Wind loading on cladding and glazed façades

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Summary

The accuracy of wind loading calculations have a considerable affect on the sizing of glass facades elements, however there are substantial differences between wind loading codes in different countries. There are also significant differences between the wind loading data obtained from these codes and that obtained from wind tunnel testing.

This paper therefore reviews the nature and effects of wind loading on facades and compares the current simplified methods for predicting wind loading provided in recent international codes of practice. A numerical analysis based on computational fluid dynamics (CFD) is subsequently used to compare the accuracy and versatility of the simplified methods to the detailed modelling in wind tunnels and computational fluid dynamics methods. It is shown that the latter can offer considerable savings and highlight problem areas that are overlooked by the codes of practice.

Keywords: Wind loading, CFD, façade pressure.

1. Introduction

Wind induced pressure is a major design consideration for determining the glass thickness and glass selection in façades. However, there are often several discrepancies between the existing guidelines available for determining wind loading on façades and the corresponding pressures obtained from wind tunnel testing. Furthermore the use of emerging computational techniques for determining the wind loads on façades, such as Computational Fluid Dynamics (CFD), is relatively untested.

A façade can constitute up to 25% of the total building costs with the average cost of a façade in the region of £400 per m^2, possibly reaching £1500 per m^2 for a high specification bespoke façades. In addition, there are various safety implications inherent to glazing design such as glass breakage through imposed dynamic pressures or by flying debris and the possible domino effect in façade failure caused by the breakage of a single glass pane. Furthermore windstorms account for about 70% of total insured losses and a direct link is apparent between major storms and world wide insurance losses from major natural disasters. It is therefore evident that an accurate method for determining wind loading on façades is essential for ensuring a safe and economic glazing design.

The numerical comparisons performed in this paper are based on previous notable research in this field. Namely the full-scale test measuring surface pressures on a 6m cube in natural wind, reported by Hoxey *et al.* [5] and the corresponding evaluation of different turbulence models for use in wind engineering presented by Easom [7].

The first part of this paper consists of a brief introduction to five international wind loading codes of practice along with an introduction to wind tunnel testing and computational wind engineering and their application in the design of glazed façades. This is followed by a series of wind load predictions for a notional test case using both existing wind loading codes and CFD analysis. Finally the load predictions are compared to the results from a number of wind tunnel studies and full-scale measurements that were performed by others on an identical notional test case.

2. Prediction of wind pressures and implications for glazed façades

The critical structural design parameter for a façade is normally deflection due to wind loads in the serviceability limit state. Accurate prediction of the effects of wind pressures on glazed façades is continually developing due to the complex nature of the problem and innovation in construction methods.

This complex nature is illustrated by the dependence of the strength of structural glass on load duration. The statistical variation of negative wind pressures on façades is not well described by a normal distribution, due to the influence of turbulent flow around obstructions. Most of the subcritical crack growth in glass is caused by large pressure peaks, which may be considerably greater than the damage predicted by a normal distribution of pressure. This increased damage is shown by Ko *et al*. [1] when comparing equivalent 1-minute loads used for American glass design charts derived from actual measurements to those predicted by a typical normal distribution. Such predictions can only be performed by detailed simulations.

At a macroscopic level, the development of more complex façades often increases the building surface roughness, by the introduction of setbacks, protrusions, balconies or brises soleil, which can have an accumulating effect in tall buildings. Pressures on glass façades behind such features are very different from those on smooth façades as shown by Maruta *et al*. [2] and Rofail and Kwok [3]. Such features are difficult to form in scale models used for wind tunnel testing and vary widely from one building to another.

In summary there are three methods that may be used to predict wind loads on facades: using national codes of practice; performing wind tunnel tests; and more recently, perfuming a numerical analysis using Computational Fluid Dynamics (CFD).

2.1 Wind Loading Codes

Most consulting engineers have a very basic background of wind engineering which is often limited to the application of codes of practice. These codes of practice are based upon generic building geometries and simplified models of wind loading and great accuracy cannot be expected of them. The following characteristics are common to most advanced codes of practice:

- Specification of a reference wind speed for various locations. This is generally based on a meteorological standard of 10m in height in open country terrain.
- Calculation of site wind speed as a function of terrain type, topography and wind direction.
- External and internal pressure coefficients (possibly combined) for various simple geometries.
- Account of resonant dynamic effects of wind on flexible structures.

2.1.1 British Standard (BS6399-2:1997) [4]

Wind speed statistics are based on hourly mean wind speed and direction, along with maximum gusts recorded during each hour, as opposed to records of annual maximum gust speeds which were the basis of wind charts in previous British codes of practice. It is this superior method that has enabled the separate prediction of wind pressures for individual directions in the directional method, which is lacking in other codes of practice.

Dynamic effects on large span roofs and tall façades are not considered by the procedures in this standard and care should be taken if a façade has a low natural frequency. The standard method often provides conservative magnitudes of wind loads. The directional method requires a considerable computational effort but the resulting pressures are more accurate. Unfortunately the code provides no guidance for the possible shedding of high level winds onto low rise buildings caused by adjacent tall buildings and detailed consideration of dynamic effects is very limited.

2.1.2 Eurocode (EN 1991-1-4:2005) [5]

This paper reviews the wind loading Eurocode and accompanying British National Annex [6]. The latter was still in unpublished draft form at the time of writing. This standard is more exhaustive than most other national codes. It commendably addresses particular design issues that were previously not considered including the effects of neighbouring high-rise buildings, amplification of loads on flexible structures, detailed internal pressures and multiple skin façades.

Computerisation of the code is kept well in mind, with formulae accompanying tables and graphs. Unfortunately design charts are not always accompanied by formulae in the draft British National Annex. Moreover, the combination of main document and national annex makes it rather difficult to follow procedures, however guidance documents are currently being produced and should deal with these shortcomings

2.1.3 ESDU Datasheets (71016, 82026, 83045) [7, 8, 9]

Although not a code of practice, the Engineering Sciences Data Unit (ESDU) wind engineering series provides a comprehensive set of data sheets covering areas from global wind climate to dynamic analysis.

The ESDU data sheets are very comprehensive, offering detailed methods with specific parameters, leaving applicability and adaptation very much at the discretion of the designer. The detailed derivations and background information are very useful universal design application. Although there is no explicit methodology to follow, design is possible by following referencing along with examples provided.

2.1.4 American Code (ASCE 7-05) [10]

Despite the wide scope of this code of practice, due to the wide range of climates covered, it has some technical shortcomings such as failing to relate the internal pressure coefficients with dominant openings or the external pressure coefficients.

The commentary to the code, which is included in the same document, provides necessary design clarifications. The factors converting the basic wind speed to a site wind speed adopted by the code often account for the effect of more than one parameter. This makes it difficult for the user to appreciate the true significance of the individual parameters, although the commentary does clarify these issues.

2.1.5 Australian Code (AS/NZS 1170.2:2002) [11]

This code of practice is organised into a clear step-by-step method where appendices are set up to avoid disrupting the design flow for common wind loading scenarios. The supplement provides a useful introduction and presents references to the theory upon which the standard is based. Procedures are not always intuitive, particularly with respect to zoning of cladding pressures which is divided into multiple steps.

As a result of a history of failures attributed to fatigue and wind borne debris, the code recommends additional prototype testing for cladding and their connections within regions affected by tropical cyclones. The frequency of category 5 cyclones between 1998 and 2002 exceeded the predictions from historical data. Since cyclones often do not pass over recording stations, this recent data is based on interpretation of wind speeds from satellite imagery, and is reflected in the larger factors of safety.

2.2 Wind Tunnel Testing

The surface pressures obtained from wind tunnel testing are very sensitive to the successful simulation of the natural wind flow. This involves the artificial 'growing' of the Atmospheric Boundary Layer (ABL) by the modelling of artificial ground roughness in order to develop the required turbulence levels. In most structurally related tests, more rapid boundary-layer growth must be promoted by fins and other barriers at the start of the test section. The simulation of flow for a particular construction also requires a more accurate modelling of the surrounding areas including the topography and local characteristics such as urban layout.

Flow measurements in wind tunnels are normally restricted to surface pressure. However, when assessing façades, difficulties arise due to geometrical constraints. Measurements are normally taken by ducting the pressure through tubes from holes in the surface, known as tappings. The combined response of the tubing and transducers is of great importance, particularly when localised peak pressures are required. Area and time averaging of pressures can be achieved by physically connecting the ducts, or computationally. More expensive laser anemometers are able to measure flow data at a distance without disturbing the flow.

Although wind tunnel testing is an established technique used extensively in wind engineering, it is still a simulation prone to error and must therefore be benchmarked. Comparisons between full scale tests on existing buildings and wind tunnel tests have shown good correlation although discrepancies do exist [12]. Comparisons among different wind tunnel tests for the same scenario have been used for sensitivity analyses and to quantify the reliability of the modelling process. Such reliability comparisons have shown small but systematic errors indicating modelling discrepancies as opposed to random variation [13].

2.3 Computational Fluid Dynamics

Although simulations in wind tunnels can give accurate measurements, such information is limited to a number of particular points on the building surface. Instrumentation is expensive and requires skill for use and calibration. As an alternative, simplified analytical methods can be used to describe very simple flow problems. However, for more complicated flow problems, numerical methods must be used where the fundamental mathematical equations of fluid flow are converted into a form solvable by computer.

CFD offers little advantage over experimental tests when overall wind forces for building stability calculations are required, as the effects of localised differences of wind pressure on the building surface tend to cancel each other out. However, when the detailed and localised flow structure is required, such as when pressures are required for façade design, the set up used in experimental techniques becomes complicated and the design loading data is very sensitive to errors in localised pressures. In such cases numerical methods can be useful for determining the detailed pressures over a façade.

Unfortunately, in flows above a particular Reynolds number (governed by fluid density, velocity and viscosity), the fluid motion is turbulent and apparently random. Although it is possible to model fluid flow to the scale of the smallest turbulent vortex, this would require substantial computational power. To overcome this problem, instantaneous flow velocities are divided into mean and fluctuating components, which are replaced into the equations of motion. Reynolds Averaged Navier-Stokes (RANS) turbulence models are used to predict the effects of the fluctuating components on the mean flow. Several turbulence models are available, some much more widely validated than others, such as the k-ε model. Easom [14] provides a comprehensive review of different turbulence models relevant to computational wind engineering. As the processing power of computers increases, there has been a trend to use turbulence models that directly compute the fluctuating large turbulent eddies while still relying on RANS models to compute the less significant small scale turbulence. Two such techniques are Large Eddy Simulation (LES) and Detached Eddy Simulation (DES).

Both wind tunnel testing and CFD methods are very sensitive to the inlet boundary conditions which define the simulated atmospheric boundary layer. This means that in either simulation, the mean and gust wind speed alone are not sufficient to perform a simulation. The ‘growing’ of an artificial boundary layer within a wind tunnel is quite well understood and validated from full scale measurements. In CFD simulations, this is replaced by formulae defining the inlet conditions for the flow. However this practice is not widely validated, particularly for transient turbulence models such as LES. Mean pressures are generally much better predicted than peak pressures in such simulations.

Computational methods are not sufficiently understood and are only used occasionally, with validation against experiment. However they are very promising since very detailed flow information can be extracted. Additionally, CFD has applications in dynamic analysis of sensitive constructions that are dynamically sensitive to lateral deflections such as large span suspended glass facades. The use of fluid-structure interaction analysis, which is a combination of CFD and dynamic structural analysis, can be used for most dynamic applications. Its use however, is still in relative infancy, particularly in the field of building structures.

3. Numerical Investigation

A test case was required to make an objective comparison of the methods described in Section 2 and to quantify the accuracy of these methods. In order to remove any modelling errors, it was decided to use data from a full-scale and widely validated test that was performed by researchers at the Silsoe Research Institute (SSI) [15] as a control reference point. A number of CFD calibration studies were also carried out by Easom [14], which served as an initial verification for the CFD simulations in this study. Detailed data from the full scale test were available in the form of a CFD competition which was reviewed by Richards *et al*. [16].

The SSI experiment comprised of a simple 6m cube in a natural atmospheric boundary layer in an open country site in Bedford, UK. Two cases are contemplated, one with wind arriving normal to one of the cube faces and another with wind arriving at 45˚ to a cube face. This relatively simple experiment generates most of the complex flow features encountered around building structures. The measured 10 minute mean wind speed was of 10m/s at a height of 10m and this was used for the analyses reported in this paper.

3.1 Calculations using wind loading codes

The 6m cube was analysed using the five different codes of practice listed in Section 2.1. In all cases the most accurate method provided by the individual standard was adopted. Calculations were performed to determine the effective peak gust speeds as well as the respective internal and external pressures. The internal pressures were calculated assuming a uniform permeability over all walls with no dominant openings. Results of the code of practice calculations are presented in Table 3-1 and Fig. 3-2 to 3-8.

Table 3-1 Wind Loading Code wind speeds and Internal Pressures

Result	BS 6399	Eurocode	ESDU	ASCE	AS/NZS
Basic wind speed*	9.55 m/s	10 m/s	9.55 m/s	14.04 m/s	14.04 m/s
Averaging time	1 hr	10 min	1 hr	3s	3s
Design gust speed	14.52 m/s	13.92 m/s	13.21 m/s	13.32 m/s	13.03 m/s
Internal Pressure	-30.4 Pa	-35.61 Pa	-21.39 to -42.79 Pa	±19.58 Pa	0.0 or -20.37 Pa

* Conversion of basic wind speeds carried out using ESDU 83045

3.2 CFD Simulation

No internal pressure predictions were made using CFD simulations due a lack of comparative data. The geometrical model used for the CFD simulation is shown in Fig. 3-1. The cross-section of the computational domain was chosen to give a blockage ratio of 2%. The outlet distance was selected to be far enough to develop equilibrium with the inlet conditions.

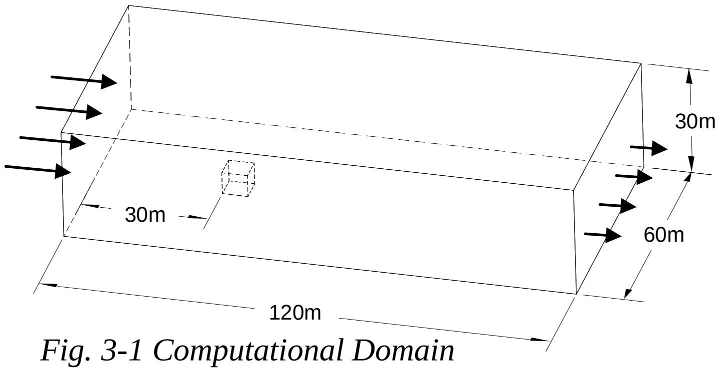

Fig. 3-1 Computational Domain

A parametric mesh sensitivity analysis was carried out. However an acceptable convergence was not reached due to memory limitations. Further refinements by means of adaptive meshing helped to achieve better convergence within the memory limitations. This technique involves generating an initial rough mesh and performing an analysis. Depending on the gradients found within the results, the mesh is then refined automatically where needed. The process is repeated a number of times with refinement being guided by custom parameters. Data generally used to describe the boundary conditions of the CFD study are presented in Table 3-2, based on full scale measurements where relevant. Steady state analyses used to develop the adaptive mesh were performed using an RNG k-ε turbulence model following recommendations by Easom [14]. The final transient analyses were performed using a DES turbulence model.

3.3 Results

The numerical results of the various analyses are best compared using non-dimensional, external aerodynamic pressure coefficients (C_{pe}). These values are multipliers to the dynamic pressure at a particular location, present due to the effective peak gust speed and are normally used directly for design purposes.. This direct combination of gust speed and C_{pe} is based on quasi-steady theory, where it is assumed that all the fluctuations of load are due to the gusts of the boundary layer, thus ignoring the turbulent fluctuations generated by the building. Fig. 3-2 to 3-10 show the values of C_{pe} predicted by the different codes of practice and CFD analyses.

The directional method of BS6399-2 enables calculation for the two wind directions separately. On the other hand, the values resulting from the other standards represent an envelope for the most onerous values evaluated for wind directions of -45˚ through to +45˚.

It should be noted that the C_{pe} values from the ESDU datasheets are not directly applicable to façade design as they are derived from a uniform flow as opposed to a turbulent ABL. However, they are presented here to illustrate the distribution of measured values.

Table 3-2 CFD Boundary layer parameters

Parameter	Value	
Inlet Data		
Normal speed	$u_z = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right)$	(1)
u_* (frictional velocity)	0.625 m/s	
κ (Von Karman constant)	0.4	
z (height)	0 → 30 m	
z_0 (ground roughness)	0.01 m	
k (turbulent kinetic energy)	3.805 m^2/s^2	
ε (Eddy Dissipation)	$\frac{u_*^3}{\kappa(z+z_0)}$	(2)
Outlet Data		
Type	Opening	
Relative pressure	0 atm	
k (turbulent kinetic energy)	as inlet	
ε (Eddy Dissipation)	as inlet	
Cube Surfaces Data		
Type	No slip, rough wall	
Roughness height	0.005 m	
Floor Surface Data		
Type	No slip, rough wall	
Roughness height	0.01 m	
Side and top wall Data		
Type	Free-slip wall	

Fig. 3-9 shows the results of the transient CFD analysis. C_{pe} values are based upon the mean of 1200 values calculated for each of the two simulations. The initial values necessary to kick-start the simulations were provided by the steady state simulations, which were also used to generate the adaptive grid.

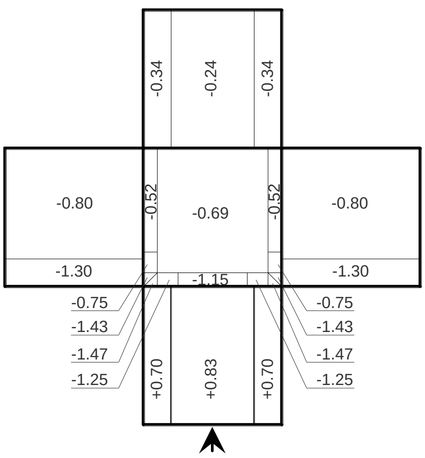

Fig. 3-2 BS6399 C_{pe} values (Wind normal to cube)

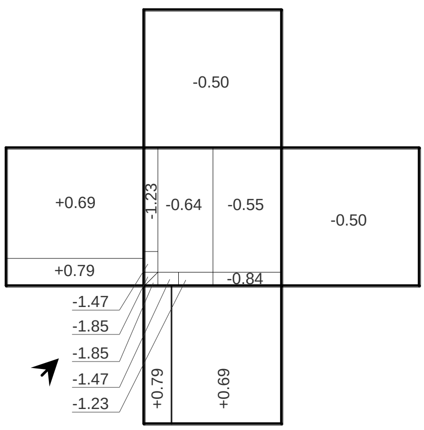

Fig. 3-3 BS6399 C_{pe} values (Wind 45˚ to cube)

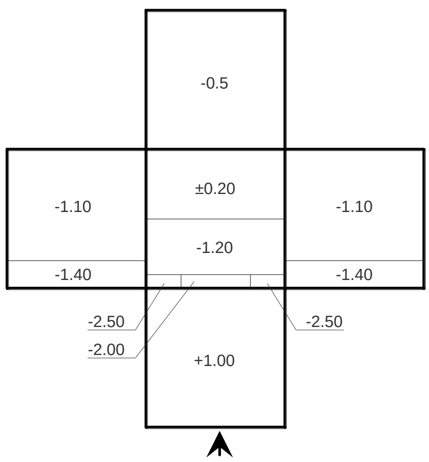

Fig. 3-4 Eurocode C_{pe} values

Fig. 3-10 and 3-11 illustrate a small sample of the flow velocity data generated by the transient CFD simulation. Fig. 3-10 is a vertical section through the centre-line of the computational domain where a number of important flow characteristics can be seen, namely, the stagnation point (S), flow separation (F), reattachment point (R) and downwind reattachment (D). The successful prediction of these characteristics determines the overall accuracy of pressure predictions on the cube surfaces. Fig. 3-11 is a horizontal section through mid-height of the 6m cube and clearly depicts the flow characteristics that lead to high negative pressures near the upwind edges of the side faces of a façade. It also shows the generation of downwind vortices which are eventually shed alternately from the structure as new vortices form.

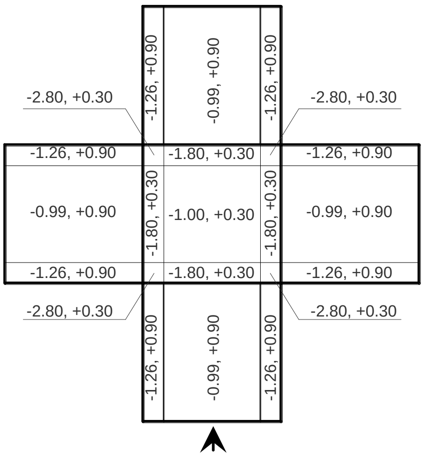

Fig. 3-5 ASCE C_{pe} values

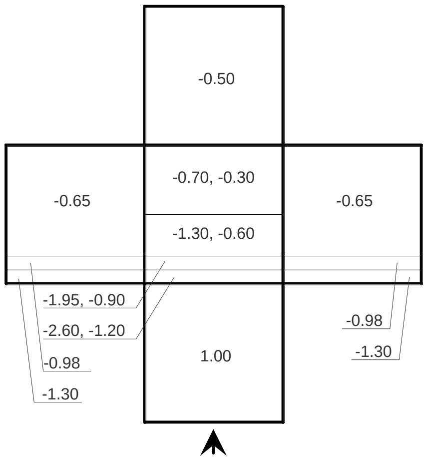

Fig. 3-6 AS/NZS C_{pe} values

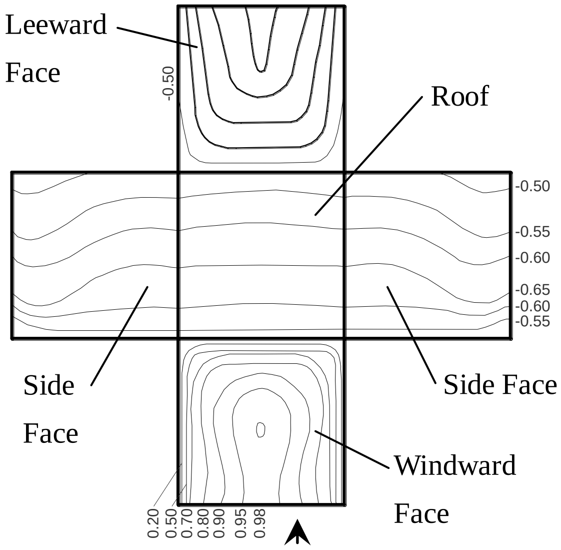

Fig. 3-7 ESDU C_{pe} values (Wind normal to cube)

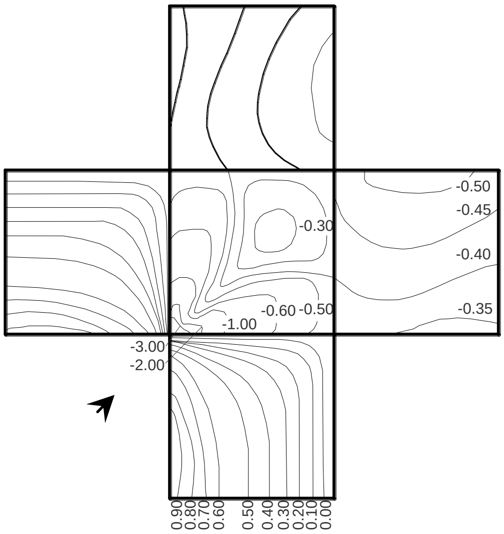

Fig. 3-8 ESDU C_{pe} values (Wind 45˚ to cube)

3.4 Comparison and discussion

An examination of the results of the code of practice C_{pe} diagrams will reveal that the directional method of BS6399-2 predicts the lowest values, followed by the ASCE 7-05, the Eurocode and the AS/NZS 1170.2. Comparisons of particular values should be performed with care since some diagrams consider the effects of wind direction whereas others do not. For example, the ASCE 7-05 diagram is a complete design chart considering wind coming from any direction. Comparisons between the code values and those in Fig. 3-7 and 3-8 provide an indication of the simplifications adopted by the codes of practice. This gives an insight as to how complex pressure distributions can be, particularly in dense urban contexts. However this would be difficult to codify into a standard since each large building modifies the urban wind flow thereby modifying the pressure distribution over surrounding buildings. The possibility of construction of new tall buildings further complicates the problem, increasing the number of load cases. The general flow

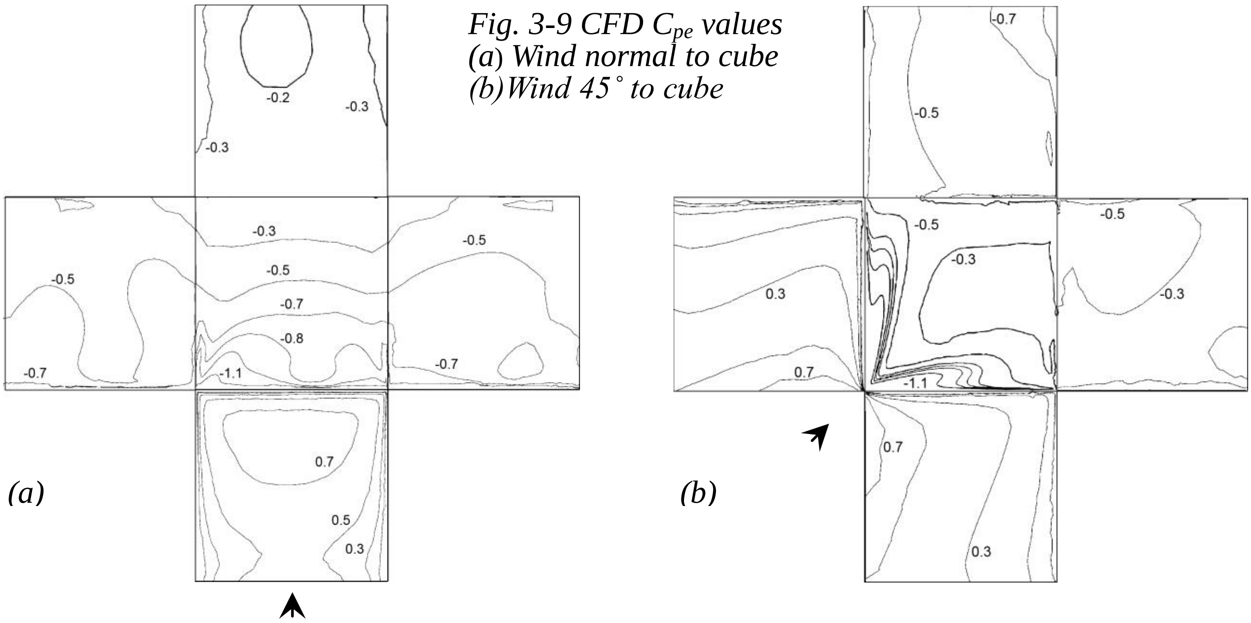

Fig. 3-9 CFD C_{pe} values
(a) Wind normal to cube
(b) Wind 45˚ to cube

characteristics such as flow separation and reattachment were all simulated as shown in Fig. 3-10 and 3-11 and this is reflected in the correct distribution of surface pressures. Positive pressures are particularly well correlated with full scale measurements as shown in Fig. 3-12.

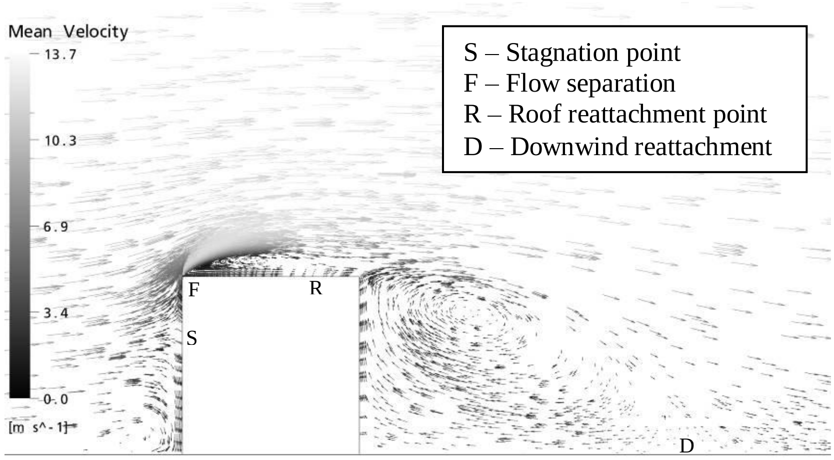

Fig. 3-10 Vertical section through flow normal to cube

Unfortunately, the location of reattachment points was not accurately predicted (35% error). As a result, locations where flow separation occurred produced less accurate results.

Fig. 3-12 shows the pressure distribution along the vertical centre line of the cube. The roof pressures predicted by the DES turbulence model produce the poorest correlation with the full scale pressures, with a mean error of 36%.

Results are however, within the scatter plot of a number of wind tunnel tests reported by Hoxey *et al*. [12]. In addition, the results obtained using DES and an adaptive grid show an improvement over previous CFD simulations for the same problem [16].

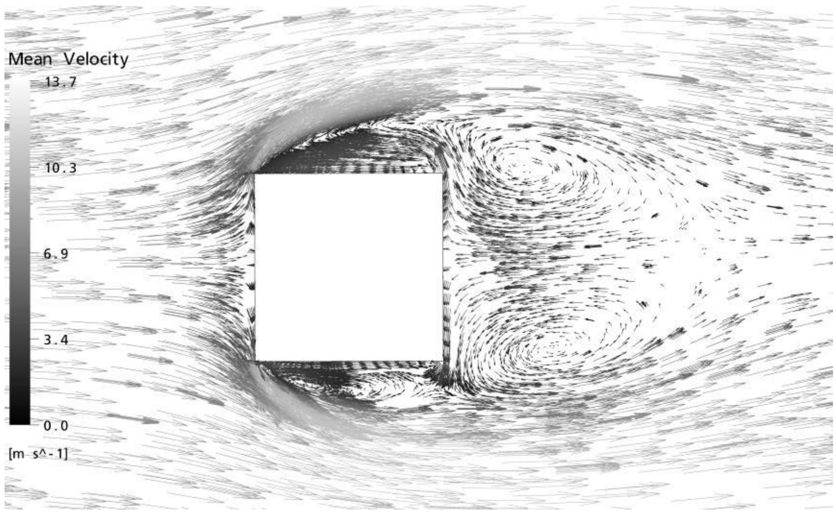

Fig. 3-11 Horizontal section through flow normal to cube

4. Conclusions and future work

This study has reviewed the nature and effects of wind loading on façades and qualitatively compared the recent international codes of practice to computational wind engineering and wind tunnel testing. A basic quantitative comparison was also achieved by determining the external pressure coefficients on a notional 6m cube test case through CFD analysis. The results from this analysis were compared to those obtained from international codes of practise, a full scale test in a naturally occurring wind environment and the respective wind tunnel tests.

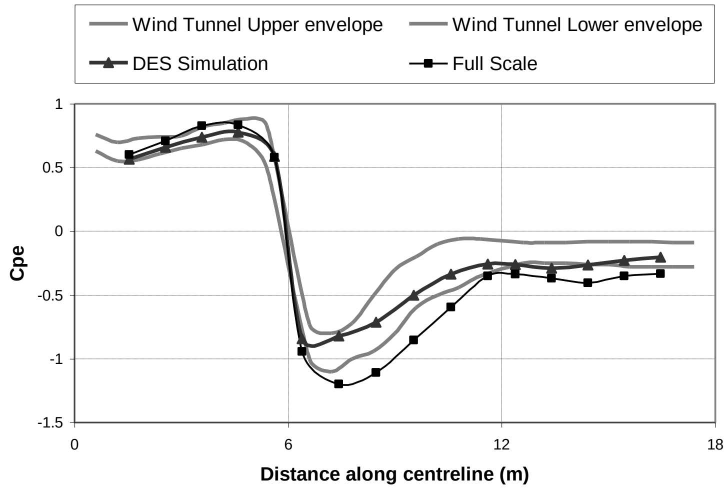

Fig. 3-12 Vertical centreline C_{pe} values

From the numerical investigations carried out, the generic accuracy of the methods in descending order is: wind tunnel testing, computational wind engineering and wind loading codes of practice. Furthermore the CFD results in this research provide an improvement in accuracy over previous studies. This was mainly due to the use of an adaptive grid coupled with the selection of a Detached Eddy Simulation turbulence model.

Design wind speeds predicted by different codes of practice did not differ significantly among each other, except for wind speeds from the British and European codes of practice which are explained by different definitions of terrain roughness. Internal pressures predicted by the same codes varied widely due to different simplifying assumptions made by the standards.

Despite being limited to simple geometries, codes of practice, were found to significantly overestimate façade pressures for the simple notional cube reviewed in this study. This overestimation is most pronounced in local pressure calculations, which are critical for designing façade elements. However in some instances codes of practice underestimated the wind pressure to an extent that it could affect the design of isolated façade or cladding components.

6.2 Limitations of the study

The numerical aspect of this study has only considered a very simple test case. Although such a configuration produces most of the different flow characteristics occurring around a building, more complex flow occurs in urban contexts and intricate building geometries. Unfortunately full scale and wind tunnel results are less readily available for such cases. In terms of the CFD analysis a number sensitivity analyses were performed, it could not be conclusively shown that a grid independent solution (i.e. optimum convergence) was found.

6.3 Future studies and recommendations

A number of such studies would be required to increase the confidence placed in computational wind engineering. In this respect a study with an increased level of complexity should be preformed. This would typically include a tall building in a dense urban context. The data obtained from computational wind engineering should subsequently be compared and validated with wind tunnel data and full scale measurements of the building in question.

The DES turbulence model used in conjunction with an adaptive grid has proven to be a promising method. Definition of boundary conditions is simpler than that required in LES making it more amenable to routine design methods. However further assessments for its use in computational wind engineering should include the investigation of mesh sensitivity, the blending of LES flow calculations with steady-state modelling within the DES turbulence model and the coupling of the RNG k-ε turbulence model within DES methods instead of the SST model used in this study.

At this stage however, overall validation by wind tunnel experiment remains essential for any computational wind method including CFD. However, CFD can be a very useful tool in façade design as this computational method produces a level of detail of flow information that would be very difficult to extract from a wind tunnel. Such information can be used to inform the geometrical design of the façade and give indications of the effects of a new construction on surrounding buildings along with pedestrian comfort predictions. To enable CFD to be used as a practical design tool there is an urgent need for guidelines for computational wind engineering. The development of these guidelines would require a thorough sensitivity analysis of the parameters used in CFD simulations along with validation procedures for common flow problems and verification of accuracy and convergence criteria.

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