What scaling means in wind engineering: Complementary role of the reduced scale approach in a BLWT and the full scale testing in a large climatic wind tunnel

Olivier Flamand
CSTB, Centre Scientifique et Technique du Batiment, 11 rue Henri Picherit, 44300 Nantes, France.

E-mail: olivier.flamand@cstb.fr

Abstract. Wind engineering problems are commonly studied by wind tunnel experiments at a reduced scale. This introduces several limitations and calls for a careful planning of the tests and the interpretation of the experimental results. The talk first revisits the similitude laws and discusses how they are actually applied in wind engineering. It will also remind readers why different scaling laws govern in different wind engineering problems. Secondly, the paper focuses on the ways to simplify a detailed structure (bridge, building, platform) when fabricating the downscaled models for the tests. This will be illustrated by several examples from recent engineering projects. Finally, under the most severe weather conditions, manmade structures and equipment should remain operational. What “recreating the climate” means and aims to achieve will be illustrated through common practice in climatic wind tunnel modelling.

1. Introduction

Structures studied in wind engineering are usually of large dimensions. Bridges, towers, slender industrial buildings, cutting edge artistic works etc. all require a careful study of the design wind loads because their unusual dimensions and cost open the opportunity for structural optimization.

Boundary layer wind tunnels (BLWTs) are more often than not the right tools for this problem. They have been used since the middle of 20th century to reproduce the natural turbulent wind at small scale, with size ratios ranging from 1/200 to 1/3000. Turbulence generators, often of rectangular or triangular shape, are placed upstream of the test section in order to generate the reduced-scale boundary layer, characterized by mean wind speed increasing with height and fluctuation of wind velocity in three dimensions, called turbulence. Turbulence scales and spectra are tuned to best fit the target values, using one time scale and one length scale. Because the behavior of air is very similar at such a small scale as in full-scale, modeling the spatial correlation of wind turbulence is often sufficient to reproduce the wind conditions experienced by large structures during a storm.

Looking carefully at this point it was made clear that only part of the natural turbulence can be reproduced in the BLWTs, the one corresponding to the input from kinetic energy, while the thermal part of the turbulence is neglected. BLWT is efficient in reproducing a neutral atmosphere, corresponding to most storm wind characteristics but is not convenient for reproducing everyday types of wind, such as relevant when studying wind power harvesting and pollutant dispersion [3]. Nevertheless, if the experiment is used to reproduce the local dispersion of plumes or the wake of one
wind turbine impacting a neighboring one, all considered at short distance, a boundary layer simulation can be very effective. There are of course some other limits in the use of BLWT for reproducing wind effects on buildings and offshore structures, due to downscaling effects, which lead to the use of large wind tunnels in a complementarily full scale approach.

![Figure 1. Typical BLWT study of high rise buildings in a 4m x 2.5m section at CSTB (left) and the case of great arch over the Tchernobyl reactor, with Reynolds number effect on a round shape building and on truss (right)](image)

2. Scaling in fluids mechanics

Pioneers in fluid engineering have long time ago faced this difficulty: how to reproduce natural phenomena at smaller scale? In 1780, Euler was probably the first to work seriously on scaling in engineering mechanics, followed by Fourier in the 1800s. In 1878, French mathematician Joseph Bertrand was the first to demonstrate the theorem that was reused by Aimé Vaschy [1] and latter popularized by Edgar Buckingham [2]. It is now known as the “Vaschy-Buckingham” or “Buckingham-Pi” theorem, giving a number of non-dimensional parameters necessary to describe a physical phenomenon. Because they are non-dimensional, these numbers opened the gate to the Dimensional Analysis which gives the rules (Rayleigh’s method) to be respected when linking a full-scale prototype and a reduced scale model analysis.

In the 18th century, seven basic physical quantities were chosen as elementary dimensions, the combination of which can represent any physical quantity: Length L, Mass M, Time or duration T, electric intensity I, thermodynamic temperature θ, number of molecules N and light intensity J.

Reynolds, Froude, Prandtl, Scruton, Strouhal, Grashof and Mach have all been immortalized by giving their name to a dimensionless quantity. Does this mean everything has already been said concerning scale effects in wind tunnel simulation?

It is well known that the Froude number must be respected in the reduced scale modeling when gravity is the main force governing the stability of the structure, as for suspension bridges or oscillating pendulum. Main numbers are (Equation (1)):

$$Fr = \frac{u}{\sqrt{gL}}; \quad St = \frac{f \cdot L}{u}; \quad Re = \frac{u \cdot L}{v}$$

When the vortex shedding or the wind turbulence applies an alternated force on an elastic structure, with a given stiffness, Strouhal number is the key parameter to respect. Grashof number is the most important to take into account when buoyancy of hot fumes must be represented experimentally. Let us try to consider the practical rules commonly applied in scaling for wind tunnel studies.

3. Downscaling limits in boundary layer wind tunnels

The first limit for downscaling encountered in boundary layer wind tunnels is related to the Reynolds number. This non dimensional term expresses the balance of viscous forces to inertia forces acting
on flow particles. It is, in practice, the main parameter governing the reproduction of actual loads on a model. For a reduced geometric scale of 1/200 in wind tunnel, the wind speed should be 200 times the real one to maintain the same value of the Reynolds number, which cannot be achieved. Consequently, wind engineers developed the know-how to compensate for the effects of a Reynolds number 100 to 1000 times lower in the BLWT simulation than the full scale one.

A very common example of the Reynolds Number scaling effects is found in the study of lattice structures. For elements of the lattice having sharp edged profiles it is commonly accepted that the drag force does not change at low Reynolds number. This assumption is based on drag coefficients measured on isolated squares, I, H and U-shaped beams, but is not fully verified when the lattice is so dense that it begins to behave as a mesh structure. Nevertheless, it is characteristic for rounded elements of lattice structure that the drag force is very dependent on the flow regime, i.e. the Reynolds number. In such a case there are two ways to change the lattice shape with the aim of better representing the wind loads on the model than via simply homothetic scaling.

The first possibility lies in decreasing the diameter of the round bars of the lattice by the ratio of drag coefficient at full scale (say 0.6 for a given wind speed and a given roughness) to the drag coefficient at reduced scale in wind tunnel, (say 1.2 because of the subcritical Reynolds regime). In practice, reducing the diameter of round bars by a factor of two is very common, and relies on the assumption of high wind speeds producing a drop in the drag force coefficient when exceeding the critical Reynolds number, usually called drag crisis, at full scale [4]. The second possibility consists of replacing round bars by square bars, with a thickness giving the same drag force. Actually these improvements in the representation of wind loads on reduced scale models cannot replace the accuracy and advantages of the measurements at full scale, in a large wind tunnel reproducing the correct Reynolds number.

Figure 2. On this powder sintered model of a round shape building at a scale 1/250 in BLWT, details of the surface are well reproduced, but it was necessary to add extra roughness trips to achieve the correct “apparent Reynolds number”

The second limitation when studying buildings in small size wind tunnels is the blockage effect, inherent with the presence of the model in the test section, especially in closed loop circuits with solid walls. When the wind collides with a real building, streamlines are deflected around the bluff body with no constraint in the vertical direction which is infinite, and sometimes very few in the lateral direction. In a wind tunnel, ceiling and lateral walls act out as a limit to the expansion of deflected streamlines. Even if correction methods can be applied, as commonly practiced in aeronautics on 2D streamlined bodies for measuring mean loads, these are not effective in boundary layer wind tunnels where wind speed and direction change all the time. Not only the mean flow is deflected here by the model, but additionally the large eddies composing the lowest frequency part of the atmospheric turbulence cannot “extend” vertically and laterally. It is challenging to look for a universal limit of
the blockage ratio, as the effect of walls depends on the size of eddies and the shape of the model, but a 10% blockage ratio is often considered the largest tolerable value.

A third boundary in downscaling lies in surface state and precision of current machining techniques. At a geometrical scale of 1/500, a 0.1 mm error on the model of a building corresponds to 0.5 m at full scale, which can be larger than acceptable when leading to major changes in the aerodynamic behavior. This means models should be ideally machined with a precision of 0.01 mm, which is very expensive and often impossible to attain on models with complex shapes, made of materials suitable for easy manufacturing. Today’s standard in 3D printing and classical machining gives precision close to 100 microns, what accordingly limits the downscaling to 1 to 10 for a very good geometrical precision and 1 to 100 for a rather good precision. There the machining precision meets the ability of classical boundary layer wind tunnels to recreate turbulence features at a scale not larger than 1/200. Making detailed models of buildings at a geometrical scale 1 to 1000 is often considered as “coarse” and maybe insufficient for delivering accurate results. Another difficulty when fabricating the models to represent the downscaled manmade structures is the surface roughness.

A typical painted steel structure roughness lies in the range 10^{-6} to 10^{-7} compared to its overall size. Reproducing the same roughness ratio on a model downscaled 1 to 100 for wind tunnel purpose would mean making surface with asperities less than 1 µm, which is referenced as a mirror surface state. In real life and with today’s techniques, it is at the same time very difficult (if not totally impossible) and costly to achieve such precision. But, is it a real issue for wind engineers? Actually they may find an interest in reproducing rougher surfaces on the small scale model to compensate for a too low Reynolds number at model scale. Similarly to the drag crisis phenomenon on circular cylinder that can be triggered at lower wind speeds, i.e. lower Reynolds numbers, the critical state at low wind speed can be provoked by increasing the roughness of the surface, making a building model rougher than its homothetic downsizing [5]. Various kinds of calibrated roughening have been developed for wind tunnel models, including glued sand, added strips or ligneous material as wood or dots. In all cases, the aim is to counterbalance the lack of inertia forces compared to predominant viscous forces, by forcing the flow separation to occur at a given point of the boundary layer, at the skin of the model. This strategy called “increase of the apparent Reynolds number” must be calibrated by making models of the same structure at different scales and comparing the surface pressure patterns and aerodynamic loads measured in the wind tunnel. This approach requires the use of a large wind tunnel, with the capability of testing models of the same shape with a scale ratio close to one to ten without blockage effects, providing the reference measurements at high Reynolds number for comparison with those at small scale with added roughness. In practice, this strategy works only for subcritical Reynolds numbers, larger than 200 in wind tunnel, and aiming to reproduce a full scale roughness larger than 2.10^{-3} [6].

In summary, challenges related to downscaling effects in wind tunnel modelling cannot be handled by simple recipes that would work in all cases. The effect of scaling in wind tunnel tests should be studied first, for instance by repeating the experiment at various Reynolds numbers, looking for a stable result that demonstrates a supercritical state. Attention must be paid to each aerodynamic phenomenon involved in a complex study: two aerodynamic phenomena acting in a single study in wind tunnel may not have the same downscaling requirements.

4. Practical examples in scaling the drag of cylinder shape buildings

Such a reference study was achieved in the 1990’s for a high rise tower in Paris, the shape of which was close to a circular cylinder. This cylindrical tower, designed by the famous French architect Jean Nouvel, was named “la Tour Sans Fins”, which means “the endless tower”, because its summit was vanishing in the sky, its outer skin becoming more and more porous with altitude. This kind of variable porosity is now frequently seen in recent towers design. At the time it was decided to build 1/300 scaled model for BLWT testing. Following the necessity to achieve concept of previous high Reynolds number referencing, a first model 10 times the diameter of the tower model was built (thus, corresponding to a 1/30 scale of the real tower), but not with the same diameter to height ratio, and
subjected to high Reynolds flow in the large high-speed Jules Verne wind tunnel [7] with careful measurement of the pressure pattern around it. With a diameter of 0.8 m and a flow speed of 80 m/s a Reynolds number value of $4.0 \times 10^6$ was reached in this “high Reynolds number” wind tunnel experiment. This was considered high enough upon the limit of critical state to be representative of the full scale value of $7.0 \times 10^7$, corresponding to the same supercritical state of the flow. Keeping this pressure pattern as reference, the 1 to 300 scaled model was tested with slower flow, in the wind speed range corresponding to the BLWT, looking for the best arrangement of added roughness on the model surface to give a similar pressure field. It was found that meridional strips with a thickness of 0.6mm and a step of 15° provided the best artificial surface roughening in this case, leading to a mean pressure pattern similar to the high Reynolds number one.

The same question was addressed some years later, when studying wind loads on the European Launcher Ariane 4 on its launching pad, with models at a scale of 1 to 100. Similar tests were conducted, first in high Reynolds number conditions in the large wind tunnel, then at lower wind speed in the boundary layer wind tunnel with calibration of the relevant roughening. It must be underlined that in both cases longitudinal strips proved to be the only efficient manner to reach the required apparent Reynolds number, while sand roughness was not large enough. This artificial roughening method is commonly used on all kind of buildings with rounded shapes.

![Figure 3. Roughening cylindrical models in BLWT by use of meridional strips.](image)

5. **Simplifying models at reduced scale**

Real built structures are made of a collection of small elements, each potentially having an impact on the wind load applied on the whole. What should be the refinement of a reduced scale model, taking into account the many difficulties with machining of such a delicate object?

Such a question was answered for O&G companies TOTAL and DORIS through wind tunnel tests measuring the loads on a FPSO, first with a very detailed model reproducing all elements of this complex structure, then with a model made of simplified bluff bodies and porous screens and finally with a model composed of a single solid volume.

As expected, the simplified model gives results very similar to those obtained with the very detailed one, when wind loads on the single volume are fundamentally different. The simplification process of a complex, three dimension building, regarding the wind effect, must be achieved with advice from a specialized wind engineer.

Ensuring the same drag force whatever the wind direction is one key of this “cleaning” process, a group of small items being easily reproduced by a porous plate having the same plain/void ratio in a mean. Concerning the reproduction of small moldings and faceted effects on a façade, this has no effect on the wind loads when the air stream is detached.
Figure 4. Three levels of simplification for the study of wind loads on an offshore plateform, in boundary layer wind tunnel (courtesy of TOTAL and DORIS)

Any detail of a surface with a size smaller than the thickness of the boundary layer developed on this surface will not influence the wind loads. Therefore, only streamline bodies require the faithful reproduction of their surface details, for most of buildings which have sharp edges, facades can be considered as flat, for the BLWT modelling.

6. Scaling the porosity of cladding elements
There are many recent examples of high-rise buildings incorporating sun shades for the reduction of solar energy input in summer time. Architects also try to use such external structures to give the building a unique appearance, changing the shape and size of these elements across the façade, requiring the design engineer to carefully design them. Due to their exposure at the façade, they are subject to high wind loads, sometimes in accelerated flow areas.

But at the usual scale of buildings in BLWT, even if the detailed shape and porosity of the shades is carefully reproduced following a homothetic design, the porosity of these screens is especially poorly represented from the aerodynamic point of view because the viscous part in the Reynolds number is considerably increased at such reduced scale. Therefore, a two-step strategy is employed. The classical BLWT model is first used to measure global wind forces and local flow fields around the building in its environment. Then a second model of the façade is built, at a larger scale, say 1/50, for the fine modeling of wind loads on the shading structures. This larger model is built to resist high wind speeds and can be set in a large high-speed wind tunnel outside the ground boundary layer. The kind of wind applying loads on this large model is uniform, contrarily to the BLWT wind which is turbulent.

Figure 5. High rise building scaled 1/200 in BLWT (left) and model of the top of the same tower at a scale 1/50 in a high-speed wind tunnel (right) for measurements at high Reynolds number.

The size of the shading elements is assumed to be small compared to the mean dimension of eddies composing the wind turbulence, what justifies the testing in the uniform flow. Loads can be measured directly on the model, as well as pressure drop or local air velocity, with a good accuracy, when high wind speed and a large model size provide sufficiently high Reynolds numbers. This approach
is relevant for windbreaks, solar panels assembly, safety barriers, porous canopies and any kind of wall alternating solids and voids.

7. Wind studies of small elements of building
Not only landmark buildings need careful wind resistant design. Looking at post-storm reports by insurance companies, what arises as the main candidate for failure under heavy wind load? Not the buildings themselves, but the small elements constituting our urban environment, such as lighting poles, advertising boards, transportation signs, chimneys, antennas, garden sheds…

These objects are parts of the build environment and, if none of them is as visible as a high rise headquarters of a powerful company, the sum of their individual repair and replacement usually makes up the major part of storm losses. Therefore, there is a real need for an industrial wind proofing service that the large wind tunnels can fulfill with wind load reproduction on full-scale prototypes.

In that case, contrarily to the BLWT approach, there is no need to simulate with care the characteristics of the wind turbulence, its spatial correlation and its length scales. Wind is a local phenomenon, uniformly distributed on an area of several square meters. The main question is not to faithfully reproduce the unique wind field created in a given place by the particular location of surrounding buildings and terrain: the question is “what is the highest speed this type of object will stand in its life” and consequently which way it will be fixed/attached/interacted and interact with its environment.

The wind speed representative of such a small element’s life is not easy to assess. It mainly depends on the height above ground where it will stand. For instance, a photovoltaic solar panel standing on a roof will not be loaded the same way as the same panel on the ground.

For this reason full-scale testing in a large wind tunnel is often preceded by another study at reduced scale or by CFD modelling, for the assessment of the local wind speed. It is therefore very convenient to associate in the same location a BLWT with a HSWT (High Speed Wind Tunnel), the former being used to determine the wind conditions to be reproduced in the latter. After the maximum local wind speed and its various directions have been determined by small anemometers placed in the vicinity of given building on the reduced scale model coupled with a climate survey, the same level of wind will be applied on a full scale prototype of the item in question in a high speed wind tunnel.

Figure 6. Some examples of full scale testing on prototypes, using an industrial high speed wind tunnel.

Avoiding blockage effects must be a constant concern, whatever the type of the wind tunnel, which frequently fixes the choice of the test section and the power of the facility.

Because the shapes of prototypes to be tested are many and various, from slender vertical light poles to bluff electric boxes, as well as wide, flat solar panels and quasi-cubic individual houses, the shape of the optimal testing section is difficult to define. For this reason, large wind tunnels are usually composed of successive testing chambers of different cross sections, sometimes with moving wall or
ceiling in order to adapt the test section shape and size to the prototype to be windproof.

8. Scaling snow in climatic wind tunnel

Scaling issues is not reserved to wind modeling; the same questions arise in geotechnical science, in marine studies etc. And when it comes to wind tunnels that not only use air, but a mixture of air and water (rain drops, water proofing, fog...), solid particles (sand storms, dust transportation...), snow, then downscaling the physical properties of phenomena becomes impossible. This is another good reason for full-scale tests in wind tunnels, an example of which will be illustrated hereafter.

There are many questions raised by researchers involved in the investigation of snow loads. Failures induced by snow ingress in systems, snow accretions on structures and vehicles are efficiently studied by full-scale approaches either outdoor or in laboratory environment. On the other hand, questions dealing with large environments, typically interaction between various buildings and their surroundings can only be studied with reduced scale models. Snow accumulation around buildings belongs to this category. A reliable experimental modeling in wind tunnel depends on geometric, dynamic and kinetic criteria: snow particles (shape, density, velocity, drag, lift, liquid water ratio) and wind (temperature, speed, turbulence) must be modeled. Experiments are commonly based on theoretical approaches first introduced by Kind [8] and Iversen [9].

Many attempts have been made to use BLWT with some material replacing snow for the reproduction at reduced scale of snow deposition and snow drift events. Snow particles have been modeled by sand, sawdust, glass balls which do not reproduce all inter-particle forces. Plastics and potato flakes have proved more convenient, showing some similarity with the real snow behavior in the inter-particles affinity. Nevertheless, even if man-made snow does not reach the same tree-like shape as natural one, because snowflakes need a long time to grow and artificial snow consists of small ice oblongs, the most appropriate choice is often to make artificial snow in a cold wind tunnel.

Evaluating snow properties involved at reduced scale by similitude laws yields Table 1. A noticeable disagreement of the full scale Froude number with a small scale model one’s, based on the threshold friction velocity weighted by the particle/fluid density ratio, indicates that the trajectory of the model particle will be different from the natural snow particle one. According to Kind [8], if the Froude number is not conserved in the experiment, it is particularly important to verify that saltation length, which represents 10 times the saltation height, is shorter than the building reference length and the typical size of the snow drifts.

| \( D_p / L \) | Geometric ratio particle length/building |
| \( u^* / D_p g (\rho / (\rho_p - \rho)) \) | Froude number for particle friction threshold |
| \( u^* / L g (\rho / (\rho_p - \rho)) \) | Froude number for friction on the building |
| \( u^* / u^* \_t \) | Threshold speed/friction speed ratio |
| \( u^* / u \) | Friction/fluid speed ratio |
| \( u^2 / D_p g (\rho / (\rho_p - \rho)) \) | Froude number for particle transport |
| \( u^2 / L g \) | Conventional Froude number |
| \( \rho_p / \rho \) | Particle/fluid density ratio |

\( D_p \) particle diameter, \( L \) reference length, \( g \) gravity, \( \rho \) fluid density, \( \rho_p \) particle density, \( u_t \) threshold friction velocity, \( u^* \) friction velocity, \( u \) reference wind velocity
In practice, this may be verified when using moderately reduced scale models in a cold wind tunnel with artificial snow guns. Concerning snow transport by wind, forces on particles are better modeled if the Reynolds number based on the saltation height is greater than 30. This also leads to scaling ratio limited to 10 or close to.

Regarding the suspended particles, the particulate Froude number, weighted by the density ratio, is the physical quantity describing the similarity of the transport mechanism at the vicinity of buildings. It also drives the accumulation process, locally. Finally a choice has to be made between the saltation mechanism (close to the ground) or long distance transport processes.

**Figure 7.** Testing snow accumulation in CSTB climatic wind tunnel [11] at full scale (left) and reduced scale for complex buildings (right).

In practice, the wind/snow engineers set simple rules for common applications, considering essentially the simulation of the drifting volume $v_0$. The basic similitude parameter is $v_0/L^3$, where $L$ is the reference length of the structure, which leads to the straightforward criterion

$$
\left(1 - \frac{u^*}{u}\right) \left(\frac{u^2}{Lg}\right)_p = \left(1 - \frac{u^*}{u}\right) \left(\frac{u^2}{Lg}\right)_m
$$

where indexes $p$ and $m$ stand respectively for prototype and model. This relationship does not imply any constraint regarding the particle density and size. Hence, the model particle scale does not interfere with the drifting volume simulation.

A major parameter of reduced scale simulation, the experiment duration, can be calculated according to several dimensionless time numbers. Various expressions can be found in the literature. Each of the dimensionless time expressions in Table 2 leads to a different snowstorm duration and there is no real agreement about what criteria should be used.

| Table 2: Dimensionless time used to assess the equivalent snow event duration |
|-------------------------|-------------------------|
| $ut / L$                | $\rho / \rho_p \cdot ut / L$ |
|                         | $1/2 \cdot \rho / \rho_p \cdot u^2 / gL \left[1 - u_0 / u\right]. ut / L$ |
|                         | $\eta Q_\eta / \rho_p L^2$ |

Therefore, it is advisable to rely on actual measurement of a real outdoor accumulation and tune the snow fall duration in wind tunnel to achieving the same, scaled behavior.
References

[1] Vaschy A 1892 Sur les lois de similitude en physique *Annales Télégraphiques* 19 pp. 25-28

[2] Buckingham E 1914 On physically similar systems. Illustrations of the use of dimensional equations *Phys. Rev.* 4 pp. 345-76

[3] Davenport A G, Vickery B J, Holmes W H 1975 *The structural and environmental effects of wind on buildings and structures* (Post graduate course of the University of Sidney, School of Civil Engineering)

[4] Roulle C 1980 Reproduction du régime hypercritique sur formes rondes en soufflerie à couche limite atmosphérique *CSTB report n°EN-ADIM 80-20L* (Unpublished)

[5] Basu R I 1985 Aerodynamic forces on structures of circular crosssection part 1. model-scale data obtained under twodimensional conditions in low-turbulence streams *J. Wind Eng. Ind. Aerodyn.* 21 pp. 273-94

[6] Szechenyi E 1975 Supercritical Reynolds number simulation for two- dimensional flow over circular cylinders *J. Fluid Mech.* 70(3) pp. 529-42

[7] Lemoult B et al. 1990 Caractérisation des efforts aérodynamiques développés sur un cylindre en régime supercritique, simulation en soufflerie (CSTB report n°EN-SC 90.11-C)

[8] Kind R J 1976 A critical examination of the requirements for model simulation of wind-induced erosion deposition phenomena such as snow drifting *Atmos. Environ.* 10(3) pp. 219-27

[9] Iversen J D 1979 Drifting snow similitude *Proc. Asce, J. Hydraulics Div.* 105, pp. 737-53

[10] Delpech P et al. 1998 Snowdrifting simulation around antarctic buildings *J. Wind Eng. Ind. Aerodyn.* 74-76 pp. 567-76

[11] CSTB, *Jules Verne Climatic Wind Tunnel* [Available online] http://recherche.cstb.fr/en/facilities/climatic-wind/