University of Reading

Effect of building gap to improve pedestrian comfort levels and ventilation

Conference or Workshop Item

Accepted Version

Effect of Building Gap to Improve Pedestrian Comfort Levels and Ventilation

Arpan Pal[1,*], Zhiwen Luo[2] and Li Biao[3]

[1& 2] School of Construction Management and Engineering, University of Reading, United Kingdom
[3] School of Municipal Environmental Engineering, Harbin Institute of Technology, Harbin, China

[*]Corresponding email: arpanpal83@gmail.com

ABSTRACT

Rapid rates of urbanization have resulted into increased concerns of urban environment. Amongst them, wind and thermal comfort levels for pedestrians have attracted research interest. In this regards, urban wind environment is seen as a crucial components that can lead to improved thermal comfort levels for pedestrian population. High rise building in modern urban setting causes high levels of turbulence that renders discomfort to pedestrians. Additionally, a higher frequency of high rise buildings at a particular region acts as a shield against the wind flow to the lower buildings beyond them resulting into higher levels of discomfort to users or residents. Studies conducted on developing wind flow models using Computational Fluid Dynamics (CFD) simulations have revealed improvement in interval to height ratios can results into improved wind flow within the simulation grid. However, high value and demand for land in urban areas renders expansion to be an impractical solution. Nonetheless, innovative utilization of architectural concepts can be imagined to improve the pedestrian comfort levels through improved wind permeability. This paper assesses the possibility of through-building gaps being a solution to improve pedestrian comfort levels.

KEYWORDS: *(Computational fluid dynamics, through-building gaps, predestriuan comfort level. velocity ratio, retention time.)*

1 INTRODUCTION

Rapid urbanization and resulting increase in land cost in urban areas over the last century has led to growing numbers of high rises in urban areas in the North American cities of New York, San Francisco etc (1). Similar trends of rapid increasing land values in Asian cities such as Hong Kong have resulted into high density of high rises, driven by the massive population movement from rural to urban areas. Such high density of tall buildings often imparts a “wall-effect” resulting into improper ventilation and high pollutants retention time in street canyons to have a negative impact on pedestrians (2). This also results into sudden gush of wind on the pedestrian level, leading to uncomforting experiences of pedestrians. In response, a number of studies employing experimental as well as numerical modeling methods have established a reduced velocity ratio (V_r) in street canyons (2). Systems like the Pedestrian Ventilation System (PVS) have been proposed to improve pedestrian comfort level by actively guiding air from the building roofs through vertical ducts to surrounding street levels (3). However, passive designing strategies such as street design aspect ratio (height to width ratio of the walls and base of street canyons) and solar orientation can be effectively used for such purposes (4). Innovative passive architectural building designs such as through-building gaps can also be employed to improve the pedestrian comfort level. These through-building gaps can be imagined in forms of mid-level sky gardens and refuge floors. Where sky garden are generally used for improving the aesthetic and commercial value of the property, refuge floors are primarily used in response to mandatory fire safety regulations for high rises (5). However, their importance in terms of improving urban microclimatic conditions is yet to be assessed.

Various studies employing Computational Fluid Dynamics (CFD) assessment on different aspects of through-building gaps have been reported. Niu et al performed a CFD analysis to ‘estimate the wind and thermal comfort in a mid-level sky garden’ revealed varying thermal comfort within the sky garden with seasonal variation (6). Similarly, reported presence of sky gardens in linked buildings have shown to increase the building permeability to wind by Yau (7). This improved permeability has also been reported to result into a 43% increase in ventilation coefficient. Nonetheless, the architectural configuration of the sky garden will be significant in determining the extent and levels of wind permeability. Niu et al’s considered two case models, one with large openings on two sides and openings on all four sides. These designs can vary in different cases. Studies conducted by To et al on the dynamics responses of a high rise to a through-building gap considered two different set of configurations. One consists of an opening through the central portion of the through-building gap whereas the other consists of openings along the periphery with a solid central structure.

With the high levels of complexity of wind flow around high rise buildings and the increased computational capabilities, Computational Fluid Dynamics (CFD) will be used for determining the Velocity ratio (V_r). The flow field around a building is primarily characterized by ‘impingement, separation, reattachment, circulation, vortices etc’ that can be described as a turbulent flow field [9]. Most of the studies conducted on wind flow around buildings in urban areas have used RANS (Reynold’s-averaged Navier Stokes) type models such as k-ε model. For example, ‘Working Group for CFD Prediction of the Wind Environment around a Building’ used standard k-ε model and/or modified k-ε model for assessing flow fields around different types of urban settings. In their study, Computational results using standard *k*-ε model and modified *k*-ε model showed higher accuracy in weak wind regions (backside of a high rise) as compared to strong wing regions (frontal sides of a high rise) [10]. The study also pointed out LES (Large Eddy Simulation) modeling are more accurate for wind flow around buildings, however, a dramatically high computer speed would be required. Murakami also described 'over-production of turbulence energy (k) around the frontal corners' of a building due to EVM (Eddy Viscosity Modeling) as the primary shortcoming of the *k*-ε model that can be overcome in LES [9]. Also, LES uses a time-dependant inflow boundary, unlike a steady RANS simulation, that is responsible for its high accuracy [11].

This aim of the current study is to investigate the effect of through-building gap on the pedestrian wind comfort and ventilation performance. CFD analysis will be employed to determine the velocity ratio (V_r) on the leeward side of the high rise. The study will firstly consider a simple model of one single high rise without any through-building gap and a through-building gap configuration where the openings are present on the periphery with a central solid structure, as described in To et al's study. The single high rise case will be used as validation case for grid refinement. This validated grid will be further employed in the actual case with the through-building gap. Figure 1 shows the two different models adopted for this analysis.

2 MATERIALS/METHODS

2.1 Geometry and computational domain

As evident from Figure 1, the case contains of a through-building gap along the periphery of the building with a solid central structure. The dimension of the building in both the single high-rise (Case 1) and the building with through-building gap (Case 2) was maintained at a scale-ratio of 1:1:5 (Length: Breadth: Height), as adopted from the single building case reported by Luo et al [8]. The two scenarios are illustrated in Fig. 1. Based on the recommendation of the paper, a larger computational domain size was set. The inflow boundary was kept at a distance of 5H whereas the outflow boundary was set at 10H. The H here represents the building height. The height of the computational domain was also set at 5H. The location of the through-gap building was placed at a height of 50 meters from the ground. The location of the gap was based on the assumption that the impact of the gap on the pedestrian level would be insignificant if placed on the upper half of the high-rise.

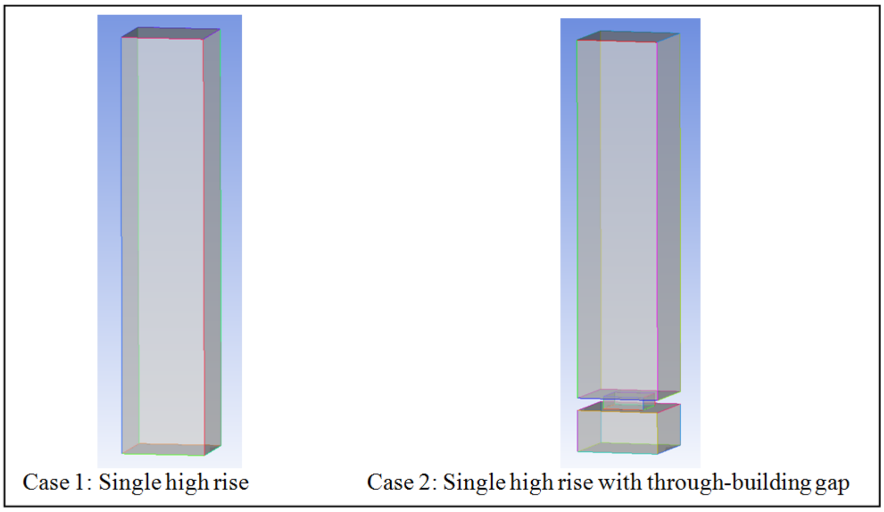

Figure 1: Building geometry used for CFD analysis

2.2 CFD Approach

A Realizable k-ε turbulence model was chosen for performing the CFD analysis. The choice of the model is primarily based on accuracy and cost. Although Standard k- ε turbulence model consume lesser computational time, it lacks accuracy in regions of separation and re-attachment. Ideally, Large Eddy Simulation (LES) modeling is highly desirable for any sort of turbulence modeling, but not widely used due to its complexity and higher requirement of large computational strength and time. On the other hand, Realizable k-ε model have improvements over the Standard k-ε model in terms of accuracy with the use of an alternative formulation for kinetic viscosity. CFD analysis on the wall-effect imparted by high rises, studied by Yim et al [2], also employed a Realizable k- ε turbulence model. Thus, in order to maintain balance between accuracy and computational time, a Realizable k-ε model was employed through commercial CFD software Fluent 14.0.

In order to achieve an acceptable accuracy in predicting the flow field around the building features, a fine grid arrangement will need to be achieved near the building surfaces. The grid distribution is shown in Figure 2. As evident from the figure, grid distribution employs a denser distribution near the building walls and less dense away from it. This results in coarse resolution in less-significant regions that ultimately assists in reducing computational time. The first cell near the building in x direction has been maintained at b/54, b/20 in the y-direction and b/200 in the z-direction. A second order upwind discretization scheme was used for kinetic energy (k), turbulent dissipation rate (ε) and momentum.

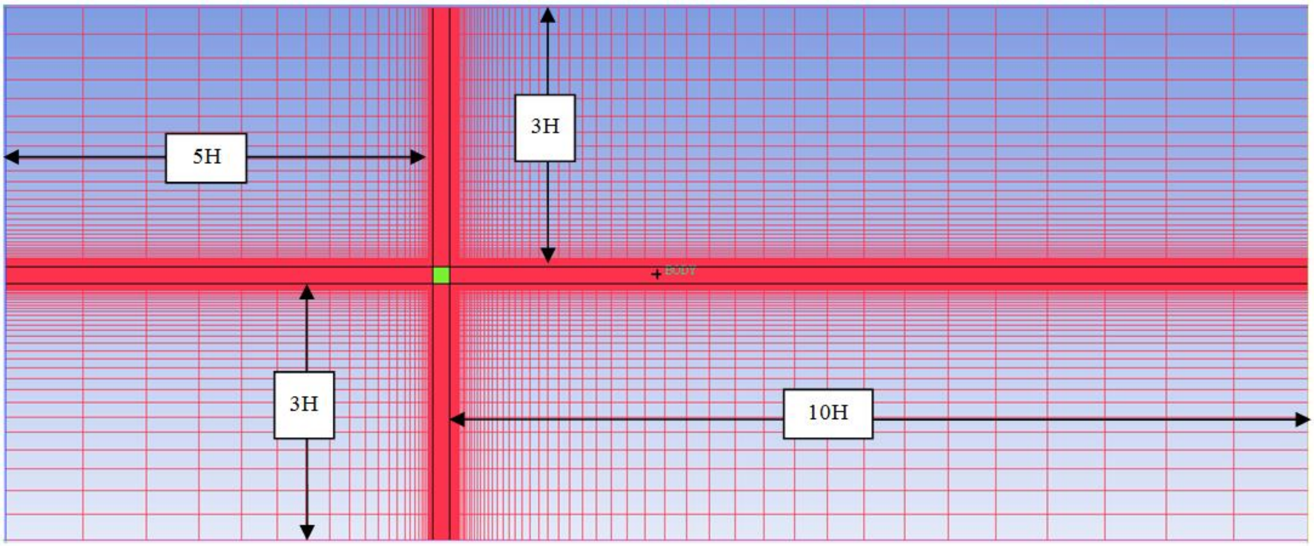

Figure 2: Horizontal computational domain employed for the CFD analysis

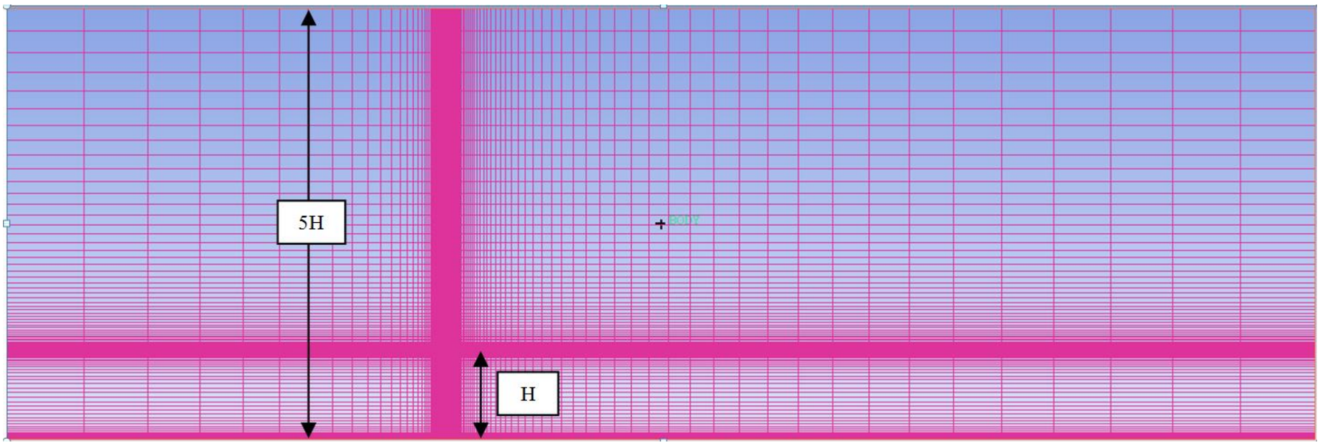

Figure 3: Vertical computational domain employed for the CFD analysis

2.3 Boundary Condition

The boundary condition for the approaching wind-profile was determined by the power law stated in Eq.(1).

$$\frac{U}{Uref} = \left(\frac{Z}{Z\,ref}\right)^{0.09} \qquad (1)$$

The reference height (Z_{ref}) was set to the height of the building and the velocity at that height (U_{ref}) was determined kept at 7 m/s. In absence of the experimental data on kinetic energy of turbulence and dissipation rate, the following equations (Eq. 2 – 4) were used for determining these values.

$$k(z) = \frac{3}{2}(U_{avg}\, I)^2 \qquad (2)$$

$$\varepsilon(z) = \frac{u^3}{\kappa z} \qquad (3)$$

$$k = \frac{u^2}{\sqrt{C_\mu}} \qquad (4)$$

Where U_{avg} is the inlet mean velocity, turbulence intensity at different heights are represented by I, u is the frictional velocity and κ is von Kaman constant (0.41) and C_μ is 0.09. The conditions at the inlet boundary are illustrated in Fig. 3 whereas the other boundary conditions are listed in Table 1.

Table 1: Boundary Conditions applied on the computational domain

Inlet	Power-law based on wind tunnel experiment
Outlet	Outflow Boundary conditions, Gauge Pressure = 0
Building Surface	Smooth wall using log-law wall functions
Top	Free Slip, Flux is zero normal to the boundary
Lateral Sides	Symmetry boundary conditions applied

3 RESULTS AND DISCUSSION

3.1 Grid Refinement and Domain Size Test

The accuracy of CFD simulation is determined by the quality of computational grids and domain. As evident in Figure 2, that a refined mesh is employed near the building surface and coarse mesh away from it. The coefficient of wind pressure (C_p) along the centre line of the building, is being used as the indicator of grid qulity. Three different types of mesh districution was tested for grid refinement as shown in Fig. 4. The C_p calculated for these three mesh distribution strategies were compared with experimental data to identify the most suited mesh distribution, as shown in Fig. 4.

Mesh Startegy	Number of grid cells	First cell near the wall
Mesh 1	440,000	b/7 in X-direction b/10 in Y and Z direction
Mesh 2	556,000	b/15 in the X direction b/20 in the Y and Z direction
Mesh 3	675,000	b/30 in X direction b/40 in the Y and Z direction

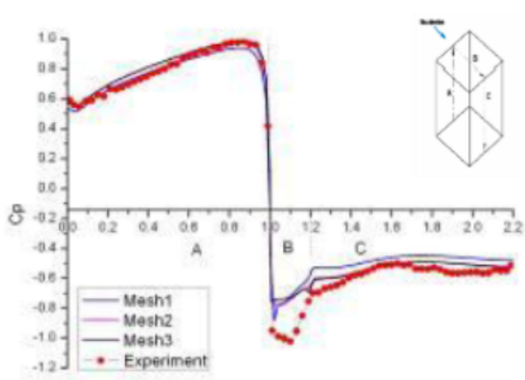

Figure 4: Grid refinement test results

3.2 Effect of Through-gap building on pedestrian comfort level

In order to assess the impact of the through-building gap, as represented in Case 2, on the pedestrian comfort level, the air velocity ratio (V_r) at the pedestrian level was compared with that of Case 1 (validation case). The Velocity Ratio is defined here as the ratio between the velocity at pedestrian level (V_p) to the velocity at the reference height (U_{ref}). The results are presented diagramatically in Fig. 5 & 6. As evident, the difference in V_r in both cases, arising due to the presence of the through-building gap is not distinct. Consequently, a comparison of the velocity ratios along a line normal to the building surface, both on the windward and leeward side of the building was performed, as shown in Fig. 7. The comparison highlights the slight difference that occurs due to the presence of the through-building gap on both sides of the building. The points of measurement are placed 4 meters apart till a distance equal to the the height of the building.

Pedestrain comfort can be holistically described by Velocity Ratio (V_r) and Retention Time (T_r) of pollutant [2], which represent the dispersion potential of pollutants. The retention is primarily significant on the leeward side of the building where, the low wind velocities prevent dilution of pollutants. Therefore, ideally a a highly V_r would be desirable to enable pollutant dilution and favourable wind flow. Contrastingly, retentions time is not significant on the windward side of the building, which is characterised by high velocities resulting into pedestrian discomfort. Therefore, unlike the leeward side, a lower wind velocity is desired on the windward side. Results presented in Fig. 7, shows that the through-building gap delivers the desired lower wind velocities on the windward side and higher velocities on the leeward side. be potentially used to obtain pedestrian comfort through desirable wind flow characteristics in urban areas with high-rises.

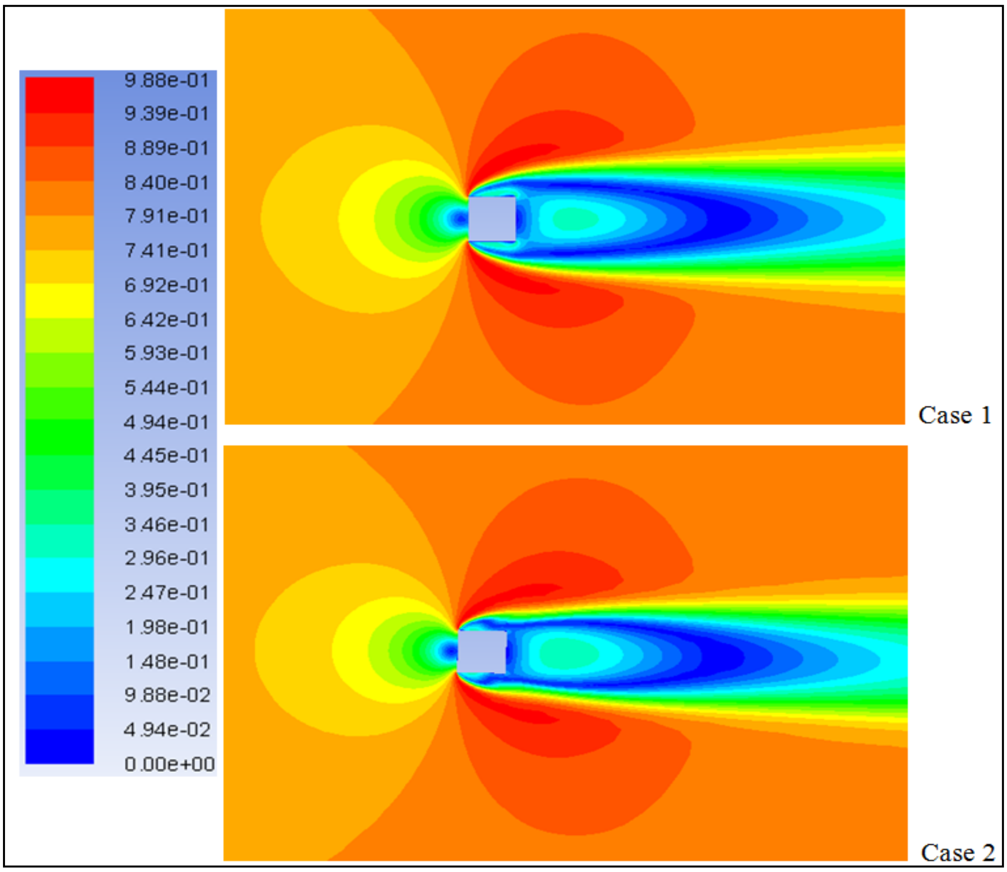

Figure 5: Velocity Ratio contours along the pedestrian level

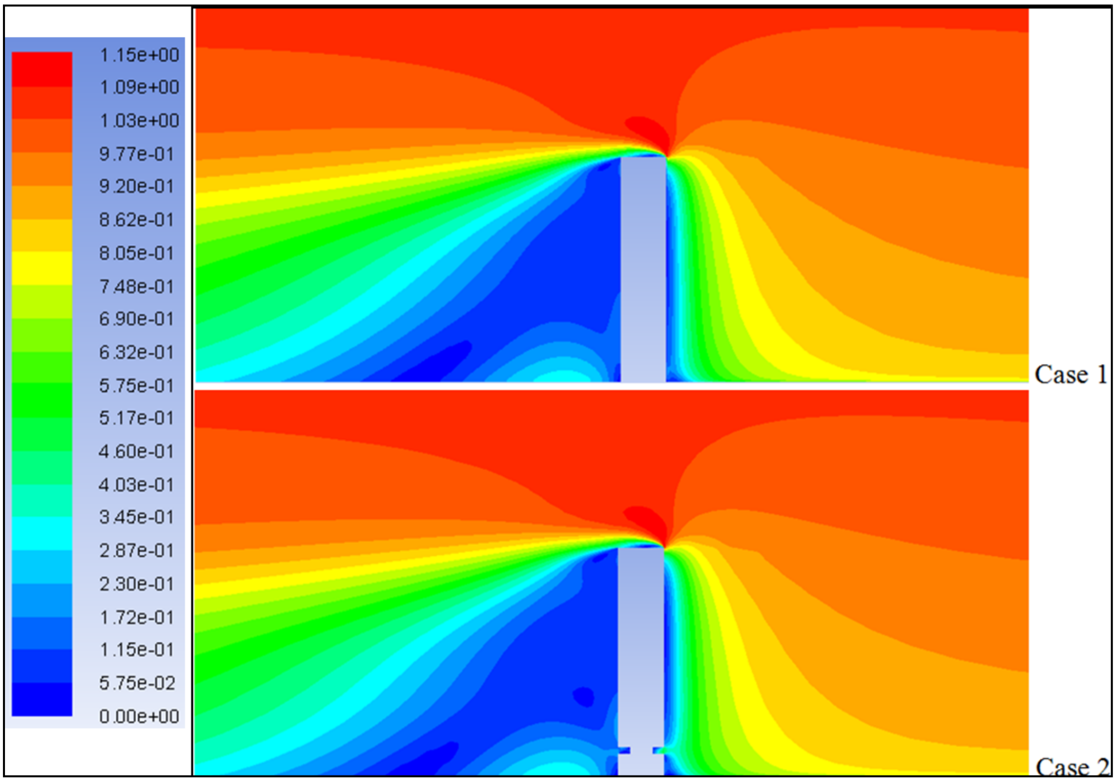

Figure 6: Velocity ratio contour along the vertical plain along the central line of the building

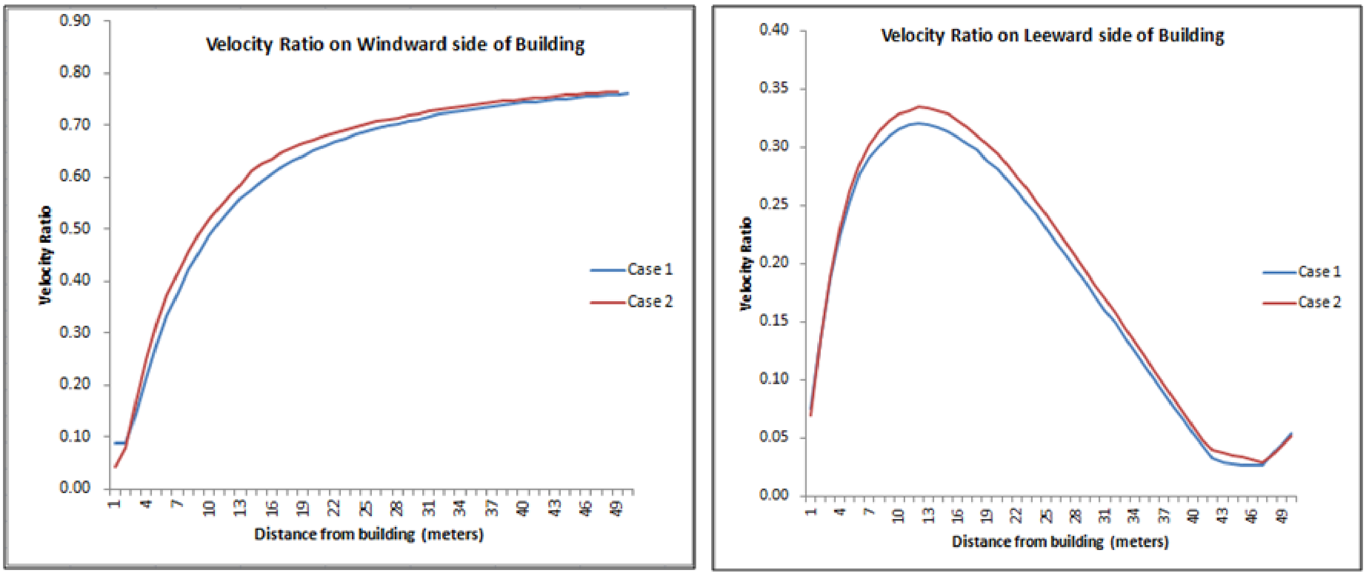

Figure 7: Velocity ratios along the central line on windward and leeward sides of the building

A careful study of the velocity vectors near the building with the through-building gap shows that the presence of the gap allows higher wind permeability through the building thus decresaing the wall-effect. However, the comfort level at the gap and the resulting wind flow downstream to the building is worth discussing. As expected, the gap in the building is allowing a higher wind flow through it. However, a majority of the wind passing through the gap is diverted to the lateral sides leading to vortexes near the building edges on the leeward side. Fig. 8 shows the velocity contours along a plain cut through the middle of the through-building gap. The void in the middle represents the solid central structure as illustrated in Fig. 1. Evident from Fig. 8, the leeward side of the through-building gap is lower than the windward side that can result into a distinct difference in comfort levels. Comfort levels in the through-building gaps are important parameters that determine the designing. Extreme weather conditions resulting into higher wind velocities can raise discomfort levels and pose safety threats at the through-building gap [6]. Therefore, it is essential to optimize the design parameters of such through-building gaps.

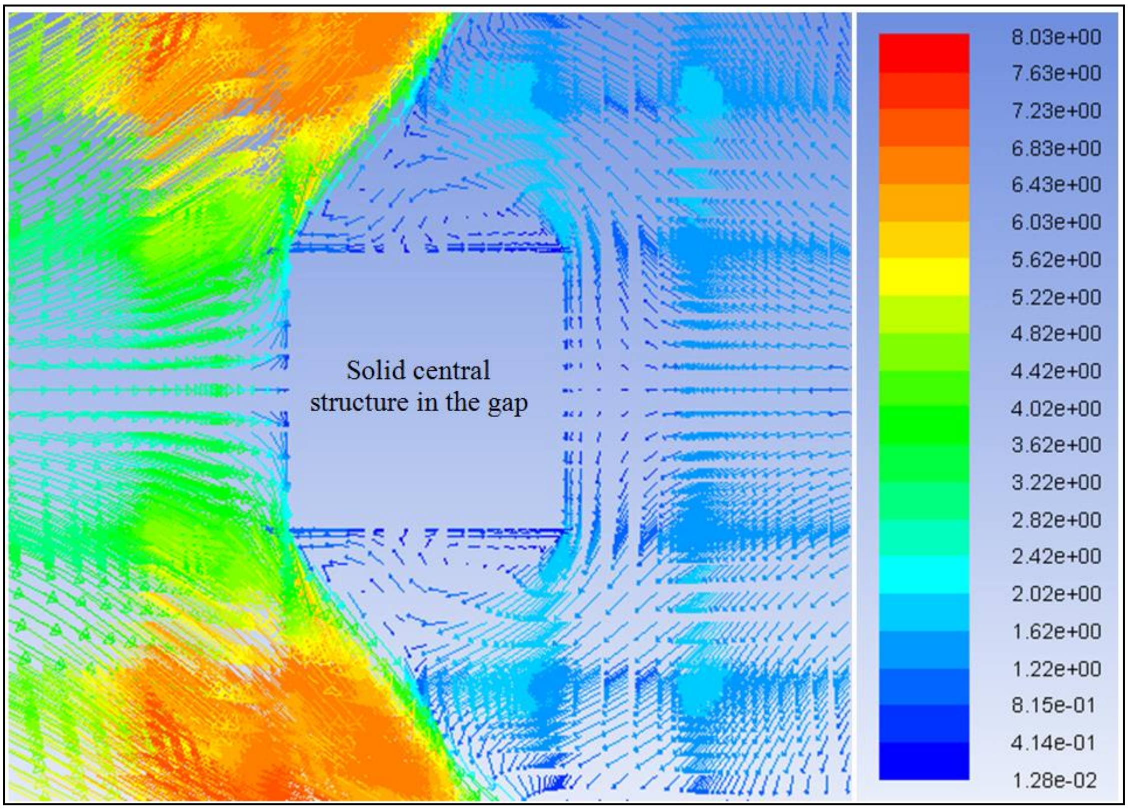

Figure 8: Velocity vector of wind flow through a plain through the middle of the through-building gap

Based on the above discussion, the scope of further research in the potential of through-building gaps in improving pedestrain comfort level is promising. Recommendation on further research scopes, based on this study, can include the location and design parameters of the through-building gaps to further improve the pedestrian comfort level on both sides of the building. The current study consists of a single building structure in the entire computational domain. This is a preliminary study, more work is being carried out to include different gap design scenarios and their locations. This can be also extended to an urban context with a network of buildings.

4 CONCLUSIONS

The study assesses the impact of a through-building gap on the pedestrain comfort level which is primarily determined by the Velocity Ratio (V_r). Two scenarios have been investigated, Case 1 consisting a single high rise building and Case 2 consisting of a single high rise with a through-building gap. As evident from the discussion in Section 3.2, the through-building gaps are found to have positive impacts on the pedestrian comfort level. Nonetheless, further research is required to assess different through-building gap designs that can potentially enhance the pedestrian comfort level. Innovative and state-of-art designs can not only have positive impacts on the urban microclimate but also improve the aesthetic and commercial value of the property.

ACKNOWLEDGMENT

The corresponding authors would like to thank The Department of Construction Management and Engineering, University of Reading to provide their infrastructure to conduct the analysis.

REFERENCES

[1] http://www-sre.wu-wien.ac.at/ersa/ersaconfs/ersa04/PDF/171.pdf. Accessed on March 25 2013, Frenkel A.

[2] S.H.L Yim, J.C.H Fung, A.K.H Lau, S.C Kot, Air ventillation impacts of the “wall effect” resulting from the alignment of high-rise buildings, Atmospheric Environment 43 (2009) 4928 – 4994.

[3] P. Mirzaei, F. Haghighat, A novel approach to enhance outdoor air quality: Pedestrian Ventilation System, Building and Environment 45 (2010) 1582 – 1593.

[4] F. Toudert, H. Mayer, Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate, Building and Environment 11 (2006) 94 – 108

[5] A.P. To, K.M. Lam, S.Y. Wong, Z.N. Xie, Effects of a through-building gap on wind induced loading and dynamic responses of a tall building, Wind and Structures 15 (2012) 531 – 553.

[6] J.L. Niu, Y.M Tang, C.M Mak, The application of computational fluid dynamics to the assessment of green features in buildings: Part 2: Communal sky gardens, Architecural Science Review 48 (2013) 337 – 344

[7] R. Yau, Building environmental and sustainable approach to housing development, *Proceedings of the Innovative Buildings Symposium, Housing Conference* (2002) 49 – 60.

[8] Z. Luo, Y. Li, M. Rosler, J. Seifert, Surrounding building and wind pressure distribution on a high-rise building, *Proceedings of the 9th International Symposium on Buildingand Urban Environmental Engineering* (2010), Hong Kong

[9] S. Murakami, Current status and future trends in computational wind engineering, Journal of Wind Engineering 67 -68 (1997), 3 -34

[10] R. Yoshie, A. Mochida, Y. Tominaga, H. Kataoka, K. Harimoto, T. Nozu, T. Shirasawa, Cooperative project for CFD prediction of pedestrian and environment in the Architectural Institute of Japan, Journal of Wind Engineering 95 (2002) 1551 – 1578

[11] A. Dagnew, G. Bitsuamlak, LES evaluation of wind pressure on a standard tall building with and without neighboring buildings, *Proceedings of the 5th International Symposium on Computational Wind Engineering* 2010.