

An assessment of the Eurocode provisions for the Wind Loading on Low-rise Buildings

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Abstract

The Eurocode provisions are cheaper alternatives to wind tunnel studies in the consideration of wind loading on a structure. Very tall buildings and large structures have enough economic justification for expensive wind tunnel studies in their design stage. Such wind tunnel studies feature simultaneous scanning and acquisition of loading data from hundreds of pressure tappings with subsequent high-speed computer data processing and analysis. This is not the case for low-rise buildings which do not find their way into the wind tunnel except in the case where they are unusual edifices. However, low-rise buildings are the most damaged in wind storms. In addition, their shapes are increasingly different from

the traditional and generic forms considered in the Eurocode. Additionally, the current data acquisition techniques are more advanced than were used for the wind tunnel studies in the 80s from which the Eurocode provisions were collated. Pressures are now sampled simultaneously at all taps rather than sequentially and tubing response is now corrected numerically rather than by optimised tubing methods. Thus, it is of interest to assess the performance of the Eurocode on present building shapes. This defined the aim of the study and its focus on low-rise buildings. In addition, the limit on the required number of pressure tapping to obtain adequate and reliable wind loading information from wind tunnel studies is investigated. The study is based on models of a simple cuboidal building, a quasi-rectangular building with inset faces in its plan, and a building plan featuring a re-entrant corner possessing curved surfaces at the internal and external junctions of its wings. It is concluded that adapting the Eurocode wind loading provisions to irregular building plans characteristic of modern times may give unsafe solutions. The variations of pressure with wind direction on the internal walls of the wings and the curved surface at the internal junction of the re-entrant corner follow coherent wave forms that are mutually similar. These can be further investigated for codification purposes.

Keywords: Cuboidal building, Irregular building plan, Pressure tapping, Tributary area

1 Introduction

Wind loading is the dominant horizontal force on buildings. It can be estimated from pressure coefficients (C_p) or force coefficients (C_f). The Eurocode wind loading provisions are often the only basis by which designers account for wind effects on their structures in the United Kingdom (UK). This is because designers are under legal obligation to adopt them in instances where “deemed to satisfy” clauses do not apply. However, the Eurocode recognizes wind tunnel testing as an alternative to the wind loading provisions, provided that the criteria for their applicability are met. The relevant part of the Eurocode to this study is EN 1991-1-4:2005 +A1:2010 (E) [1] and its annex used in the UK [2]. The pressure coefficients in the Eurocode are specified by zones. These zones are obtained with the use of a subdividing length (the scaling length), e , which is the smaller value from 2 times the height or the acrosswind dimension of the building. The centre bay of the roof is subdivided by $e/10$ and $e/2$ into three zones starting from the leading edge [3]. The zones represent regions of expected flow features such as stagnation (zone D), separation (zone A, F and G), separation/attachment (zones B and H), unstable re-attachment (zone C and I) and wake (zone E). The specified values of the pressure coefficients are for the orthogonal wind directions 0° , 90° and 180° . The values represent the most unfavourable values obtained in a range of $\theta = \pm 45^\circ$. Additionally, they

can be used for wind directions $\theta = \pm 45^\circ$ either side of the relevant orthogonal direction [1]. These pressure coefficients are specified for loaded areas, A , of $1m^2$ and $10m^2$ as $C_{pe,l}$, for local coefficients, and $C_{pe,10}$ for overall coefficients, respectively [1, 4]. The overall pressure coefficients on the vertical walls are primarily required for the overall structural design of the building. The local coefficients are significant for cladding design. The relation between these values has also been specified. However, sometimes some national annexes (NA) such as the UK NA specify same values for both [2]. The specified basic wind speed (on which the coefficients are based) is a $10min$ mean wind speed at a $10m$ height in open country terrain with an annual probability of exceedance of 0.02 (50-year return period) [5]. The service level wind loads that are specified with this basic wind speed are combined with other loads on a building. The load factors (partial safety factors) to be applied to achieve an acceptable small risk of failure are specified [4]. These are not given in EN 1991 – 1 – 4, but are described in EN 1990 ‘Basis for Design’. The values to be used for these are specified in the national annexes of EN 1990. So, they may have varying values across countries [4].

However, concerns have been expressed about the adequacy of these provisions in predicting a design load that ensures the required level of safety without being uneconomic in an ever changing wind and an ever-changing world of building designs [6–10]. Thus, it is necessary to assess the compatibility of the codes with contemporary architectural trends.

Buildings can be classified as tall or low-rise. Low-rise buildings are almost always completely within the atmospheric boundary layer (ABL). Wind tunnel studies on models of large structures including tall buildings, stadia, arenas, and long span bridges usually feature in the design process. The results of these project-specific studies contribute to the database on the wind loading of structures. However, most structures are low-rise buildings that have no economic justification for such wind tunnel studies unless they are of unusual shapes [6]. Thus, designers of low-rise buildings usually have to employ the wind loading provisions in codes [7]. These designers often have to be conservative when using the codes due to the considerable variations in instantaneous pressure distributions that can occur in their designs [8, p.59]. For most UK low-rise buildings, the wall design (e.g. brick cavity walls) is prescribed by the Building Regulations.

The codes define the approaching wind as a function of height for a number of generic exposure conditions or categories which may be difficult for a designer to choose from. Making this choice is also compounded by the fact that, in actual cases, a site is almost always a combination of a number of categories. Additionally, these categories may be varied for different wind directions [7].

Buildings are usually in clusters such as in the middle of a city [9]. Thus, the building might be shielded from the full force of the approaching wind (shelter effect). Shelter effect in urban areas is included in code provisions by the use of zero-plane displacement. However, provisions must be made for the

possible demolition of upwind sheltering buildings during the lifetime of the structure. The loading on a sheltered building may be lower than predicted by the codes. Sometimes, a given arrangement of surrounding buildings can increase the load a building experiences by accelerating the oncoming wind into a narrow gap. These are difficult situations for the codes to handle [9], and experts have recommended studying the errors amounting from the stated variability and ways to accommodate them in the codes.

The wind loading on a building is greatly dependent on its shape. The wind loading provisions in the codes are mostly for rudimentary quasi-rectangular shapes. However, contemporary buildings sometimes possess interesting non-rectangular forms and shapes. The numerous geometrical possibilities of buildings coupled with the complex interactions of buildings with their environment preclude any precision in the definition of the appropriate wind loads [11]. Even for the quasi-rectangular building shapes, the critical wind direction may actually be different from the square-on situation documented in the codes. This may be due to possibilities of directional influences by exposure condition or the wind climate itself. The ABL wind is a “dynamic and random phenomenon in both time and space” [12, p.16]. As such, exact predictions of the wind speed at any specific time of interest is not possible. This can only be satisfied by statistical means. Additionally, the three-dimensionality of the flow around the building compounds the situation [8, 13].

These difficulties in form the recommendation that relevant recognized literature or the wind tunnel procedure should be used for buildings outside the scope of the codes. The codes, in the first place, were generated from wind tunnel experiments performed in the 1980s and before [14]. However, the wind tunnel testing and technology have advanced much from what they used to be at the time. Many more pressure taps can be fitted and simultaneously scanned on wind tunnel models. Also, the data can be gathered and processed with much more precision than before [14, 15]. This is suspected to have some effects on the adequacy of the codes.

Some past reviews of the Eurocode with wind tunnel and/or full scale studies predated the official adoption of the Eurocode in 2010. They were based on the annexes in use where the researchers were domiciled. General mismatches, albeit small, were found between the code reported coefficients and experimental values [3, 16]. These were especially true of roof corners [3]. The sign of the errors were found to be uncertain [16]. Peak pressures in a zone were sometimes observed to be significantly different from those specified uniform values in the code. This was especially true of the intermediate zone B [3]. Thus, the sub-division of side walls into zones in the Eurocode were observed to be faulty. However, very good agreement between the Eurocode and wind tunnel experiments at the mid-region (zone H) of the roof was observed [3]. There is a rapid reduction of wind load with increasing tributary area from very high local peak values at roof corners to lower values in the inner regions of the roof [17].

Therefore, the aim of this paper is to review the Eurocode and its UK annex in light of some of the highlighted deficiencies with an extended view to assess the quality assurance of using more pressure tappings in obtaining wind loading information from wind tunnel experiments. To achieve this, three building geometries were identified as case studies based on the perception of the difficulty level the Eurocode would experience to predict the wind loading on them (simple, intermediate, and difficult levels) on the Cranfield University (CU) campus, Cranfield, Bedfordshire, UK. The models of these buildings were constructed and fitted with as many pressure tappings as possible to be able to determine any gain in precision in the wind loading estimate with the number of tappings. Sufficient wind tunnel tests were conducted on these models varying the azimuth of the approaching wind (Section 2). The data is then analyzed and the relevant results are compared with the corresponding information from the Eurocode in Section 3. Section 4 summarizes the observations from the study and concludes the paper.

EN 1991-1-4:2005 +A1:2010 (E) [1] (and its UK annex [2]) contains information not only about the wind loading of low-rise structures, but also about medium-height buildings, large ware-houses, bridges, towers, chimneys, etc. However, the scope of the present study is limited to the provisions of the code for low-rise buildings. There is no consideration of the possible dynamic responses of the case studies and the provisions of the Eurocode for dynamic responses. Furthermore, this study only considers the effectiveness of the code in predicting external pressure coefficients in the buildings studied. The buildings models were constructed with bare surfaces. As such, effects of the roof design and furniture effects are out of the scope of the present study. The building models were also tested in a lone environment with a homogeneous roughness exposure from all wind directions. Therefore, this study neglects any possible terrain effects that may be present in the actual full scale situation.

2 Methods

2.1 Case studies

Three buildings were selected on the CU campus as illustrated in Figure 1; 1 - the Sports Hall (SH), 2 - Building 83, Hangar building (HB), and 3 - the Trafficmaster building. This choice of buildings and the Cranfield terrain are adequate for the present research. The CU campus site can be correctly categorized as an 'open' terrain. The Eurocode specifies reference wind speeds for 'open' country terrain. It contains far-reaching information on simple cuboidal building shapes such as that of the SH in Figure 2.

The Hangar building (Figure 3) possesses a good intermediate level of difficulty since it is just a combination of vertical walls. The faces outlined in red ink in Figure 5a are inset faces to their adjoining lower roof surfaces outlined in blue ink in the same figure. An adjoining lower roof serves as the ground plane for an inset face [18]. The flow on this face interacts with that on the



Fig. 1 Building form selection from CU Campus [7].



Fig. 2 The SH viewed from the south-west.



Fig. 3 The HB (in the fore-ground) viewed from the south-west.

lower roof such that when the face is windward, positive pressures are experienced on the lower roof. The extent of this region of interaction is defined by some fraction of the scaling length of the inset face [18]. However, the Eurocode specifies loading data for roofs having no such flow interactions.

The idea is that the Trafficmaster building in Figure 4 provides the combination of forms which may just pose some more difficulty to the Eurocode. It is a re-entrant corner with a V-plan and with circular faces at the internal and



Fig. 4 An aerial view of the Trafficmaster building from the south-west.

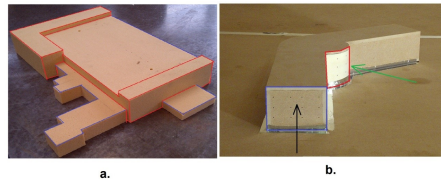


Fig. 5 Wind tunnel models of (a) HB and (b) Trafficmaster building.

external junctions of the two wings of the building. When the wind flow over the building is in the direction of the black arrow in Figure 5, the circular face at the internal corner outlined in red ink is essentially a windward face with positive pressures. The positive pressures on this face act on the downwind end of the face adjoining it from the upwind direction which is supposed to be a side face experiencing suction [18]. In the same figure, local high-suctions do not occur on the face outlined in blue ink for winds in the direction of the green arrow over the building. In general, surface pressure distribution on faces of re-entrant corners is dependent on the whole plan shape [18]. This shape is not dealt with in the Eurocode.

There are numerous roof forms including the pitched (duo-pitch, mono-pitch, mansard and multi-pitch, hipped, skew hipped), the hyperbloid, barrel-vault and flat roofs. A flat roof may have sharp eaves with or without parapets; or curved or mansard eaves [18]. Flat roofs with sharp eaves are of significance to the present study (because the SH is flat roofed).

2.2 Models construction and pressure tapping locations

With the exception of the model of the HB which had been constructed prior to this study, information regarding the geometric dimensions of the buildings was sought and gathered from the Estates services of CU.

The aerodynamic model of the HB illustrated in Figure 6 was constructed at a 200th scale of the real building. This model appears to be a good representation of the HB at such a scale. Aerodynamic models of the Sports hall and the Trafficmaster building were also constructed at the CU workshop at this scale. More detailed information about the dimensions as well as pressure tappings positions in non-dimensional forms is included in Appendix A.

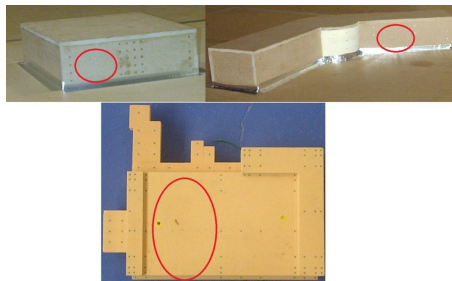


Fig. 6 Constructed 1:200 scale aerodynamic models of the case study buildings fitted with pressure tappings.

Table 1 Important parameters at wind tunnel scale and full scale

Parameter	Model scale	Full scale
Geometric dimension	1 unit	20 units
Roughness length, z_0	0.15mm	0.03m
Velocity, U	10m/s	5.43m/s
Sample frequency	400Hz	1.09Hz
Sample period	30s	11,041.6s(3.1hr)
Number of samples	400/s	$\sim 1/s$

The locations of the tappings on the models were arrived at after a number of considerations. The demands on an acceptable wind tunnel experiment require an adequate number of tappings on all external surfaces of the building considered for wind loading estimation [2, pp.2–3]. Additionally, the tappings should be present in designated loading areas defined in the codes. Fulfilling these would require a large number of pressure tappings considering that the designated loaded regions on the buildings vary with wind direction. However, the number of tappings which could be used for this study was limited to 100. By contrast, Aylanc and Kasperski [3] used 92 tappings concentrated on a half side of their simple block model. Similarly, Lin and Surry [17] used a total of 82 tappings concentrated just in a roof corner region of their block models. The Eurocode demands that the pressure measurements to be used for overall wind loading estimation should be simultaneously taken so as to ensure that measured pressures on all surfaces are of the same time series, and the problem of non-correlation of fluctuating pressures can be taken out [2]. Moreover, regions of expected increase in magnitudes of local loads (such as roof corners and upwind corners of side walls) and other regions of interest like the intermediate loaded zone B in the codes were desired to be fitted with adequate tappings. Thus, the present study was carried out with a close scrutiny of possible symmetry of flow around the models and the prevailing wind direction in Cranfield (which is South-West (SW)). All the models were fitted with 100 tappings except the Trafficmaster building model which was fitted with one less.

The SH model being a cuboid was expected to have a symmetrical flow around it. Accordingly, only the roof and the west and south faces were tapped

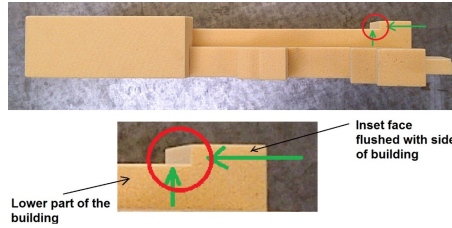


Fig. 7 An elevation view of the HB model focusing on one of its inset faces (the approaching wind is assumed to be flowing into the present page. Its directions of flow at this corner of interest are signified by the green arrows).



Fig. 8 Setup of the wind tunnel for simulating the Cranfield ABL.

(see Figure 12 for cardinal point orientation). The Trafficmaster building is also symmetrical about an imaginary centreline drawn at the centre of the curved surfaces. Thus, the tappings were concentrated on the roof and walls of the western half of the building (see Figure 12 for cardinal point orientation). However, some tappings were put in limited areas of the other half adjoining the curved parts to assess the assumed flow symmetry. The HB is not symmetrical at all. A very complex flow field was expected over the roof and the entire model roof. For instance, the interaction of two crossing flows at their point of convergence close to the internal corner of an inset face which is flushed to the side of the building causes very high suctions on the roof of the lower part and the side wall of the higher inset part as depicted in Figure 7 [9]. The suction peaks are not correlated across the entire roof surface and the whole building. As a result, it was better to obtain complete information (of the same time series) of the complex flow at least in one of the wind directions. Thus, the tappings were distributed only on the roof to obtain the complete across-wind information in the x-y plane. These choices were not without consequences; relatively large areas on the models highlighted with the red ellipses in Figure 6 and in other parts not highlighted have been left without tappings.

2.3 Wind tunnel tests

The SH model is the benchmark, and the quasi-steady method of data analysis was adopted.

All the experiments were carried out in the Cranfield ABL wind tunnel. It is an open return circuit wind tunnel comprising of an axial three-bladed fan powered by a 165 kW direct current (DC) electric motor, a settling chamber with a 4 : 1 contraction ratio, and a 15m long flow fetch upstream of a closed test section. The cross-sectional area of the test section is $2.4m \times 1.2m$. The roof of the tunnel is not adjustable and is without a constant slope. The test section does not feature slotted walls with a plenum chamber. The diameter of the turn table in the test section is 2m. It is automatically operated and capable of rotating a full 360 degrees. The maximum achievable wind speed in the tunnel is 14m/s for the setup used. The control room housing the monitoring system that has the Labview software installed is next to the working section.

The CU school of engineering has ready-made information for simulating the ABL flow on Cranfield (and other choice locations) using the roughness, barrier and mixing devices methods [19]. The setup in Figure 8 uses uniformly distributed lego blocks on the fetch floor to represent the surface roughness. The elliptic wedge vortex generators which produce the initial momentum deficit can be seen far upstream. The barrier which induces turbulence is not visible in this figure. The wind velocity and turbulence profiles of the generated boundary layer are presented in comparison to Engineering Sciences Data Unit (ESDU) estimates in Figure 9. The boundary layer was modelled at a geometric scale of 1 : 200 to full scale and with roughness length, $z_0 = 0.03m$ (full scale). This z_0 corresponds to the open country terrain category in the Eurocode.

The models were attached to the tunnel floor with strips of aluminium tape which has a very strong grip. In addition, the HB model was screwed to the tunnel floor through two screw holes on its roof. The dynamic pressure and reference wind speed were measured simultaneously as the model surface pressures with a pitot-static tube positioned at no less than 30cm away to the side of the models at its closest to any part of the biggest model (the HB model). This is depicted in Figure 10. Its vertical position at 50mm to the tunnel floor corresponds to 10m in full scale.

The tubes from the pressure tappings on the models were taken through a hole at the centre of the turntable under the models. They were fitted on to the transducers as illustrated in Figure 11. The tubes had been blown through with a hand pump and numbered 1 – 100 before-hand to ensure they were not blocked and mixed up. They were also made long enough to avoid them crippling when the turn table rotates through large angles. This is not ideal as the transient response of the transducers is dependent on the length of the tubes [5]. However, it was very necessary due to the limitation of the setup used. The pressure transducers were built in-house at the CU school of engineering. They were calibrated prior to the experiment. Five sets of these transducers which are of similar kind were used. Each transducer takes 21 tubes. The first transducer was connected to tappings 1 – 20, the second to

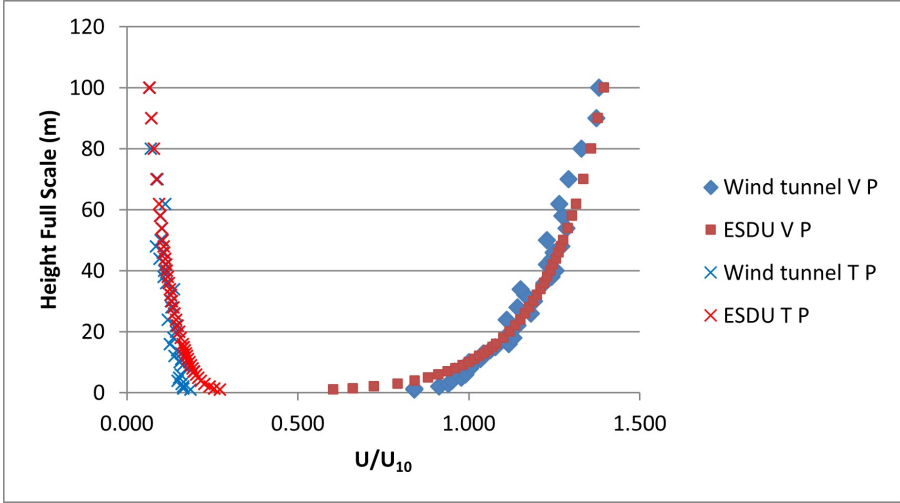


Fig. 9 Comparison between the wind tunnel data and ESDU predictions for wind velocity profile (VP) and turbulence profile (TP).

tappings 21 – 40, and so on to tapping 100. The extra ports on each transducer were connected to the reference static pressure from the pitot-static probe. The pitot-static probe was also calibrated prior to the experiment.

Using Figure 12, the models were orientated to the approaching wind from the tunnel fetch with North at zero degrees. After a complete setting up, a measurement was taken at zero wind. Then, the fan was ramped up to the mean wind speed of 10m/s . The atmospheric temperature and pressure were regularly updated in the Labview software used for data acquisition. For each run, a set of measurements was taken for 16 wind directions starting from zero (0) with an automatic left rotation in angular progressions of 22.5 degrees. For each building, 3 runs returning mean values of 12000 samples each were obtained. These were taken per wind direction and at 400Hz over 30s periods to accurately capture the mean value. Each reported C_p value is the average of the 3 runs. With a geometric scale of 1 : 200, the corresponding calculated values of the frequency and period for the full-scale are presented in Table 1.

The average wind speed over Cranfield is 5.43m/s , and the wind speed used for the tests was 10m/s . These give a velocity scale of 1.84 that is within the common range[4]. There was not enough justification for the variation in wind speed (and Reynolds number) since the maximum achievable wind speed was 14m/s .

2.4 Error analysis

Only errors due to blockage effects and imperfections of the measurement devices were assessed in this study. The blockage ratio for the HB model which is the biggest is less than 1.22% (and less than 5% which is the threshold above which corrections are needed [5]). The repeatability analysis and assessment

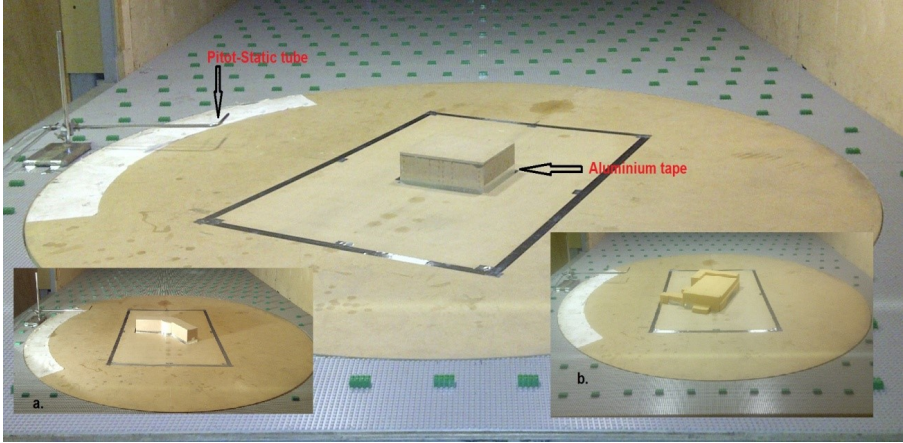


Fig. 10 The setup of the SH and inset a. the Trafficmaster building b. the HB showing the aluminum tape and the pitot-static tube.

of the pressure transducers for sensitivity to wind direction are presented in Figure 13. Pressure readings at tappings 1, 21, 41, 61 and 81 on the SH model representing the five identical transducers respectively were followed for the 3 runs of the experiment. Despite the high turbulence in the simulated ABL, the transducers possess high precision which was not affected by wind direction and/or position of tapping relative to the oncoming flow. As such, the measured pressure values being the averages of the mean values of the 3 runs were expected to be very close to their true values detectable by the transducers.

However, the accuracy of the transducers needed to be taken into consideration as well to assess the inherent errors in measurement. The transducers are fitted with HCLA0075...U pressure sensors with typical accuracy of $\pm 0.05\%FSS$. The measured pressures are pressure differentials and not absolute pressure values. The resolution of the transducers is 12bits (analogue to digital). The dynamic pressure and the surface pressures were expected to have the same amount of measurement error quantified in Equation 1

$$\sigma_m = \frac{\sigma_{datasheet}}{\sqrt{n}} = \pm \frac{0.0005}{\sqrt{36000}} psi = \pm 0.02 Pa \quad (1)$$

where σ_m is the standard deviation in the measured mean, $\sigma_{(datasheet)}$ is the published standard deviation from data sheet, and n is number of samples. The maximum error in the C_p values for this study (that is for the SW and W wind directions) was quantified to be 7%. This is for the worst case scenario when the accuracy of the transducers have been given as stated earlier. However, the accuracy of the pressure sensors is within $\pm 0.02\%FSS$. Thus, the maximum expected error in the C_p values would be less than 7%.



Fig. 11 Tubes from pressure taps fitted on to the transducers located under the turntable.

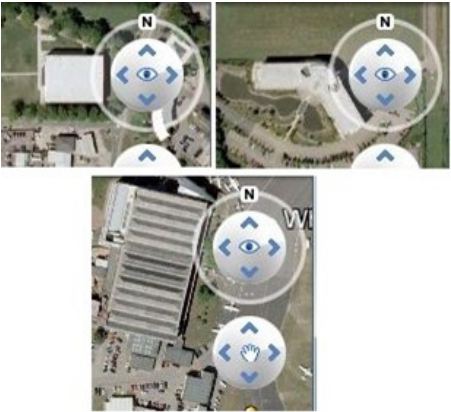


Fig. 12 Orientation of the case study buildings relative to north.

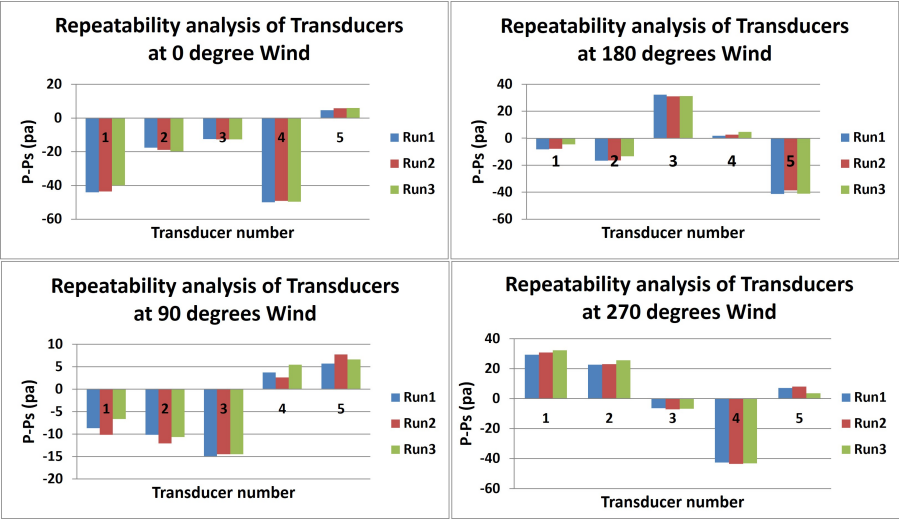


Fig. 13 Repeatability analysis of the transducers.

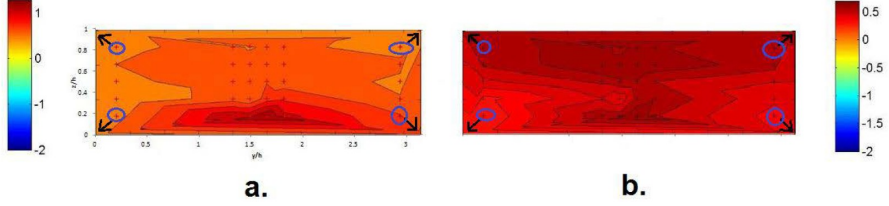


Fig. 14 Matlab generated contours of surface C_p for a westerly wind on the west face of the SH model based on (a) mean wind velocity at different heights and (b) mean wind velocity at $50mm$.

3 Results and Discussion

As depicted in Figure 14, measurements fromappings closest to corners were extrapolated to the corners. This is because the pressureappings could only be located at some distance away from the model surfaces' corners and edges. The locations of the pressureappings are signified by the cross-hairs in Figure 14 and every other relevant figure. Additionally, the contour plots may present incomplete information on the pressure variations due to the limited number ofappings. Thus, the discussion is focused on the locations of the pressureappings. The colour bar in Figure 14a extends beyond $C_p = 1.0$. This is because the pressure coefficients are based on the calculated mean wind velocity, U , at the different heights of theappings. The dynamic pressure, q_{10} , was only measured at the height of $50mm$ equivalent to $10m$ full scale. Consequently, the dynamic pressures at the different heights, q_h , of theappings were calculated with the knowledge of the mean wind velocity profile. These were estimated with Equation 2

$$q_h = q_{10} \times \left(\frac{U}{U_{10}} \right)^2 \quad (2)$$

using the rearranged log law in Equation 3

$$\frac{U}{U_{10}} = \frac{\ln z/z_0}{\ln 10/z_0} \quad (3)$$

where U_{10} is the measured wind velocity at the equivalence of $10m$ above the tunnel floor, and z is the distance above the tunnel floor.

However, studies have shown that these correction errors to the different heights on the building may be avoided when the dynamic pressure is measured at the wind tunnel equivalent location to the $10m$ full scale height [11]. Where comparisons are made to the Eurocode values, the reported C_p values from the current study are based on the measured dynamic pressure in the wind tunnel. The contour of such C_p values is illustrated in Figure 14b.

The Eurocode specified values are designated EN. The 'experiment mean values' and the 'experiment peak values' are designated EMV and EPV respectively. These are also comparable to EN specified values for $C_{pe,10}$ and $C_{pe,l}$

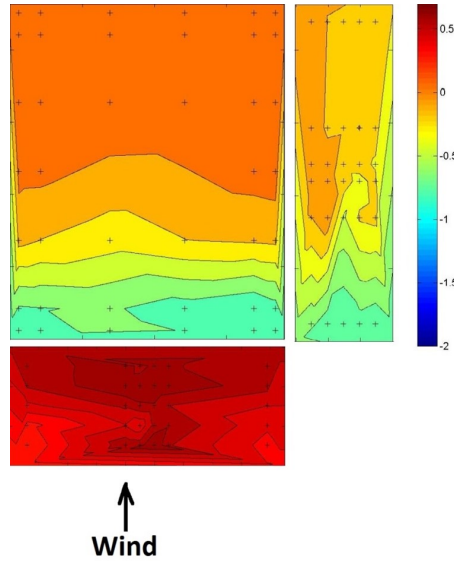


Fig. 15 Contours of surface C_p for a westerly (270°) wind flow over the SH model.

respectively. The EPVs are usually the measured values with the highest magnitude for 270° (westerly) and 225° (south-westerly) wind directions considered for this discussion.

3.1 The Sports Hall

In Figure 15, the experimental pressure contour follows theoretical expectations. However, the stagnation C_p on the windward face is less than the theoretical value of 1.0. This is due to viscous dissipation of the total pressure. The pressure decreases generally away from and particularly downward from the stagnation region. This is because of the acceleration of the flow away from this region and the decrease in flow velocity with decreasing height in the simulated atmospheric boundary layer respectively. The roof and the side walls experience negative pressures with high suctions in the eaves and corner where the flow separates. In the eave above the roof, there is a cylindrical vortex [18] that causes mild suction with $C_p = -1.0$. This is very similar to the upwind corner of the south face (the side wall). Just downwind of these suction regions, the flow experiences some pressure recovery because the cylindrical vortices reenergize the flow downstream of the separation, causing a tendency toward reattachment [18]. However, the sense of the mean pressure is still negative. The flow reattachment tendency is aided by the long dimension of the building in the streamwise direction. The reattachment is not fully stabilized, and the pressures on these regions of the roof and side walls are characterized by sporadic changes in sense.

For a quartering (SW) wind in Figure 16, the trails of the corner vortices on the roof that are characterised by high suctions are noticeable. The suctions

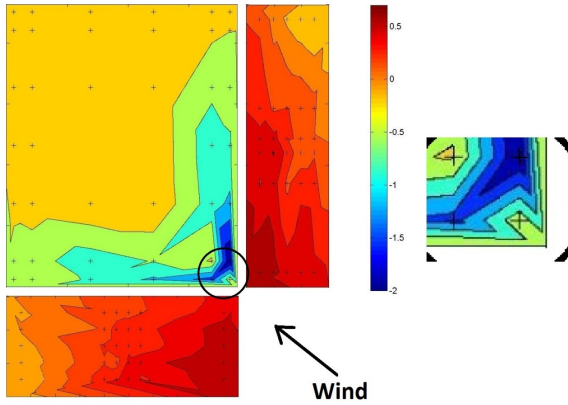


Fig. 16 Contours of surface C_p for a SW (225°) wind flow over the SH model.

are highest along the inclined axis of the vortices and not exactly at their origin. Cook [18] reports of some debate about how close to a roof corner can representative pressure be obtained. The results of Lin and Surry [17] support a side of this debate that predicts unlimited negative pressure values toward the corner of the roof. They observed the highest suction on their models at $0.026H$ radial distance to the corner (where H is the height of the building) [17]. The current study (where the suction at $0.347H$ is higher than at $0.099H$ radial distance from the corner) agrees with the other side of the debate and the theory of vortices [18]. The theory suggests that the smaller the radius of the vortices becomes, the more viscosity will impose limits on the negative pressures. These localised high suctions are only significant for cladding design. The stagnation region moved to the junction of the west and the south faces of the building. The variation of the pressure with height on the west face appears not to follow theoretical expectations. This is different than the south face on which the pressure can be seen to decrease with height as expected. This anomaly is suggestive that there was an inadvertent flipping of the plot. However, it has no negative bearing on the subsequent comparisons.

Figure 17, Figure 18 and Figure 19 present an overview of the comparison between EN and EMV for the roof, south face and west face of the building respectively for a westerly and south-westerly wind flow. The Eurocode generally over-predicts the suctions over the roof by about 50%. This is because the UK NA uses the most unfavourable values of localised suctions in each of the defined zones to specify the corresponding overall loading coefficients. However, the suctions vary in strength across the area of the zones. Despite this, the striking agreement between the EN and EMV in zone H on the roof for the normal wind to the eave (westerly wind) is noticeable. This is consistent with the findings of Aylanc and Kasperski [3]. In Figure 18, the EN over-predicts the suctions in each of the three zones of the side wall for the wind normal to the west face. A particular problem arises in Figure 18 and Figure 19 for the case of the quartering wind which is the predominant wind direction in Cranfield. The ENs are specified for a range of angles $\theta = \pm 45^\circ$ around the rel-

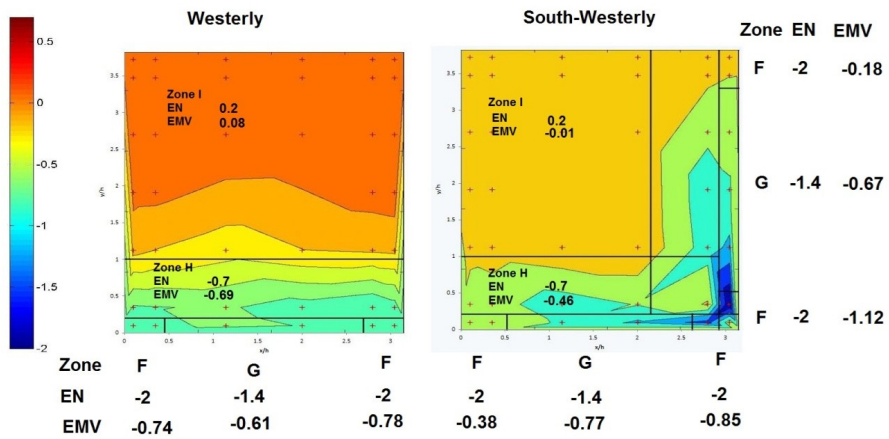


Fig. 17 Comparison of surface C_p between EN and EMV on the roof of the SH model for W and SW wind.

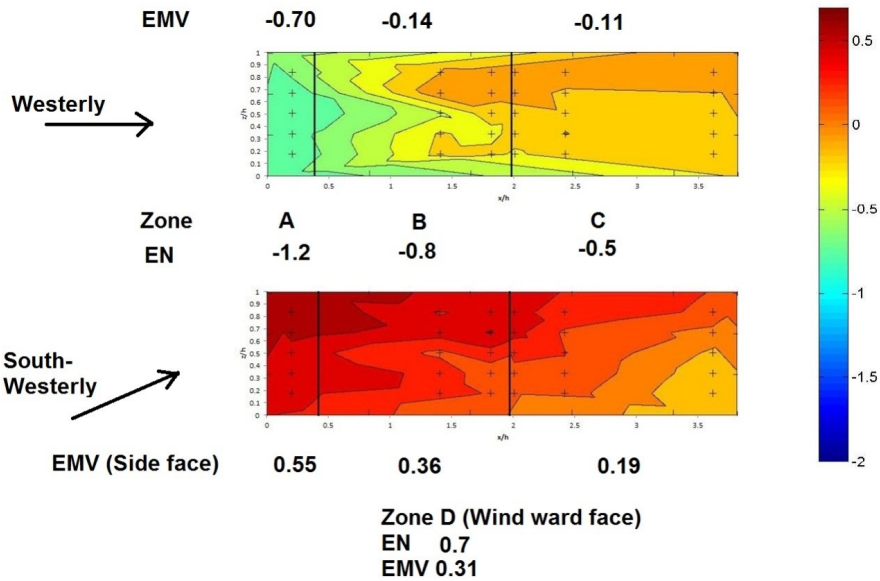


Fig. 18 Comparison of surface C_p between EN and EMV on the south face of the SH model for W and SW wind.

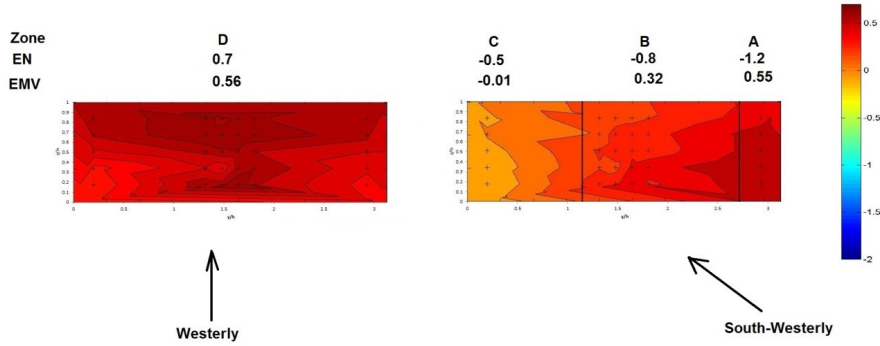


Fig. 19 Comparison of surface C_p between EN and EMV on the West face of the SH model for W and SW wind.

evant orthogonal direction. They represent the worst-case loading found over the range of $\theta = \pm 45^\circ$ around this angle.

Figure 20 presents the pressures measured by pressure taps 1 and 6 on the west face of the building model, showing that the surface pressures are functions of the wind direction. In addition, the spatial variation of the pressures on the face is obvious. While pressures measured by tap 1 have a polynomial relationship with the wind direction, it is difficult to define a specific relationship of pressures from tap 6 with the wind direction. The spatial correlation of the pressures on the face are noticed only for the 90° and 270° wind directions when the face is leeward and windward respectively. So, the questions arise. How is the quartering wind to be effectively treated with the Eurocode for the building walls? Which of the west and the south faces is the windward or side face in the present provisions? What will be the consequences of whichever choice is made? If the south face was taken to be a windward face (as zone D in the Eurocode) in Figure 18, the EN would be over-predicting the pressure on it by about 50%. However, it would be dangerously unsafe to treat either of the faces as a side face since the predictions of the Eurocode would then be in the wrong sense. The west face may be the design wind ward face since the next predominant wind direction after *SW* is the *W* in Cranfield [20]. For a normal wind on the west face, the EN over-predicts the pressure by 25%.

The wind, however, has a dynamic nature, and strong winds can come from any direction. Consequently, it may be a one-sided discussion to base the current review on the analysis of just 2 wind directions. This view may be well-founded especially since the Eurocode states that the specified coefficients are “the most unfavourable values obtained in a range of wind directions $\theta = \pm 45^\circ$ either side of the relevant orthogonal direction” [1, p.33]. Similarly, making the tubes which connected theappings to the transducers as long as was necessary for the experiment could have affected the frequency response

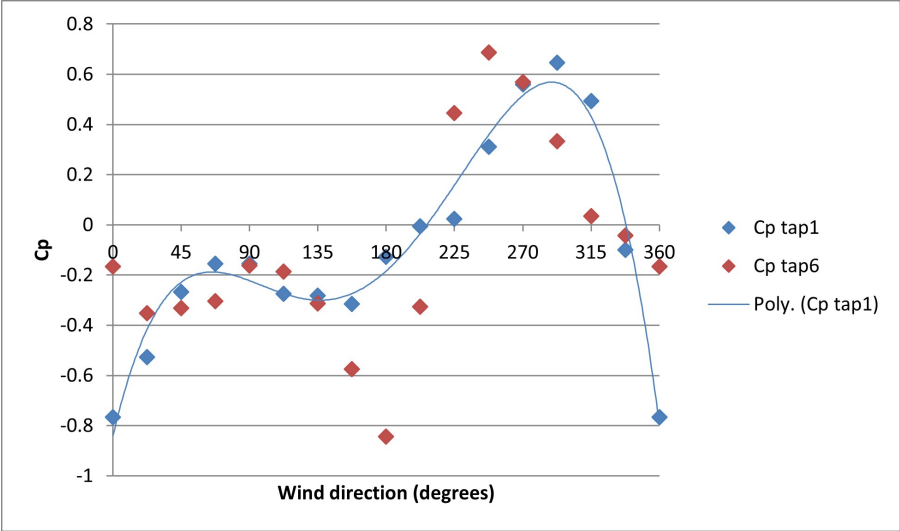


Fig. 20 Variation of C_p with wind direction for pressure taps 1 and 6 on the West face of the SH model.

Table 2 Comparison of surface C_p between EN and EPV for the SH.

Zone	EN	EPV $\pm$ 7%
A	-1.2	-0.76
B	-0.8	-0.38
C	-0.5	-0.25
D	0.7	0.67
E	-0.3	-1.3
F	-2	-1.9
G	-1.4	-0.97
H	-0.7	-0.8
I	0.2	0.2
I	-0.2	-0.2

of the measurement system and attenuated the measured peaks. However, these arguments appear to be refuted with the observation that some excellent agreements exist between the EN and EPV on the wind ward face (zone D) and some zones of the Roof (F, H and I) as is evident in Table 2. In fact, both signs of the coefficient and the exact magnitude were observed in zone I. The EPV for zone E was obtained for 45° and 90° wind directions.

3.2 Building 83, Hangar Building

Due to the inclination of the building to the north (see Figure 12), both the SW and the W winds obliquely flow through the building, as shown in Figure 21. The complex flow over the building is characterized by interactions of positive pressures on the walls of the inset faces with the suctions on the adjoining lower roof, such as in the regions bounded by the white boxes in Figure 22 and Figure 23 that are annotated ‘1’. The extent of these regions may cover

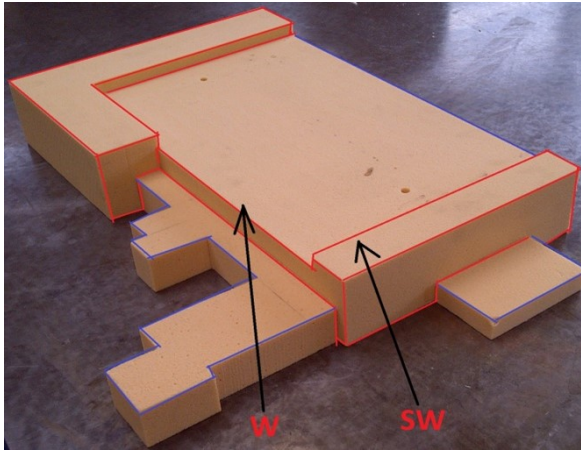


Fig. 21 Pictorial representation of a westerly and a south-westerly wind flow over the HB.

Table 3 Comparison of surface C_p between EN and EPV on the HB

Zone	EN	EPV $\pm$ 7%		
		C_p	Tap number	Wind direction ($^\circ$)
A	-1.2	-0.74	45	270
B	-0.8	-1.01	67	270
C	-0.5	-0.92	69	225
D	0.7	0.36	96	225
	0.7	-0.54	77	225
E	-0.3	-0.56	87	225
F	-2	-2.1	38	270
G	-1.4	-1.31	32	270
H	-0.7	-1.55	90	225
I	0.2	0.04	36	225
	-0.2	-1.6	82	225

the whole spread of the lower roof or some part of it depending on the scaling length of the inset face.

This mean that suctions may or may not be present at the eaves of the lower roof. Also, the white boxes that are annotated ‘2’ signify regions of interaction of cross flows where the more negative pressures can be observed. Most of the tappings on the roof of this building were located in these regions of interaction. This is good for the current review because it makes it possible to check if the provisions of the Eurocode can be adapted to these regions. However, extrapolating measurements from some of these tappings (in the region bounded by the black boxes in Figure 22, for instance) to the corners next to them as it was necessary to generate the figures may not be representative of the true complex flow. Additionally, as a consequence of the non-uniformity in the distribution of the pressure tappings over the roof surface, defining EMVs for the identified zones in Figure 24 is considered erroneous. As such, the review of the EN is based on the EPVs in the zones. This is summarised in Table 3. From this table, it is observed that the EN prediction results gener-

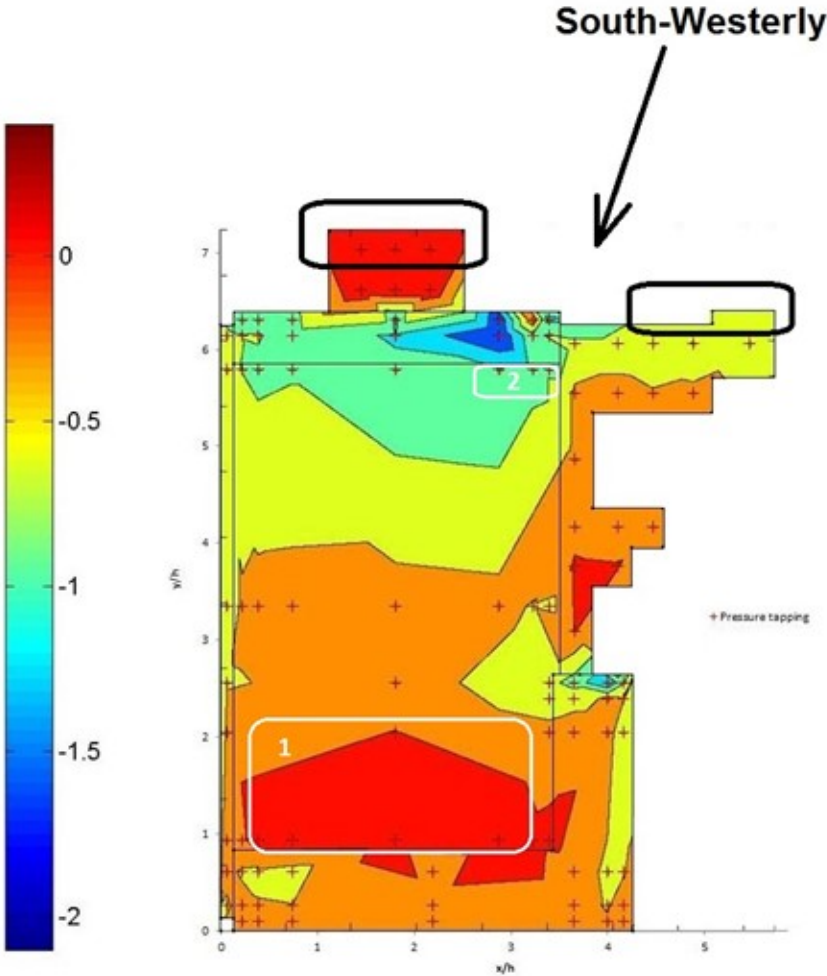


Fig. 22 Contours of surface C_p for a south-westerly flow over the HB model.

ally into unsafe conditions. Zone H, where the code under-predicts the suction by about 100%, is noteworthy. If tap 90 is taken to be in zone G or F, the prediction is not of much concern. However, tap 89 which is interpreted to be in the same zone as tap 90 (H) returned $C_p = -0.04$. The division into the zones follows the guidelines provided by Cook [18]. The current zoning is based on the assumption that the wind loading on an irregular plan can be adapted from the data on a regular plan. Cook notes that “the division [of an irregular plan] is made into logical parts according to the flow characteristics and the particular interactions. . . must be separately accounted for” [18, p.272]. Hence, getting a good representation of the current complex flow with the codes is

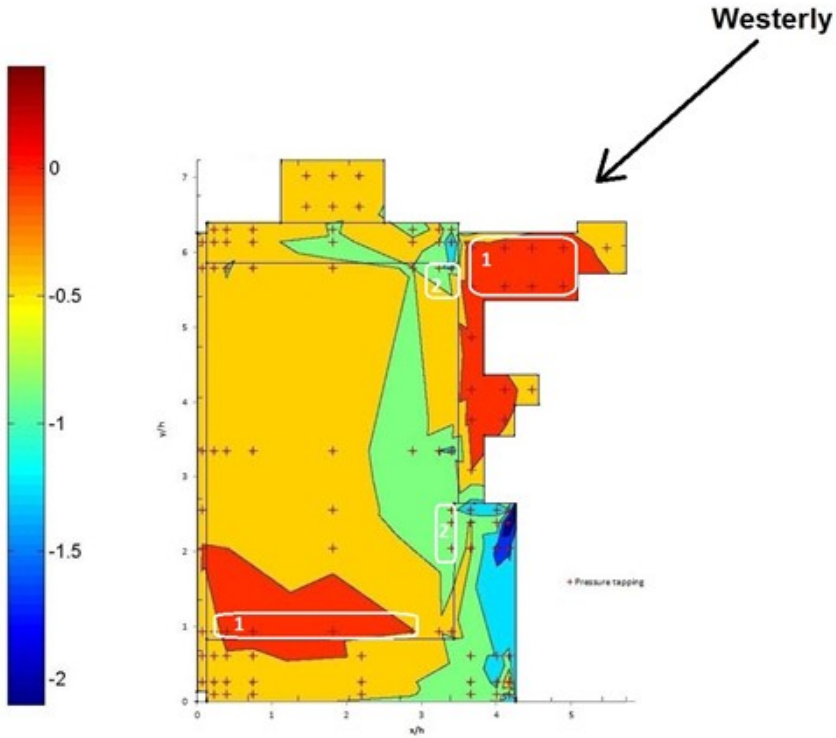


Fig. 23 Contours of surface C_p for a westerly flow over the HB model.

not straightforward. Nonetheless, in Figure 23, there is an agreement in zones F and G where the local flow effectively sees a simple cuboidal building.

3.3 The Trafficmaster Building

Figure 25 is the key figure to the nomenclature adopted for this building. Figure 26 presents a description of the flow around the building for a westerly and south-westerly wind. In the westerly wind, the west wing behaves like a simple cuboidal building. The flow sees the cross-wind dimension of Face 1 as the scaling length of the wing. It stagnates on Face 1. The EN underpredicts the localised pressure on this face, but its agreement with the EMV is commendable ($EN=0.7$, $EMV=0.67$, and $EPV=0.89$). The flow accelerates away from the stagnation region until it separates at the sharp edges of Face 1. At the upwind edges of Faces 2 and 4, negative pressures are recorded due to the flow separation. On Face 2, the flow separation with the consequent suction at the upwind corner is affected by the interaction of the positive pressures from Face 6 which the flow sees as a setback windward face. This region of interaction is wide ranging in Figure 27. In this figure, the Eurocode

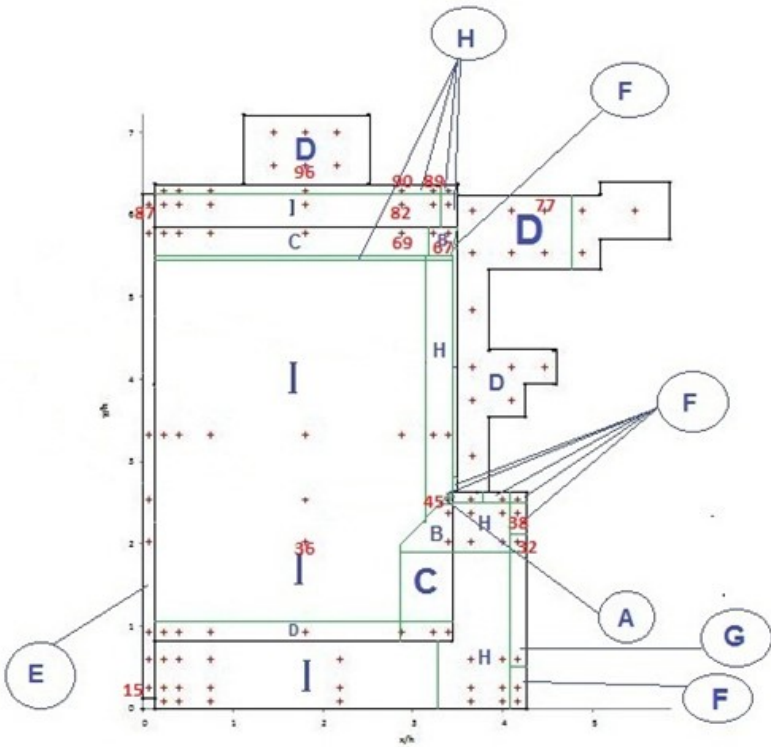


Fig. 24 The HB model roof divided into zones using the Eurocode.

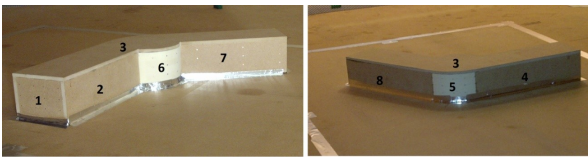


Fig. 25 Key figure for the dimensions and pressure tapping locations on the Trafficmaster building model.

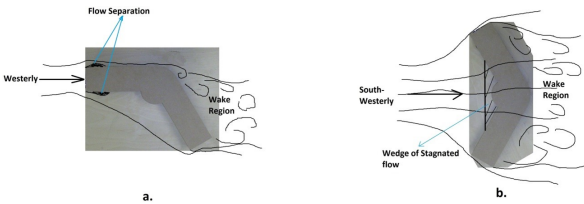


Fig. 26 Schematic diagrams of the flow around the Trafficmaster building model for (a) a westerly and (b) a south-westerly wind.

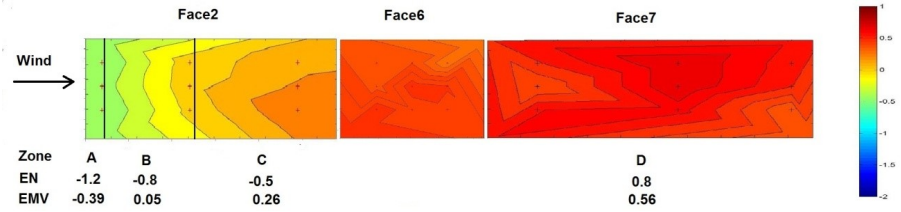


Fig. 27 Contours of surface C_p for a westerly wind flow over the Trafficmaster building model (Faces 1,6 and 7).

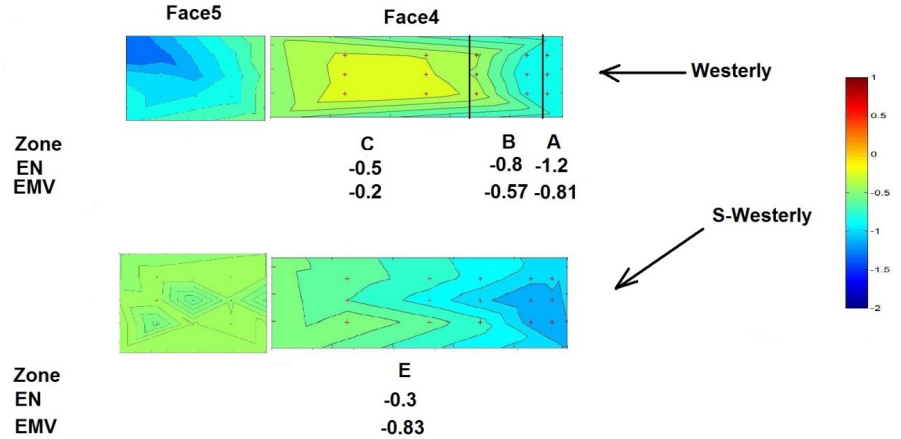


Fig. 28 Contours of surface C_p for a westerly and south-westerly wind flow over the Trafficmaster building model (Faces 4 and 5).

Table 4 Comparison of surface C_p between EN and EPV for Face 4 of the Trafficmaster building model in a westerly wind and south-westerly flow.

Zone	EN	EPV $\pm 7\%$
A	-1.2	-0.83
B	-0.8	-0.83
C	-0.5	-0.27
E	-0.3	-1.14

expected suctions in zones B and C are damped out into positive pressures, and the EMV is significantly less (in magnitude) than the EN in zone A. The situation is different for Face 4 which is a long face relative to the scaling length. The flow attempts to re-attach (in an unstable manner) towards Face 5 as it deflects around the external corner in to the wake. The results presented in Figure 28 and Table 4 suggest that if the adaptation of the Eurocode to Face 4 is to be valid, there will be no need for zone A on this face (or its extent will be reduced). Otherwise, the EN over-predicts the suction in zones A and C. For a south-westerly flow (Figure 26b), the flow enters the re-entrant

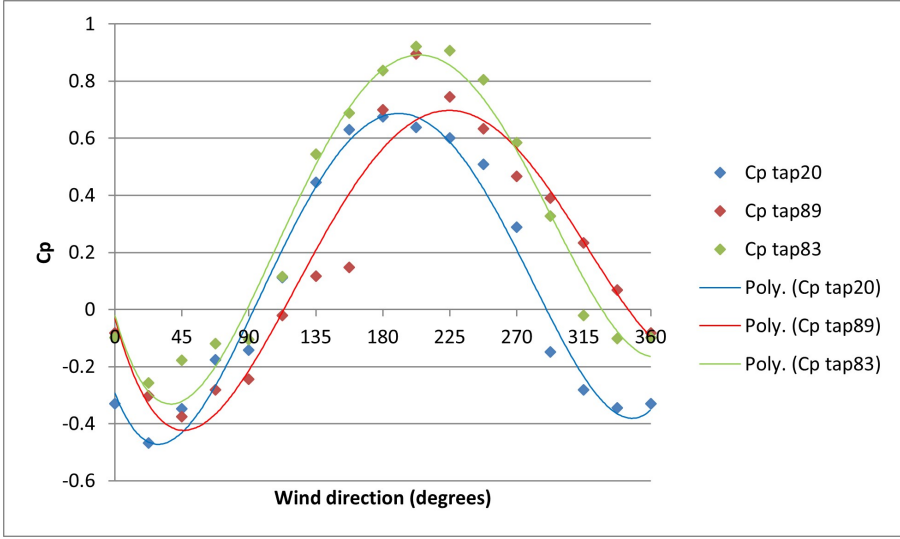


Fig. 29 Graph of C_p variation with wind direction for pressure tapplings 20, 83 and 89 on the Trafficmaster building model.

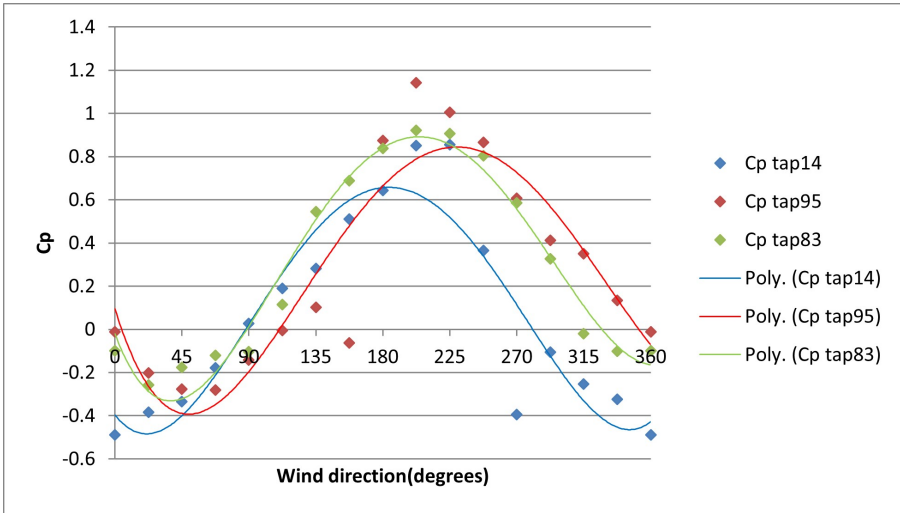


Fig. 30 Graph of C_p variation with wind direction for pressure tapplings 14, 83 and 95 on the Trafficmaster building model.

corner and gets trapped into a region of stagnated flow before it rises over the building into the wake region [18]. The stagnated flow region is defined by the wedge in the figure. In Figure 28 and Table 4, the EN under-predicts the suctions (both EMV and EPV) by very substantial amounts on Face 4 (which falls in the wake).

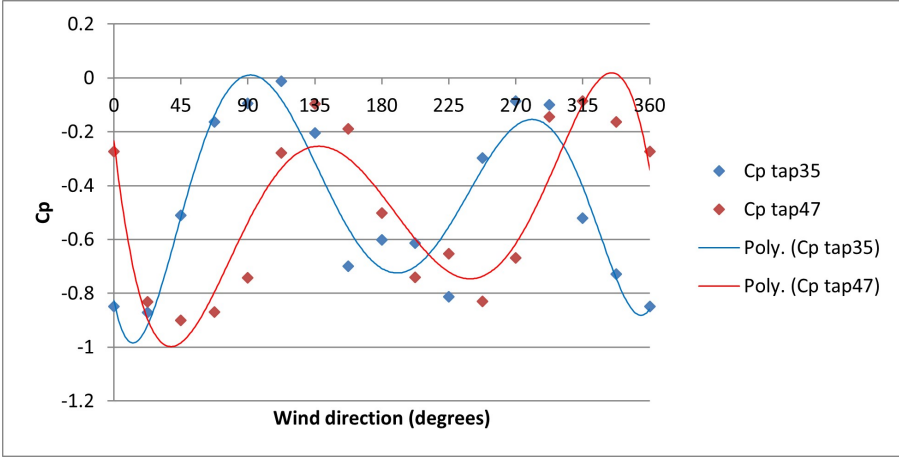


Fig. 31 Graph of C_p variation with wind direction for pressure tapplings 35 and 47 on the roof of the Trafficmaster building model .

The outward bulge of the circular Face 6 extends the effect of the positive pressures from the stagnation region beyond the extent of the wedge. The wedge is usually defined by the scaling length of the building. This can be observed in Figure 29 and Figure 30 where the pressures and the suctions on the internal and (towards) the external corners of Faces 2 (taps 20 and 14 respectively) and 7 (taps 89 and 95 respectively) follow the variation of pressure with wind direction on (circular) Face 6 (tap 83). Refer to Appendix A for the locations of these tapplings and tapplings 35 and 47 in Figure 31. The C_{ps} in these graphs are based on the calculated dynamic pressure at the various heights of the tapplings. The variation of C_{ps} with wind direction in these figures follow some coherent forms. The plots are suggestive that the flow pattern on the curved surfaces of the building dominates the whole flow. This is because the wave forms in Figure 29 and Figure 30 do not share a similar form with the trend in Figure 20 which represents the variation of pressure with wind direction on a wall of a cuboidal building. A consequence of this is that the Trafficmaster building is Re sensitive.

The flow around the building is very complex. It does not appear to be symmetrical except for a 45° wind. Therefore, the loading data on a wing of the building may not be appropriate to be used on the other. Figure 32 and Table 5 summarise the assessment of the EN on the roof of the west wing of the building. The EN over-predicts both EPV and EMV in zone F. It agrees with EMV and under-predicts the EPV in zone G. It over-predicts EMV and under-predicts EPV in zone H. It also under-predicts the suctions (both EPV and EMV) in zone I. These disagreements are likely because the EN does not account for the three-dimensional nature of the complex flow over the building which may come from building-induced turbulence and/or oncoming wind turbulence. The Eurocode provides no data on flat roofs of circular cylinders. Hence, no comparison could be made on this part of the roof of

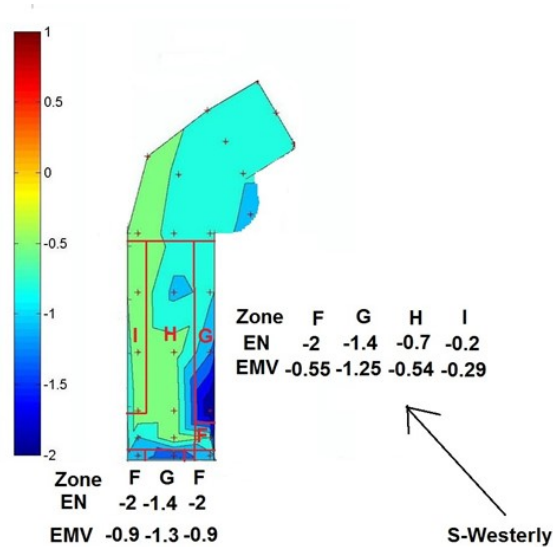


Fig. 32 Contours of surface C_p for a south-westerly wind flow over the Trafficmaster building model (Faces 3 – the roof).

Table 5 Comparison surface C_p between EN and EPV on the roof of the west wing of the Trafficmaster building model for a south-westerly wind

Zone	EN	EPV $\pm 7\%$
F	-2.0	-0.94
G	-1.4	-1.9
H	-0.7	-0.89
I	0.2	0.12
	-0.2	-0.47

the building. However it is suspected that interactions between the individual building shapes (cuboid and cylinder) will make the flow on that part of the roof to be different from that on the roof of a lone cylinder. Additionally, Faces 5 and 6 have not been analysed because they are curved surfaces, and it is not straightforward to get the provisions of the codes for the wind loading on them.

3.4 Effects of tributary area variation

Figure 33 and Figure 35 present the configurations used to assess the effect of tributary area variation on a flat and a curved surface respectively. The roof of the SH model and the curved surface Face 5 of the Trafficmaster building model are analysed respectively. These surfaces are chosen for the assessment because of the relatively uniform distribution of the tappings on them. The force coefficients compared for the different configurations in the bar charts in Figure 34 and Figure 36 are based on the dynamic pressure measured at 50mm in the wind tunnel and a reference area H^2 (where H is the height of the building). Where it is possible in the configurations, a tapping closest to

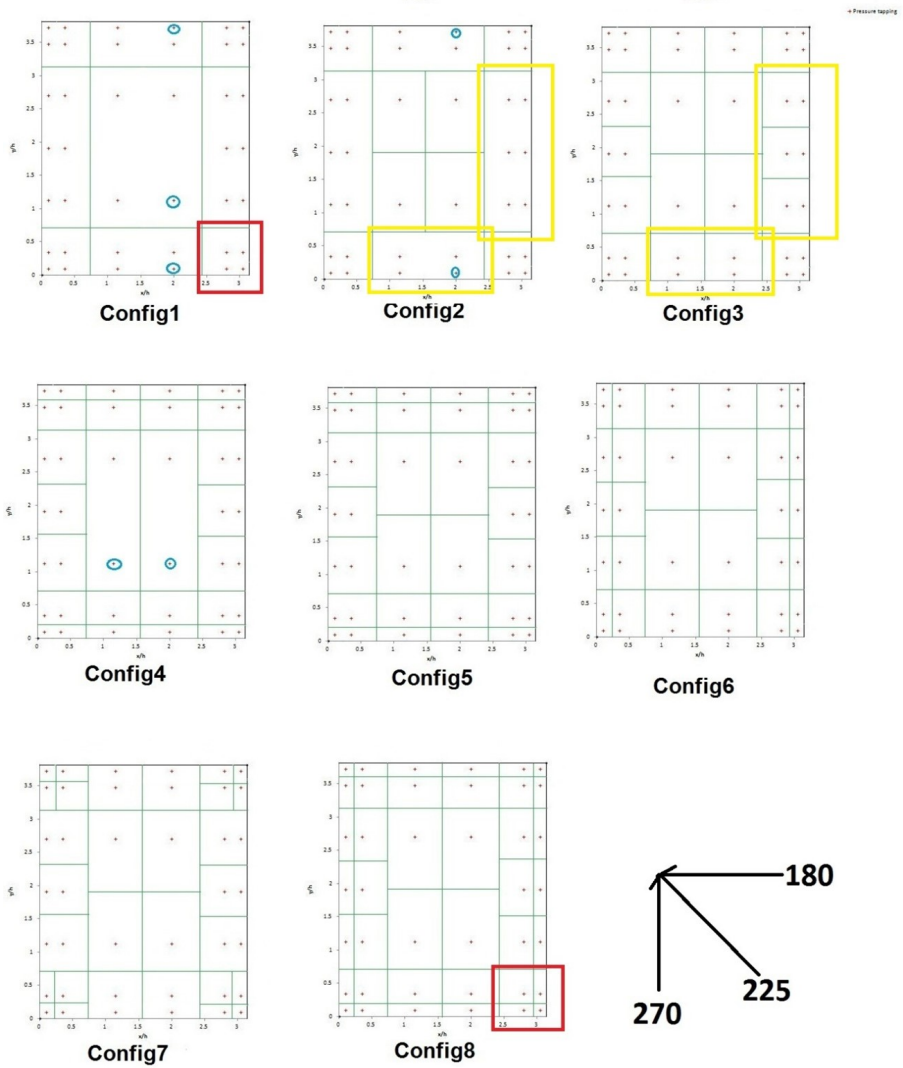


Fig. 33 Tributary area variation on the roof of the SH model for 8 different configurations.

the centre of a defined tributary area is used to estimate the wind loading on that area. Otherwise, the tappings used have been identified with the blue circles such as in some tributary areas in Configs 1, 2 and 4 in Figure 33. There are other variations of these configurations which can be assessed as well. However, the variations used are adequate for the present discussion.

The entire wind loading estimates have the negative sense. Thus, only the relative magnitude of the quantities are compared.

Table 6 presents the number of tappings in each of the configurations assessed on the roof of the SH model. Config 1 contains 9 tappings. It is the

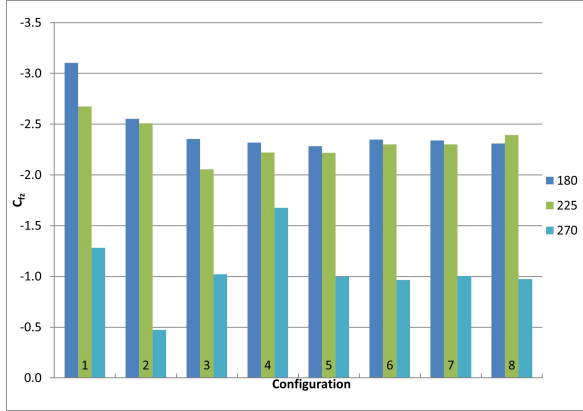


Fig. 34 Effect of tributary area variation on the wind loading on the roof of the SH model.

crudest of the configurations. Large portions of the surface like the centre region are untapped. However, Figure 17 shows that this region spans an area where the sense of the pressure changed downstream for a 270° wind because of the long span of the roof in this direction, resulting in an unstable flow re-attachment. In a 225° wind, the suction at the roof corner becomes higher. This is evident in the upshot in the cross-wind force or lift coefficient, C_{f_z} , compared to the 270° wind. For a 180° wind, the dimension of the roof in the streamwise direction is short. There is no possibility of flow re-attachment downstream of the upwind eave. Even though the suction at the roof corners becomes less compared to the 270° wind, C_{f_z} is higher because of the relatively higher suctions which cover the whole centre region. This trend can be observed for all the configurations except in Config 8 where C_{f_z} for 225° wind is higher than for 180° wind. This is because the suctions along the axis of the corner vortices which are the highest (for all wind directions) are factored in for the estimation. Refer back to the tributary areas bounded by the red boxes in Figure 33 to observe this.

Factoring in the individual pressures (from the tappings) in the centre region in Config 2 reduces C_{f_z} when compared to Config 1 because the changes in the sense of the pressures over this region are accommodated. The reduction in load is particularly observable for 270° wind when the roof experiences positive pressures in the downstream extremity of this region.

For normal winds (180° and 270°), the highest suctions are experienced in the middle of the eave and verge [18](the regions bounded by the yellow boxes in Figure 33 for Config 2 and 3). Accordingly, using more tappings in these regions of the roof increases the load in Config 3 when compared to Config 2 for a 270° wind. This is not observed for the other wind directions because increasing the number of tappings all over the roof gives the opportunity to capture regions where less suctions are experienced for these wind directions. So, the load reduces.

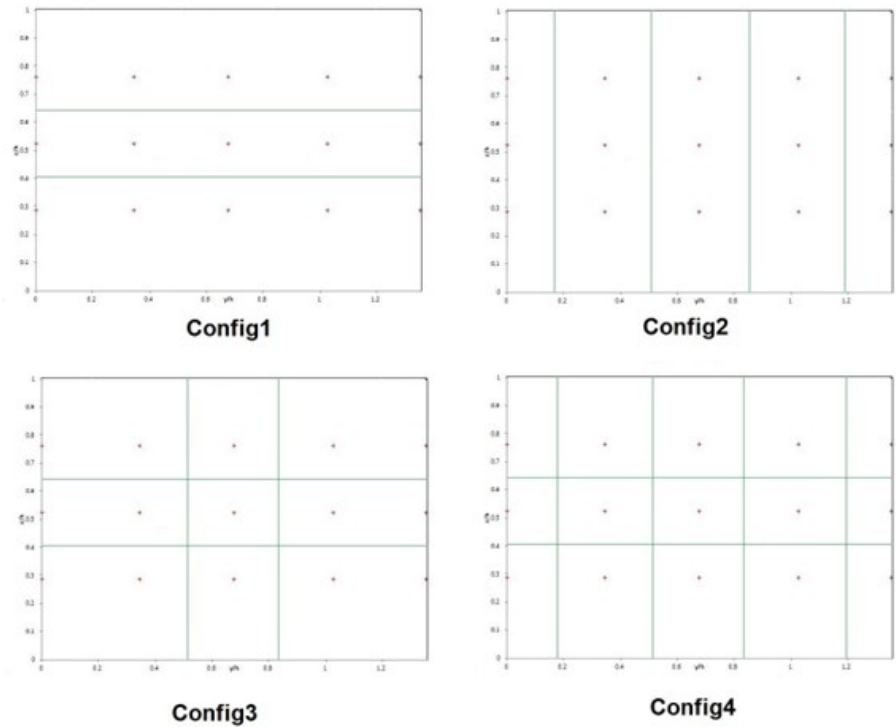


Fig. 35 Tributary area distribution over Face 5 of Trafficmaster building for configurations 1-4.

Table 6 Number of tappings in each of the configurations used for tributary area variation assessment on the roof of the SH model.

Config	No of taps
1	9
2	12
3	18
4	24
5	26
6	28
7	30
8	40

C_{fz} increases in Config 4 when compared to Config 3 for a 270° wind because positive pressures downstream in the centre region are excluded. This is rectified in Config 5 where more tappings are used in this region compared to Config 4.

Configs 5 with 26 tappings do not present much of variations in the C_{fz} when compared to Config 8 with 40 tappings. However, between Config 1 and Config 8, the load reduces on the roof with increasing number of tappings.

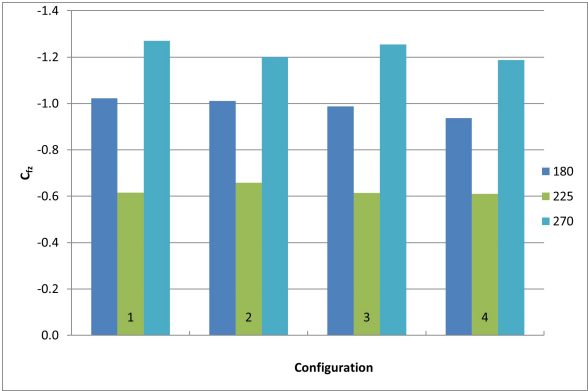


Fig. 36 Effect of tributary area variation on the wind loading on Face5 of the Trafficmaster building model.

Table 7 Number of tappings in each of the configurations used for tributary area variation assessment on Face5 of the Trafficmaster building model.

Config	No of taps
1	3
2	5
3	9
4	15

This trend is expected to extend beyond Config 8. Additionally, the load is a function of wind direction on a flat roof of a cuboidal building.

Accordingly, the knowledge of the expected flow features and their expected variations with wind direction on a building geometry is key to getting reliable wind loading estimates from wind tunnel studies when there is a limitation on the number of tappings to be used. All the configurations assessed in Figure 36 and table 7 on the curved Face 5 of the Trafficmaster building present about the same magnitude of load. This is suggestive that the load on a curved wall is fairly constant with tributary area. However, it varies with wind direction.

4 Conclusions

The Eurocode provisions for wind loading on low-rise buildings are cheaper alternatives to wind tunnel studies. Very tall buildings and large structures have enough economic justification for expensive wind tunnel studies in their design stage. Such wind tunnel studies feature simultaneous scanning and acquisition of loading data from hundreds of pressure tappings with subsequent high-speed computer data processing and analysis. This is not the case for low-rise buildings which do not find their way into the wind tunnel except where they are unusual edifices. Low-rise buildings, however, are the most damaged in wind storms. Their shapes are also increasingly different from the traditional and generic forms that are considered in the Eurocode. Additionally, the current data acquisition techniques are more advanced than were used for

the wind tunnel studies in the 80s from which the Eurocode provisions were collated. Thus, it is of interest to assess the performance of the Eurocode on present building shapes. This defined the aim of the study and its focus on low-rise buildings. In addition, the limit on the required number of pressure tapping to obtain adequate and reliable wind loading information from wind tunnel studies is investigated.

Three buildings on the Cranfield university campus are the subject of this study. The SH which is a simple cuboidal building with a flat roof. Building 83, HB features inset faces in its plan and elevation. and the Trafficmaster Building is a re-entrant corner with a V-plan having curved surfaces at the internal and external junctions of its wings. Wind tunnel experiments were carried out on the 200th model of these buildings, and the results are discussed.

4.1 Summary of observations

1. Surface pressure coefficients based on the wind pressure measured at the equivalence of 10m in the wind tunnel are more consistent with theoretical and practical expectations than those based on calculated wind speeds at different heights on the buildings tested.
2. Generally, the Eurocode over-predicts the $C_{pe,10}$ in designated zones of the roof and side walls of the SH. However, a striking agreement was noticed in zone H of the roof between EN ($C_{pe,10}$) and the result of the experiment for a normal wind to the eave. In addition, $C_{pe,l}$ in zone D (on a windward wall) as well as in zones F, G and I of the roof were accurately predicted by EN. Where disagreements are noticed, they are because the UK NA to the Eurocode specifies the same values of localized pressure coefficients for $C_{pe,10}$ and $C_{pe,l}$.
3. A particular problem arises for a quartering wind on building walls for which the Eurocode provisions can result in both unsafe and uneconomic solutions.
4. The adaptation of the Eurocode provisions on a simple cuboidal building to predict the C_p on the roof of the HB results, generally, into unsafe conditions. The flow over the building is very complex having interactions of positive pressures from its windward inset faces with suctions on their adjoining lower roofs. In addition, the interaction of cross-flows close to the junction of its inset faces flushed with the building geometry on all sides and a lower roof results into high suctions on the lower roof. However, some agreement between EN and experiment result is noticed at some roof corner of the building (that bear resemblance to roof corners of simple cuboidal buildings) where complex cross-flow interactions are absent on the building (zones F and G).
5. Generally, the adaptation of the Eurocode for wind loading prediction on the Trafficmaster building results into unsafe conditions. Where agreement is observed between EN and EMV (or where EN over-predicts EMV), unsafe disagreement exists between EN and EPV. This is also attributed to the inability of the Eurocode to adequately predict the complex flow around

the building that is dependent on the whole plan shape and affected by freestream and building-generated turbulence [18].

6. The variation of C_p with wind direction on the internal side walls of both wings of the Trafficmaster building follow some wave form similar to that followed by the curved surface present at the internal junction of the wings. The variation of C_p with wind direction on the roof of the building also follows a wavy trend.
7. On the roof of the SH model, the overall load reduces with increasing number of tappings i.e. decreasing size of tributary areas of the tappings. However, on a curved wall (Face 5 of the Trafficmaster building), the overall load remains fairly constant with tributary area size. In addition, the magnitude of the load depends on wind direction.

4.2 Concluding remarks

The following conclusions are drawn from the observations made:

1. The Eurocode in use in the UK may over-predict the load on the structure of a simple cuboidal building with a flat roof. However, it is adequate for the design of cladding elements on such a building. This notwithstanding, it is in need of some minimal updates in that regard. Generally, adapting its provisions to buildings of irregular plans, particularly those featuring inset faces and re-entrant corners, may result into unsafe conditions. This is because the complex flows around these irregular buildings depend on their whole planforms.
2. When the predominant wind direction is skewed on a simple cuboidal building, some difficulties may be encountered in the the safe design of its walls using the Eurocode provisions. Also, the Eurocode may not be adequate for the design of buildings with irregular plans in skewed approaching winds.
3. The quality of the wind loading estimate from a wind tunnel study is better with more pressure tappings. However, where there is a limitation on this, the knowledge of the expected flow features on the building geometry in the particular wind direction can inform the distribution of these tappings that will give very reliable loading estimates.
4. A building with sharp edges and curved surfaces will be Reynolds number sensitive.

4.3 Future work

Concluding remarks 1 and 2 are only preliminary. This is because the Eurocode C_p s are pseudo-steady coefficients that are processed through the Cook-Mayne method after an extreme value analysis [18], whereas the C_p s in the current study are mean values. The measured mean values are devoid of time-dependence and possible correlations between pressure taps, ignoring contributions from the building-generated turbulence. Additionally, the analysis method involving Hermite transformation into a Gaussian process model [21] has become popular. Consequently, evaluating the Eurocode provisions in

the present case studies through these lenses is a subject of future work and publication.

List of abbreviations

ABL	- Atmospheric boundary layer
CU	- Cranfield University
Config	- Configuration
DC	- Direct current
EN	- Eurocode specified value
EMV	- Experiment mean value
EPV	- Experiment peak value
ESDU	- Engineering Sciences Data Unit
HB	- Hangar Building
NA	- National annex
SH	- Sports Hall
SW	- South-West
TP	- Turbulence profile
UK	- United Kingdom
VP	- Velocity profile
W	- West

Declarations

- Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.
- Competing interests
The authors declare that they have no competing interests
- Funding
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- Authors' contributions
TOA wrote the main manuscript text and prepared figures, with contributions from KO and KM. OAO provided technical guidance on the interpretation and presentation of results. All authors reviewed and approved the final manuscript.
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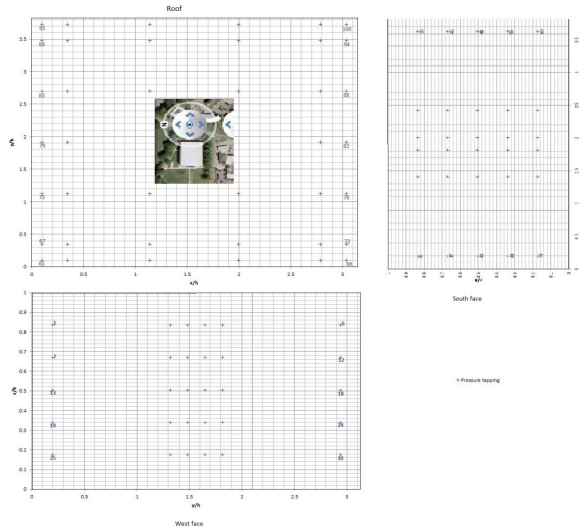


Fig. A1 Key figure for the dimensions and pressure tapping locations on the SH model.

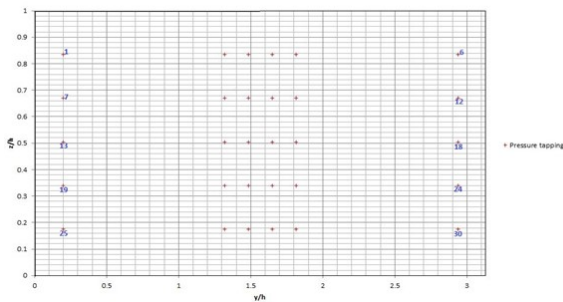


Fig. A2 The West face of the SH model.

Appendix A Building models dimensions and pressure tapping location

Figure A1 is the key figure for the SH model dimension and pressure tapping locations presented in Figure A2, Figure A3 and Figure A4. The normalizing parameter $h = 60.55mm$ which is the height of the SH model.

Figure 25 is the key figure for the dimensions and pressure tapping locations on the Trafficmaster building model presented in Figure A5 all through to Figure A12. The normalising parameter $h = 67.32mm$. This is the height of the Trafficmaster building model.

The vertical axis in Figure A5 adjoins Face 4. The vertical axis in Figure A6 adjoins Face 1.

The vertical axis in Figure A8 adjoins Face 5. The vertical axis in Figure A9 adjoins Face 8. The vertical axis in Figure A10 adjoins Face 2. The vertical axis

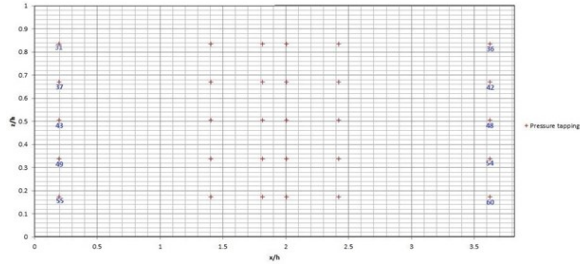


Fig. A3 The south face of the SH model.

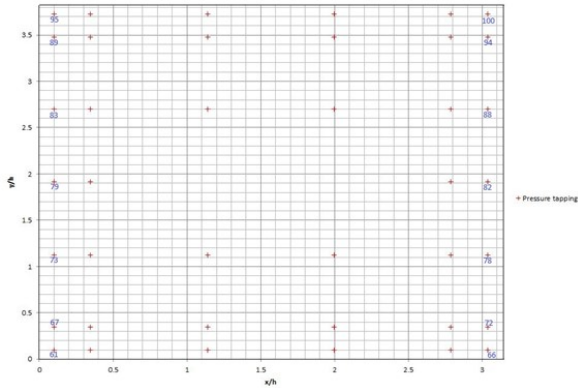


Fig. A4 The Roof of the SH model.

in Figure A11 adjoins Face 6. The vertical axis in Figure A12 adjoins Face 5.

Figure A13 presents the plan dimensions of the HB model and pressure tapping locations. The part where tapping 1 is located is the highest part of the model with $h = 74mm$. This is the normalising parameter for the dimensions of this model.

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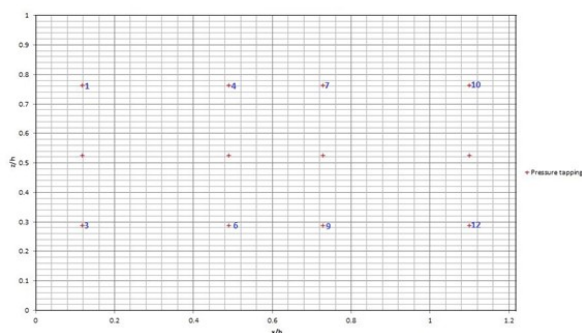


Fig. A5 Face 1 of Trafficmaster building model.

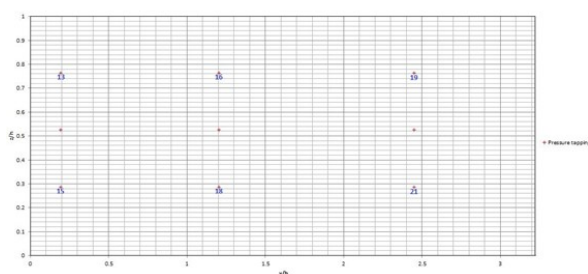


Fig. A6 Face 2 of Trafficmaster building model.

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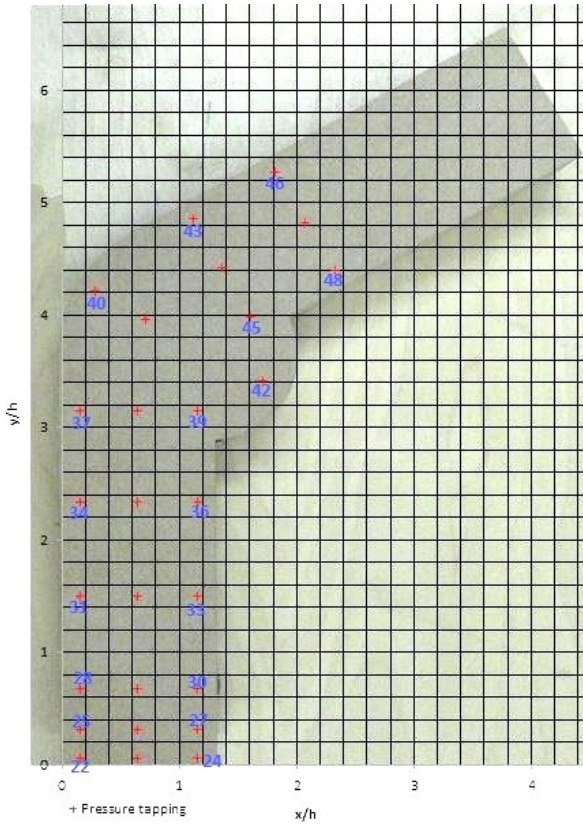


Fig. A7 Face 3 (the roof) of Trafficmaster building model.

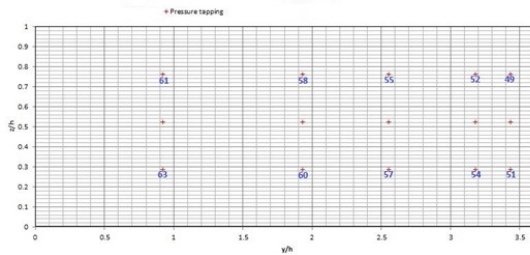


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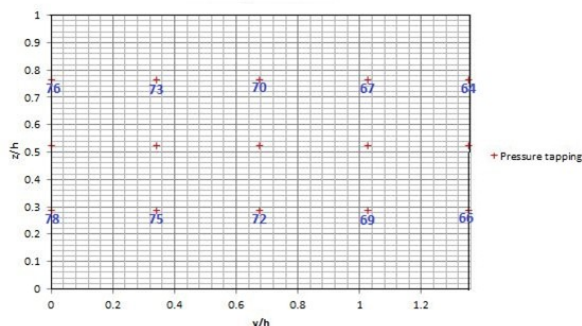


Fig. A9 Face 5 of Trafficmaster building model.

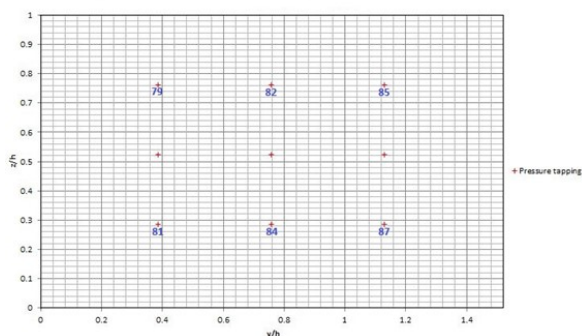


Fig. A10 Face 5 of Trafficmaster model.

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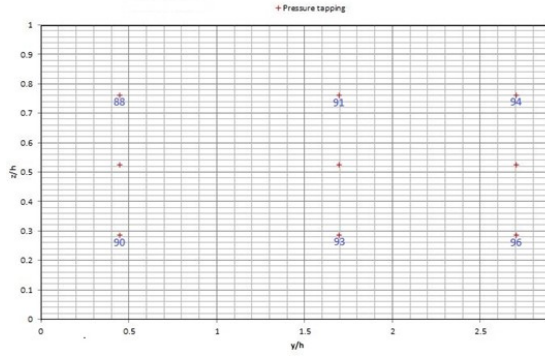


Fig. A11 Face 7 of Trafficmaster building model.

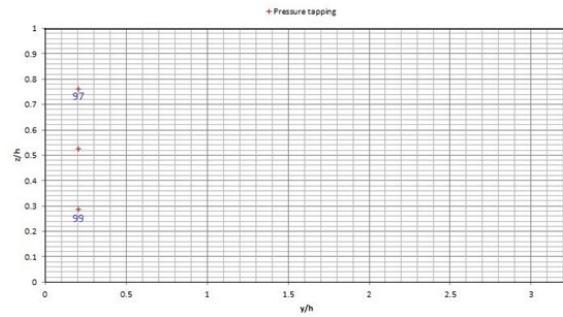


Fig. A12 Face 8 of Trafficmaster building model.

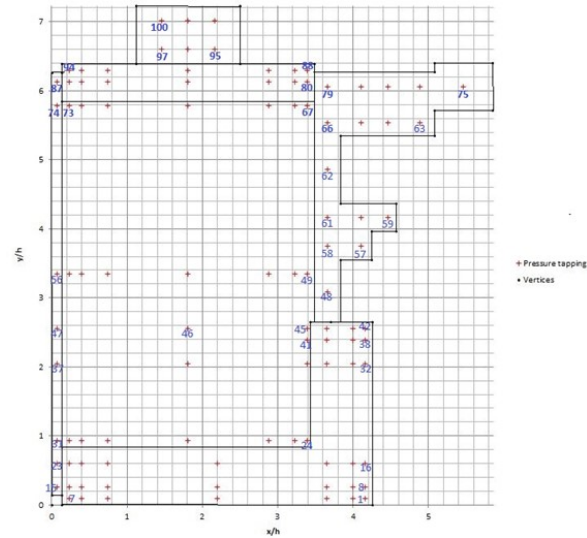


Fig. A13 The HB model plan dimension and tapping location.

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