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Improved computational methods for determining wind pressures and glass thickness in façades

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Wind induced pressure is a major design consideration for determining the glass thickness and glass selection in façades. However, the effects of wind loading history on glass are largely neglected or grossly simplified. The use of computational techniques, such as Computational Fluid Dynamics (CFD), to tackle these issues is relatively untested in contrast to other fields of engineering where CFD is used as a routine design tool. This paper firstly addresses the use of boundary conditions which maintain the wind speed profile as it varies with height above the ground, a problem afflicting several CFD studies in the atmospheric boundary layer. It is then shown how CFD can be used together with wind tunnel studies to tackle difficult design situations. Subsequently, the effects of fluctuating wind loads on the structural strength of glass are assessed using transient, geometrically non-linear analyses and improved glass failure prediction models. Results are compared to those from current glass design standards where only peak gust pressures are considered, where it transpires that such a detailed analysis can give up to a 35% increase in efficiency.

Keywords: Glass strength, Wind, General crack growth model, CFD

1. Introduction

1.1. Background to the problem

New and exciting buildings are being constructed, pushing forward the boundaries of engineering knowledge. The effects of wind flow over these tall and / or geometrically complex structures are often outside the scope of wind loading codes of practice and require detailed wind tunnel investigations in order to establish overall and local wind pressures.

Modern wind loading codes of practice are based on wind tunnel studies with their main focus dedicated to overall building loads. These are generally measured using a high frequency base balance measuring overall shear and overturning moments at the base of the building. In contrast, façade loads are measured using pressure taps distributed over the model surface.

Façades are also becoming increasingly intricate, with diverse overall and detailed geometry often stemming from requirements of energy efficiency. This, along with pressures to achieve a high profile image desired by clients, has resulted in dramatic increases in façade cost, sometimes exceeding £1500 per m^2. In such façades, wind tunnel testing can easily be justified for façade design given the significant cost benefit.

Although glass is the predominant material in modern façades, it is a relatively new material when one considers that the float process was commercially developed in the 1960s. Consequently, glass design codes of practice are very often limited to specific design situations with restricted design procedures. There is also little agreement between codes of practice in different countries. As a result, there is a need in the façade industry to bring wind engineering and glass design together to form a clear basis for design. This is even more important when considering that the specialist façade market is international with designers operating in different countries, often leading to disputes when the design basis is not clearly defined.

1.2. Limitations of existing techniques

Wind loading codes of practice are limited to simple building geometries and offer little to no guidance on complex façade geometries. Moreover, predicted façade pressures tend to be considerably higher than those measured in wind tunnel tests as shown in Table 1. Great care needs to be taken when simple codes are used in complex situation since these can easily produce unsafe designs.

Table 1: Wind Loading Code wind speeds and Pressures [1]

Result	BS 6399 [2]	Eurocode [3], [4]	ESDU [5], [6]	ASCE [7]	AS/NZS [8]	Measured Pressures	CFD
Design gust speed (ms^{-1})	40.42	41.15	38.39	37.12	36.31	38.39	38.39
Max. External Pressure (Pa)	-1301.9	-1453.3	-1174.9	-1064.3	-1050.8	-858.55	-813.37

Glass codes of practice often use large factors of safety covering different aspects of glass design making it difficult to adapt to new design situations. As a consequence of this it is also difficult to address load combinations with different durations, although this is currently being tackled within the development of prEN13474 [9]. All codes of practice however, give very limited consideration to the wind-induced stress history which gives rise to sub-critical crack growth in the glass. The effects of this stress corrosion are not explicit in the code safety factors and are at best represented by a generic equivalent load duration.

Wind tunnel testing is based on scaled models (about 1:200) of the entire building, giving a physically limited number of pressure taps over the whole façade area. This results in substantial extrapolations of pressure distribution which cannot give an accurate representation of pressure integration over façade areas. In order to address the effect of non-simultaneous action of peak pressures, these can be averaged in time instead of being averaged over an area. However, there currently is lack of agreement among different countries on such temporal averaging, which can give substantially different figures. The scales used in wind tunnels also give rise to modelling limitations, where complex façade geometries cannot be represented, once again leaving loading values open to interpretation. Recent advances in computational power enable the capture of transient and simultaneous load data, however these are not normally used in façade design.

1.3. Paper outline

This paper firstly outlines the developments in Computational Fluid Dynamics (CFD), addressing simulation issues which often afflict computational wind engineering. This section also shows how information extracted from CFD analyses can be used to tackle some of the limitations of wind tunnel testing. The second part of the paper describes the transient analysis carried out using existing time varying field measurements, to assess the effects of fluctuating wind loads on the structural strength of glass within a single skin façade. This is undertaken using transient, geometrically non-linear analyses and improved glass failure prediction models. Finally, results are compared to those from current glass design standards where only peak gust pressures are considered.

2. CFD Simulation

2.1. Existing and future modelling

Although simulations in wind tunnels can give accurate measurements, such information is limited to a number of particular pressure taps on the building surface or anemometers placed around the buildings. 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, the finite differences method is used to solve the Navier-Stokes equations for fluid flow which are discretised and solved iteratively.

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. Mean pressures are generally much better predicted than peak pressures in CFD simulations.

Indeed, much of this is due to the prevalent use of steady Reynolds-Averaged Navier-Stokes (RANS) turbulence models, which were predominantly designed for streamlined flow in the aerospace, automotive and chemical industries. When surface-mounted bluff bodies such as buildings are present, RANS models perform particularly poorly by failing to predict, in particular, the correct separation and reattachment on the roofs of low-rise buildings [10]. Recently, Hanjalic [11] wrote a critical review of the future of RANS models for all engineering applications. He indicated that while RANS models had found successful niches in certain applications, this was not true for all – indeed this can be said for wind engineering. The future of CFD modelling in the prediction of structural loads in wind engineering lies firmly in the use of unsteady simulations, making use of unsteady RANS, Detached Eddy Simulations (DES) and Large Eddy Simulations (LES). This will put a strain on computer resource but the switch to unsteady simulations also opens up a number of other possibilities to the modeller. Rather than focussing on the mean pressures on a building in a well-characterised Atmospheric Boundary Layer (ABL), unsteady CFD modelling could be used to assess the validity of the quasi-steady theory. Modelling single, high speed gusts could become possible, initially only for a few seconds of real time, but with longer periods and more gusts being added as simulation capabilities increase with time.

2.2. Consistent inlet boundary conditions

Both wind tunnel testing and CFD methods are very sensitive to the boundary conditions which define the simulated ABL. This means that in either approach, 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 [12], [13]. However this practice is not widely and accurately adopted, particularly for transient turbulence models such as LES. Indeed, LES simulations require the specification of inlet conditions that vary both spatially and temporarily. The generation of such conditions is the focus of much current research (e.g. Xie and Castro, [14]) and represents a real sea change in the approach to the specification of inlet conditions.

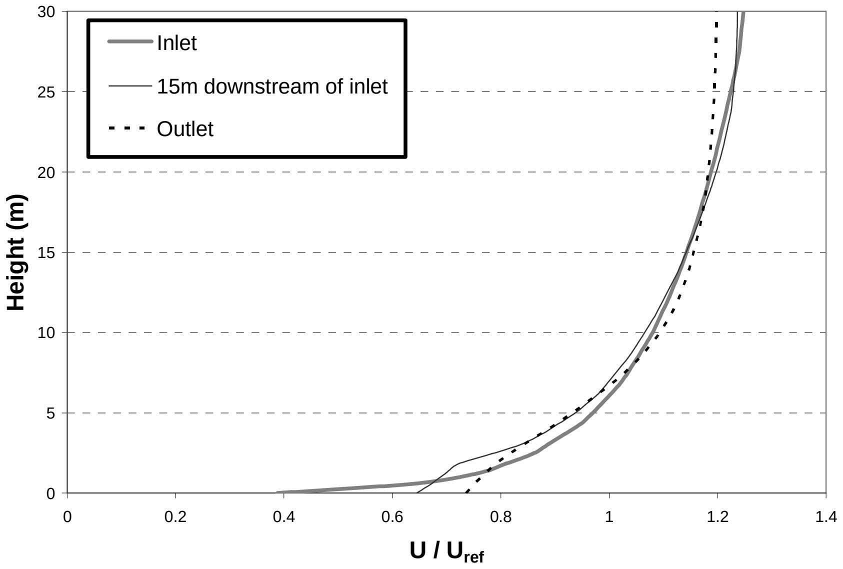

Figure 1: Decaying ABL from CFD simulation showing varying wind speed with height

The ABL described by inlet conditions is often not maintained in CFD simulations as represented in Figure 1. This results in errors easily in the region of 36% on overall pressure distribution where turbulent flow separation occurs. However pressures on the windward and leeward faces are predicted with much greater accuracy as shown in earlier work by the authors [1]. By introducing a shear stress at the top of the boundary layer as suggested by Richards and Hoxey [15] and modifying the standard definition of the near wall treatment of the rough surfaces, Hargreaves and Wright [12] manage to maintain the ABL over a fetch of 4km.

These improvements to the CFD boundary conditions and the move to unsteady simulations are currently being implemented to assess the effects on surface pressure distribution accuracy.

2.3. The use of CFD simulation to augment wind tunnel data

As noted in Section 1.2, wind tunnel testing, despite its accuracy has physical limitations, particularly when addressing façade pressures. When assessing overall overturning loading, forces due to the action of wind are measured at the base of the model. This automatically summates the action of pressures over all surfaces without the need for accurate pressure measurements at particular locations. In this case, CFD can offer little additional information as long as the building geometry has a single base and is not aero-elastic both of which complicate wind tunnel testing procedures.

When measuring local pressures for façade design, we are interested not only in discreet pressure values at particular points over the surface, but also in the variation of pressure over the surfaces. Only where the building geometry is very simple, with known distributions of flow extracted from detailed testing, can the wind tunnel be used to give accurate local pressure distributions for use in structural analysis.

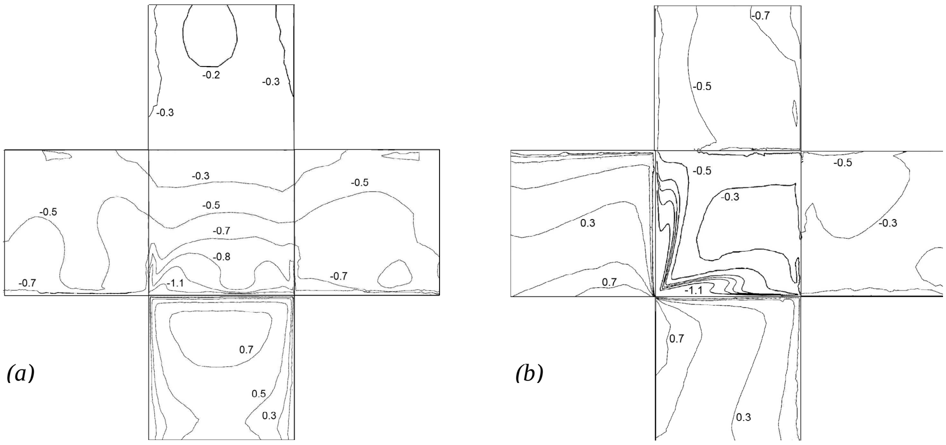

Figure 2: CFD Pressure distribution diagrams (a) Wind normal to cube (b) Wind 45˚ to cube

In contrast, CFD can give a very detailed description of surface pressures and wind flows around buildings at any point in the computational model. Therefore, if wind tunnel testing is used to calibrate a CFD model, it would take relatively little effort to predict accurate pressure distributions, once standard modelling procedures are defined. Such information could be used to predict forces on larger cladding elements, façade secondary structures and also local main structural elements.

Moreover, an accurate CFD model is not limited by scale. Once the pressure distribution is calibrated, CFD be used to predict pressures on intricate external façade elements such as shading devices and externally ventilated double skin façades. This would address a much needed aspect of façade engineering where codes of practice give very little guidance.

3. General Crack Growth Model transient simulation

3.1. Existing research

A number of studies have been carried out by other authors in attempt to characterise the effects of fluctuating wind load on glass structural design. Holmes [16] showed that although upwind velocity fluctuations can be described by a normal (Gaussian) distribution, pressure histories for side walls of buildings where flow separation occurs are characterised by different probability distributions. This phenomenon also holds true for windward walls of low rise buildings where higher turbulence intensities occur. Holmes [17] then also postulated that this pressure distribution had a significantly different effect on glass strength, although geometrically non linear effects due to large plate deflections were ignored.

Das et al. [18] carried out dynamic analysis for vibrating glass plates in simulated fluctuating wind. They proceeded to show that wind acceleration contributes very little to fluctuating wind pressure. Maximum principal stresses only were considered in this study and surface pressure fluctuations were assumed to follow the parent wind speed fluctuations, which is not the case particularly for side faces of buildings. Dynamic amplification of stresses is also low on glass plates used in practice, since these have high natural frequencies.

Reed [19] integrated the pressure fluctuations modelled using a statistical simulation to estimate the damage on glass panels. Geometrically non linear effects due to large plate deflections were considered using analytical solutions. In agreement with Holmes, Reed showed that a non-Gaussian model of windward pressure causes more damage to glass. However, the statistical superposition of peak stress and critical flaw was only tackled qualitatively.

Calderone [20] used a slight modification to Browns integral [21] for load duration on glass. This was done to convert stress history to load history in order to avoid non-linear transient analyses. Unfortunately, since stress and pressure are not linearly related, this would require calibration for different load distributions, pane geometry and glass thickness. A log-normal distribution is also proposed by Calderone and Jacob [22] to achieve a better fit to weathered glass tests. They propose the use flaw density and distribution of flaw depths as design parameters, particularly for limit state design. In these studies, pressures for integration were based on free wind speed records as opposed to surface pressure data. This may sometimes be unsafe since pressure distributions are distorted by local turbulence and vary over the surface of a building as shown by Ko et al. [23]. The latter authors used wind tunnel pressures from the side face of a building and showed that Gaussian simulation of pressure fluctuations again give unsafe results for glass strength proposing a statistical simulation pressure simulation that gives a better fit to data.

Despite this, Calderone and Jacob [22] postulates that pressure history from previous storms do not contribute glass strength reduction with age. However, it appears that full meteorological data was not used in their simulations of 20 to 50 year glass strengths.

3.2. Description of the analysis

In the work carried out by the authors of this paper, façade pressures taken at 5Hz for a period of 1 hour from existing field measurements on the Silsoe cube [24] were used. This was done in order to eliminate any modelling errors involved in scale models and to ensure that a sufficient number of pressure taps were present on the surfaces of interest. The mean wind speed at the time of measurement was of 9.17ms^{-1}. This was converted to a 1 in 50 year storm wind speed of 26.74ms^{-1} expected at the same site of the cube. The converted pressure history on the windward face of the cube is represented in Figure 3.

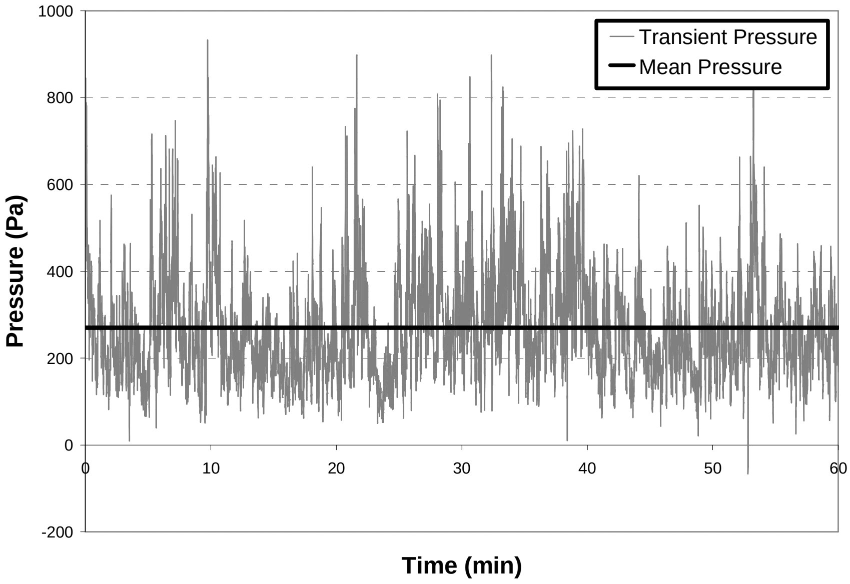

Figure 3: Wind Pressure History

Pressures were measured at multiple locations over the façades as shown in Figure 4. In wind tunnel tests, there are insufficient pressure taps to average readings over the glazing area. In the UK, temporal averaging is used in to overcome this. BS6399 [2] requires the averaging of pressures over 1s (in full scale) for cladding areas of up to 5m in diagonal length. In order to avoid any errors associated with temporal averaging, pressures measured simultaneously over a height of 3m, were applied to the glass plates analysed. This also avoided temporal scaling effects due to the required shift of wind speed from an hourly average of 9.17ms^{-1} to 26.74ms^{-1} used in the analysis.

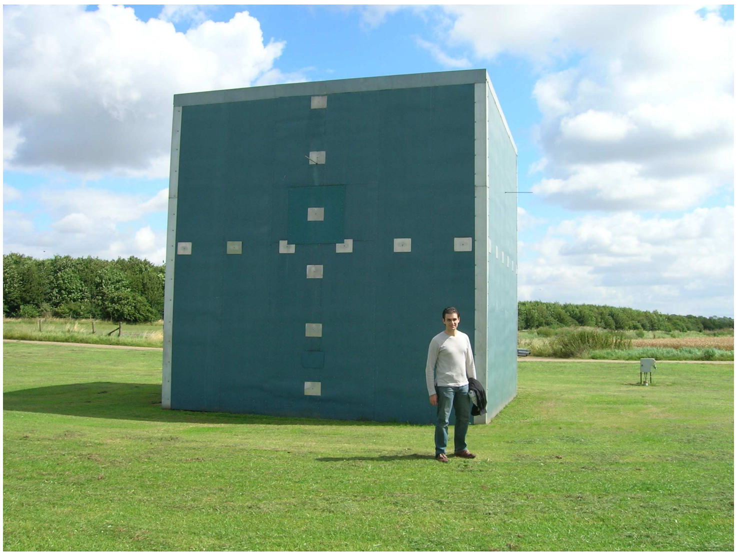

Figure 4: Silsoe cube tapping points

This gave 18000 pressure readings used for each time step in the Finite Element (FE) transient analysis, carried out using LUSAS version 14 [25]. The model, shown in Figure 5, consisted of a 3m x 2m plate, 8mm thick and simply supported on four edges. Based upon comparison with analytical solutions of non-linear plate analysis, a mesh of 8 x 12 elements was adopted wherein each element was an 8 noded, quadrilateral, thin shell element with quadratic inter-nodal interpolation.

Membrane stresses induced by the large deflections of the glass plate were taken into account using the total lagrangian non-linear solver of LUSAS. Ten load steps were sufficient to give accurate static results, however these were increased to take into account the variation of pressure within the 18000 data points.

The FE analysis results were post processed using a Visual Basic scripting algorithm developed by the authors, based upon the work of Overend [26] to calculate the equivalent uniform stress σ_p acting on the stressed glass surface (Equation 1). This is based upon fracture mechanics principles and the random distribution of surface flaws on the glass. A detailed description of the theory upon which this is based can be found in Overend et al. [27].

$$\sigma_p = \left[\frac{1}{A} \int_{area} \left(c_b \sigma_{\max} \right)^m dA \right]^{\frac{1}{m}} \tag{1}$$

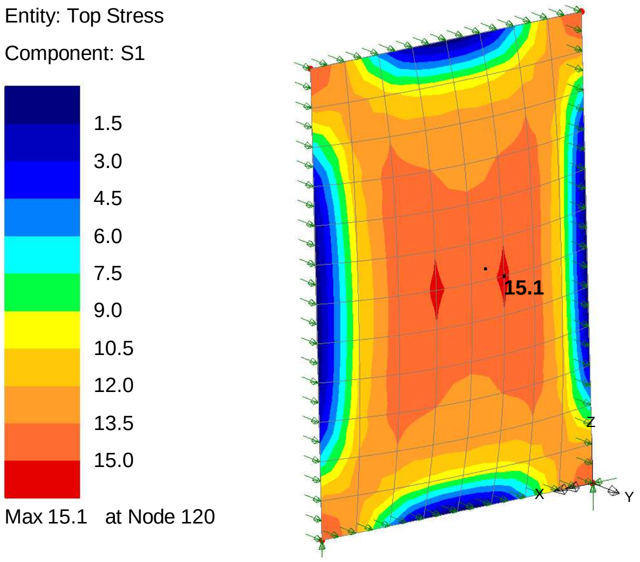

Figure 5: FE Analysis output

Once the equivalent uniform stress for each load step was calculated, the effects of crack growth during each 1/5 of a second were integrated using Equation 2, based on the well known Brown's integral [21] for load duration effects on glass. This effectively completes the transformation of the real-world surface stress distribution caused by the transient wind pressures into an equivalent uniform stress σ_{pe}, acting constantly for a given load duration T_{eq}. This stress would cause the same amount of crack growth in the glass surface as that in the real world condition.

$$\sigma_{pe} = \left\{ \int_{t_r}^{t_f} \frac{\left[\sigma(t)^n \, dt\right]}{T_{eq}} \right\}^{\frac{1}{n}} \qquad (2)$$

However, a lower stress limit exists below which sub-critical crack growth does not occur. This was taken as 34.6% of the glass strength for instantaneous loads based on the work of Fischer-Cripps and Collins [28]. A probability of failure, P_f of 1/1000 was used, giving a minimum equivalent uniform stress σ_f of 5.4Nmm^{-2} which is the sub-critical crack growth threshold stress on a glass plate of Area, A = 6m^2 derived from equations 3 and 4.

$$k_{\text{mod}} = \frac{K_{ISCC}}{K_{IC}} = \frac{\sigma_f}{\sigma_s} \geq 0.346 \qquad (3)$$

$$P_f = 1 - \exp(-kA\sigma_s^m) \qquad (4)$$

3.3. Results

Table 2 gives the equivalent constant stress from Equation 2 for different static load durations, which would give the same amount of crack growth on annealed glass, as that caused by the transient pressure of a 1 hour storm. Therefore the stress values in the table and the stresses induced by the transient wind pressures have an equal probability of failure. Data reported here is generally based on pressures measured on the windward face of the Silsoe cube with wind incoming perpendicular to this face. The maximum load acting on the glass plate was identified in the load history, and the corresponding maximum equivalent uniform stress was of 11.78Nmm^{-2}. If this maximum stress is used, as is commonly done in design situations, it can be seen from Table 2, that its equivalent static load duration is of just under 5 seconds.

Table 2: Static Stresses equivalent to 1 hour of wind loading on the windward face

Load duration, T_{eq}	Equivalent Static Stress, σ_{pe} (Nmm^{-2})
10 minutes	8.64
60 seconds	9.98
5 seconds	11.65
1 seconds	12.89

If one were to apply a 10 minute load duration to the glass strength parameters in design, as recommended in prEN 13474 [9], the appropriate equivalent static stress to use would be that of 8.64 Nmm^{-2}. It would therefore be very conservative to take the maximum measured wind pressure, and assume a 10 minute static load duration for the same load.

It should also be noted that crack growth was only detected for 30% of the duration of the 1 hour storm. In the remaining 70% of the storm duration, the wind induced stresses where below the sub-critical crack growth threshold. This is however specific to the intensity of storm combined with the glass configuration chosen. In the case of a storm with the most likely annual maximum wind speed (with an annual probability of 0.632 [2]), there would be no effect on crack growth as the maximum stress would be lower than 5.4Nmm^{-2}. The use of safety factors on the applied wind pressure also dramatically reduce the effects of weaker storms since the design stresses are higher than those resulting from the expected storm intensities. Table 3 gives results of the analysis performed using data from different surfaces and wind direction. All analyses were performed using the same wind speed, therefore the maximum stress reflects the varying external surface pressure coefficients (C_{pe}).

Earlier comparisons by the authors [29], using different international codes of practice for wind loading and glass design, showed that glass thickness required for a 3m x 2m annealed glass pane at the site of the Silsoe cube, could vary between 6mm to 12mm thick, depending on which codes of practice are used. In most cases, prEN13474 gave the higher thicknesses.

Table 3: Results for different data sets

Cube Surface	Stress due to max. pressure (Nmm^{-2})	Equivalent duration of max. stress (s)	% of time where crack growth occurs
Windward - wind @ 90º	11.78	4.3	30%
Leeward - wind @ 90º	7.75	1.3	0.6%
Roof – wind @ 90º	14.55	1.9	65%
Windward – wind @ 45 º	9.79	1.8	10%
Leeward – wind @ 45 º	8.11	5.6	5%
Roof – wind @ 45 º	10.19	4.4	22%

4. Conclusions and Future Work

Effects of the load history experienced by glass panes in wind storms are largely simplified or ignored by current glass codes of practice. This has been investigated by assessing the damage occurring on the surface of a glass pane in terms or crack growth. Using existing full scale field data and transient FE analysis, equivalent uniform glass stresses have been calculated, giving an equivalent static load duration of just under 5 seconds for wind pressures.

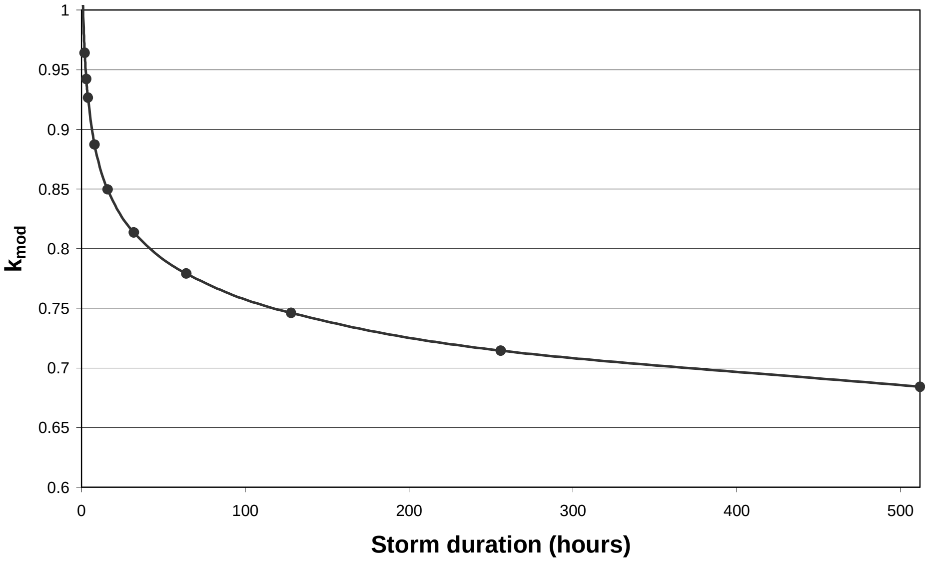

Figure 6: Variation of k_{mod} with extrapolated storm duration

Following the recommendations of prEN13474, a 5 second pressure has a load duration factor k_{mod} of 1. Even if the 1 hour storm history used is repeated 3 times, k_{mod} remains above 0.94. The recommended effective load duration of 10 minutes in prEN13474 (giving k_{mod} = 0.74) is comparable to a storm lasting 128 hours with no reduction in intensity over time, as seen in Figure 6. The recommended values therefore seem largely conservative leading to higher glass thicknesses. A load duration closer to the 1 to 3 second design gusts as given by wind loading codes seems more appropriate, although further research is required to quantify this precisely.

When designing glass, difficulties may arise in obtaining wind load histories for new buildings, however conservative assumptions can be taken to cover a range of situations. Wind tunnel tests for façades are now common practice for large projects due to direct cost benefits. Data from these tests can be used directly to extract the wind loading history to design glass more efficiently. In addition, advances in CFD make it possible to give further information on pressure distribution over façades, particularly over intricate geometries such as brises soleil and double skin façades.

4.1. Future work

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

- The effects of multiple storms and crack healing were not considered
- Limited wind data sets were used

Research in the is field is being undertaken jointly by the Glass & Façade Technology Research Group at the University of Cambridge and the Environmental Fluid Mechanics Research Group at the University of Nottingham. These studies will address some of the above-mentioned limitations by:

- Incorporating multiple storm statistics and critical surface flaw design into the current model
- Performing analysis on further full scale and wind tunnel data sets
- Assessing the adequacy of wind tunnel test temporal averaging for glass design
- Performing weathered glass testing to refine the failure prediction models
- Performing IGU and laminated glass testing to extend the results of these findings to different products

In parallel, CFD analysis and wind tunnel testing will be used together to enable the accurate design of double skin glass façades. This will be done through calibration of CFD models using wind tunnel test data of large scale façade models. The goal of the research is to use the results of this calibration to give a universal glass façade design method combining physical wind tunnel testing, CFD simulation and glass failure prediction.

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6. Notation

A	surface area
c_b	biaxial stress correction factor
k	surface strength parameter
K_{IC}	critical stress intensity factor (plane strain fracture toughness)
K_{ISCC}	plane strain fracture toughness for sub-critical crack growth
k_{mod}	stress corrosion ratio
m	surface strength parameter, Fourier series numerical factor
n	static fatigue constant
P_f	probability of failure
T_{eq}	equivalent static load duration
t_f	load duration
t_r	time at which the applied tensile stress exceeds the surface pre-compression
$\sigma(t)$	stress at time t
σ_{pe}	constant equivalent failure stress acting for a time T_{eq}
σ_f	surface tensile strength of glass
σ_{max}	maximum major tensile stress
σ_p	equivalent uniform stress
σ_s	instantaneous failure stress