COMPARISON OF WIND FLOW THROUGH AN ENCLOSED SHOPPING MALL UTILISING CFD AND FULL-SCALE MEASUREMENT TECHNIQUES

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Abstract

Computational Fluid Dynamics predictions of wind flow through an enclosed shopping mall are compared with full-scale measurements. The suitability of CFD to predict the acceptability of environmental wind conditions in an enclosed mall setting is investigated in terms of mean and gust wind speed.

Background

A series of full-scale wind speed measurements were undertaken by Vipac Engineers and Scientist Ltd within a Sydney CBD shopping mall to determine the acceptability of wind conditions throughout the mall passageways in terms of pedestrian comfort. A series of measurements were taken at discrete locations within the mall during three separate synoptic gale events in late winter 2001. A CFD simulation of wind flow through the mall was performed to assist with the extrapolation of full-scale results. This paper will compare the full-scale results with the Computational Fluid Dynamics (CFD) model simulation for one wind direction.

The mall is unsealed with large dominant passageway openings at its eastern and western boundaries and through a central roof cavity (Figures 2 and 3). Ground floor level of the mall comprises a central plaza space linking the east and west passageways. Lower ground level also includes smaller stairway openings onto the eastern and western perimeters of the site as well as an underground train station. The subject mall is located at the base of a highrise tower toward the southern end of the Sydney CBD area and is surrounded by medium to high-rise Sydney CBD developments.

Full Scale Measurements

A 3-cup type anemometer and vane at a reference height of 1.5 metres were used to log wind speeds at various locations throughout the mall as marked in Figure 2. Measurements were taken for approximately 30 minutes at each location to capture the micrometeorological peak frequency range. Data was sampled at a frequency of 5 Hz and stored onto a portable laptop computer. The response length of the lightweight anemometer cups was estimated to be less than 3 metres considered sufficient to capture 3-second gusts [2]. The test anemometer was calibrated against a pitot tube/manometer both before and after the current tests in Vipac's Melbourne Laboratories.

Wind speed measurements contained in Table 1 were acquired during the late winter period to capture strong westerly synoptic gales that characterise the season. For the current study Bureau of Meteorology weather stations at Fort Dennison and Sydney Airport were used as reference velocity points. Met Bureau wind data collected over the measurement periods were found to remain stationary in direction and magnitude during the measurement periods as determined from run-test analysis of the data [1]. Stationary reference wind speeds induced by large-scale gales (of the order of hundreds of kilometres) are suited to the current study given the separation of the measurement site to each reference anemometer (approximately 2.5 km to Fort Dennison and 10 km to Sydney Airport). For convenience, a reference wind speed at 10 metres height in open country was used as a common reference for the study. Turbulence and terrain roughness information contained in Australian Standard 1170.2 [5] was used to adjust wind data at both weather stations to the one common reference.

Cumulative probability distributions of wind speeds for the Sydney CBD region were fitted with Weibull distributions for each wind direction to provide polar plots with lines of constant probability level using methodology described by Melbourne [3] [4]. Referenced 3-second gust wind speeds measured in the mall are plotted in terms of peak velocity squared ratios against Melbourne's wind acceptability criteria in Figure 1.

Table 1
FIELD WIND VELOCITY MEASUREMENT RESULTS

Date	Time	Locn	Reference wind direction (degrees)	Measured peak gust $\hat{v}_{local}$ (m/s)	Measured mean $\bar{v}_{local}$ (m/s)	Reference mean $\bar{v}_{10mcat2}$ (m/s)	Peak Velocity squared ratio $\left\|\frac{\hat{v}_{local}}{\bar{v}_{10mcat2}}\right\|^2$
28/7/01	13:35-14:07	1	211	**12.6**	**4.8**	13.6	0.86
"	14:11-14:46	2	211	**5.0**	**2.1**	13.6	0.14
"	14:51-15:20	3	211	**5.0**	**1.0**	13.6	0.14
"	15:28-15:55	4	211	**7.2**	**3.3**	13.6	0.28
"	15:55-16:22	5	211	**6.3**	**1.8**	13.6	0.21
6/8/01	14:29-15:05	1	249	**7.7**	**4.1**	7.4	1.09
"	15:06-15:32	2	249	**5.4**	**2.3**	7.4	0.54
"	15:34-15:49	3	249	**0.9**	**-**	7.4	0.01
"	16:05-16:38	4	249	**4.5**	**2.6**	7.4	0.37
8/8/01	12:34-13:03	1	266	**8.1**	**4.1**	10.5	0.59
"	13:14-13:47	6	266	**5.9**	**2.6**	10.5	0.32
"	13:49-14:25	7	266	**5.0**	**2.0**	10.5	0.23
"	14:30-14:53	8	266	**1.8**	**-**	10.5	0.03
"	15:13-15:34	9	266	**5.9**	**2.7**	10.5	0.32

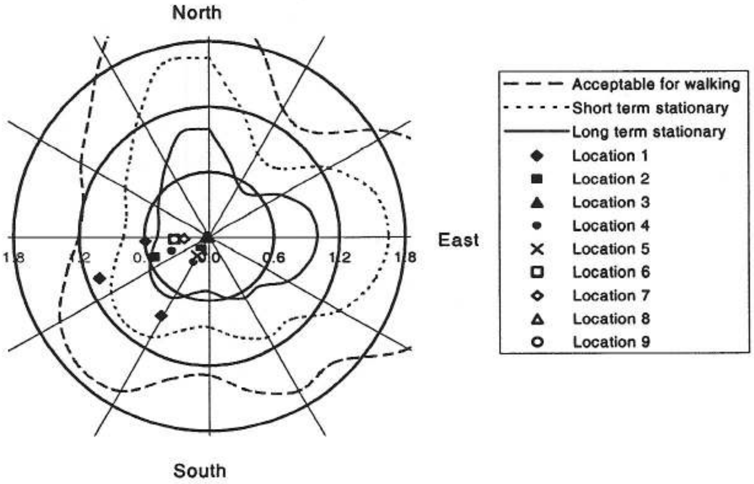

Figure 1 Peak velocity squared ratios $\left|\frac{\hat{v}_{local}}{\bar{v}_{10mcat2}}\right|^2$ *measured in full-scale*

CFD Modelling

CFD analysis of wind through the mall was performed using the commercially available software code Phoenics. Phoenics was used to solve the Navier-Stokes conservation equations for continuity, energy and momentum to predict steady state airflow inside and around the building.

The boundaries of the model shown in Figure 2 and 3 are aligned along a 270° bearing with a velocity inlet boundary condition specified 400m upstream of the mall approximating a category 4 velocity profile [5] with 20% turbulence intensity. A four storey building to the east of the site was the only upstream development modelled with the effect of other medium to high-rise developments catered for by the velocity inlet boundary condition. For the current analysis more than 668 000 non-uniform grid cells covered the computational domain. All computations were conducted on a pc computer with a 2GB processor and 2.1 GB of memory. Converged solution required more than 25 hours of CPU time.

A Standard k-ε turbulence model was used during the current study whereby the transport equations are obtained using a time averaging procedure known as Reynolds (ensemble) averaging. The Standard k-ε model is a semi-empirical eddy-viscosity model in which the Reynolds Stresses are assumed to be proportional to the mean velocity gradients, with the constant of proportionality being the turbulent viscosity. The model adopts an isotropic description of the turbulence through this assumption and is thus not well suited for flows in which anisotropy of turbulence significantly effects the mean flow.

Results and Discussion

Coloured contour plots of steady flow velocity through the mall are provided in Figures 2 and 3 for the westerly wind condition. The mall is observed to receive considerable shielding from westerly winds by the four storey building upstream to the west. Re-circulation in the lee of the upstream building and against the eastern windward face of the mall is clearly evident in the velocity vector diagram of Figure3. The highest velocities inside the mall occur through the main western entrance between locations 1 and 2 as anticipated from the full-scale measurements. Once inside the central plaza flow dissipates into the large volume of the central cavity. Velocities at all other entrances to the mall are of considerably lower magnitude as flow passes through both the open roof cavities and leeward (eastern) entrances.

Steady flow velocities at each measurement location obtained from CFD simulation are compared to the corresponding full scale mean velocity measurements in Table 2. Velocities have again been normalised to a common reference velocity (10 metres height in open country) for ease of comparison. Good agreement is found between the full-scale and CFD mean velocity ratios, particularly for yaw angles approaching the westerly wind condition modelled in the CFD analysis. For the 249° and 266° yaw angle cases the correlation coefficient between the mean velocity ratio data sets is 0.73.

For a normally distributed process it is appropriate to assume the 2-3 second mean maximum gust will exceed 3.5 standard deviations above the mean. Based upon this assumption, gust velocities were derived from the mean and turbulence intensity data calculated from the CFD analysis and listed in terms of peak velocity squared ratios in Table 2. Good agreement is again found between the full-scale and CFD peak velocity squared ratios with the best correlation found generally in those areas with higher mean velocities.

It is considered medium to large eddy structures are effectively filtered as turbulent flow penetrates the internal mall cavity (Figure 3). A Reynolds averaging prediction such as the Standard k-ε turbulence model is then more suitable for modelling the regeneration and dissipation of small-scale isotropic turbulence within the mall. Nevertheless, further investigation of turbulence spectra within the mall should be conducted to validate the predicted gust wind speeds since low frequency energy below the inertial subrange was not modelled. One possible solution to be investigated is the superimposition of large scale turbulence energy measured directly on site (low pass filtered at say 0.1 Hz) with higher frequency turbulence predicted using a Reynolds averaging prediction.

Conclusions

Computational Fluid Dynamics predictions of wind flow movement through an enclosed mall were found to compare well with the results from full-scale scale measurements particularly in terms of mean flow. Preliminary results suggest a standard k-ε turbulence model is suitable for modelling small-scale isotropic turbulence within the mall however some further investigation is needed to incorporate large-scale turbulence energy into the prediction of gust wind speeds.

Acknowledgements

Hanif Miah and Peter Matthews of the Vipac Sydney Office assisted during the full-scale measurements.

References

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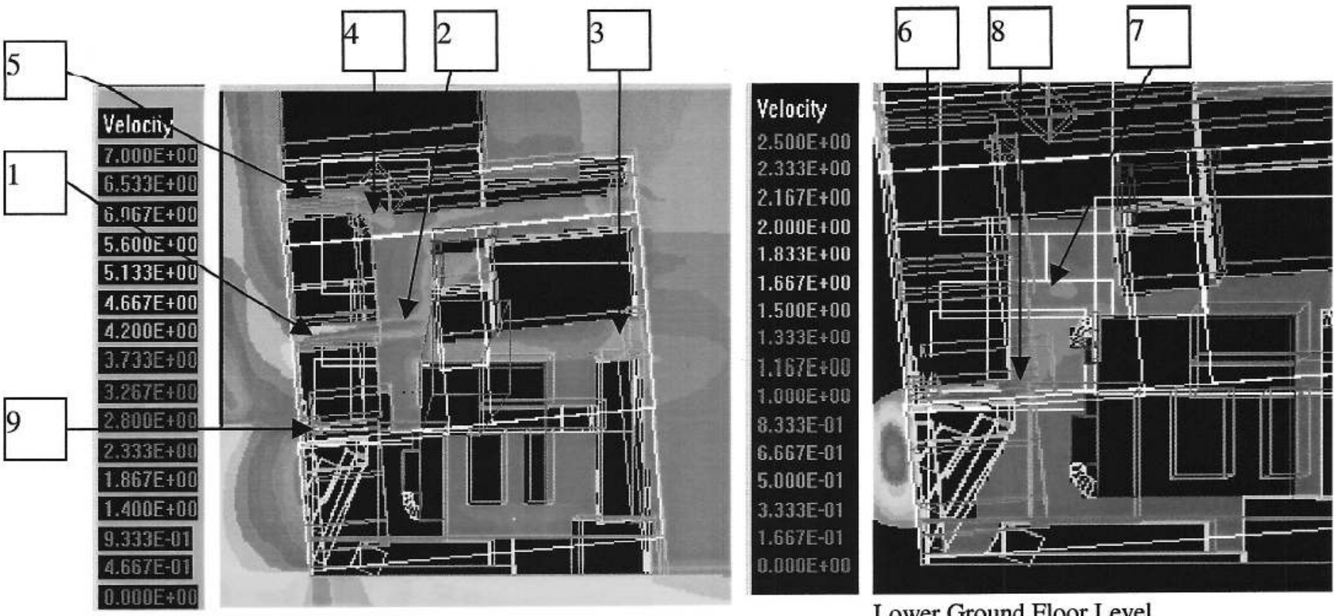

Ground Floor Level

Lower Ground Floor Level

Figure 2 CFD wind speed contours (m/s) through sections 1.5m above ground level.

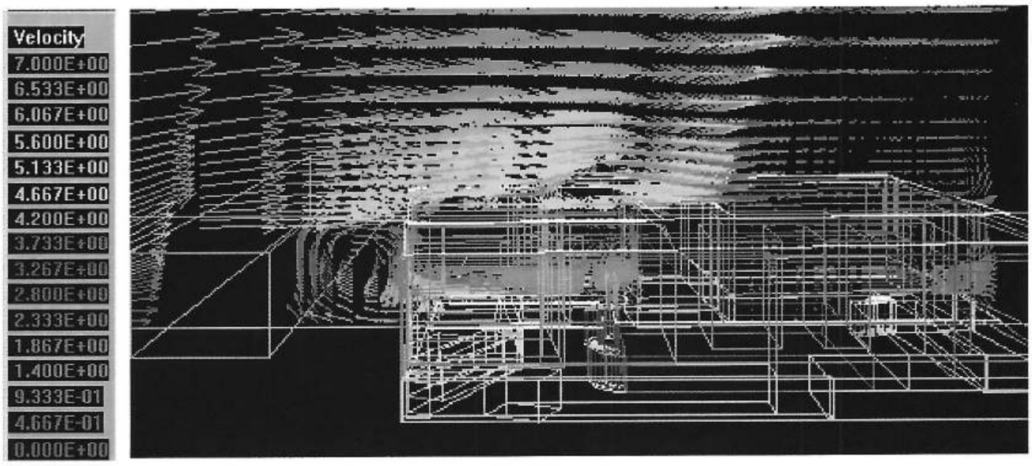

Figure 3 CFD wind velocity vectors (m/s) - vertical section through locations 1, 2 and 3.

Table 2

FIELD VS CFD WIND VELOCITY RESULTS

Full-Scale Results				CFD Results	
Locn	Reference wind direction (degrees)	Mean velocity ratio $\frac{\overline{v}_{local}}{\overline{v}_{10mcat2}}$	Peak velocity squared ratio $\left\lvert\frac{\hat{v}_{local}}{\overline{v}_{10mcat2}}\right\rvert^2$	Mean velocity ratio $\frac{\overline{v}_{local}}{\overline{v}_{10mcat2}}$	Peak velocity squared ratio $\left\lvert\frac{\hat{v}_{local}}{\overline{v}_{10mcat2}}\right\rvert^2$
1	266	0.39	0.59	0.46	0.82
1	211	0.35	0.86	0.46	0.82
1	249	0.55	1.09	0.46	0.82
2	211	0.15	0.14	0.33	0.44
2	249	0.31	0.54	0.33	0.44
3	211	0.07	0.14	0.21	0.28
4	211	0.24	0.28	0.14	0.17
4	249	0.35	0.37	0.14	0.17
5	211	0.13	0.21	0.29	0.38
6	266	0.25	0.32	0.24	0.15
7	266	0.19	0.23	0.10	0.02
9	266	0.26	0.32	0.30	0.37