Towards a reliable design of facade and roof elements against wind loading

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The most vulnerable parts of buildings with respect to wind loading are facades and roofs. Current standards on wind loading provide data to determine design loads for the elements in facades and roofs. These data are available for a limited number of simple building shapes. Up to now there is no common procedure to determine local loads for situations not covered by our codes, e.g. by applying wind tunnel data. Secondly, the effects of pressure equalization are not covered completely in our current generation of wind loading codes. Thirdly, in densely populated areas, the influence of nearby buildings on the local loads is very important. No design rules are available, and wind tunnel measurements are the only reliable technique available. This paper discusses the consequences of these three aspects, and gives recommendations on where to focus future research with respect to the reliability of the local wind loads.

Key words: Wind loading, facades, roofs, wind tunnel

1 Introduction

Wind-induced damage on structures most frequently occurs on facade- and roof elements, such as tiles, cladding and windows. For roofing and cladding of buildings, including their fixings, the wind is in most cases the dominant load effect. The current generation of wind loading codes specify the wind loads for such elements as local loads. The rules to account for these local wind loads in building codes and standards have been developed since the early 1990's.
On October 27, 2002, a wind storm struck large parts of the Netherlands, being the most severe storm since January, 1990. During this storm, a large amount of damage occurred on light-weight cladding and roofing. This damage has shown that current building practice, including the building codes, is still not able to safeguard against local wind loads for every situation. This leads to large costs for contractors and building owners and finally leads to an increase in the costs for insurance.
Also, damage to facade elements often leads to additional damage to surrounding buildings and extra costs for precautions necessary to secure the safety of the people in the public space. Indeed, wind loading codes fall short on a number of issues, of which three are discussed here.

1. For simple cases, such as buildings with square plan, values are available, e.g. in building codes, to determine local design loads. Many buildings however, are not covered by these standard shapes. In these cases wind tunnel experiments would be a natural option, but a widely accepted, clear procedure how to conduct and analyze wind tunnel measurements is not available. Two problems occur: firstly the current set of local design loads lacks a probabilistic basis, which may lead to either unsafe or uneconomical design of our roofs and facades, and secondly, commonly applied wind tunnel measurement equipment does not live up to the standards required for an adequate assessment of local wind loads.
2. The effect of pressure equalization may play an important role for the design of roof covering products and facade elements. Pressure equalization may under certain conditions lead to a reduction of the local loads, but may in other cases lead to an increase in the loading. Both effects are not covered well in our codes.
3. The effect that neighbouring buildings may have on the local loads is not included in our standards.

The lack of rules for determining these effects may lead to either less economical or unsafe designs of facade and roof elements. This paper addresses the issues mentioned above, and gives guidance on future developments of rules of practice to determine the local wind loads.

2 Wind loads in building codes

The current generation of wind loading codes usually specify the following:

1. A maximum level of probability of failure that should be obtained for a structure, depending on the consequences of that failure. This leads to the definition of safety classes.
2. A model for calculating the design loads, usually using partial safety factors. These safety factors are defined as function of the safety class, as determined under point 1.
3. A wind loading model.

Nowadays, building codes on wind loading in the world are all based on the principles set out by Davenport, when defining the wind loading chain (see figure 1). In general, the wind loading is defined by the following elements:

1. A dynamic pressure Q, based on a statistical analysis of the wind climate, and including the effects of gusts and terrain effects;

2. An aerodynamic coefficient *C*, translating the dynamic pressure into a pressure or force on the structure;
3. An adjustment for resonance effects of the structure, C_{dyn};
4. An appropriate safety factor γ, ensuring an appropriate level of safety during the lifetime of the structure.

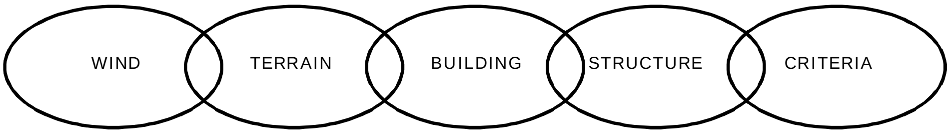

Figure 1: Wind loading chain

The characteristic value for the wind load P_{kar} follows from:

$P_{kar} = C\ Q\ C_{dyn}$

The design value follows from:

$P_d = \gamma\ P_{kar}$

The characteristic value P_{kar} is defined as the wind loading having a certain return period X, this loading is exceeded on average once during this period X. This characteristic value is calculated as a function the wind velocity v, having a return period X, where $Q = ½\ \rho\ v^2\ C_{exp}$. The coefficient C_{exp} includes the effects of gusts and exposure. The coefficient C_{dyn} is usually treated in a deterministic way in this procedure, this coefficient will not be discussed further in this paper. The coefficient *C* should be chosen so, that it is the appropriate value to arrive at P_{kar} with the required return period. The design value P_d is defined by the required reliability defined in the 'basis of design' codes.

3 Specification of local loads in building codes

The aerodynamic coefficient *C* depends on the load effect that is calculated. For the definition of the loads on facades and roofs, usually, this coefficient is expressed as a pressure coefficient. These pressure coefficients usually pertain to a loaded area, which is relevant to the effect under study. For facade elements and their fixings, this area is usually small, in the order of 1 m^2 or even smaller. This corresponds to a wind loading having a short duration, in the order of less than 1 second.

Most building codes specify pressure coefficients for small areas. These coefficients are referred to as local pressure coefficients. In building codes, local pressure coefficients are given for general cases, such as buildings with rectangular plan. Usually, figures are given with the building geometries considered, and tables or figures defining the values for the pressure coefficient depending on the location on the building envelope.

The values given in the codes, necessarily, are assumed to be safe values for a wide range of applications. For many building shapes and situations, no local coefficients are available in the codes (Geurts et.al., 2001). For buildings with a shape not covered in building codes, it may be useful or even necessary to perform wind tunnel tests to determine the local loads on facades. For those cases we need to have a clear procedure which leads to local loads which meet the performance requirements of our loading codes. These cases include:

- Buildings with a plan other than rectangular;
- Buildings with large roofs and complex roof detailing
- Local loads on the upper and lower side of canopies
- Interaction effects between buildings

In Annex A, examples are given of such cases.
The local coefficients available in current building codes, such as the ASCE specification of wind loads, EN 1991-1-4 and NEN 6702, are all based on extensive wind tunnel testing carried out, mainly in Canada, since the nineteen seventies (e.g. Stathopoulos, 1979). These codes give a wide range of coefficients for roofs and facades of mainly rectangular plan buildings having a range of roof shapes. The procedures used to obtain these coefficients are based on extreme value analysis of the measured data, however without explicit probabilistic basis. Worldwide, different analysis methods are in use to determine the local wind loads. In (ASCE, 1999) the following text is given related to the estimation of local wind loads by wind tunnel experiments:

> ***The largest peak pressures on a structure can vary by 30% or more from one measurement to another, because of a natural variation in the largest peak during a measurement period. Several methods are available to obtain a stable estimate of the peak value corresponding to the mean or mode of the probability distribution of the largest values. The methods include averaging peaks from several measurement records, extrapolating the peak values obtained at a number of subrecords to the full record using analysis, obtaining the distribution of the largest peak by measuring all independent peaks in a record followed by analysis, and direct measurement of the distribution using a large number of sample periods with one measured peak in each. All these techniques work well.***

This commentary on local loads only gives an idea of what to do when performing a wind tunnel study, i.e. one should focus on extreme values obtained. It provides a very rough idea of the accuracy we can expect when performing wind tunnel experiments according to this guideline. According to this guideline, a wind tunnel institute is more or less allowed to follow its own procedures.

Most of the analysis procedures mentioned in (ASCE, 1999) lack a probabilistic basis. The result therefore is not explicitly related to a probability of exceedence. This is not consistent with the performance-based requirements set out in e.g. the Eurocode system. Nevertheless, the values currently available for local loads have been obtained by such procedures.

We need to have an idea on the level of safety we find when applying these local loads and when measuring local loads by applying these procedures. We will discuss this later in this paper.

4 Pressure equalization

Many roof and facade systems consist of multiple layers, with an impermeable inner leaf and a more or less permeable outer leaf. This outer leaf has the function of rain screen, and is not necessarily air tight. The permeability allows a pressure equalization over the outer leaf, leading to a pressure in the cavity between the leafs that is related to the outer, rather than to the inside pressure in the building. Besides this effect, pressure equalization may occur inside the cavity between the leaves. When there is a pressure gradient on the outside, the pressure will adopt itself locally to the outside pressure, thus creating a pressure gradient in the cavity. This will lead to air flows inside the cavity. The following situation may be relevant in design of facades, see figure 2:

a)

b)

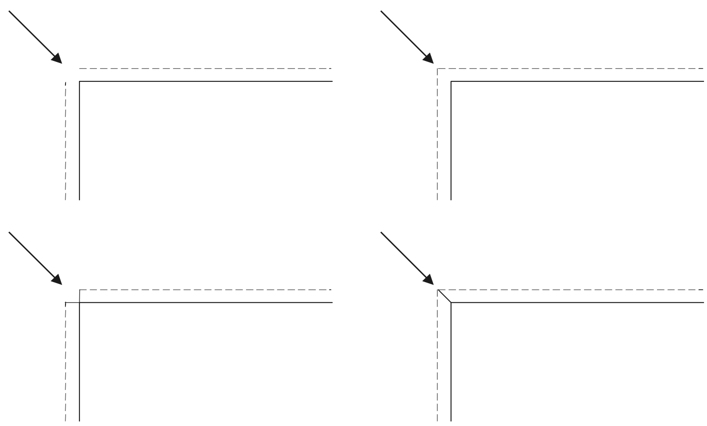

Figure 2: Schematic section over building corners. Impermeable wall (solid line) with a permeable outer leaf (dotted line). The effect of pressure equilisation depends on the situation:
Situation a leads to an increased pressure difference over the outer layer;
Situation b leads to a reduction of the pressure difference over the outer layer.

a. The pressure inside the cavity adopts itself to the outside pressure only, and cavity flows are neglected. The pressure coefficient inside the cavity has the same sign as the pressure coefficient outside. This leads to a wind load on the outer leaf that is lower than the wind load determined by the external pressure coefficient only.
   This situation usually occurs when the cavity is divided in compartments, and when there is no exchange of air between the cavities around corners of buildings of facades and roofs (see figure 2b).
b. The pressure inside the cavity near corners can have an opposite sign compared to the pressure outside. This is the case when the cavities of both sides next to the corner have an open connection (see figure 2a). This may lead to an increase of the pressure coefficient inside the cavity especially around corners. The outer leaf in this location is loaded by a larger load than obtained by applying the local pressure coefficient only.

The effect a is incorporated in some building codes by giving guidance how to determine the cavity pressure coefficient, related to the permeability of the outer and inner layer (e.g in EN 1991-1-4), or by defining a reduction of the loading by the external pressure coefficient only (e.g. in NEN 6702 by the coefficient C_{eq}). If the reducing effect of pressure equalization is not covered in the codes, usually no pressure equalizing effect is applied, and the design of facade and roof elements will be less economical but safe.
Effect b is not explicitly covered by current building codes. In EN 1991-1-4, a descriptive rule is given to avoid this situation when possible, but a rule for calculating the effects, when this situation occurs is not given. When this effect is ignored, unsafe situations may occur, leading to a too large damage probability.
Values for this effect should be included in the standards to increase the safety of our facade and roof elements. Mainly there are two ways to deal with such rules:

1. As an indication what you get when you do not take appropriate measures to avoid this effect, so that in the design stage of a facade element, these measures can be taken.
2. To give clear calculation rules for those situations that it is for some reason not possible or not economic to take measures. For those cases it should be accepted that there is an increase in local wind loading around corners of facades and roofs.

Currently, there is no uniform method available with a procedure on how to obtain these values. Wind tunnel experiments are probably not suited to estimate these effects, since scaling of the effects inside small cavities to a model scale in the wind tunnel may lead to unrealistic results. Alternative experimental techniques, based on full scale research, need to be specified for these situations, and these techniques need to be based on the probabilistic basis of our current generation of building standards. These techniques will be discussed briefly later in this paper.

5 The influence of neighbouring buildings

There is a development towards more high rise buildings closer to each other in our cities. The presence of nearby buildings may lead to an increase in the local wind loads and ultimately to damage on roofs and facades. These effects are not fully covered by our current wind loading standards. NEN 6702 gives no rules, and EN 1991-1-4 gives a very brief guidance on the effect of tall buildings on nearby smaller buildings. An example may illustrate the possible problems. Let us assume a building A that was built a while ago, which is higher than the existing surrounding buildings. In the direct vicinity, a new building B is planned. It is worth while considering the following effects (see figures 3 and 4):

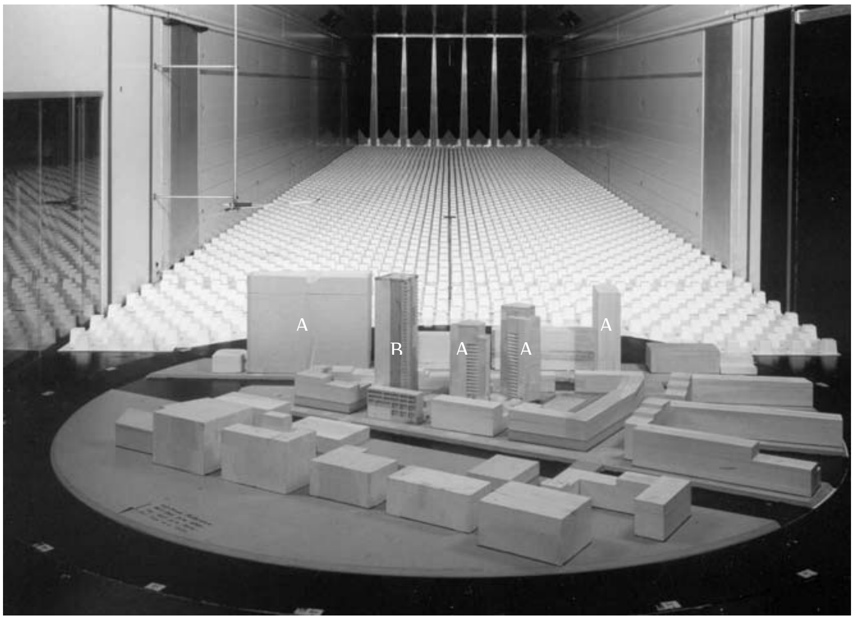

Figure 3: Wind tunnel model of a building in its intended situation to measure the effect of buildings A to the new building B

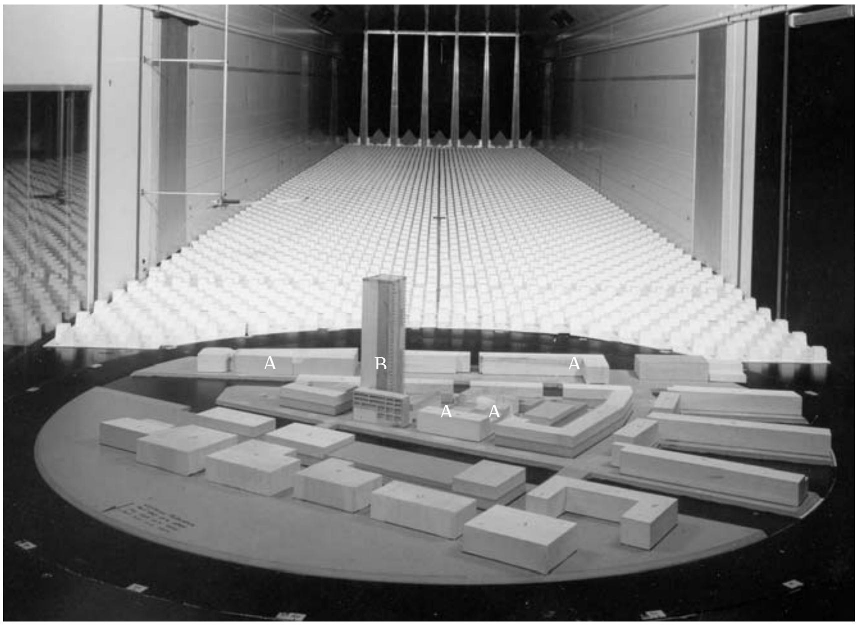

Figure 4: The same model of the building, with the height of the surrounding buildings reduced to measure the effect of removal of buildings A to the new building B

1. The effect of the existing building A on the loads of the new building B. This should be done by the designer of building B, since it is his duty to show that a structure can deal with all loads during its lifetime. In the current generation of wind loading codes however, there is no obligation, other than applying a certain terrain roughness, reference wind speed and appropriate pressure coefficients to determine the wind loads (including local loads). The assessment of the effect of nearby buildings usually is only possible by a wind tunnel investigation, or by careful selection of data from the literature based on wind tunnel experiments.
2. The effect of the new building B on the loads of the existing building A. Assuming the existing building A is designed according to the current standards the presence of a new high building may lead to local loads that can not be withstood by the facade and roofs. The designer of building A did not have to count on such unforeseen developments. The designer of building B is in the public law only responsible for the design of his 'own' building. Here again, there is no legal obligation to undertake action, apart from the possible future claims of damage, by the owner of building A, but it is up to the subjective judgement of designers whether or not this risk has been taken into account.
3. The effect on B, when building A disappears. This is a situation that is theoretically conceivable. In fact, this is the situation that is considered when straightforwardly applying the building codes.

These situations described above occur frequently, which shows the need for design guidance and inclusion in our building standards of the effects of high buildings on the wind loading on the neighbouring buildings. For individual cases, nowadays only wind tunnel research is available to estimate the effects. This increases the need for well developed guidelines for setting up, carrying out an analyzing wind tunnel experiments.

6 Wind tunnel measurements to obtain local wind loads

Wind tunnel measurements are the basis for the values given in the current building codes. Wind tunnel measurements are also used to obtain the local loads for arbitrary cases, where the building codes do not supply values. Examples are shapes of buildings not covered in the codes, but also the effects of adjacent buildings.
Current building codes do not give specific guidance on how to use wind tunnel data for the design of roofing and cladding. For instance, in ENV 1991-2-4, 'specialist advice' is mentioned, but this is a very subjective term, and there is no way to define what is a specialist, and no choice is made on the procedure to follow when studying local loads in experiments. Recently, guidelines have been published on the use of wind tunnel research in building studies (ASCE, 1999, WTG, 1995, BLWTL, 1999). These guidelines give general rules on how to set up a wind tunnel experiment for determination of wind loads on buildings an structures. In these guidelines however, no analysis procedure is given with a relation to the reliability obtained.
All three issues described before require a consistent method to obtain the local loads. Consistency means that a reliable estimate is obtained of the pressure coefficients. In the 1980's, N.J. Cook and coworkers developed an analysis model for wind tunnel data to obtain pressure coefficients with a prescribed probability of exceedence. The key question in estimating the value for *C* is formulated by Cook (1989) as:

> ***What is the value for the aerodynamic coefficient leading to a wind load with a given return period, given the wind speed with the same return period?***

Cook and others have worked on solving this question in a range of papers. The method developed uses extreme value analysis of both the wind climate and the pressure coefficients to define the probability of exceedence of the wind loading. The pressure coefficients valid for $10m^2$ in NEN 6702 and EN 1991-1-4 are based on this procedure. As discussed earlier, the values for the local loads in our current codes have not been based on this procedure, but are based on the procedures described in (ASCE, 1999). This seems not logical, but there are reasons for this discrepancy.

In a wind tunnel, the geometric scale, the wind velocity and the time are scaled. Usually, a geometric scale is applied in the range between 1:100 – 1:500, to realize an optimum of the amount of detail required in the building studied and the area of surroundings modeled on the wind tunnel turn table. The time scales in the wind tunnel usually are much shorter than in full scale. The relation between time *t*, wind velocity *v* and length scale *L* in wind tunnel (wt) and full scale (fs) is expressed as:

$$\left(\frac{tv}{L}\right)_{wt} = \left(\frac{tv}{L}\right)_{fs} \qquad (1)$$

Local loads are associated with short time scales. As a first estimate, the relation given first by Lawson can be applied (Lawson, 1980):

$$t.v = \text{Constant} \,.\, L \qquad (2)$$

In literature, values for this Constant ranging between 1 and 10 are reported (a.o. Lawson, 1980, Holmes, 2001). In the example given below, the consequences for the time scales involved in full scale and in the wind tunnel are given.
An experimental limitation is the frequency response of the pressure acquisition system. Usually, small holes are made in models, connected by flexible tubing to differential pressure transducers. The frequency response of this system is determined by :

a. the characteristics of the transducers
b. the length and diameter of the plastic tubes applied;
c. the shape of the pressure hole.

The response time of the transducers is usually not critical. Usually, the length and diameter of the plastic tubes yields an upper limit for the frequencies that can be measured accurately. This frequency lies in the order of 200 Hz in the wind tunnel.

Example:
We want to find a pressure coefficient equivalent to 1 m² in full scale. The design wind speed is 25 m/s. A typical length scale for 1 m² is about 1,5 metres in diagonal. Applying the formula (2) gives a typical loading duration of about 0,3 seconds. This requires a full scale data acquisition frequency of at least 7 Hz.
A wind tunnel model is geometrically scaled. In this example we use 1:200. The velocity in the wind tunnel in this example is 50% of the wind speed under design circumstances. The required frequency in the wind tunnel is then 7 * 200 / 2 = 700 Hz. Using higher wind velocities in the wind tunnel requires higher sample frequencies. However, currently used tubing systems are not able to follow these high frequencies.

As a result of the problems described above, it is practically impossible to obtain local loads according to the methods of Cook and others, since experimental limitations prevent wind tunnel labs to measure data with a loading duration that is short enough to be representative for local loads in full scale.
A breakthrough in the instrumentation applied is needed to solve this problem. Other solutions may be to use a much lower wind speed in the wind tunnel, but in that case the accuracy of the measurement equipment may become dominant. Using larger scales in the wind tunnel may solve this problem, but this usually leads to an increase in costs. Larger wind tunnels are much more expensive than currently used. Another solution is to base the values in our codes on full scale experiments. Full scale experiments however are very time-consuming and costly, but more important, not suited to predict local loads on a building that is in the design stage.

7 Full scale experiments

The scaling problems described above indicate that experimental data obtained in full scale nowadays are the only available option to estimate reliable data for the local loads on buildings. Full scale data however usually are obtained only for specific situations under specific local conditions. Translating these results into generally applicable models is not only possible, and at least introduces a new source of uncertainty.
However, full scale data can be analysed according to the principles by Cook, not being limited by scaling demands. Procedures for full scale data are described by (Van Staalduinen and Vrouwenvelder, 1992). These procedures are based on the work by Cook. However, only few full scale experiments are available which can be used for such analysis, and this approach can never be applied to study the loads for buildings in the design stage.

8 Recommendations

Despite being in use for about two decades now, no explicit probabilistic link has been established between the method given by Cook and others and the procedures applied in Canada and the USA when specifying the local loads, neither in various guidelines available, nor in our building codes. The authors strongly recommend to carry out a research into this link, for the following reasons:

1. Many of the wind tunnel studies into establishing wind loads deal with the specification of local loads for specific projects. In order to get agreement between the results of such studies and the reliability requirements in our building codes, a probabilistic basis is a must. If this is not achieved, either unsafe or uneconomical choices are made, and

building authorities may choose to deny wind tunnel studies as an alternative for our codes.

2. The current values for local wind loads in our codes might be too conservative or possibly unsafe. This situation can only be judged with a common procedure to compare the backgrounds of the values of local loads with the probabilistic procedures.
3. A widely accepted, probability based, procedure to obtain local loads will lead to a higher quality in our building codes and will therefore lead to reduced damage figures, thus helping the building industry to be more cost-efficient.
4. The procedures applied for the local loads in our wind loading standards may be calibrated against the probabilistic method. This gives insight into the accuracy and level of safety achieved by this method, and may provide a basis to apply this method in future work, and link it to the performance requirements of our building codes.

In the Netherlands, CUR installed a working group to draft a guideline on wind tunnel research including analysis procedures (CUR, 2003). This guideline will be finalized in 2004. This guideline will provide analysis procedures, based on probabilistic analysis to achieve the required reliability as set out in our basis of design building codes. It is recommended to perform a calibration study, as mentioned under (4) on the different analysis methods for local loads, before allowing these methods to be used. The basis as defined by Cook and others serves as the benchmark for the other methods. Full scale data my be used to perform this calibration study, since this excludes the effects of the geometrical scaling. This must be followed by a wind tunnel exercise where the outcome of various analysis procedures are verified.

9 Conclusions

Storm damage occurs most frequently at edges of buildings, where local loads are dominant. Local wind loads are given in our current codes for the external pressures on buildings. The applicability of these values is limited to the shapes given in the codes. For special cases, wind tunnel results may be needed to define the local loads. Despite the availability of many wind tunnel results and recently, guidelines on wind tunnel research, a widely accepted and probability based method to determine the local wind loads on buildings is not available. A calibration study is needed to obtain the relation between the procedures currently applied and the performance requirements of our codes.
The lack of a uniform method in our codes to determine local loads in these zones on the building may lead to an unsafe design of elements and fixings. This inevitably leads to more damage and unnecessary costs for building owner, contractors and insurance companies.

A procedure is available which is based on a probabilistic basis, but this procedure has not been applied to specify the local loads in our current codes, mainly because of experimental constraints. There is a mismatch between the required frequencies and time scales in a wind tunnel experiment on the one hand and the capabilities of current experimental techniques on the other hand.
The effects of pressure equalization are not properly covered by current building codes and can not be obtained by wind tunnel experiments. The permeability and small distances between layers in roofs and facades can not be modeled accurately enough in a scale model. Full scale experiments are needed to obtain design data for inclusion of these effects.
The effects of neighbouring buildings on local loads can only be studied well by wind tunnel investigations. The scales involved demand a compromise between the scaling requirements on one hand and the probability based procedures on the other hand.

Acknowledgements
The authors wish to acknowledge the inspiration they have received in the past and expect to get in future by the enthusiasm of Ton Vrouwenvelder, as a supervisor but most of all as a colleague.

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Annex A. Examples of building shapes not covered in our current generation of codes

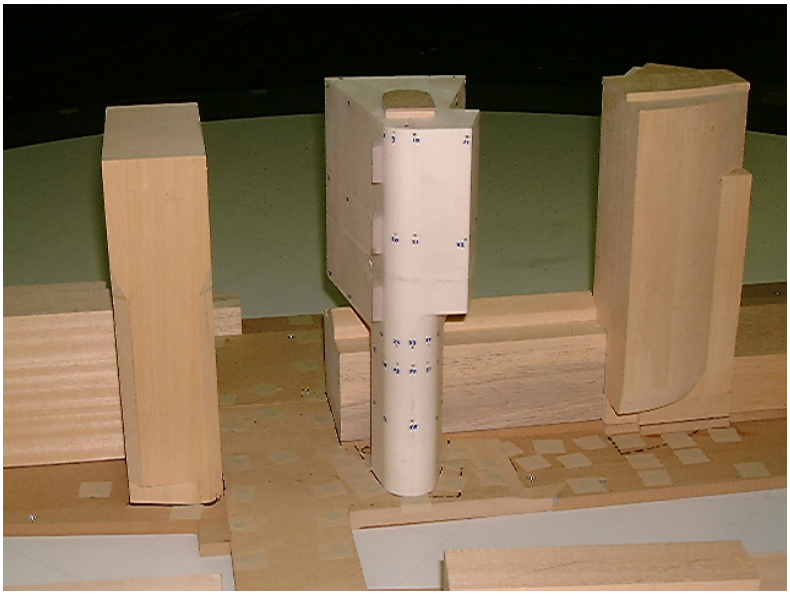

Figure A1: Building with changing plan in height; upper floors are trapezium shaped, with rounded corners

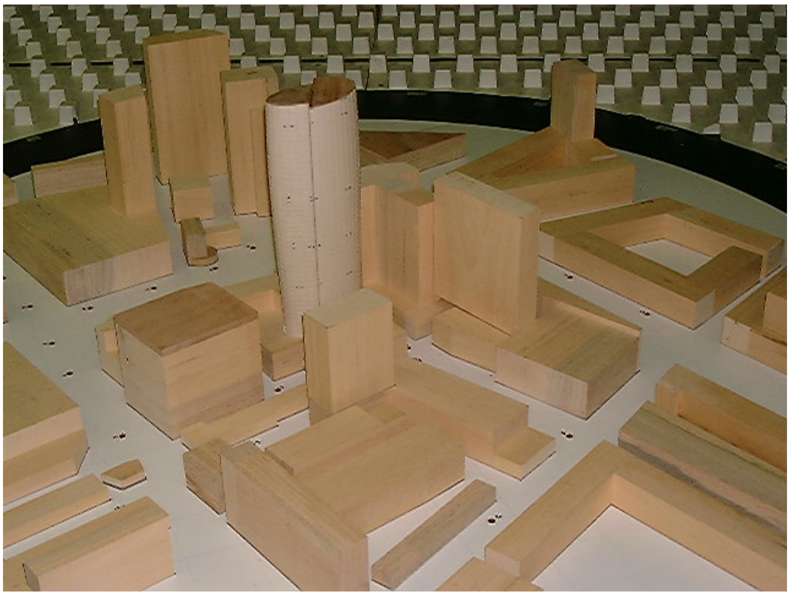

Figure A2: Ellipsoid shaped building with changing plan dimensions in height

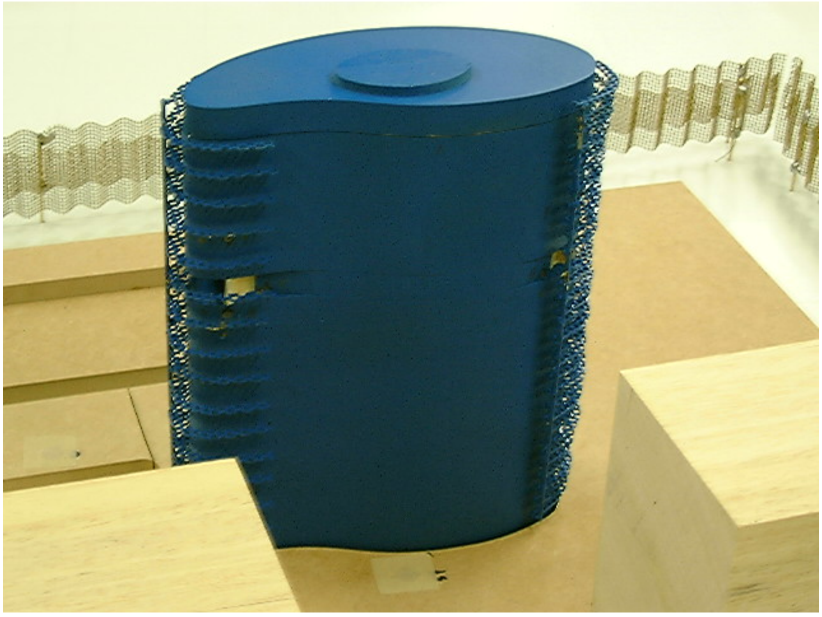

Figure A3: Building with a Kidney-shaped plan.

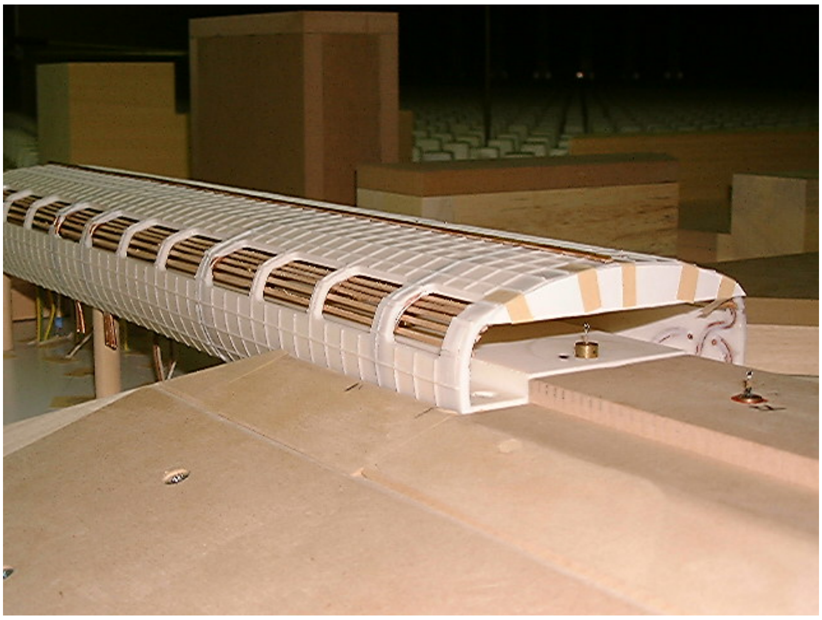

Figure A4: Station hall with a rounded shape

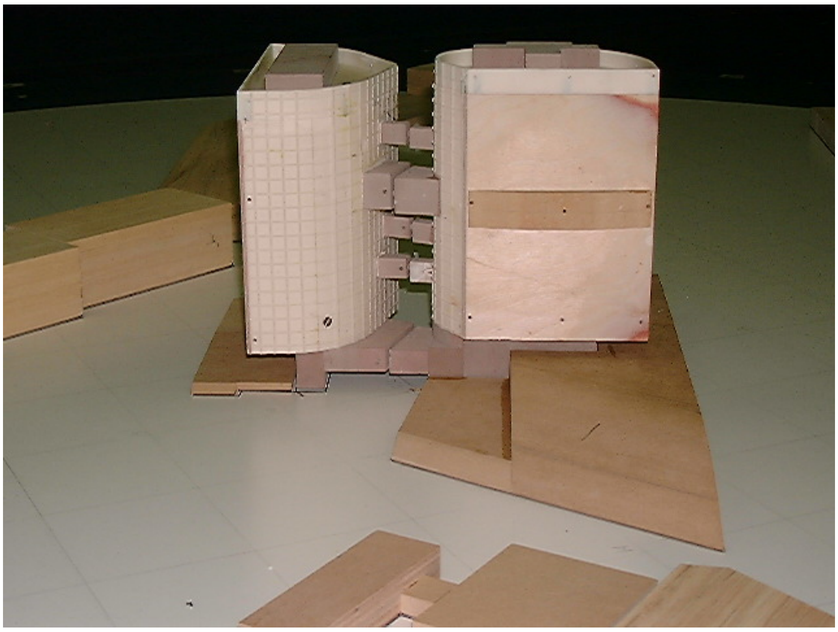

Figure A5: One building made of two towers very close to each other

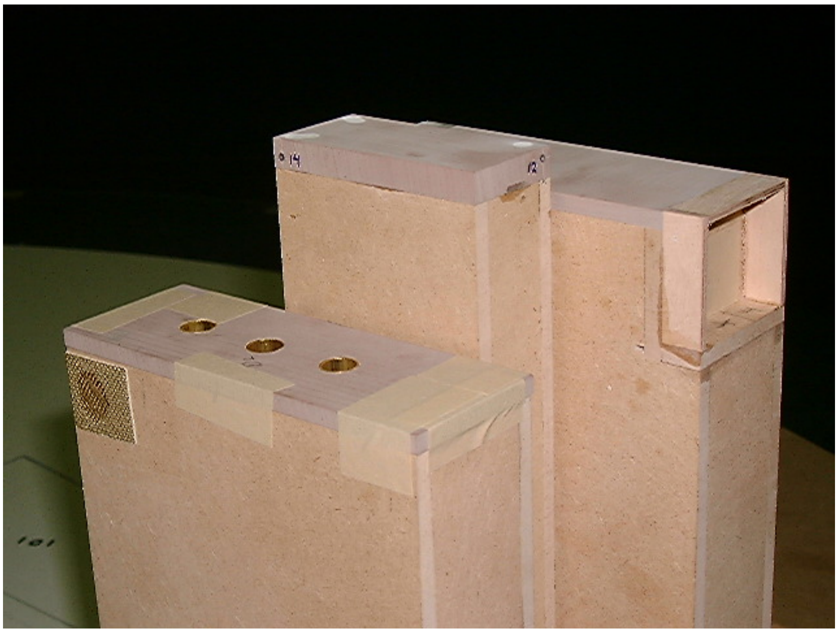

Figure A6: Detail of the top of a building model.