THE ROLE OF WIND IN NATURAL VENTILATION SIMULATIONS USING AIRFLOW NETWORK MODELS

Joel Good[1], Andrea Frisque[1], and Duncan Phillips[2]

[1]Rowan Williams Davies & Irwin Inc., Vancouver, BC, Canada
[2]Rowan Williams Davies & Irwin Inc., Guelph, ON, Canada

ABSTRACT

Buildings have been naturally ventilated without detailed analyses for hundreds and thousands of years. For many standard and smaller buildings it can be possible to achieve satisfying designs based on experience alone. However, as a means to conserve energy while providing superior thermal comfort, natural ventilation is increasingly considered as a means to ventilate large, complex buildings, including buildings with high loads for which high performance is critical. For these types of buildings it is important to have tools for analysis of design to evaluate a design's predicted performance in order to achieve high confidence in the design. These tools are described in the present paper as well as a proposed process on designing buildings for natural ventilation. An example case study is discussed.

INTRODUCTION

High-end analyses for natural ventilation are becoming increasingly important, as we are pushing the envelope on its application. Larger and more complex buildings are designed to be either fully naturally ventilated, or partially, when mixed with mechanical ventilation.

The major tools that are used for design analyses are airflow network models and Computational Fluid Dynamics (CFD), sometimes complemented by wind tunnel studies. As the design of fully or partially naturally ventilated spaces is a complex design task, demanding thorough knowledge of fundamental physics, expert knowledge is a crucial skill as well. No design tool has yet come to the point of providing reliable answers that can be trusted without expert review. Design teams are often unclear about the different roles of these tools. These roles will be explained below.

Natural ventilation in buildings is driven by two forces: buoyancy (or stack effect) and wind. Wind is often the dominant of these forces (CIBSE, 2005).

For natural ventilation analysis, whole-building simulation programs determine the airflow across an opening by determining the pressure differential that exists across that opening. One component of the pressure differential across the opening is the pressure inside the building, which mostly depends on temperature. The other component is the wind pressure on the opening.

The flow around simple buildings in simple terrain is reasonably well understood by most. For a cube-like building, the flow approaches the building, there is a stagnation zone in front of the building and flow is diverted around the top and sides. The relative amounts of flow that are diverted around the top or sides vary depending on the dimensions of the building, the proximity of the location of interest to the top of the building and the oncoming wind conditions. The stagnation zone at the front of the building results in a positive pressure. As the flow travels across the top and around the sides of the building it tends to separate leaving a recirculation bubble on both the sides and the top. The length and strength of the recirculation bubbles depend on similar factors described above. In some cases the flow reattaches, in others it remains detached from the building. The pressure applied to the building in these locations is outwards - negative. Finally, at the rear of the building, the flow completely separates from the rear of the building and large negative pressure wake is left. In all cases, the separation zones result in pressures that fluctuate in time. If there is an upstream building, then the wake of that building and the additional turbulence can significantly change how the flow behaves as it traverses around the building of interest.

As the architecture of the proposed building becomes more complex, the elements on this building can affect other locations on the building. These impacts are not always intuitive. In order to design a naturally ventilated building using wind as one of the driving forces, one needs to have a firm understanding of the wind patterns around the proposed building. Given that the wind conditions at the openings drive the natural ventilation airflows inside the buildings, it is important to choose these adequately. The following section will discuss the tools commonly used in natural ventlilation design analysis and will examine the methods in which each determines wind pressure coefficients.

.

NATURAL VENTILATION DESIGN TOOLS

Airflow Network Models:

Airflow network models calculate the bulk airflow movement through the building. To include all the details about the building they are coupled to thermal dynamic simulation models which resolve all the energy flows in the modeled building spaces as a result of the weather, their usage, and the construction details. Two example software tools are IES Virtual Environment (IES VE, 2008) and the combination of DesignBuilder (2008), and EnergyPlus (2008). Dynamic thermal simulations coupled with airflow network models investigate the performance of a building over the course of a typical year. Weather data and usage/operations schedules are resolved down to a one hour time step. These kinds of simulations provide information on the bulk airflow through the building and the average temperatures that can be expected in the different zones of the building that are modeled.

The airflow into the building through the openings is determined by the outside weather condition, particularly wind and temperature. The wind condition at a building is not only determined by the overall wind information from weather statistics, but also from the geometry of the building itself as well as its surroundings. Overhangs, alcoves, recesses, neighboring buildings, trees and other features influence the local wind situation significantly.

The way in which this localized wind pattern information is entered in the simulation programs is through C_p values. These parameters specify the pressure for a location on a building face depending on the overall wind situation. For natural ventilation scenarios, where all internal airflows are driven by these airflows entering the building through its openings, any errors in the C_p values will translate into the simulated overall building performance. For example, if a simulation with a thermal model coupled with an airflow model predicts a certain number of hours outside of comfort range – say 25 hours out of the occupied hours are over 27°C – the reliability of this result will be directly depending on the reliability of the C_p values.

There are default C_p values provided in the airflow network model simulation tools. These are based on the Air Infiltration and Ventilation Centre's (AIVC) Guide to Energy Efficient Ventilation (Liddament, 1996), which consists of a number of wind tunnel tests for generic, low-rise buildings. Typically these C_p values only apply as acceptable initial approximations for buildings with a shape that is close to rectangular and which does not exceed 3 or 4 storeys in height.

Computational Fluid Dynamics:

Computational Fluid Dynamics (CFD) for natural ventilation can be used for internal building flows as well as external building flows.

For internal building flows, CFD provides details about the airflow distribution within the naturally ventilated spaces. If there are stagnant zones, a CFD study will identify their location and mitigation measures can be tested in additional studies. Airspeeds in different locations within the spaces can be calculated. As well, the temperature distribution can be evaluated, providing information on areas that might be too hot or too cold. These detailed studies can include radiative heat transfer calculations, which can be used to show the effect of radiant heating and cooling, direct solar radiation through windows and openings and more. The very detailed level of information from CFD enables detailed thermal comfort evaluations. This increased level of detail and information comes at a cost as the computational time is much higher than that of an airflow network model. Thus, only snapshots in time or brief transient simulations can be calculated. To obtain information on frequency of events (such as overheating) over the course of a typical year, it is better to use airflow network models. Similar to airflow network models, the flow inside the space is driven by the airflow into and out of the space at its boundaries. Again information is needed on the airflow condition at these boundaries, which need to be input into the simulation model. The accuracy of CFD simulations of interior building flows, though not perfect, is sufficient and satisfying for these types of applications. This has been tested and validated in multiple studies (CIBSE, 2005; Ji et al., 2004, Jiang et al, 2004; Mora et al, 2002).

In general it is possible to model the flow around a building using CFD. Many commercial, freeware and proprietary packages are available that provide access to flow solvers (FLUENT, 2008; OpenFOAM, 2008; STAR-CD, 2008). These have a variety of physics and, for the purposes of modelling flow around buildings, the most important piece of physics is the manner in which turbulence is represented. Turbulence models range from simple one-equation empirical models to multi-equation sets. Recent interest has been focused on a turbulence model referred to as Large Eddy Simulation (LES) that does a better job of modelling the large-scale turbulent fluctuations at the cost of additional computer power. This better representation of the larger scale turbulence is acknowledged as contributing to a better representation of the average wind characteristics and therefore surface pressures (Castro, 2003). Even then, it is important to understand that all CFD modelling has trouble predicting the flow around the downstream side of a building. This is doubly important for natural ventilation. The flow leaving the downstream side of upstream building impacts the building of interest and the wind driven pressures at the rear and top of the design building are critical for appropriate representation of the building ventilation flows.

As described above, both airflow network models and CFD models need information about the air inflow/outflow conditions. Even though CFD for exterior building flows are not sufficiently accurate at this point in time to replace wind tunnel testing, they nevertheless can provide good qualitative information on the local wind climate around a building that is considered for natural ventilation. Particularly in the early conceptual stages this can be very helpful while keeping the effort (time and cost) below that for a wind tunnel test. These types of CFD models can be used as a basis of early C_p value estimates for a range of options. This allows for simulations of a building at early conceptual stages including several “what-if” scenarios, which can include changes of the building shape.

C_P CALCULATION METHODS

As discussed previously, the wind pressure coefficients (C_p) used to estimate the wind-induced airflow through openings in the building façade play an important role in natural ventilation analysis. During the design phase, methods are needed to determine the C_p values. There are several methods for approximating these values, each resulting in varying levels of accuracy. Determining the appropriate level of accuracy depends on the study to which the values will be applied. These methods vary from estimates based on previous experience to detailed wind-tunnel analysis for façade and location-specific pressures.

Desktop Estimates

The desktop estimate is based on

- Known C_p values from wind tunnel tests and measurements on existing buildings,
- the shape of the building that is currently under investigation,
- site exposure, and
- expert’s experience in determining the wind pressure coefficients on other structures.

The advantage of the desktop estimate is that it can be completed quickly. The level of accuracy will depend greatly on the availability of relevant data. The constrains of this approach often lead to a very rough approximation of building wind loads.

External Flow Modelling using CFD

A simplified three-dimensional computer model of the building and its surroundings is built. The surroundings (usually called the environmental domain) need to be large enough so that the blockage of the building(s) in the model is small (~5%) and some researchers recommend that the blockage be less (Franke, 2006). In addition, it is critical in these simulations of the wind environment around buildings to represent a sufficiently large domain around the building of interest in order to capture the upstream building effects.

Boundary conditions for the atmospheric boundary layer are applied. These need to represent the atmospheric boundary layer profile appropriate for the upwind terrain. Typically this means a power-law representation for the velocity profile (Smits, 2000). In addition, the incoming turbulence properties are also important and the characteristics of turbulent fluctuations vary in the three directions and are a function of altitude.

Other details of importance include the use of adequate cell resolution, grid-independence and convergence. In some cases, the presence of very large openings in the building can impact the flow around the building. This too needs to be assessed.

As mentioned before, the accuracy of CFD studies for external flows is still quite limited and needs to be carefully considered. However, a CFD study of the airflow around the building will provide an expert with more information on the specific conditions for the particular building. This additional information helps to improve the quality of an estimate of the wind pressure coefficients C_p.

Wind Tunnel Testing

The most effective method of predicting wind pressures acting on the natural ventilatoin openings of a building is through scale model testing in a boundary layer wind tunnel.

A scale model is created of the building and is fitted with pressure taps located at each specific location on the façade where an opening is planned. In order to include the effect that adjacent terrain will have on the wind profile the surrounding terrain as well as natural and constructed obstructions are also modelled.

The wind tunnel test provides measurements of the detailed C_p values for all the openings in their respective locations.

Prediction Methods Provided in Common Software Tools

A commonly used approach in airflow network models is to transpose wind pressure information from generalizations and comparisons to stock building shapes, orientations, and terrain types tested in wind tunnels onto the study building. IES Virtual Envrionment and DesignBuilder/EnergyPlus, two widely used simulation tools for natural ventilation studies, both employ a version of this technique. Both simulation tools have based their wind tunnel reference data on the Air Infiltration and Ventilation Centre's (AIVC) Applications Guide: A guide to energy-efficient ventilation (Liddament, 1996). Limitations exist with the transferrability of the default values as the C_p data is garnered from wind tunnel tests on buildings of 3 storeys or less with square surfaces and 3 levels of site exposures.

IES Virtual Environment uses MacroFlo for bulk airflow predictions. A number of surface types (referred to as Exposure Types) are considered for a range of wind directions (i.e. angles of attack). The exposure types consider both surface orientation and degree of sheltering by nearby obstructions. The C_p values for the exposure types are based on the AIVC data mentioned above. A range of 66 exposure types are provided within MacroFlo with C_p values for 16 varied angles of attack (IES VE, 2007).

DesignBuilder is a front end interface for the EnergyPlus simulation engine, which has been coupled with the AIRNET bulk airflow module for zonal airflow predictions. Custom wind pressure coefficients in DesignBuilder (2005) can be entered by the user for wind incidence angles in 45° increments (i.e. 8 varied angles of attack) for each surface in the model. Default data for each surface is transposed to the model from the AIVC database of wind pressure coefficients as described previously

The relevancy of this approach can vary greatly depending on the complexities of the building, surrounding terrain and obstructions, as well as the modeller's ability to translate the default data appropriately to the building being studied. This derivation for C_p values is a good first level of approximation for basic design purposes but ideally these would be overridden with data specific to the application via CFD simulations or physical models tested in a wind tunnel. This is especially true for buildings greater than 3 stories in height.

CPCALC+

A hybrid prediction method has been developed by Grosso et al. (1995). Acknowledging that wall-averaged values of C_p usually do not match the accuracy required for multizone airflow models, Grosso et al. developed a numerical model (CPCALC+) to predict C_p values for any location on the building envelope. The algorithms they created calculate site-specific coefficients based on a parametric analysis of wind tunnel test results for a rectangular shaped building with flat or tilted roof for given conditions of terrain roughness, density of surounding buildings, shape ratios, and wind dirction. This method would likely provide an improvement over the method used by the two software tools mentioned above, but is still limited to low-rise buildings and building shapes that are close to rectangular forms.

PROPOSED APPROACH

Based on the available tools described above, we propose the following best-practice approach to natural ventilation design:

1. ***Outline of analysis:*** Identify the internal/external loads, specify the target flow and temperature conditions, and determine the range of flow rates required to balance.
2. ***Obtain site specific wind data:*** Meteorological information on the wind conditions at the site is necessary to accurately describe the wind speeds and direction the building is exposed to. This is a wide field in itself, which is not discussed in the present paper in detail. Instead the focus is on C_p values and airflow network models.
3. ***Obtain Cp values:*** As described above, the most accurate approach is to use specific wind tunnel data for the proposed building. If a wind tunnel study is not feasible and it is

appropriate for the project, estimates can be provided by experts. These estimates can be improved by exterior CFD studies.

4. ***Airflow network model***: Ideal for determining yearly performance of natural ventilation designs due to the ease in which one can evaluate a large number of opening arrangements, control strategies, construction materials, etc.
5. ***CFD study***: If an analysis of the detailed performance of internal airflows is required, particularly for elements such as thermal chimneys, wind towers, etc., a computational fluid dynamics study is needed.

CASE STUDY

An example case study of estimating C_p values is provided here for a laboratory and research building in eastern Canada. The C_p values were entered into the IES Virtual Environment whole building energy modelling software which was used for the natural ventilation study. Figure 1 shows an image of the IES VE model of the building. As can be seen, the building shape deviates strongly from a 3-storey rectangular building.

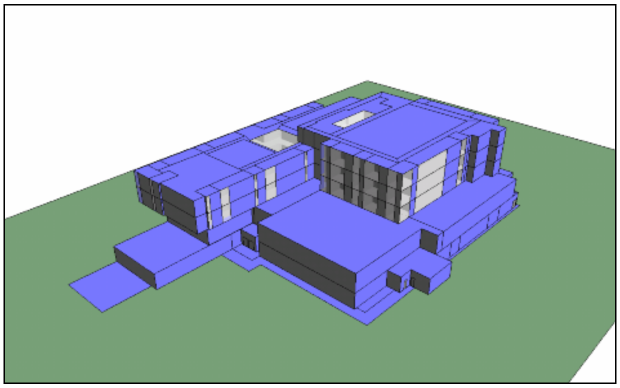

Figure 1: IES VE Model Rendering of Proposed Building

The study team had previously completed a wind tunnel study for a neighbouring building which incorporated very similar localized topology and surrounding obstructions. The model building was tested for an open/suburban profile (alpha=0.17) on a blank disk (no surrounding buildings). This data and experience of the wind engineer were used to develop estimates of the C_p values for the opening locations. Twenty-four external façade wind pressure zones were designated for the proposed building based on exposure, height and orientation (as shown in Figure 2). Wind pressure data from the wind tunnel testing were transposed on each of the 24 zones in order to approximate C_p values for 10° wind directional increments.

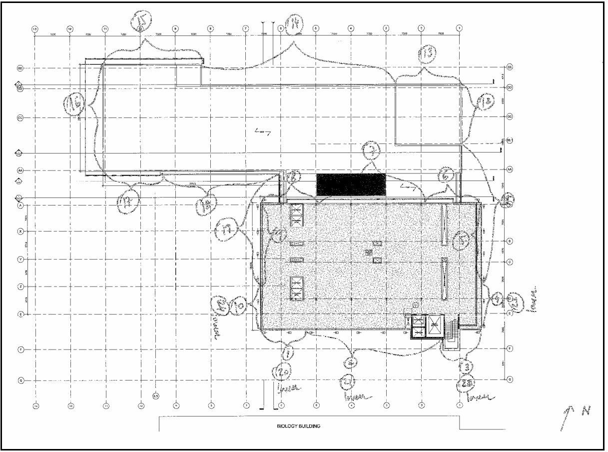

Figure 2: Cp Zoning Diagram of Building Exterior

The wind tunnel approximated C_p values are shown in Table 1 for a few selected angles of attack (0°, 90°, 180°, 270°) in the columns marked "Est". The values for each of the 24 zones are compared with default values available within IES VE. In order to provide adequate comparison, appropriate exposure types were selected as described in columns 2, 3 and 4. Each façade was assigned C_p values based on exposure type (exposed, semi-exposed, sheltered), wall ratio (rectangular long and short, cubic), and opening height (low-rise or < 3 storey and high-rise or > 3 storey). These exposures types were selected based on criteria as set out by the IES VE's MacroFlo Calculation Methods manual (IES VE, 2007).

It can be seen that there are significant differences between the two estimates. Average differences range from 28% for the 90º angle of attack case to 46% for the 270º case. The difference for specific cases exceeds 200% for some instances. Also of significance is that not only do the magnitudes of C_p predictions differ significantly for certain zones, but the sign is different as well. For zone 19 it can be seen that for an angle of attack of 0º the wind tunnel generated predictions give a negative C_p value (-0.51) while the IES predictions are positive (+0.39). The opposite is true for a 270º angle of attack (+0.53 for wind tunnel and -0.56 for IES). Reviewing Figure 2 it can be seen that zone 19 is located on the inner bend of the approximately "L-shaped" building. The shape of the building creates localized airflow patterns that are not accounted for in the default method created by testing on cubic building shapes. A C_p variation from positive to negative is the difference between an opening having an inflow vs.

outflow of air. As can be imagined, this will greatly alter the results of a natural ventilation analysis.

CONCLUSION

The major tools and wind pressure calculation methods essential to simulate natural ventilation design are described in this paper.

A best practice natural ventilation approach was proposed in which the varied methods of wind pressure coefficient derivation were prioritized. The best precision is achieved through scale model wind tunnel testing of the proposed building. Expert estimates based on data for other similar buildings can also improve the relevance of the C_p values to be used in airflow network model simulations. External flow modelling (CFD) can provide valuable additional information to the wind engineer providing a qualitative estimate for C_p values, thus improving the estimate.

To show the significance of C_p derivation a case study was presented comparing an expert estimate based on a wind tunnel test for a building in almost the same location, transposing site specific wind tunnel data to a proposed façade, to common practice airflow network derivation techniques. The case study showed that not only do the magnitudes of C_p values vary sifnificantly for the differing techniques, but also the prediction of whether the opening is in a positive or negative pressure location can differ. This can make the difference between air entering the building through an opening and exhausting.

The case study outlines that common airflow network C_p derivation techniques are reasonable for cubic shaped buildings but for buildings of more complex shape, and thus airflow patterns, more accurate prediction methods, such as wind tunnel testing, are recommended.

ACKNOWLEDGMENTS

The authors would like to acknowledge the annonymous reviewer for their thoughtful comments and suggestions.

REFERENCES

Castro, I.P. 2003. CFD for External Aerodynamics in the Built Environment. The QNET-CFD Network Newsletter, Vol. 2, No. 2, pp 4-7. (See http://www.qnet-cfd.net/newsletter/6th/n6.html).

CIBSE, 2005. Natural Ventilation in Non-Domestic Buildings: CIBSE Applications Manual AM10: 2005. London: Chartered Institution of Building Services Engineers (CIBSE).

DesignBuilder Software Ltd. 2005. DesignBuilder Program Help. DesignBuilder Version 1.2.2.002

DesignBuilder Software Ltd., 2008. http://www.designbuilder.co.uk, sourced April 22, 2008.

EnergyPlus, 2008. http://www.eere.energy.gov/buildings/energyplus/, sourced April 22, 2008.

FLUENT, 2008. http://www.fluent.com, sourced April 22, 2008.

Franke, J. 2006. Recommendations of the COST action C14 on the use of CFD in predicting pedestrian wind environment. Presented at the 4th Intl. Symposium on Computational Wind Engineering (CWE 2006), Yokohama, Japan.

Grosso, M., Marino, D., Parisi, E. 1995. A Wind Pressure Distribution Calculation Program for Multizone Airflow Models. International Building Performance Simulation Association Conference Proceedings, p.105. Madison, WI., USA.

IES: Integrated Environmental Solutions Limited. 2007. MacroFlo Calculation Methods Manual. Virtual Environment (VE) Version 5.6.2.

IES VE, 2008. Virtual Environment (VE) by Integrated Environmental Solutions (IES), http://iesve.com, sourced April 22, 2008.

Ji, Y., Cook, M.J., and Hunt, G.R. 2004. CFD modelling of atrium-assisted natural ventilation. Proc. 9th Intl. Conf. on Air Distribution in Rooms, Portugal, 2004.

Jiang, Y., Allocca, C., and Chen, Q. 2004. Validation of CFD simulation for natural ventilation. International Journal of Ventilation, 2(4), 359-370.

Liddament, M. W. 1996. A Guide to Energy Efficient Ventilation, International Energy Agency, Air Infiltration and Ventilation Centre, UK.

Mora, L., Gadgil, A.J., Wurtz, E. and Inard, C. 2002. Comparing Zonal and CFD Model Predictions of Indoor Airflows under Mixed Convection Conditions to Experimental Data. 3rd European Conf. on Energy Performance and Indoor Climate in Buildings, Lyon, France, 2002.

OpenFOAM, 2008. http://www.opencfd.co.uk/openfoam/, sourced April 22, 2008.

Smits, A.J. 2000. A Physical Introduction to Fluid Mechanics, John Wiley & Sons, 2000.

STAR-CD, 2008. http://www.cd-adapco.com/, sourced April 22, 2008.

Table 1: Wind C_p as Predicted by Wind Tunnel Estimations (Est) and Zonal Airflow Model (IES)

	IES C_p Derivations			**Angle of Attack**											
Building Zones	***Exposure Type***		***Wall***	***0º (Est)***	***0º (IES)***	***% DIFF***	***90º (Est)***	***90º (IES)***	***% DIFF***	***180º (Est)***	***180º (IES)***	***% DIFF***	***270º (Est)***	***270º (IES)***	***% DIFF***
Zone1	high-rise (h/H=0.8)	exposed	long	0.36	0.65	81%	-0.68	-0.65	5%	-0.49	-0.28	43%	-0.30	-0.65	115%
Zone2	high-rise (h/H=0.8)	exposed	long	0.58	0.65	12%	-0.56	-0.65	15%	-0.46	-0.28	39%	-0.50	-0.65	29%
Zone3	high-rise (h/H=0.8)	exposed	long	0.36	0.65	81%	-0.32	-0.65	102%	-0.49	-0.28	43%	-0.66	-0.65	2%
Zone4	high-rise (h/H=0.8)	exposed	short	0.50	0.65	30%	-0.60	-0.65	8%	-0.25	-0.28	12%	-0.63	-0.65	2%
Zone5	high-rise (h/H=0.8)	exposed	short	0.49	0.65	33%	-0.57	-0.65	13%	-0.26	-0.28	8%	-0.70	-0.65	8%
Zone6	high-rise (h/H=0.8)	exposed	long	0.38	0.65	71%	-0.66	-0.65	2%	-0.43	-0.28	35%	-0.31	-0.65	108%
Zone7	high-rise (h/H=0.8)	exposed	long	0.62	0.65	5%	-0.52	-0.65	24%	-0.40	-0.28	30%	-0.52	-0.65	24%
Zone8	high-rise (h/H=0.8)	exposed	long	0.37	0.65	76%	-0.32	-0.65	102%	-0.43	-0.28	35%	-0.70	-0.65	8%
Zone9	high-rise (h/H=0.8)	exposed	short	0.53	0.65	23%	-0.66	-0.65	2%	-0.24	-0.28	17%	-0.55	-0.65	17%
Zone10	high-rise (h/H=0.8)	exposed	short	0.52	0.65	25%	-0.63	-0.65	2%	-0.25	-0.28	12%	-0.62	-0.65	4%
Zone11	high-rise (h/H=0.4)	exposed	short	0.56	0.39	31%	-0.65	-0.56	14%	-0.26	-0.27	4%	-0.72	-0.56	22%
Zone12	high-rise (h/H=0.4)	exposed	short	0.32	0.39	20%	-0.56	-0.56	0%	-0.26	-0.27	4%	-0.76	-0.56	26%
Zone13	high-rise (h/H=0.4)	exposed	long	0.33	0.39	17%	-0.71	-0.56	21%	-0.47	-0.27	43%	-0.26	-0.56	115%
Zone14	high-rise (h/H=0.4)	exposed	long	0.58	0.39	34%	-0.48	-0.56	17%	-0.46	-0.27	41%	-0.48	-0.56	17%
Zone15	high-rise (h/H=0.4)	exposed	long	0.31	0.39	24%	-0.27	-0.56	107%	-0.47	-0.27	43%	-0.74	-0.56	24%
Zone16	high-rise (h/H=0.4)	exposed	short	0.48	0.39	20%	-0.71	-0.56	21%	-0.26	-0.27	4%	-0.64	-0.56	13%
Zone17	high-rise (h/H=0.4)	exposed	long	0.32	0.39	20%	-0.74	-0.56	24%	-0.53	-0.27	49%	-0.24	-0.56	133%
Zone18	high-rise (h/H=0.4)	exposed	long	0.53	0.39	27%	-0.51	-0.56	10%	-0.53	-0.27	49%	-0.45	-0.56	24%
Zone19	high-rise (h/H=0.4)	exposed	short	-0.51	0.39	175%	-0.53	-0.56	6%	-0.45	-0.27	40%	0.53	-0.56	206%
Zone20	high-rise (h/H=0.4)	exposed	long	0.32	0.39	20%	-0.74	-0.56	24%	-0.53	-0.27	49%	-0.24	-0.56	133%
Zone21	high-rise (h/H=0.4)	exposed	long	0.53	0.39	27%	-0.51	-0.56	10%	-0.53	-0.27	49%	-0.45	-0.56	24%
Zone22	high-rise (h/H=0.4)	exposed	long	0.29	0.39	33%	-0.27	-0.56	107%	-0.55	-0.27	51%	-0.71	-0.56	21%
Zone23	high-rise (h/H=0.4)	exposed	short	0.31	0.39	24%	-0.67	-0.56	16%	-0.27	-0.27	0%	-0.61	-0.56	8%
Zone24	high-rise (h/H=0.4)	exposed	short	0.34	0.39	13%	-0.61	-0.56	8%	-0.26	-0.27	4%	-0.69	-0.56	19%