFFB (High Frequency Force Balance) technique
- vibration service-limit-state studies and equivalent static wind load analysis based on HFFB results
- in the case of vibration-problematic buildings, an aeroelastic testing.

A wind-tunnel procedure takes typically some months to be completed. Thus, initial assessment of structures is thereof based on analytical methods. A wind-tunnel procedure can be used with or without site specific meteorological wind statistics. If site specific wind statistics are used for extreme events, one has to deal with the reliability of data in the prediction of wind speed extremes. Meteorological institutes are aware of mean wind velocities and have computational routines to predict mean wind profiles in changing topography roughness. The models for gust wind speeds, that forms the codification bases of wind loads on structures, are not well established nor routinely used. The boundary-layer wind-tunnel testing technique basically overcomes this issue, as it will be the turbulence generated by obstacles and topography closest to building that determines the peak wind velocities. These are in turn precisely modelled with the proximity model. Several authorities internationally allow the usage of local wind statistics in structural design when, and only when, the wind-tunnel testing procedure is used. Basic wind velocities have a strong influence on the vibration response, as illustrated by Eq. (1). Therefore, at least the environmental and vibration service-limit-state studies are usually conducted by means of local wind records for reliable results.

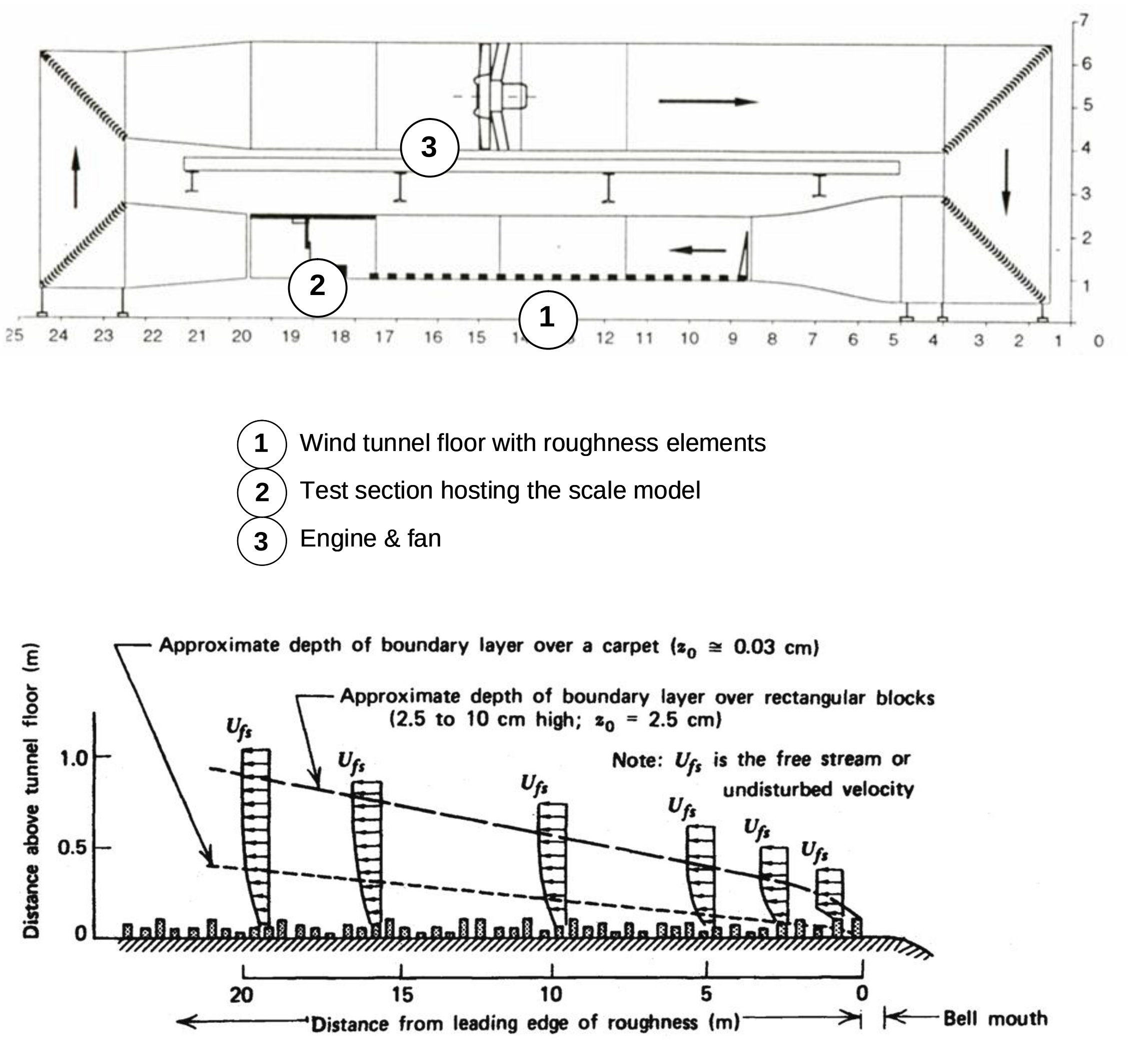

Fig. 1. Principle of a boundary layer wind tunnel: schematic on the wind engineering tunnel owned by the Helsinki University of Technology, and sketch [4] of the development of wind profiles over the wind tunnel floor.

Due to modern wind-tunnel testing, issues are invoked like how rapid fluctuations and peaks need to be incorporated into the structural analysis. Another issue is how the wake buffeting due to other existing or future new tall buildings should be taken into account. In certain cases, this appears to double or treble the nominal acceleration response of the building. The acceleration will in-turn increase the equivalent static wind load. Loosely speaking, in the past, the consensus of wind load criteria has been better than today.

As the pressure load P for the surface of the body is defined as

$$P = qC_p \; ; \qquad q = \frac{1}{2}\rho V^2 \; , \tag{2}$$

where q = wind velocity pressure; C_p = pressure coefficient; and ρ = density of air, one finds that peak actions could be addressed in three ways: modifying the peak wind velocity (gust) definition, modifying pressure coefficient (as function of loaded area size) or doing the both. New wind design standards including EN 1-1-4:2005 [1] and BS 6399-2:1997 [2] contain updated models for peak effects, which are strongly dependent on the size of loaded area. The aforementioned standard uses pressure coefficients as proportional to the size of the loaded area; and the latter mentioned standard a constant pressure coefficient with alteration of the gust definition time t^* as

$$t^* = 4.5\frac{a}{V_0} \; , \tag{3}$$

where a = diagonal length of the loaded area and V_0 = mean wind velocity. This relation is approximate and empirical.

Regardless of the approach, the wind gust definition time should always be consistent with the definition of the pressure coefficients. For example, EN 1-1-4:2005 [2] gust wind velocity is implicitly defined by the peak factor of 3.5. This can be given in the form

$$V = (1 + 3.5 I_u) V_0 \; . \tag{4}$$

where I_u = longitudinal component of turbulence intensity. Eq. (4) appears to be consistent with empirical models of [4] and yields about 1 s gust definition. The former Finnish practise has been to use a constant ‘gust factor’ 1.5 (peak value divided by mean value) for 3 s gust definition, which appears to be an over-simplification in many practical cases. In wind-tunnel studies, peaks are assessed via the fundamental time scaling

$$\left(\frac{Vt}{d}\right)_M = \left(\frac{Vt}{d}\right)_P \; , \tag{5}$$

where the subscripts M and P refer to the wind-tunnel model and the prototype (real structure), respectively. Considering e.g. the geometric scale d_M / d_P = 1:400 and a storm onset, 1 s. peak in full scale means about 0.005 s peak (= 200 Hz frequency band) in wind-tunnel tests. As electrical and acoustic noise issues generally get more problematic with the increased measurement frequency band, the quality of instrumentation used in the testing is an important issue in progress of understanding the peak effects. Here, typical noise issue includes inducted voltages due to alternating electromagnetic fields due to mains power lines and electronic devices nearby; including the wind tunnel engine. Due to the origin of this type of noise, it may disturb the measurements in frequencies around of order 50 Hz. True peaks of the measured quantity itself are slightly random, meaning that they could be defined in a probabilistic sense or conducting the test over sufficient long time to capture the maxima.

High-rise case study: SR-Bank Headquarters 'Føniks', Stavanger

SR-Bank's new headquarters office building will be situated in Stavanger, Norway. The building, 100 m in height, is wind-exposed as situated in the open flat terrain and being notably taller than any other building in the area. Wind environment in Stavanger, in terms of basic design wind velocity and number of breezy days, is one of the harshest in Europe.

The author conducted the wind-tunnel tests in 2008. The test setup has for the first time in Finland followed the testing specifications routinely used by international tall building specialists. A general view of the setup is shown in Fig. 2. The geometric scale used has been 1:400.

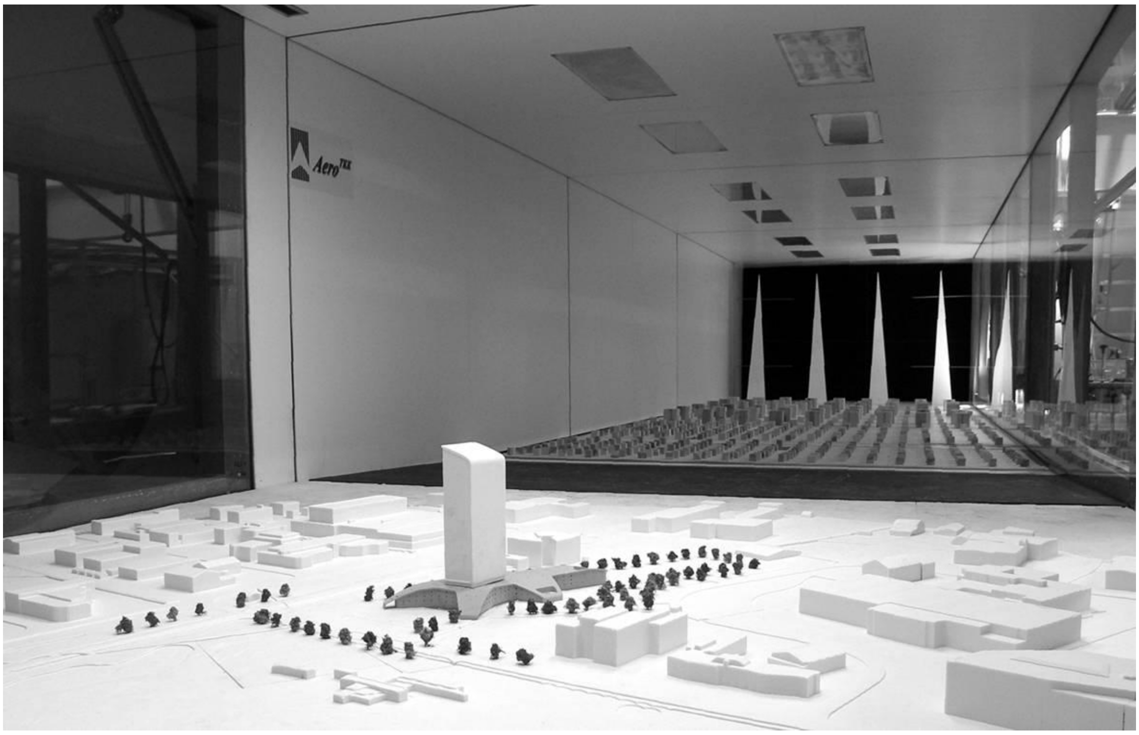

Fig 2. Overview of the test setup in testing of the SR-Bank Building.

An environmental wind study revealed that the tower boosts wind velocities at ground level (as typical to wind-exposed tall buildings). Short duration gusts (1 s) in storms could be dangerous at certain points, which lie in corner streams of the tower. Corner stream generally refers to flow that rounds the corner of a tall building and can cause high local pressures in its vicinity. The podium shape of the SR-Bank Building is favourable as it guides streams onto the podium roof instead directly onto the courtyard. To improve wind comfort, the green plan (trees and hedges) are important and were taken into account in testing. Due to harsh winds and possibly low temperatures in Stavanger, it has been questionable to check any general-purpose windiness criteria. These criteria are dealt e.g. in [5]. Nevertheless, summer months could be separated when atmospheric temperatures are modest, and people may expect to use balconies and courtyards. The analysis gives the average duration of time when such activities are inconvenient due to windiness.

HFFB testing shows that in basic configuration, i.e. without other tall buildings in the area, both EN 1991-1-4:2005 and wind-tunnel tests give along-wind response reasonably close to each other. In HFFB testing, time histories of resultant forces and moments are measured at the basement of the tower using a miniature 6-component balance. The test object is made of light-weight material to keep the fundamental natural frequency of the tower-balance system high, to allow reliable extraction of small fluctuations of forces and moments at frequencies below it. Using the results with random vibration theory and normal-mode-summation of structural dynamics, it is further possible to assess acceleration response of the tower. This type of analysis revealed that acceleration response of the building is actually bigger in across-wind direction than in along-wind direction. This is due to normal wind buffeting and is typical to tall buildings [1]. It should be remarked that the analytical model of EN 1991-1-4:2005 [2] is only applicable for the along-wind response, and that it is the acceleration response that fixes the lateral stiffening system of most tall buildings. Generally, allowable accelerations are of order 0.15…0.3 m/s^2 in frequent storms (1…5 y return period storms).

The HFFB-based analysis shows that if a new tall building will be built near (in distance about 200 m), the acceleration response could be doubled in the wind direction where the new building is at the upstream side. This is due to wake buffeting. The result reproduces author’s findings with aeroleastic testing technique in another alike project [6].

Pressure tap testing has been conducted with miniature pressure taps (1.4 mm in diameter). In this technique, taps (i.e. pressure transducers) are generally mounted either directly on the surface of the tests object, or the surface pressures are transmitted via pneumatic tubing onto the tap. The aforementioned method, known as flush mounting, has been used in the preset study as being more reliable in the sense that tubing will not cause erroneous attenuation at high frequencies. The used taps are gage-based transducers that measure both static and time-dependent pressures. Setup has been used to measure the differential (net) pressure of a nominally sealed building, i.e. a building where façade openings are non-significant and are about uniformly distributed over the building. Net pressure means here that the pressure difference between the outside and inside of the building is measured, i.e., the value is extracted that matters in structural design of the cladding in analogue to structural design standards. Measurement points are spread over the podium, tower facades and the roof (Fig. 3).

Typical results are illustrated in Fig. 4. These results (point 220, see Fig. 3) are chosen to make remarks as follows:

- in peak suction (in this case mainly in wind direction 0^{o} standing for North wind) the effect of peak definition time is drastic
- the point illustrated is located at a relatively low altitude. In the present case, a high suction value at this particular point is related to the funnelling effect of the podium and the tower enforcing the stream to go round the building at that point. Generally, a doubled wind velocity means a quadruple pressure
- for many wind directions, both a positive and a negative peak is present. If the results are expressed in terms of pressure coefficient, the pressure coefficient has a negative and a positive value.

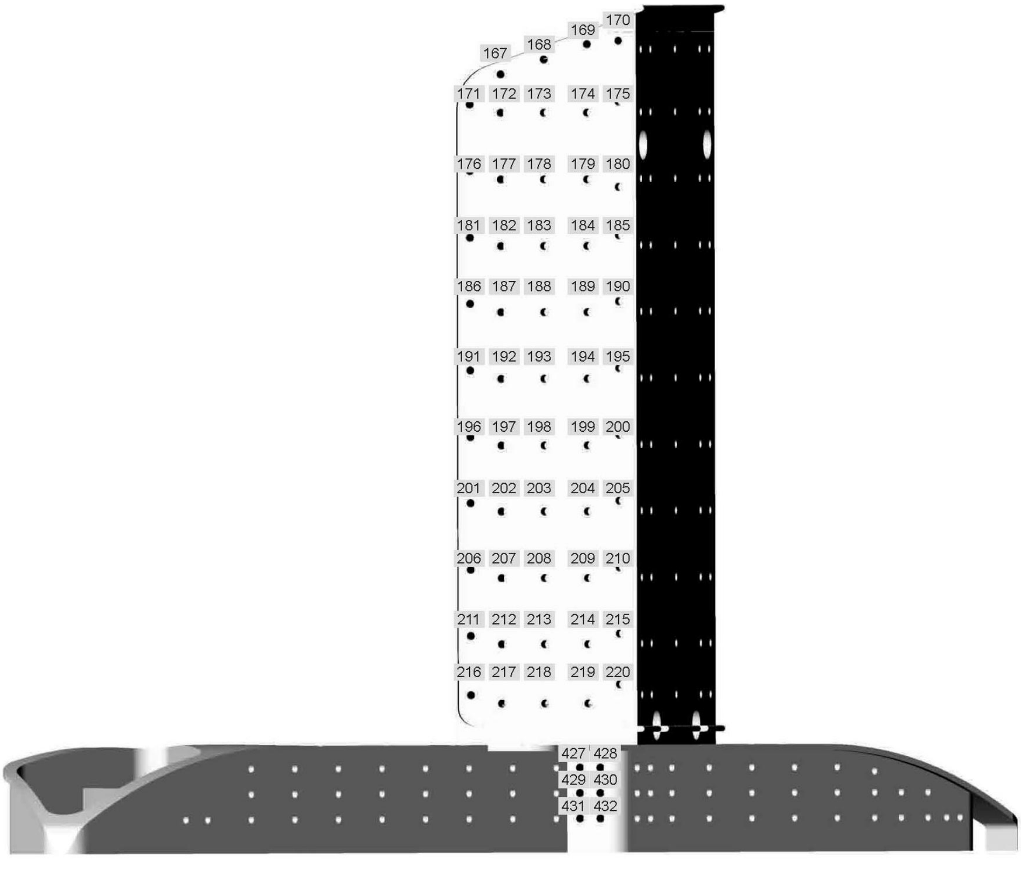

Fig 3. Illustration of pressure-tap coverage in cladding pressure tests.

To characterise the general need of efficient data handling and computer processing, it can be remarked that in this project pressure tap testing alone have produced 20 GB of numerical data.

Structural engineers have a tradition of understanding the cladding pressure and wind load to be single-valued. An improved approach would distinguish between at least three peak definitions: 1 s for design of small elements, 3 s for design of bigger elements and 10…20 s for comparing HFFB-based overall wind load. The peak definition time should always be indicated for glass manufacturers to design a proper cladding. The risk level for glass fracture is a complex issue where the glass panels tend to bear more load when the load is applied at a short duration [1, 4]. Furthermore, fatigue and integrity-loss issues may exist in sealing and supports of panels.

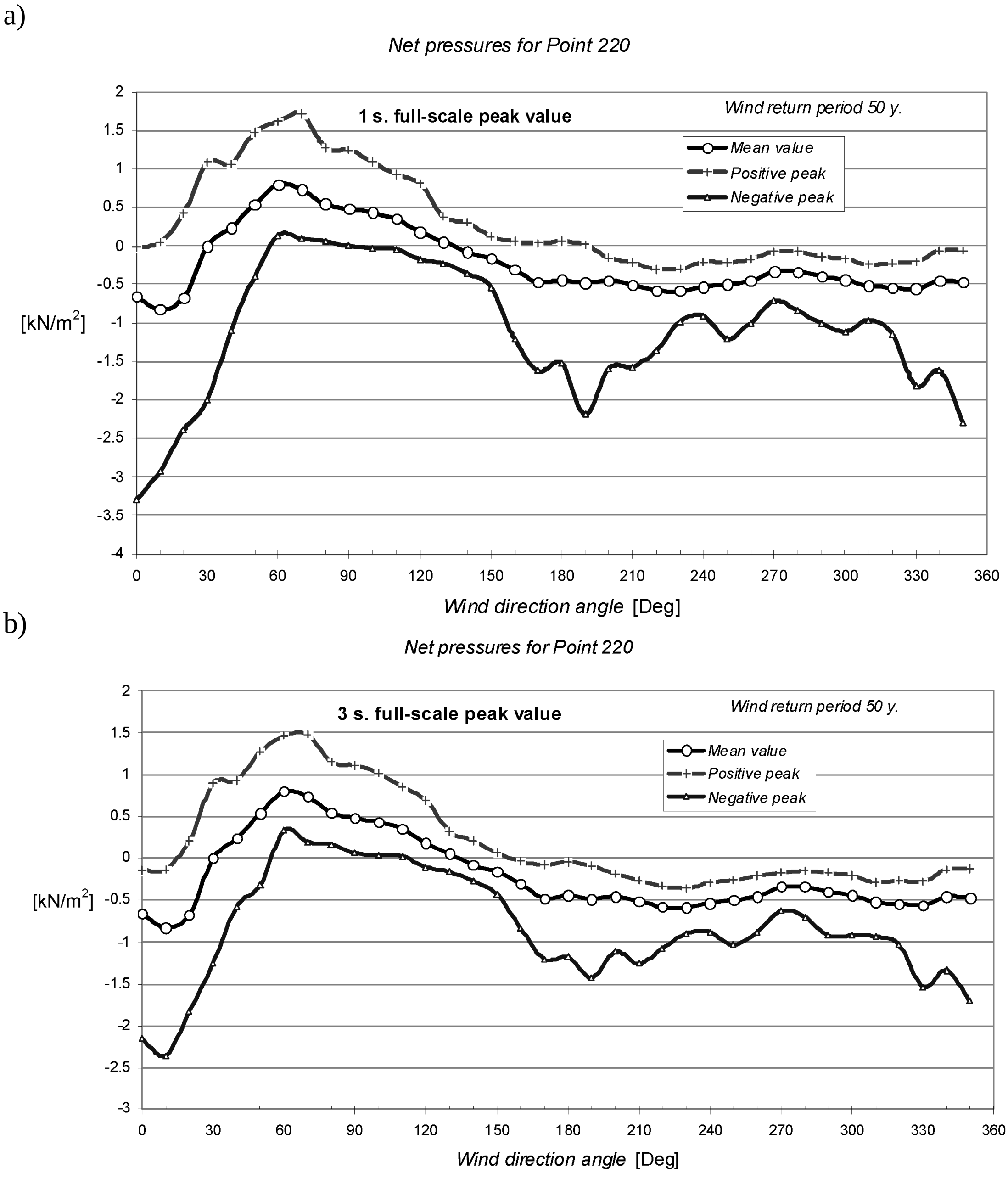

Fig. 4. Typical pressure-tap test results at a high-suction location: a) 1 s peak definition and b) 3 s peak definition.

Low-rise structure case study: Paddington Railway Station, London

Paddington Railway Station in London is an example of a low-rise structure in a city terrain. The author conducted wind-tunnel testing in 2007 for assessing the wind loading for the roof structure refurbishment study. The station is a Grade 1 listed structure, meaning that any changes to the structures and appearance should be minimized. Furthermore, as the station is fully operational during the refurbishment, the structural safety is especially important. The length of the studied roof section, known as Span 4, is 213 m. It is supported by metallic arches having a span length of 33 m.

Wind-tunnel testing has been conducted by pressure tap technique using the geometric scale 1:300. To account for possible wind relieving effects, the proximity model of the vicinity of the station has been faithfully reproduced (Fig. 5). The roof is surrounded by the buildings. Beside the station, Paddington Waterside redevelopment project is ongoing, meaning that several new buildings are being built near the station. Therefore, the test program included the present configuration and the study of the effect of the planned new tall building nearest to the station. Some possible refurbishment schemes have also been studied, as there will be extra openings in the roof during the works.

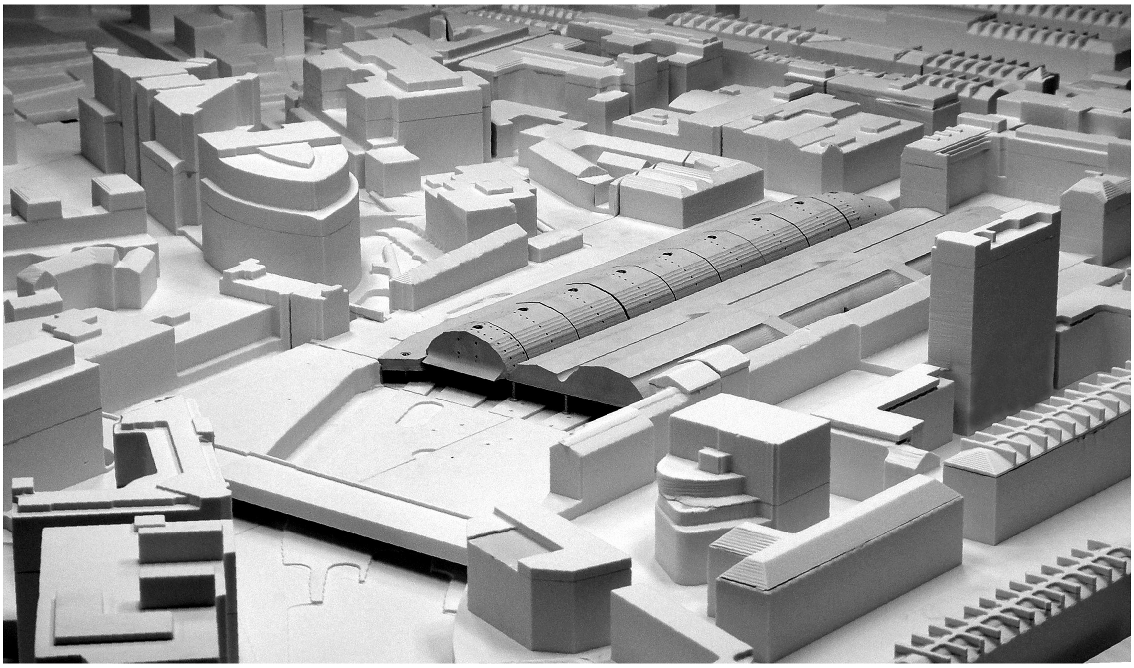

Fig. 5. Pressure tap tests of the Paddington Railway Station Span 4 Roof.

Pressure taps have been flush mounted onto the surface of the roof. They are of differential type to take into account internal and external pressures. Typical to low-rise structures, the differential pressures to be measured are relative small. To maximize the signal-to-noise ratio, the tests have been conducted near the maximum flow speed available for the tunnel, around 30 m/s, and the electrical noise has been carefully filtered out.

As the study is related to structural loading, the design standard for the project BS 6399-2:1997 [3] has been used as a reference. Especially, basic gust wind velocities have been taken from the standard as a function of the wind direction. In this kind of approach, the test can reveal funnelling effects, relieving effects, pressure coefficients and special flow effects due to nearby wind-exposed tall objects.

The test results turned out that the tall buildings near the station accelerate flows on the roof level, and this reflects as an increased wind loading of the roof. The test has been conducted with a fine wind direction interval (10^o), and it has been possible to identify the effects of individual tall buildings to loading. For example, the old tall building, shown at the right side in Fig. 5, increases the peak net pressures by some 50%. This is, aside with the effect of the peak definition time, illustrated in Fig. 6.

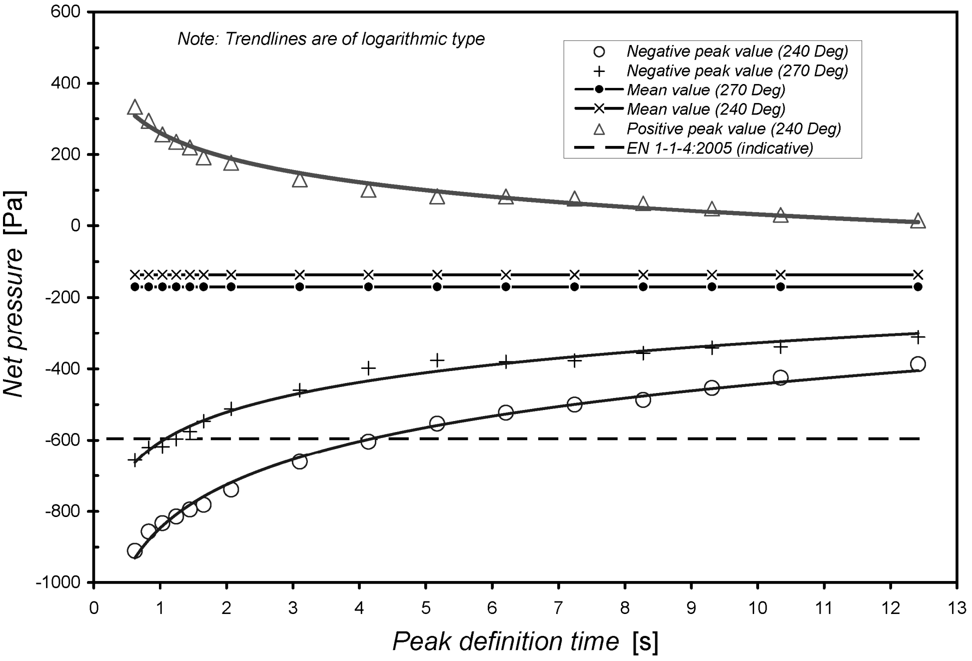

Fig. 6. Effect of the peak definition time and wind-exposed tall building's corner stream to net roof wind pressure. Wind directions 240^o and 270^o stand for with and without the corner stream.

Fig. 6 highlights the strong dependence of the peak pressure load on the peak definition time. This is an envisaged character, as flows will be highly turbulent near the ground, and the mean wind velocity will be small. For example, the turbulence intensities I_u measured at the position of the Span 4 roof (without the model of the roof itself), are 55% and 29% for wind directions 240^o and 270^o, respectively. Eqs (2) and

(4) imply that close to ground the peak velocity pressure could be as high as 9 times the mean velocity pressure.

A comparative study with EN 1-1-4:2005 [2] and BS 6399-2:1997 [3] suggested that in this project the wind-tunnel testing does not yield a substantial ‘wind load reduction’ due to the aforementioned tall building effects. Such a comparison is of course indicative only, as the standards do not have pressure coefficients tabulated for the roof shape and as various assumptions could be adopted for the effective altitude of the structures. In Fig. 6, the EN 1-1-4:2005 based result stands for roughly assuming a net pressure coefficient of 1.2.

Conclusions

- This paper deals with modern wind-tunnel-testing procedures and two case studies. The case studies are subjected to high-rise and low-rise structures in town terrain, and are conducted within actual structural engineering projects
- Referring partly to the case study results, the scope of this paper is to introduce the problematic related to wind loading on buildings. With an improved knowledge of wind actions and improved testing techniques, the wind-tunnel-testing procedure has become as a standard in tall building design, and the new wind design codes are also aware of such a procedure
- in Finland, the question of the usage of the wind-tunnel-testing procedure for structural analysis of buildings has not been topical unless recently, when plans of buildings of order 100 m in height are published. This range of buildings may have variable stiffening systems and can, as their taller counterparts, suffer from an annoying wind-induced vibration. Furthermore, such buildings will be wind-exposed, increasing the windiness at ground level and wind load of nearby structures
- the boundary-layer wind-tunnel testing technique, as described in the present paper, is fundamentally an opposite approach compared to the common structural engineering approach of using simplified assessment methods. Wind-tunnel testing is a research tool, which at the present state-of-the-art is necessary in assessment of certain types of structures.

Acknowledgements

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