The use of Wind tunnel experiments for wind loads on structures.

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Introduction

Experiments have been essential in the development of current guidelines and design procedures for wind loads on structures. Current design coefficients in codes and guidelines are almost all based on wind tunnel experiments. Wind tunnel experiments are also used as alternative for codes of practice in cases outside the scope of these codes, or when it is assumed necessary to obtain the wind loading more precisely. The choice whether or not to perform wind tunnel experiments can be based on reasons of safety or economy. This lecture focuses on the application of the wind tunnel for wind loading studies.

A brief history

The earliest attempts to model the effects of the wind on buildings experimentally date back to the 18th century. Models were moved in the air to determine the drag. Experim19ents where the models were fixed and a fluid was moved (e.g. water or air) originated in the 19th century. Large progress was made by Irminger and coworkers in the early decades of the 20th century. The fundamentals of our current techniques was developed in Göttingen in Germany, in the 30's, mostly related to developments in aerospace engineering. These experiments, and others done at that time, were performed in flows with low turbulence, without boundary layers. The need to model the atmospheric turbulence properly has lead to the design of so called Atmospheric Boundary Layer Wind Tunnels. This was first recognized in the 1950s, This led to the development of relatively long working sections in the wind tunnel. Since the 1960's, experiments to obtain wind loads on buildings are performed in such facilities. Whilst instrumentation, data acquisition and data handling techniques developed drastically over the past decades, wind tunnels are still very much based on these principles. Wind tunnels built in that period are still in use. The development of data acquisition and computing abilities made it possible to handle large amount of data. Modern wind tunnel experiments for the wind loading on buildings use statistical analysis techniques of the measurements to obtain design loads.

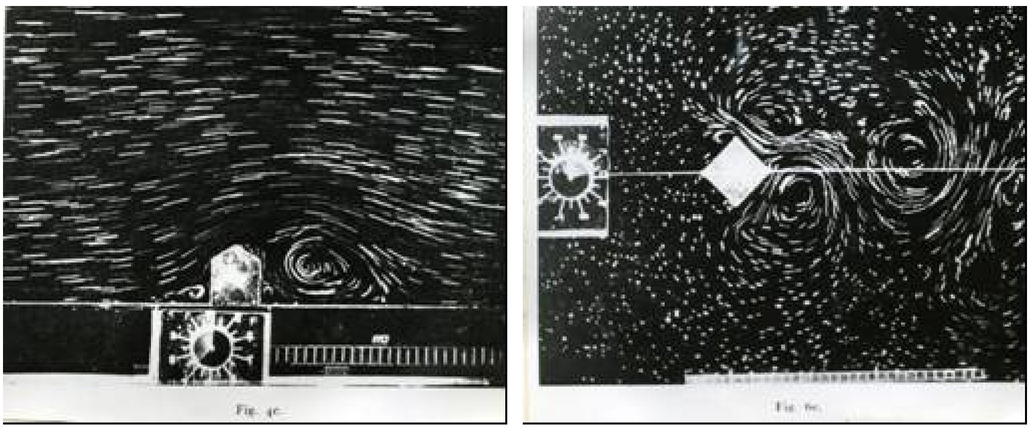


Figure 1: Pictures of flow experiments by Irminger (around 1930)

Guidelines
A number of guidelines has been developed recently to help those involved with wind tunnel experiments to carry out, analyse and apply wind tunnel data. The most extensive guideline is published by ASCE. Others are those published by WTG (in German) or the guideline of BLWTL. These guidelines however give scarce information for the end users. Therefore, in the Netherlands, CUR Recommendation 103 (in Dutch) has been published.

In a wind tunnel, the wind, the building, its surroundings, and in particular cases its behaviour are modeled on scale. It is possible to measure wind velocities, pressures, forces, moments and accelerations. For wind loading studies, mostly data are transferred into nondimensional coefficients, such as pressure coefficients. These coefficients can be defined in various ways, using a range of reference wind speeds, and defining different statistical properties.
Users of wind tunnel results, such as structural engineers, usually do not have the knowledge to decide upon these aspects. They need guidance to understand the results, and to properly evaluate the quality of the measurements.

Usually, wind tunnel research to determine the wind loading on buildings and building parts is recommended when:

- buildings have shapes that are significantly different from those given in chapter 7 of EN 1991-1-4, or any other wind loading code. This may be related to the shape of the plan, but also to the height orf the structure.
- buildings are situated in a complex environment, causing interaction effects (leading to reduced and or increasing wind loads) .This includes cases where a planned building exists of more than one independent structure (e.g. two towers on a joint lower base building).

Wind tunnel experiments are also used for:

- Validation of other methods, e.g. Computational Wind Engineering
- gathering of data to apply in the next generation of guidance and codification documents.

Usually, wind tunnel experiments are not used for:

- internal pressure coefficients,;
- friction coefficients;
- the effect of pressure equalisation,;
- the dynamic forces on slender structures with limited stiffness, such as cables, bridge decks, flexible roof coverings.

However, wind tunnel research may serve as basis for such estimations. In some cases, full scale experiments or computational wind engineering may be preferred. Guidelines on wind tunnel research should give information on how to prepare, to set up, to carry out and to analyse wind tunnel research. In this text, a brief overview of all these aspects is given. The reader is referred to the literature list for more detailed information.

Wind tunnel technique
An atmospheric boundary layer wind tunnel consists at least of the following elements:

- One or more ventilators to develop moving air.
- Devices to 'straighten' the flow coming from the ventilator before it enters the test section. These devices usually contain a contraction, to accelerate the flow, and one or more honeycombs and directional vanes to make the flow low turbulent.
- A working section which is usually adjustable. It contains the model of the building under consideration, and specific features to generate the flow in the atmospheric boundary layer. These features are, seen from upstream:
    - A barrier, or step, at the entrance of the tunnel to generate large scale turbulences
    - An array of spires
    - A large fetch of roughness elements to generate a boundary layer flow.
    - A test section, with a turn table, on which the model is placed
- An outlet of the flow

Depending on the type of wind tunnel, the flow is recirculated (closed section tunnel), or connected to the outside world (inside or outside), for an open section tunnel. Open section tunnels can have the fan places before or behind the test section.
Variations in wind tunnel technique may be adjustments to be made to the ceiling, the positions of the roughness elements. At the Boundary Layer Wind Tunnel Lab in London, Ontario, adjustable roughness elements have been installed. Some wind tunnels have walls in the test sections which are partially open, to minimize blockage effects.

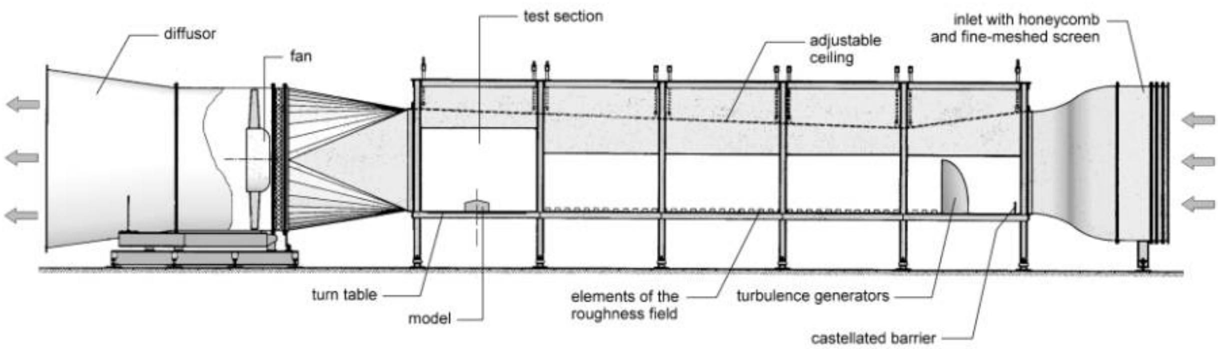


Figure 2: Open section wind tunnel of the Ruhr University in Bochum, Germany

Preparation of wind tunnel research

Before setting up a wind tunnel research, at least the following information needs to be available:

Information of the vicinity:

a map of the direct surroundings, at least corresponding to the surroundings that are modeled on the turn table, including orientation of the building and surroundings (relative to the north);
heights of the surrounding buildings, modeled on the turn table;
special objects in the surrounding area, that may be of influence on the results;
information on the roughness to determine the upstream roughness in the wind tunnel;
information on the future building plans in the direct environment.

Information on the building under study:
views and sections of the building;
drawings of special features on the building;
roughness of the facades;
main structure axes and the torsion centre of the structure.

Applied technique for analysis of data
Data obtained in a wind tunnel may be analysed in different ways. These analysis methods depend on the purpose of the study. The choice of these methods however, influence also:
the way the wind climate is modelled in the wind tunnel;
the instrumentation and measurement technique;

Three methods which are frequently applied are the methods A, B and C described below:

Method A: Measurement of mean values; quasi-steady approach
Method A requires per wind condition one time trace, with a length which is sufficient to ensure that a longer time trace will not give another mean value. This method is suited for the analysis of forces and moments to determine the wind loading on the main structure. Method A is a safe method to determine the wind loading on the main structure, but is not suited to determine the local loads.

Method B: extreme value analysis of pressure coefficients
Method B requires per wind condition more time series with a length *T*. Each time series has the same length and the same sample frequency. Method B uses extreme value analysis of the measurement results applied together with the peak dynamic pressure from the wind loading codes.

Method C: extreme-value analysis of wind tunnel data and wind climate statistics
Method C applies an extreme value analysis of the measured extremes. This analysis is combined with the wind climate statistics. A target probability of the load effect is used as the basis for the determination of the wind loads.

Other methods, more or less similar to the procedures described here, are used throughout the world. The ASCE guideline gives an overview of alternatives available.

Modelling the building and surroundings
A wind tunnel model consists of the building and the direct environment. The scale model is usually custom made for the wind tunnel research. The model has to be suited to mount specific instruments, and is of a geometric scale, that meets the relevant scaling requirements. The model needs to withstand the loads that are induced by the wind tunnel itself.

A wind tunnel test is carried out on a scale model of the building and surroundings. The geometric scale λ_g is defined as:

$$\lambda_g = \frac{L_{WT}}{L_{FS}}$$

(the index WT stands for Wind Tunnel, the index FS stands for Full Scale)

The geometric scale needs to be specified in the test report. When choosing the geometric scale, the following factors should be accounted for:

Blockage of the wind tunnel section, which is accepted;
Influence of the surrounding obstacles, which are assumed necessary to be modeled;
The amount of detail of building and surroundings that is relevant;
Roughness of the surrounding terrain.

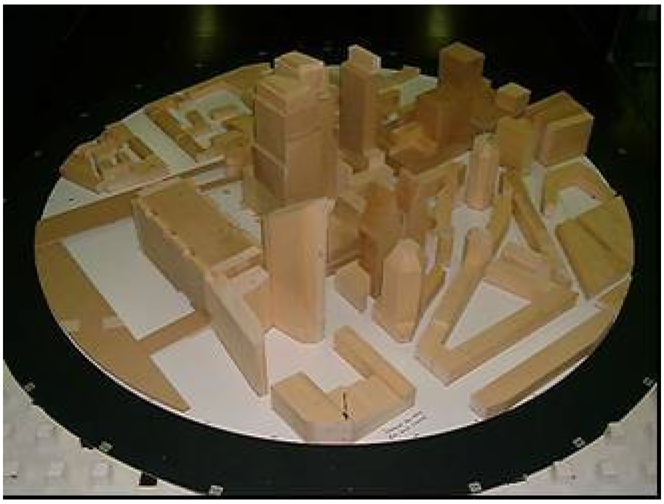


Figure 3: Wind tunnel model on the turn table

The following minimum demands are specified:

Blockage
The blockage ratio has to be given in the test report. Also, the effects of blockage on the results, and corrections applied. A blockage lower than 5% is a maximum below which no corrections are needed. In other cases the choices made should be specified in the test report. A special way to treat blockage is the application of slotted walls at the test section. This has been applied at BRE in the UK.

Figure 4: Interior of BRE wind tunnel, with slotted walls at the side and ceiling of the test section.

Surrounding buildings and obstacles
The effect of obstacles in the direct environment needs to be taken into account in connection with the principle that all loads that are assumed to work on a structure during its lifetime have to be considered. To determine the wind loads on high rise buildings and its components, the following situations are considered:

1. A wind tunnel test where the direct surroundings are modelled as known at the time the research is carried out. Both local loads and the overall loads on the load bearing structure are determined. If known, future developments should be considered in this test.
2. A second test, where the surrounding buildings on the turn table are taken away. Alternatively, the surrounding buildings may be reduced to a lower height in full scale.

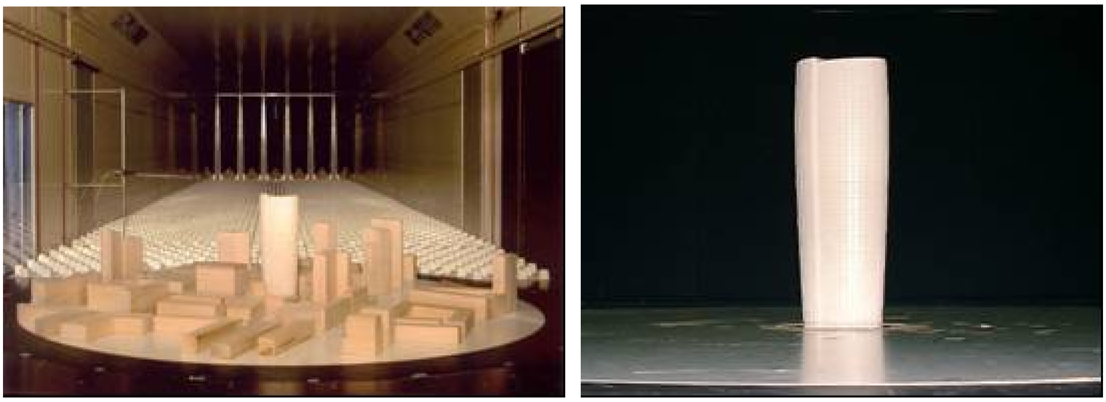


Figure 5: Left: building with surroundings; Right; building on empty turn table

Details
The amount of detail of the wind tunnel model depends on the objective of the wind tunnel test. Small details are less relevant for the overall loads. The amount of detail modelled needs to be specified in the test report. Besides the roughness of facades, all significant differences between full scale shape and wind tunnel model should be

motivated. This includes features such as parapets, roof overhangs, installations, rounded corners etcetera.

Roughness of surrounding terrain
The roughness length z_0 of the upstream fetch is scaled according to the Jensen Number Je = h/z_0. For the determination of wind loads on buildings and components (to check the ultimate limit states), application of a lower value for z0 is a conservative choice. This leads to the following minimum demand:

$$\frac{z_{0WT}}{z_{0FS}} \leq \lambda_g$$

Usually, in wind tunnel tests, the same roughness length is applied for all wind directions. The value of the roughness length should be chosen which gives the most conservative results. Usually, this is the lowest value. When the wind tunnel results are used to check the serviceability limit state (accelerations of the building), applying a lower roughness length may lead to an underestimation of the fluctuating component of the wind loads. This may lead to an underestimation of the vibration levels. The effect however is usually small.

Figure 6: Downstream view of the wind tunnel in Bochum: spires, roughness elements, turn table, fan.

Modelling the atmospheric boundary layer.
The wind in the atmospheric boundary layer varies in time and space. It depends on the terrain roughness, the local wind climate, and on variations in temperature. Usually, the effects of temperature are assumed negligible, when studying wind loads. Relevant are the proper simulation of the wind speed with height (the wind profile), and the turbulent characteristics.
The profile of the mean wind velocity is modeled by applying the Jensen law, or by applying an appropriate exponent in a power law profile. The Jensen law demands that the value of the roughness length in the wind tunnel is geometrically scaled from the full scale value. When the power law is applied, the exponent of the power law should be similar to the value expected in full scale.

The shape of the profile depends on the features installed in the wind tunnel. Modern ABL Wind tunnels have a range of profile characteristics available on request.

Minimum demands are specified to the profile of the mean wind with height, and to the specification of the turbulent components. Besides the geometric scale scaling λ_g the wind velocity scale λ_v and time scale λ_t are relevant. These are defined as follows:

$$\lambda_v = \frac{v_{WT}}{v_{FS}}$$

$$\lambda_t = \frac{T_{WT}}{T_{FS}}$$

The frequency *f* is the inverse of time *T*; For the frequency scale this yields:

$$\lambda_f = \frac{f_{WT}}{f_{FS}} = \frac{T_{FS}}{T_{WT}} = \frac{1}{\lambda_t}$$

Wind velocity
The wind velocity which is applied in the wind tunnel, has to fulfill the minimum demands specified by the Reynolds number and Strouhal number, as given below. The wind tunnel velocity has to be reported. A wind velocity scaling in the order of 1 to 5 is common for the (West) European wind climate.

Reynolds Number

The Reynolds number is defined as follows:

$$\mathrm{Re} = \frac{vL}{\nu_a}$$

Where:
L is the width of the structure;
ν_a is the kinematic viscosity of air, equal to $1{,}5.10^{-5}$ m^2/s;
v is the mean wind velocity.

The pressure and force coefficients may depend on Reynolds number. This may be the case for buildings or building parts with rounded shapes.
The wind tunnel institute should report the corrections applied to account for this effect, including:

- the value of Re in full scale;
- the method of scaling this value to the wind tunnel;
- the method of taking Re into account.

Usual methods to take Reynolds effects into account are: applying various wind speeds in the experiment, or applying roughened surfaces of the building.

Strouhal number

The Strouhal number is defined as follows:

$$St = \frac{fL}{v}$$

To scale frequency, time, length and wind speed appropriately, the Strouhal number needs to be equal in full scale and in the wind tunnel:

$St_{WT} = St_{FS}$, or: $\frac{1}{\lambda_f} = \lambda_t = \frac{1}{\lambda_v}\lambda_g$

This scaling demand is relevant for the minimum demands of:
-the length of the samples in the wind tunnel;
-the sample frequency;
-tuning the model applied in the high frequency force balance.

Boundary layer height
The height of the boundary layer in the wind tunnel, at the measurement section, should be high enough that the measured properties represent the full scale situation well. Usually this is achieved when the boundary layer height in the wind tunnel is at least twice the model height.

Reference height
The reference wind velocity at a reference height h_{ref} has to be specified. The position of this reference with velocity v_{ref} has to be chosen so, that the test results lead to reliable predictions of the wind loading.
This reference height may be taken equal to the height of the building, when the building is lower than twice the average height of the surrounding buildings. For buildings which are at least three times the average height of the surrounding buildings, the reference height may be chosen between 2/3 and the total building height. This reference height needs to be specified in the test report.

Turbulence
The turbulent characteristics can be represented by the turbulence intensity, the spectral density functions and the correlation lengths in the flow. Turbulence intensity and spectral density functions can be represented in nondimensial form. The requirements is simply that the model scale and full scale values (when presented in non-dimensional form) should be the same. The correlation lengths are represented by so called integral length scales. These are scaled down by the geometrical scale. In most wind tunnels the above demands are not met simultaneously. For wind loading studies, a lower level of turbulence than required, usually leads to higher loads, and is therefore conservative.

The turbulence intensity in the scaled wind climate in the wind tunnel needs to be smaller than or equal to the value in full scale:

$$I_{WT}\,(h_{ref}) \leq I_{FS}\,(h_{ref})$$

Measurement
As a general demand for measuring velocities, pressures and moments, instrumentation should be applied for which the calibration results are known. In the test reports the measurement techniques applied and the instrumentation used are specified, along with the accuracy of these instruments.

Measuring the simulated boundary layer
The simulation applied for the atmospheric boundary layer has to be reported. This documentation has to be available on request. The measurement techniques should be specified. The test report needs to specify how the relevant demands are fulfilled.

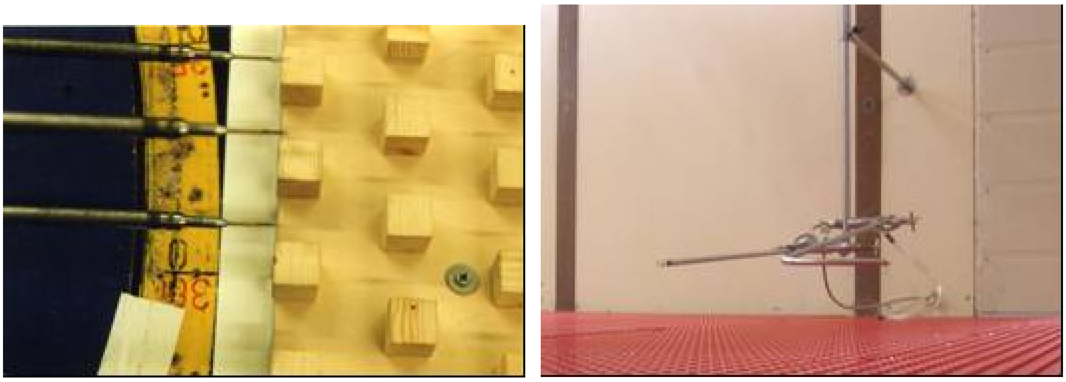


Figure 7: Hot wire anemometry (left), Pitot tube (right)

To determine the properties of the wind in the wind tunnel, pitot-tubes and hot wire anemometry are appropriate. Hot wire anemometry allows to measure the mean and fluctuating properties of the wind profile. Also, the spectral density of the wind fluctuations are determined.

Measurement of pressures
Pressures are measured as pressure differences between the building surface and a reference pressure. These measurements may be used to determine the local loads on facades and roofs, or to determine the overall loads on the load bearing structure. The minimum demands for pressure measurements are given below.

General
The following minimum demands should be fulfilled:

- The position of the reference pressure is chosen so, that this pressure is independent of wind direction or changes made to the model.
- The frequency-response characteristics of the pressure measurement equipment needs to be available on request.

Measurement of local pressures
The following additional demands are relevant for local loads:

- A selection of locations is made, at which increased local loads are expected. Usually, these locations are near extremities of facades and roofs.
- Pressure measurements have to be carried out with sufficiently high frequency, that the extreme loads are determined which correspond to the

loaded area A_{ref}, as defined in the building codes. The sample frequency is determined according to the Strouhal number.

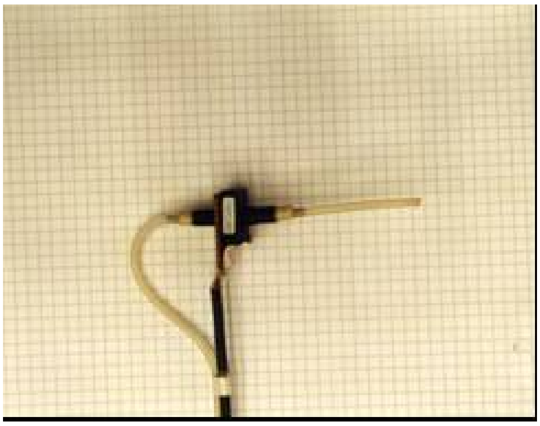



Figure 8: Pressure taps in a wind tunnel model (left); pressure transducer (right)

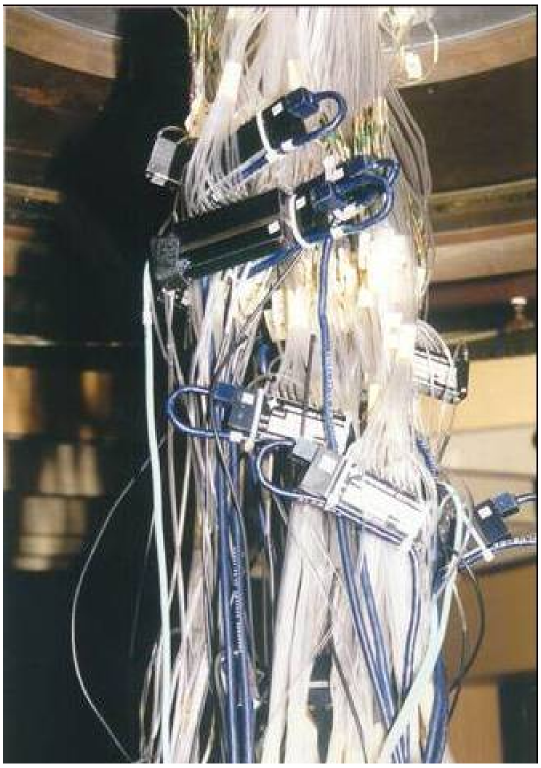



Figure 9: Pressure transducers inside a model (left), or under the wind tunnel turn table (right) (picture left from Benoit Parmentier, WTCB, Belgium)

Measurement of pressures for the overall loading

To determine the wind loads on the overall load bearing structure, additional demands to those given above, are given:

- All surfaces are provided with pressure measurement points. The number and position of the measurement points, along with the attributed area per measurement location, have to be motivated in the test report. Usually, the facades and special features on the building are provided with a large number of pressure taps, depending on the shape and dimensions of the building.

- When applying the pressure measurements in methods B or C, the pressures should be measured simultaneously.

The contribution of friction is not taken into account, when using pressure measurements to determine the overall forces and moments. The friction has to be taken into account by application of the appropriate rules of the building codes.

When integrating pressures to obtain forces, the individual pressures should be simultaneous to keep the time information. This yields new time series of forces and moments.

The resulting force $F(\theta,t)_i$ at time *t*, for wind direction θ, in direction *i* (*i* may be one of the main axes of the building) is determined from:

$$F(\theta,t)_i = \sum p_j(\theta,t)_i A_{j,i} + W$$

where $A_{j,i}$ is the projection of area A contributing to measurement location j in i-direction, and W is the total component from friction.

W is determined from a building code.

The resulting moment $M(\theta,t)_i$ at time *t*, for wind direction θ, around an axis normal to direction i is determined from:

$$M(\theta,t)_i = \sum p_j(\theta,t)_i A_{j,i} L_j + WL$$

where L_j is the moment arm of force $p_j A_{j,i}$ for rotation around axis j, *WL* is the total component from friction. *WL* is determined from the building code.

This procedure enables a detailed analysis of load patterns and dynamic response (using mode shape analysis) of the structure. More detail and procedures are given in the literature.

Measurement of forces using a high frequency force balance

Overall forces and moments on the load bearing structure should be determined with one of the following methods:

1. A static measurement (mean values) using a force balance, to be applied in method A;
2. A measurement of time series of forces and moments with a high-frequency force balance, to be applied in method A, B and C;
3. Forces and moments determined from pressures, to be applied in methods A, B and C

The techniques applied should be described in the test report. Information about the measurements should be available on request.

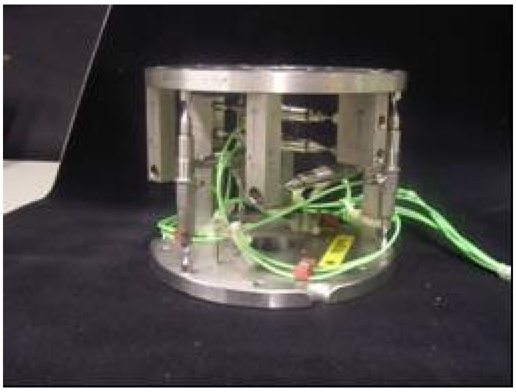
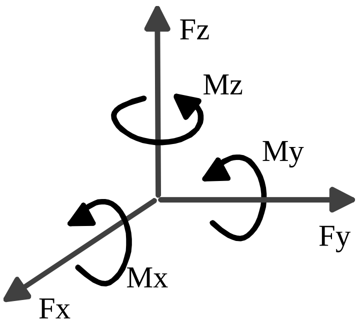


Figure 10: Example of a 6 component force balance

Forces and moments from static balance measurements
A so called static force balance is able to measure mean values of forces and moments only. This method gives three values for force; F_x, F_y and F_z, and three values for the moment M_x, M_y, M_z. This technique can be applied in method A only.



When applying a static force balance measurement, the effect of wind friction is assumed to be implicitly taken into account.

Forces and moments from high frequency force balance measurements
A dynamic balance is applied to measure time series of the win dloading. When applying a high frequency force balance, the effect of resonance of the structures, are not taken into account.

The natural frequency of the model applied should be at least 2 times the value of the highest frequency of interest for the measurement. This frequency should be determined using the Strouhal number. This should be motivated in the test report. Time series are analysed according to method Bor method C.

When applying a high frequency force balance measurement, the effect of wind friction is assumed to be implicitly taken into account.

Measurements at various wind directions
A wind tunnel test to determine design wind loads should be carried out using at least 24 wind directions, distributed evenly over the wind rose.

Sample length, number of samples and sample frequency

To determine the statistical properties (mean, maximum, minimum and root-mean square values), one or more time series should be measured, for every wind direction and for every measurement channel, per configuration examined. A configuration may be characterised by the modeling and by the method which is applied to take Reynolds-number sensitivity into account.

In method A, one time series is needed per wind condition, with a length chosen so, that a longer time series does not give another mean value.

For methods B and C, per wind condition, more than one time series is needed with a certain length *T*. Every time series is measured with the same sample frequency.

The following minimum demands are relevant, related to the extreme value analysis, which is applied:

- The time series are of the same length;
- There is no overlap in the time series (time series are independent);
- The time series each represent a full scale duration of at least 60 seconds, which should be determined using the Strouhal number
- At least 24 time series are required per wind direction;
- The sample frequency is at least twice the value of the frequency that is of interest for the wind effect studied. This frequency should be determined using the Strouhal number;

The measurement method applied is described in the test report, together with the number of time series, sample frequency and sample length.

Analysis methods
There is a wide range of analysis methods available to obtain structural loads from wind tunnel experiments. Below, three methods are described in some detail.

Method A: Mean values
In this methods, only time-averaged values of forces and moments are available. As the first step in the analysis the measured forces and moments are made dimensionless for every main direction of structural axis i (i = x, y of z) and for every wind direction θ measured.:

$$C_{F,i}(\theta) = \frac{F_{WT,i}(\theta)}{\frac{1}{2}\rho v_{ref}^2 A_{WT}}$$

$$C_{M,i}(\theta) = \frac{M_{WT,i}(\theta)}{\frac{1}{2}\rho v_{ref}^2 L_{WT} A_{WT}}$$

The wind velocity v_{ref} is the mean wind velocity at reference location in the wind tunnel. Values for $F_{WT,i}(\theta)$ and $M_{WT,i}(\theta)$ are determined directly form a force balance, or determined by integration of pressures $p(\theta)$, taking the loaded area *A*, and moment arm *L* into account.

The statistical distribution of the hourly mean wind speed for every direction may be taken into account by applying the factor C_{dir}, as defined in EN 1991-1-4. When no information is available, or it is not allowed to take wind direction effects into account, C_{dir} = 1. The reduction factor for the size of the loaded area c_s (as defined in EN 1991-1-4)is equal to 1.

The dynamic amplification factor c_d should be determined according to EN 1991-1-4 or similar procedures, The method applied should be motivated in the report.

The representative values for the wind loading for every wind direction for forces in the axis directions chosen i (i = x, y of z) should be determined from:

$$F_{rep,i}(\theta) = A_{vs} C_{F,i}(\theta) C_{dir}{}^2 c_s c_d\, p_w$$

and for the moments around the main axis i (i = x, y of z)

$$M_{rep,i}(\theta) = A_{vs} L_{vs} C_{M,i}(\theta) C_{dir}{}^2 c_s c_d\, p_w$$

Where p_w is the peak dynamic pressure, corresponding to the reference height in full scale, e.g. determined according to EN 1991-1-4.

Design values for the wind loads are found by multiplication of the representative values with the partial safety factor, as given in EN 1990.

Loading combinations
The loading combinations to be applied for the wind loading on the main structure should be determined using the results per wind direction. These loading combinations should be chosen so, that they cover all combinations. The choice should be motivated. Taking all combinations fulfills this demand. However, it might be more efficient to use less combinations, which cover all other combinations. This must be decided based on all results determined, and may depend on the structure of the building.

Method B: extreme-value analysis of the aerodynamic coefficients
In this method, time traces of pressures, forces or moments are available. These time traces will be used to perform an extreme value analysis of the coefficients associated with these pressures, forces or moments.

As a first step in the analysis of time series of pressures, forces and moments are made dimensionless per wind direction θ:

$$C_p(\theta,t) = \frac{p_{WT}(\theta,t)}{\frac{1}{2}\rho v_{ref}{}^2}$$

$$C_{F,i}(\theta,t) = \frac{F_{WT,i}(\theta,t)}{\frac{1}{2}\rho v_{ref}{}^2 A_{WT}}$$

$$C_{M,i}(\theta,t) = \frac{M_{WT,i}(\theta,t)}{\frac{1}{2}\rho v_{ref}{}^{2} A_{WT} L_{WT}}$$

The wind velocity v_{ref} is the mean wind velocity at reference location in the wind tunnel. Values for $F_{WT,i}(\theta,t)$ and $M_{WT,i}(\theta,t)$ are determined directly form a force balance, or determined by integration of pressures $p(\theta,t)$, taking the loaded area A, and moment arm L into account.

The statistical distribution of the hourly mean wind speed for every direction should be taken into account by applying the factor C_{dir}.

For every wind direction, the extreme value distribution of the factors $C_p(\theta)$, $C_{F,i}(\theta)$ and $C_{M,i}(\theta)$ respectively should be determined as follows:

1: Per wind direction, the time series is divided in N samples with a full scale time duration of length T (in seconds).
2: Per sample, the minimum and maximum value for the pressure coefficients are determined.
3: Per sample, the mode U_p and standard deviation a_p of the Gumbel distribution is obtained, by fitting the maximum and minimum values obtained under 2 to the general expression of the Gumbel distribution. This procedure is as follows:

1. All maxima and minima are ordered according to their height:
    a. For the maxima, the highest maximum x_m gets number m = N. The lowest maximum has number m = 1.
    b. For the minima, the lowest minimum x_m gets number m = N. The highest minimum has number m = 1.
2. For the maxima and minima, the value is obtained of
   y_m = -ln(-ln(m/(N+1)));
3. The relation between x_m and y_m, for all values in the range $0 < y_m < 3$, is obtained by the lineair expression $x_m = U_p + 1/a_p\, y_m$. This fitting procedure determines the values for U_p en a_p for both the minimum and the maximum values

4: Determine the value for $U_{p,3600}$ for the extreme value distribution of the pressures within an hour, as follows:

$U_{p,3600} = U_{p,T} + \ln(3600/T)/a_x$

This procedure results for each wind direction in two sets of $U_{p,3600}$ and a_p, one set for the minimum values and one for the maximum values.

The relation between reference wind speed in the wind tunnel, scaled to full scale, and the potential wind speed (basic wind velocity in EN 1991-1-4 is defined by the factor C_v,. This factor may be determined by the provisions given in EN 1991-1-4, applying the exposure factor c_e, or by an alternative method, approved by the local checking authority.

The reduction factor for the size of the loaded area c_s is equal to 1.

The dynamic amplification factor c_d should be determined according to EN 1991-1-4 or similar procedures, The method applied should be motivated in the report.

Per wind direction, the representative values for the loading are determined from:

$C_x(\theta) = U_{x,3600} + K \cdot 1/a_x$, for the maxima and,
$C_x(\theta) = U_{x,3600} - K \cdot 1/a_x$, for the minima;

The coefficient K is chosen so, that the resulting effect has a return period equal to the return period for the basic wind velocity. In literature, values for K equal to 1,4 are described. Work performed in the Netherlands, however, suggest values in the order of 2,9.

Per wind direction, the representative value for the wind loading is determined from:

$$p(\theta)_{VS} = C_p(\theta)\frac{1}{2}\rho v_b^2 C_v^2 C_{dir}{}^2$$

$$F_i(\theta)_{VS} = A_{VS} C_{F,i}(\theta)\frac{1}{2}\rho v_b^2 C_v^2 C_{dir}{}^2 c_s c_d$$

$$M_i(\theta)_{VS} = A_{VS} L_{VS} C_{M,i}(\theta)\frac{1}{2}\rho v_b^2 C_v^2 C_{dir}{}^2 c_s c_d$$

Design values for the wind loading
Design values for the wind loads are found by multiplication of the representative values with the partial safety factor.

Loading combinations
Local pressures
The resulting pressures are directly applicable as representative values for the local loads. For every measurement location and wind direction, two values are found; one for the maximum (usually overpressure, having positive sign), and one for the minimum (usually underpressure, having negative sign). For every location, the maximum (and minimum) value for all directions should be applied.
For the calculation of the loading on facades and roof products, the effect of internal pressures should be taken into account.

Forces and Moments
A combination of forces and moments should be chosen, which together covers all results obtained. This selection should be motivated in the test report. Taking all measured combinations fulfills this demand. However, it might be more efficient to use less combinations, which cover all other combinations. This must be decided based on all results determined, and may depend on the structure of the building.

Method C: extreme-value analysis and wind climate statistics

Method C uses a combined analysis of aerodynamic coefficients and wind climate statistics on the site. Method C may be used for local loads as well for the loads on the load bearing structure.
As a first step in the analysis of time series of pressures, forces and moments are made dimensionless per wind direction θ, similar as done in method B.

The time series of dimensionless parameters, relative to the potential wind are given as follows:

$$C_p(\theta,t)_{\mathrm{pot}} = C_p(\theta,t)C_v^2$$

$$C_{F,i}(\theta,t)_{\mathrm{pot}} = C_{F,i}(\theta,t)C_v^2$$

$$C_{M,i}(\theta,t)_{\mathrm{pot}} = C_{M,i}(\theta,t)C_v^2$$

The mode $U_{x,3600}$ and the dispersion a_x from the Gumbel distribution of the extreme values of the factors $C_p(\theta)_{\mathrm{pot}}$, $C_{F,i}(\theta)_{\mathrm{pot}}$ or $C_{M,i}(\theta)_{\mathrm{pot}}$ should be determined as described before, under method B.

The mode U_q and the dispersion a_q of the Gumbel distribution of the extreme values of the hourly mean dynamic pressure under potential circumstances should be determined. These are usually based on long term observations at meteorological stations. These are ideally also used when determining the wind climate in national standards or national annexes to the Eurocode.

The representative value of the wind loading should be determined by applying the following iterative procedure:

a: Determine the maximum allowed probability of exceedence of the wind loading. The characteristic value is defined having a return period of 50 years, or having a probability of exceedence of 0,02 per year.

b: Choose a value for the loading (Pressure, force or moment);

c: Determine per pressure, force or moment, for every wind direction, the probability of exceedence of the loading, by combining the extreme value distributions of the aerodynamic coefficients and of the dynamic pressure. The method applied should be motivated in the test report.

d: The probabilities of exceedence should be summated over all wind directions, for every pressure, force and moment.

e: If, for a pressure, force and moment, the result of d is larger than the predefined value, choose a higher value for the loading and repeat steps c and d.

If the result of d is smaller than or equal to the predefined value, the under point b chosen value for the loading has at least the level of safety which corresponds to the under a chosen probability.

This analysis should be carried out for the maxima and for the minima. This procedure is repeated for all pressures, forces and moments measured.

This procedure gives for all pressures, forces and moments two representative values for the loading; one for the maximum and one for the minimum. If applicable, these values should be multiplied by the dynamic amplification factor.

Closing remarks
This lecture has given relevant principles and insights for the use of wind tunnel experiments to obtain wind loads on structures. Since there is a range of demands, often conflicting, when setting up an experiment, there are still discussions going on about the optimal way to perform wind tunnel experiments. When wind tunnel experiments are commissioned, expert judgement of the modeling and analysis of the results is still an important issue. It depends strongly on the national regulations how this is treated in practice. It is recommended to have a second opinion on the final results before implementation of the results is done. Experience shows that differences in resulting values of 20 % are not uncommon, although methods applied, using the same measurements, may all meet the relevant demands.
Transparency of the wind tunnel results is therefore necessary. It should be traceable where the results come from, when discussions on the results are being made. The guidelines mentioned may be a valuable guidance for these discussions.

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All pictures in this note have been made by the author, unless otherwise specified.