Applications of computational wind engineering in the design of glass façades

Mauro Overend, Kenneth Zammit, David Hargreaves
School of the Built Environment, University of Nottingham

Keywords

1=wind loading 2=glass strength 3=computational fluid dynamics 4=façade design

Abstract

There is a general awareness within the glass design community about the discrepancies that exist between the various calculation methods for determining the load-bearing resistance of glass. One particular area where these differences are most pronounced is in the design of glass for resisting wind induced pressures. Since wind induced pressure is often the critical load in most glass façades, these discrepancies are therefore a cause of some concern for glass designers as they cast doubts on whether the glass thicknesses being specified are overly conservative or possibly unsafe. This paper attempts to quantify these discrepancies by undertaking a quantitative comparison of the various predictive methods available. The results of this study show that differences between one method and another may yield variations of up to100% in glass thicknesses and that emerging computational methods may provide an accurate and economical alternative to traditional wind loading and glass design methods in the near future.

1 Introduction

The sizing of the façade elements is often dictated by the requirement to resist the lateral action of wind loading. However, there are several methods available for determining the thickness of glass for resisting wind induced pressures. Most methods are often based on a variety of simplifying assumptions, resulting in notable discrepancies in glass thickness from one method to another.

These substantial discrepancies are also compounded by the fact that there are two main stages for designing glass panels to resist wind loading.

1. Determining / characterising the wind pressures resulting from turbulent wind flow around buildings for given geographical and physical conditions.
2. Determining the effect of the wind-induced cyclic pressures on subcritical crack growth in the weathered glass and consequently on the strength of the glass.

As with other design techniques the most efficient methodology is the one that yields maximum accuracy (construction cost saving) with minimum effort (design cost saving) thereby minimising overall cost. In view of the recent developments in the understanding of glass strength, the advances in computational wind engineering and the unflagging popularity of glass façades it is pertinent to review the current design methodologies and to propose new ones.

This first part of this paper deals with the first stage of the problem, i.e. predicting wind pressures on façades, and discusses the existing knowledge and recent developments in this field. A simple 6m cube test case is used to quantify the differences in wind loading from one method to another. The second part of the paper addresses the second stage of the problem by describing a range of national and international glass design recommendations. Calculations from these recommendations are subsequently used to determine the glass thickness required to resist the wind loads obtained from the previous stage. The paper concludes with a quantitative comparison of the various methods and with a description of the planned work in this research project.

2 Prediction of wind pressures on façades

There are three primary methods that may be used to predict wind loads on façades: using national codes of practice; performing wind tunnel tests; and more recently, performing numerical analyses by means of Computational Fluid Dynamics (CFD). The prevalent approach adopted by consulting engineers is to perform calculations using codes of practice for all buildings and to undertake wind tunnel testing for large-scale or unusual structures. This approach has stood the test of time, however it creates some disadvantages, namely that:

1. Most façades are designed on the sole basis of simplified codes of practice which are often overly conservative and sometimes unsafe
2. Pressures on glass façades in the vicinity of small scale façade roughness such as façade setbacks and protrusions, balconies or brises soleil are very different from those on smooth façades as shown by Maruta et al. [1] and Rofail and Kwok [2] Such features can have an accumulating effect in tall buildings and are notoriously difficult to model in wind tunnel testing due to modelling limitations.

An additional inconsistency that was identified and illustrated by Ko et al. [3] is that the statistical variation of wind pressures on façades is assumed to follow a normal distribution. However, the turbulence induced by the wind flow around buildings gives rise to wind pressures on façades that are not well described by a normal distribution. An accurate statistical representation would provide more a precise time-resolved stress history. This has been largely overlooked by the engineering community as it has little or no influence for most materials used in the construction of façades, however it has a significant influence on glass strength which is notoriously sensitive to stress history.

2.1 Existing data for 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 full-scale field measurements undertaken by researchers at the Silsoe Research Institute (SRI) [4] as a control reference point. The SRI experiment comprised of a simple 6m cube in a natural atmospheric boundary layer in an open country site in Bedford, UK. Two cases were considered, 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 undertaken by the authors and reported in this paper. Field measurements of wind speed, turbulence intensity and surface pressures from the full scale test were available in the form of a

CFD competition which was reviewed by Richards et al. [5]. A number of CFD calibration studies were also carried out by Easom [6], which served as an initial verification for the CFD simulations in this study.

2.2 Calculations using wind loading codes

In the first stages of this research, the 6m cube was analysed using the five different codes of practice [7]. In the instances where a code of practice provided alternative methods, the most accurate method was always 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. These results were re-evaluated in this study, using a 10 minute basic wind speed of 28m/s instead of the 10m/s wind speed which recurs frequently at the Bedford site. Results of the code of practice calculations are presented in Table 2-1

2.3 CFD Simulation

CFD simulations where undertaken to predict the external pressures on the cube, but no internal pressure predictions were made using CFD simulations due a lack of comparative data. The computational domain used for the CFD simulation is shown in Fig. 2-1 and is based closely on the domain used by Straw [15], with a slightly longer downwind fetch used in the present study to ensure the wake region was captured in its entirety. The cross-section of the computational domain was chosen to give a blockage ratio of 2%. The boundary layer parameters are listed in [7] and are not reproduced here for brevity. A transient Detached Eddy Simulation (DES) turbulence model was used as opposed to steady state models, so as to capture the effects of the fluctuating wake. Time averaged pressures were computed to calculate external pressure coefficients.

2.4 Wind assessment results

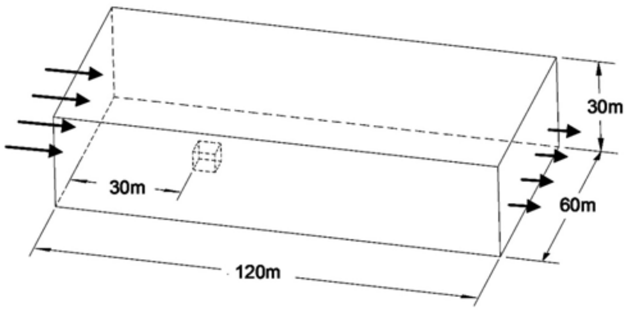
Fig. 2-2 and 2-3 show the instantaneous velocity vectors generated by the transient CFD simulation. Fig. 2-2 is a vertical section through the centre-line of the computational domain where a number of important flow characteristics can be identified, namely, the stagnation point (S), flow separation (F), reattachment point (R) and downwind reattachment (D). The successful generation of these characteristics increases the confidence in the overall accuracy of pressure predictions on the cube surfaces. Fig. 2-3 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 (X). It also shows the generation of downwind vortices which are eventually shed alternately from the structure as new vortices develop (Y), to form a von Karman vortex street.

The general flow characteristics such as flow separation and reattachment were all simulated as shown in Fig. 2-2 and this is reflected in the correct distribution of surface pressures. Positive pressures are particularly well correlated with full scale measurements.

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

Figure 2-1

Computational Domain



Result	BS 6399 [8]	Eurocode [9], [10]	ESDU [11], [12]	ASCE [13]	AS/NZS [14]	Full Scale	CFD
Basic wind speed*^{1} (m/s)	26.74	24	26.74	39.13	39.13	26.74*^{2}	26.74*^{2}
Averaging time	1 hr	10 min	1 hr	3s	3s	1 hr*^{2}	1 hr*^{2}
Design gust speed (m/s)	40.42	41.15	38.39	37.12	36.31	38.39*^{2}	38.39*^{2}
Internal Pressure (Pa)	-235.6	-311.4	-180.7	+152	0.0	-235.6*^{3}	-235.6*^{3}
Max. External Pressure (Pa)	-1301.9	-1453.3	-1174.9	-1064.3	-1050.8	-858.55	-813.37

**^{1} Conversion of basic wind speeds to 10 minute mean wind speed using ESDU 83045 *^{2} Based upon ESDU wind speeds *^{3} Based upon BS6399 internal pressures*

Table 2-1

Wind Loading Code wind speeds and Pressures

Fig. 2-4 shows the pressure distribution along the vertical centre line of the cube. The roof pressures predicted by the CFD simulations produced the poor 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. [16] also shown in Fig. 2-4. In addition, the results obtained using a DES turbulence model and an adaptive grid show an improvement over previous CFD simulations for the same problem [5].

3 Glass design

3.1 Analysis parameters and methodology

In order to illustrate the effect of the range of wind pressures on glass thickness selection, a number of analyses were carried out using the pressures obtained from the methods described in Section 2.

Calculations were carried out for rectangular glass panels measuring: 2m x 3m and 2.5m x 3.5m and simply supported along their four edges. Different glazing configurations were assessed using a variety of glass types as illustrated in Tables 3-1 and 3-2.

The predicted maximum local pressures on the vertical faces of the cube analyzed in section 2 were obtained from each code of practice calculation (Table 2-1). The location of this maximum pressure was always at the leading edge of the side face of the cube, relative to the wind direction and coincided with the point of maximum flow separation. This location is consistent with location of the maximum façade pressure measured in both the full-scale experiments and the CFD analyses. This local pressure was assumed to act uniformly over the glass surface. Unfortunately the reported wind tunnel data for the SRI cube [16] does not include wind pressures in the side faces. It was therefore not possible to perform glass thickness calculations from wind tunnel data.

Internal pressures calculated from BS6399-2 were applied separately on the innermost face the glass, where appropriate.

In determining the glass thickness, three design methods were used:

BS6262-3:2005 [17] – This standard presents a series of design charts which provide the resistance of 4-edge supported glazing panels. Parameters such as glass surface area, aspect ratio and design pressure are selected by the user in order to determine the required glass thickness.

prEN 13474-3:2007 [18] - The January 2007 unpublished revision of this draft standard gives a general method for glass design. Other parts of this standard specifically formulated for design of glass panes and other special applications are still under development. The standard is based on limit state design, therefore different load factors are used when assessing deflection (serviceability) and stress (ultimate). Notably, a factor of 0.8 is adopted for wind-induced deflections. This is statistically equivalent to using a mean hourly wind speed which will be exceeded for a maximum of 2 hours per year (BRE 346-7 [19]).

Non-linear analysis and TRLV 1998 [20] – The finite element modelling software SJ MEPLA [21], that was specially developed for glass, was used in conjunction with the allowable stresses from the German TRLV 1998. Since deflections are not limited in the German codes of practice for this type of glazing, a limit of span / 65, set in prEN13474-3:2007, was used. Figure 3-1 shows the principal stresses within one of the laminated glass panes analysed.

3.2 Glass calculation results

Tables 3-1 and 3-2 show a matrix of the results using alternative codes of practice for the 2m x 3m and 2.5m x 3.5m glass panels respectively. Upon close inspection of the analyses and comparison of results, a number of deductions were made:

- With a few exceptions, Heat Strengthened and Toughened glass thicknesses are deflection controlled.
- Different glass design methods assume a varying shear stiffness of the PVB interlayer in laminated glass. The order of descending stiffness is – SJ MEPLA, BS6262-3, prEN13474.
- Some inconsistencies can be identified in the load distribution within Insulated Glazing Units (IGUs), particularly within BS6262 where discrepancies affect the required glass thickness when compared to the other methods.
- prEN13474 generally requires a lower glass thickness for toughened glass. This can be traced back to the deflection limitations of this type of glass and the recommended application of a 0.8 factor to the wind load for serviceability limit state calculations.
- Considerable savings can be achieved by performing a detailed simulation for wind loading. When considering 4-edge supported annealed glazing, savings of up to 50% of the glass thickness are possible.
- Discrepancies among wind loading codes of practice can be traced back to basic recommendations for internal pressures, gust averaging times and the development of turbulence intensity resulting from individual definition of the upwind terrain ground roughness.
- For the specific conditions of this test case there was perfect agreement between the glass thicknesses obtained from CFD analysis and the glass thickness calculated form the full scale measurements.

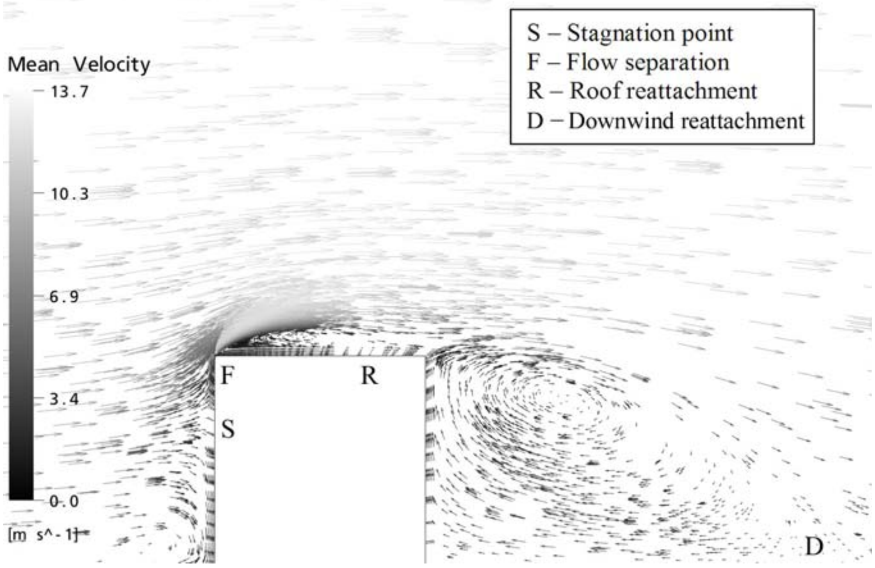


Figure 2-2

Vertical section through flow normal to cube

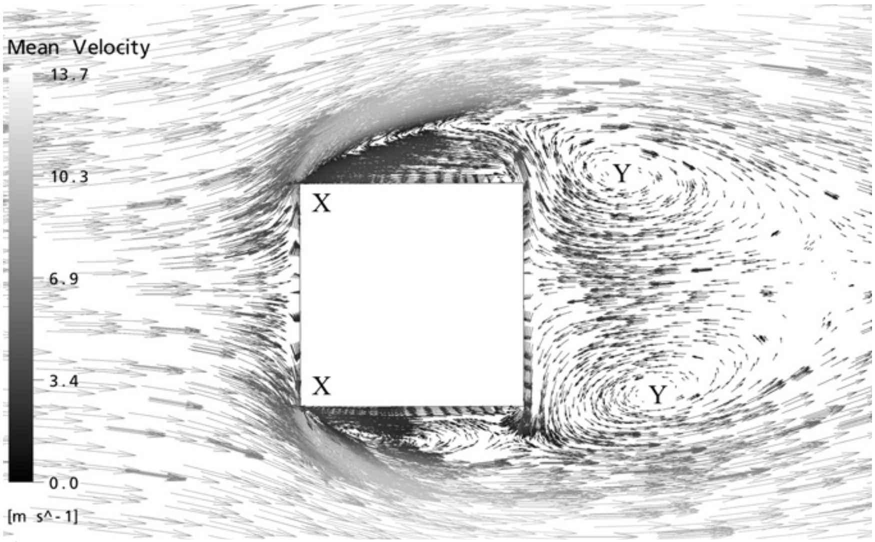


Figure 2-3

Horizontal section through flow normal to cube

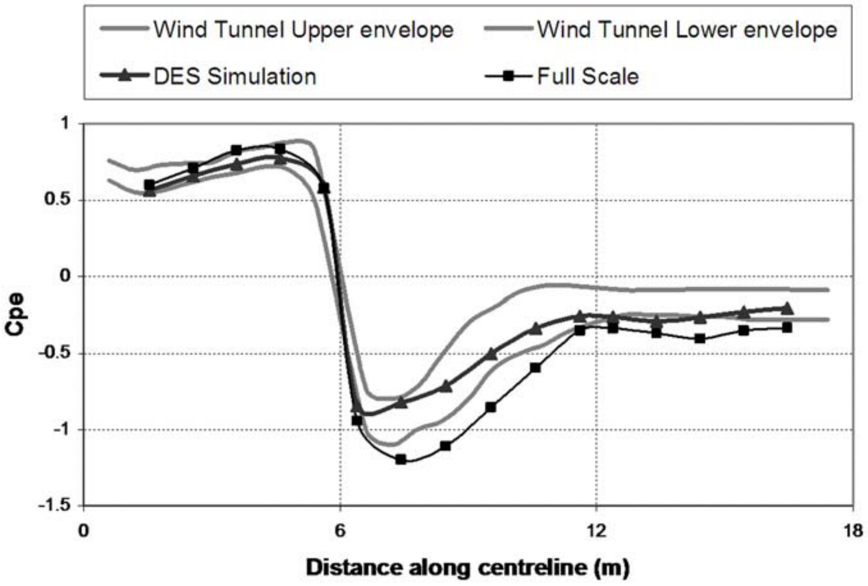


Figure 2-4

Vertical centreline Cpe values

	Glass Type	BS6399-2	EN 1991-1-4	ESDU	ASCE 7-05	AS/NZS 1170.2	Full Scale/CFD
BS6262-3:2005	Monolithic Annealed (AN)	8mm	10mm	8mm	10mm	8mm	6mm
	Monolithic Heat Strengthened (HS)	N/A	N/A	N/A	N/A	N/A	N/A
	Monolithic Full Toughened (FT)	6mm	8mm	6mm	8mm	6mm	5mm
	Laminated Glass (0.76mm PVB) (AN)	4+4mm	5+5mm	4+4mm	5+5mm	4+4mm	3+3mm
	Laminated HS Glass (0.76mm PVB)	N/A	N/A	N/A	N/A	N/A	N/A
	IGU (AN, AN)	4mm, 6mm	6mm, 6mm	4mm, 6mm	6mm, 6mm	4mm, 6mm	4mm, 4mm
	IGU fully toughened (FT, FT)	4mm, 6mm	4mm, 6mm	4mm, 4mm	4mm, 6mm	4mm, 6mm	3mm, 4mm
	IGU laminated (AN+AN), monolithic (A)	3+3mm, 6mm	3+3mm, 6mm	3+3mm, 4mm	3+3mm, 6mm	3+3mm, 6mm	3+3mm, 4mm
MEPLA + DIBt 6/1998	Monolithic Annealed (AN)	8mm	8mm	8mm	8mm	8mm	6mm
	Monolithic Heat Strengthened (HS)	6mm	8mm	6mm	8mm	6mm	5mm
	Monolithic Full Toughened (FT)	6mm	8mm	6mm	8mm	6mm	5mm
	Laminated Glass (0.76mm PVB) (AN)	4+4mm	4+4mm	3+4mm	4+4mm	4+4mm	3+3mm
	Laminated HS Glass (0.76mm PVB)	3+4mm	3+4mm	3+3mm	3+4mm	3+4mm	3+3mm
	IGU (AN, AN)	5mm, 6mm	5mm, 6mm	4mm, 6mm	6mm, 6mm	5mm, 6mm	4mm, 4mm
	IGU fully toughened (FT, FT)	4mm, 5mm	4mm 6mm	4mm, 5mm	4mm, 6mm	4mm,5mm	3mm, 4mm
	IGU laminated (AN+AN), monolithic (A)	3+3mm, 5mm	3+3mm, 6mm	3+3mm, 5mm	3+3mm, 6mm	3+3mm, 6mm	3+3mm, 3mm
prEN13474-3:2007	Monolithic Annealed (AN)	10mm	10mm	8mm	12mm	10mm	6mm
	Monolithic Heat Strengthened (HS)	5mm	5mm	5mm	6mm	5mm	4mm
	Monolithic Full Toughened (FT)	5mm	5mm	5mm	5mm	5mm	4mm
	Laminated Glass (0.76mm PVB) (AN)	6+6mm	6+6mm	5+5mm	8+8mm	6+6mm	4+4mm
	Laminated HS Glass (0.76mm PVB)	4+4mm	4+4mm	3+3mm	4+4mm	4+4mm	3+3mm
	IGU (AN, AN)	6mm, 6mm	6mm, 6mm	6mm, 6mm	6mm, 6mm	5mm, 6mm	4mm, 4mm
	IGU fully toughened (FT, FT)	3mm, 4mm	4mm, 4mm	3mm, 4mm	4mm, 4mm	3mm, 4mm	3mm, 3mm
	IGU laminated (AN+AN), monolithic (A)	3+3mm, 8mm	4+4mm, 6mm	3+3mm, 8mm	4+4mm, 6mm	3+3mm, 8mm	3+3mm, 3mm

Table 3-1

Glass Thickness Matrix for 2m x 3m, 4-edge supported pane

	Glass Type	BS6399-2	EN 1991-1-4	ESDU	ASCE 7-05	AS/NZS 1170.2	Full Scale/CFD
BS6262-3:2005	Monolithic Annealed (AN)	12mm	12mm	10mm	12mm	12mm	8mm
	Monolithic Heat Strengthened (HS)	N/A	N/A	N/A	N/A	N/A	N/A
	Monolithic Full Toughened (FT)	8mm	8mm	8mm	8mm	8mm	6mm
	Laminated Glass (0.76mm PVB) (AN)	6+6mm	6+6mm	5+5mm	6+6mm	6+6mm	4+4mm
	Laminated HS Glass (0.76mm PVB)	N/A	N/A	N/A	N/A	N/A	N/A
	IGU (AN, AN)	6mm, 6mm	10mm, 10mm	6mm, 6mm	10mm, 10mm	6mm, 6mm	4mm, 6mm
	IGU fully toughened (FT, FT)	6mm, 6mm	6mm, 6mm	4mm, 6mm	6mm, 6mm	6mm, 6mm	4mm, 4mm
	IGU laminated (AN+AN), monolithic (A)	3+3mm, 10mm	5+5mm, 6mm*FT	3+3mm, 6mm	3+3mm, 8mm*FT	3+3mm, 10mm	3+3mm, 4mm
MEPLA + DIBt 6/1998	Monolithic Annealed (AN)	10mm	10mm	10mm	10mm	10mm	8mm
	Monolithic Heat Strengthened (HS)	8mm	8mm	8mm	8mm	8mm	6mm
	Monolithic Full Toughened (FT)	8mm	8mm	8mm	8mm	8mm	6mm
	Laminated Glass (0.76mm PVB) (AN)	4+5mm	5+5mm	4+5mm	5+5mm	4+5mm	3+4mm
	Laminated HS Glass (0.76mm PVB)	4+4mm	4+4mm	3+4mm	4+4mm	4+4mm	3+3mm
	IGU (AN, AN)	6mm, 8mm	6mm, 8mm	6mm, 8mm	6mm, 8mm	6mm, 8mm	4mm, 6mm
	IGU fully toughened (FT, FT)	4mm, 6mm	5mm, 6mm	4mm, 6mm	5mm, 6mm	4mm, 6mm	4mm, 4mm
	IGU laminated (AN+AN), monolithic (A)	4+4mm, 5mm	4+4mm, 6mm	4+4mm, 4mm	4+4mm, 6mm	4+4mm, 5mm	3+3mm, 4mm
prEN13474-3:2007	Monolithic Annealed (AN)	10mm	12mm	10mm	12mm	10mm	8mm
	Monolithic Heat Strengthened (HS)	6mm	8mm	6mm	8mm	6mm	5mm
	Monolithic Full Toughened (FT)	6mm	6mm	6mm	6mm	6mm	5mm
	Laminated Glass (0.76mm PVB) (AN)	6+6mm	8+8mm	6+6mm	8+8mm	6+6mm	5+5mm
	Laminated HS Glass (0.76mm PVB)	4+4mm	4+4mm	4+4mm	4+4mm	4+4mm	3+3mm
	IGU (AN, AN)	6mm, 8mm	6mm, 8mm	6mm, 8mm	8mm, 8mm	6mm, 8mm	5mm, 5mm
	IGU fully toughened (FT, FT)	4mm, 4mm	4mm, 4mm	4mm, 4mm	4mm, 5mm	4mm, 4mm	3mm, 3mm
	IGU laminated (AN+AN), monolithic (A)	4+4mm, 8mm	3+3mm, 10mm	4+4mm, 8mm	4+4mm, 10mm	4+4mm, 8mm	3+3mm, 6mm

**FT Fully Toughened glass for monolithic pane*

Table 3-2

Glass Thickness Matrix for 2.5m x 3.5m, 4-edge supported pane

5 Conclusion

Since the interaction of wind and façades is a relatively complex phenomenon, a wide range of simplified guidelines and standards are available for determining the wind induced pressures on façades. The different simplifying assumptions adopted by these guidelines give rise to discrepancies in glass thickness selection from one standard to another. This paper illustrates the differences that exist between some of the more widely used national and international standards by comparing the glass thickness requirements for a 6m cube. The results from the standards were compared to those obtained from a CFD analysis undertaken by the authors and to field measurements reported by other researchers.

The authors identified the two key stages in this design process, namely the characterisation of the wind induced pressure and the determination of the glass strength. From the analysis of the results the authors concluded that:

1. Detailed computational analysis may yield savings of up to half the glass thickness when compared to standards.
2. There are several discrepancies in calculations for laminated glass and IGUs particularly when dealing with wind loads or other transient forms of loading.

5.1 Limitations of the study and on-going research

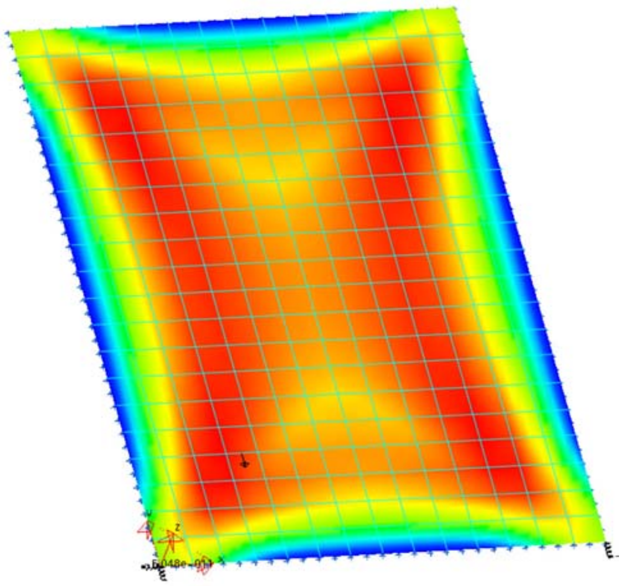
The research reported in this paper represents on-going work in this field, as such the reader should be aware of the following limitations:

- The glass thickness calculations are based on the worst single gust pressure i.e. the stress history on the glass surface was not considered in detail but the relevant wind loading factors were adopted from the standards listed in Section 3.1.
- The wind loading was assumed to act uniformly over the entire glass panel. This is unlikely to be the case, but errs on the safe side.
- Glass panels in façades are subjected to a wide range of actions other than wind loading (e.g. thermal loads, impact loads etc.) these were not included in this study.
- Other national and international codes of practice (e.g. DIN, ASTM) were not included in this study.

On-going research in the is field is being undertaken jointly by the Glass & Façade Technology Research Group and the Environmental Fluid Mechanics Research Group at the University of Nottingham.

Figure 3-1

Maximum tensile principal stresses at the bottom face of the lower layer of a 4+5mm laminated glass pane



The research will address some of the above-mentioned limitations by:

- Analysing the effects of the wind-induced stress history to glass panes by undertaking a statistical analysis of wind loading and its effect on subcritical crack growth in weathered glass.
- Determining the structural response of IGU panels subjected to wind loading by means of numerical analysis and experimental investigations.
- Improving the application of CFD to façade design by performing wind tunnel calibration studies.

6 References

[1] MARUTA E., KANDA M. and SATO J., "Effects on surface roughness for wind pressure on glass and cladding of buildings", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 74-76, 1998, pp. 651-663.

[2] ROFAIL A.W. and KWOK K.C.S., "The effect of sunshading elements on cladding pressures", 10th international conference on wind engineering, Copenhagen, 1999.

[3] KO N., YOU K. and KIM Y., "The effect of non-gaussian local wind pressures on a side face of a square building", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 93, No. 5, 2005, pp. 383-397.

[4] RICHARDS P.J., HOXEY R.P. and SHORT L.J., "Wind pressures on a 6m cube", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 89, 2001, pp. 1553-1564.

[5] RICHARDS P.J., QUINN A.D. and PARKER S., "A 6m cube in an atmospheric boundary layer flow Part 2. Computational solutions", Wind and structures, Vol. 5, No. 2-4, 2002, pp. 177-192.

[6] EASOM G., Improved turbulence models for computational wind engineering. Thesis (PhD), University of Nottingham, 2000.

[7] OVEREND M. and ZAMMIT K., "Wind loading on cladding and glazed façades", Proceedings of the 2nd International Symposium on the Application of Architectural Glass, Munich, 2006.

[8] BS 6399-2:1997. Loading for buildings – Part 2: Code of practice for wind loads. BSI.

[9] EN 1991-1-4:2005. Eurocode 1: Actions on structures – Part 1-4: General actions - wind actions. CEN.

[10] NA to BS EN 1991-1-4, Draft 4.10a, 2005. U.K. National Annex to Eurocode 1: Actions on structures – Part 1-4: General actions - wind actions. BSI.

[11] ESDU Data Item 82026, Revision E, 2002. Strong winds in the atmospheric boundary layer. Part 1: hourly-mean wind speeds. London: ESDU International.

[12] ESDU Data Item 83045, Revision C, 2002. Strong winds in the atmospheric boundary layer. Part 2: discrete gust speeds. London: ESDU International.

[13] ASCE 7-05. Minimum Design Loads for Buildings and Other Structures. American society of civil engineers.

[14] AS/NZS 1170.2:2002. Structural design actions. Part 2: Wind actions. Standards Australia, Standards New Zealand.

[15] STRAW M.P., Computation and measurement of wind induced ventilation, Thesis (PhD), University of Nottingham, 2000.

[16] HOXEY R.P., RICHARDS P.J. and SHORT J.L., "A 6m cube in an atmospheric boundary layer flow Part 1. Full scale and wind tunnel results", Wind and structures, Vol.5, No. 2-4, 2002, pp. 165-176.

[17] BS 6262-3:2005. Glazing for buildings – Part 3: Code of practice for fire, security and wind loading. BSI.

[18] prEN 13474-3:2007. Unpublished Draft. Glass in building - Determination of the strength of glass panes - Part 3: General method of calculation and determination of strength of glass by testing. CEN.

[19] BRE Digest 346-7. The assessment of wind loads. Part 7 – Wind speeds for serviceability\ and fatiue assessments. BRE, Watford, 1989.

[20] TRLV 1998. Technische Regeln für die Verwendung von linienförmig gelagerten Verglasungen (TRLV). Technical report, Mitteilungen des Deutches Institut für Bautechnik (DiBT), Berlin, 1998.

[21] SJ MEPLA. Version 2.5.5. SJ Sofrware GmbH, 2006. URL http://www.SJ-Software.de