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LARGE EDDY SIMULATION OF WIND INDUCED LOADS ON A LOW RISE BUILDING WITH COMPLEX ROOF GEOMETRY

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ABSTRACT

Wind induced damage on low-rise buildings with complex roof geometry is common in coastal areas of USA, such as Florida and Louisiana. Available design codes provide information about the design of regular roof geometries (e.g. hip/gable roofs), but refer to wind tunnel modelling for complex roof geometries. Due to time and financial constraints physical modelling may not always be possible to carry out. Computational modelling through Large Eddy Simulation (LES) has been used successfully for several wind engineering applications. This paper presents comparisons between LES and previously obtained wind tunnel data of mean and peak pressure coefficients on a low rise building with complex roof geometry. Two different cases, namely: isolated building and the effect of neighbouring buildings have been considered for the most critical wind direction of 135 degrees. Results show that the mean pressure coefficients on the low rise building roof for the case with adjacent buildings were somewhat lower in magnitude (less suction) than the isolated case. In general, excellent matching was obtained within a factor of 1.1 between wind tunnel and LES for all roof locations except at the roof ridge, where the latter predicted somewhat lower mean and peak pressure coefficient values than wind tunnel data. The velocity streamlines obtained from LES provide an excellent overview of the airflow around the buildings. This study shows the efficacy of LES for assessing wind loads on building roofs with complex geometry, since existing codes do not provide any quantitative assessment methods for such problems.

Keywords: Low-rise building; Complex roof geometry; LES; Wind load; Mean pressure coefficient.

1. INTRODUCTION

The majority of low-rise buildings in North America exist in hurricane prone regions, such as Florida and Louisiana, where wind speeds exceeding 100 miles per hour are common. The roof of a low-rise building is the most prone to wind induced structural damage because of the development of high suction regions due to flow separations (Dagnev et al. 2009). For instance, hurricane Andrew in 1992 caused large scale devastation worth 20 million dollars, which included structural damage to several low-rise buildings (Li and Ellingwood 2006). Most standards such as the ASCE 7 2010 and NBCC 2005 provide design guidelines for the design of roofs with regular geometries, but refer to wind tunnel testing for complex roof geometries.

Wind induced structural loads on buildings have been assessed by physical modelling through wind tunnel (Kumar and Stathopoulos 2000) and field measurements (Levitan and Mehta 1992). However, physical modelling is time consuming and expensive, while the advent of advanced computing facilities has enabled the use of Computational Fluid Dynamics (CFD) models in wind engineering studies (Abdi and Bitsuamlak 2014). CFD has been successfully

used for various wind engineering applications, such as assessing wind induced pressures on solar panels (Bitsuamlak et al. 2010), wind induced ventilation (Jiru and Bitsuamlak 2010), wind flows over hills (Bitsuamlak et al. 2004), besides dispersion of pollutants in the urban environment (Chavez et al. 2011). In a majority of studies devoted to computational evaluation of wind pressures on buildings, k- ϵ models have been widely used (Tsuchiya et al. 1997). However, departure in data between experiment and k- ϵ model was observed by Tamura et al. 2008, while assessing the wind induced pressures on a building. According to Tamura et al. 2008, the standard k- ϵ model overestimates the pressure coefficients on the frontal surface. On the other hand, Large Eddy Simulation (LES) has provided more accurate results as shown by past studies (Dagnew et al. 2009; Hajra et al. 2015; Elshaer et al. 2016). For instance, excellent agreement between field measurements of wind pressures on the Texas Tech University building and LES was obtained by Panneer selvam 1997. Likewise, Aboshosha et al. 2015 used LES to successfully assess the wind induced pressures on a high rise building. According to Dagnew and Bitsuamlak (2010), LES is a multi-scale computational modelling approach that offers a more comprehensive way of capturing fluctuating turbulent flow.

This paper focuses on a low rise building (hereafter referred to as FL 27) with complex roof geometry. Two cases are considered, which are isolated and surrounded for a critical wind direction of 135 degrees. The Mean and peak pressure distributions from the current LES results are compared to a similar wind tunnel testing by Kopp and Gavanski 2011 to evaluate the efficiency of LES.

2. WIND TUNNEL MEASUREMENTS AND BUILDING MODELS

The measurements were carried out at the Boundary Layer Wind Tunnel (BLWT) at Western University, Canada, which is 64 m long, 15 m wide and 6 m high. Spires and roughness elements were used to simulate a suburban terrain. The building model of FL 27 shown in Figure 1 (a) is made of plexiglass (case 1), containing 496 pressure taps on the roof surface connected to the data acquisition system through 1.6 mm tubes.

Figure 1 (b) shows FL 27 in the presence of neighbouring buildings (case 2). The pressure measurements were carried out for 6 minutes with a sampling rate of 400 Hz. Figure 1 (c) shows the plan dimensions in equivalent full scale and the critical wind direction of 135 degrees. The roof in Figure 1 (c) has been divided into five zones – roof portions ‘A’ and ‘B’ are somewhat higher than ‘D’ and ‘E’. In the present study two different cases are considered:

Case 1: FL 27 (isolated) – Figure 1 (a);

Case 2: FL27 in the presence of neighbouring building – Figure 1 (b).

The mean roof height of the building is 0.11 m (wind tunnel scale). Further experimental details can be obtained from the report (Kopp and Gavanski 2011).

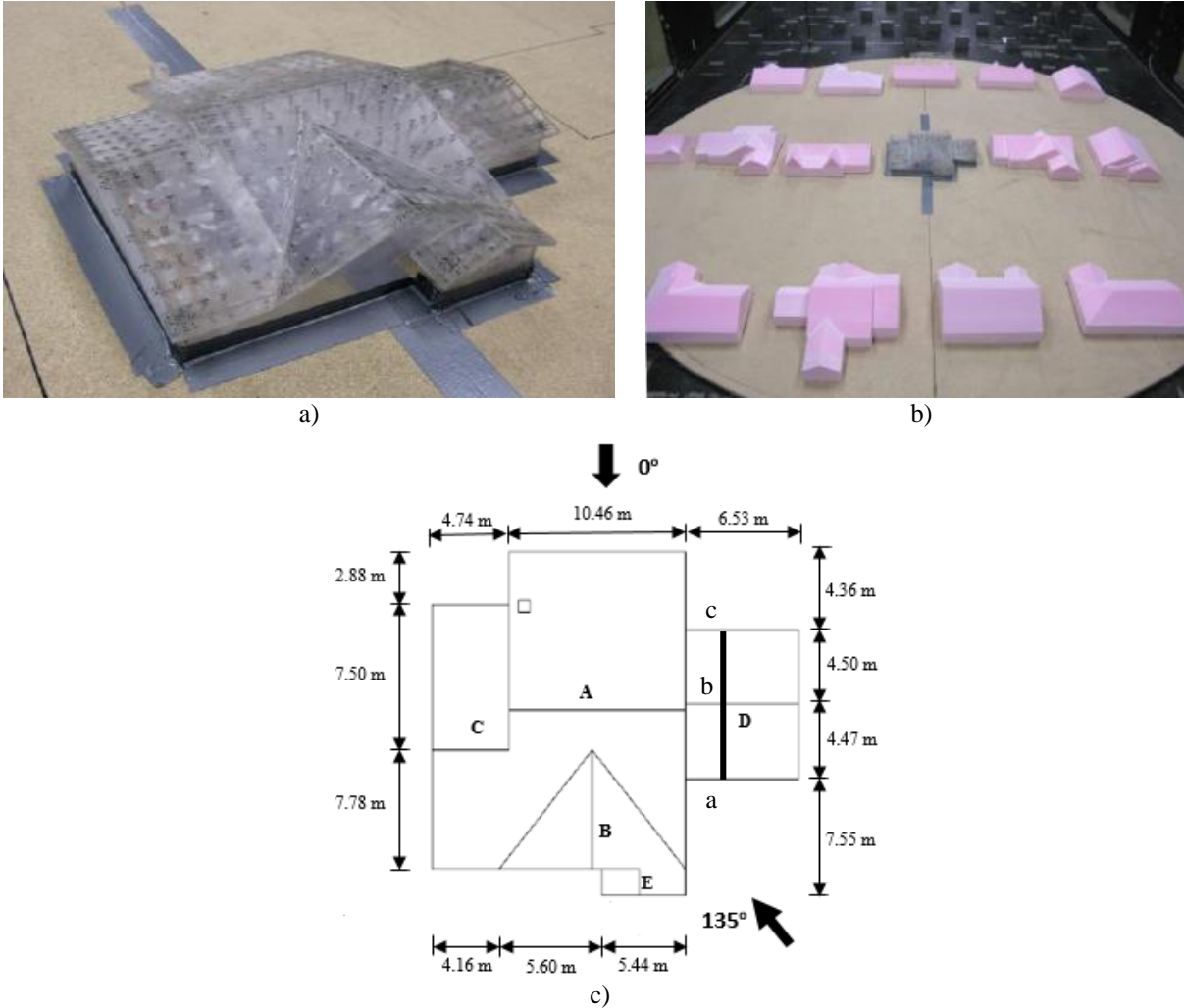


Figure 1: Building models used for the test: a) FL 27 (isolated – case 1); b) FL 27 with neighbouring buildings – case 2; c) plan dimensions of FL 27 (after Kopp and Gavanski, 2010 -- part of NSF Grant CMMI-0928563).

3. LES SIMULATIONS FOR VARIOUS CASES

The LES simulations were carried out using STARCCM+ (CD-Adapco 2009) software (<http://www.cd-adapco.com/products/star-ccm-plus>). The Computational domain (CD) and grid discretization used for the simulations are explained in this section

3.1 Computational domain for the simulations

The same Computational Domain (CD) was used for both cases, which was 5 m long, 4 m wide and 0.7 m high, as shown in Figure 2. The lateral edges of the CD were 1.72 m from the side of FL 27. Table 1 presents the dimensions of the CD and compares it to COST 2007 recommendations. The CD was large enough to avoid inaccuracies due to blockage. Symmetry boundary condition was imposed on the top and the sides of the CD, while the ground (base) was considered ‘no-slip (wall)’. The inflow and outflow were modelled as velocity inlet and pressure outlet, respectively. The average height of the neighbouring buildings was nearly the same as FL 27, which was 0.1 meter in model scale. Based on the boundary layer characteristics measured in the BLWT, a transient inflow boundary condition was applied adopting CDRFG in flow technique described in Aboshosha et al. 2015 that accurately simulates the coherency function and spectra. In order to incorporate the sub-grid turbulence, the model of Smagorinsky 1963 and Germano et al. 1991 were used.

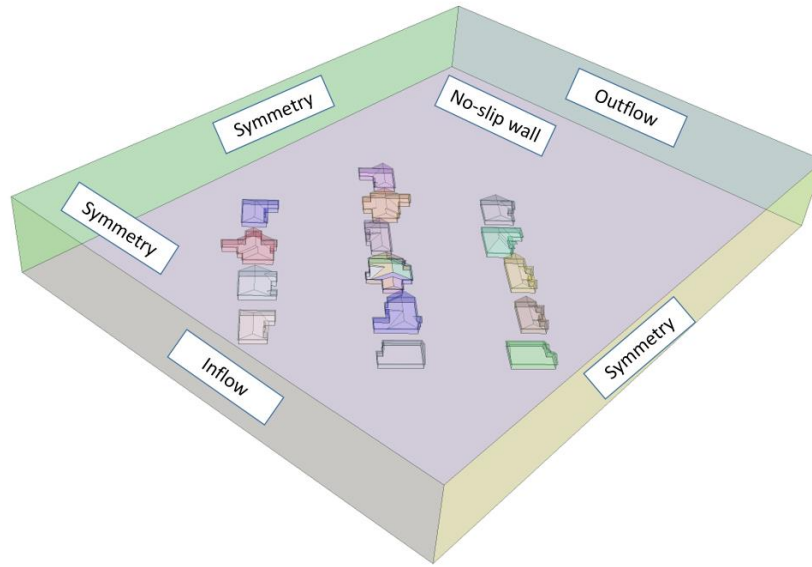


Figure 2: Computational domain and boundary conditions for case 2

Table 1: Computational domain parameters

Case	H_{\max}	Present study		COST 2007 recommendations
1	0.11 m (Height of FL 27)	Vertical extension of the CD	0.7 m	$5H_{\max}$ (0.55 m)
		Lateral extension of the CD	1.73 m	$5H_{\max}$ (0.55 m)
		Distance between Inflow boundary and building	1.15 m	$5H_{\max}$ (0.55 m)
		Distance between Outflow boundary and building	3.35 m	$15H_{\max}$ (1.65 m)
2	0.11 m (Height of FL 27)	Vertical extension of the CD	0.7 m	$5H_{\max}$ (0.55 m)
		Lateral extension of the CD	1.73 m	$5H_{\max}$ (0.55 m)
		Distance between Inflow boundary and building	1.8 m	$5H_{\max}$ (0.55 m)
		Distance between Outflow boundary and building	2.7 m	$15H_{\max}$ (1.65 m)

3.2 Discretization of the grid

For case 2, The CD was divided into three zones as shown in Figure 3. The same zones were also used for case 1. The dimensions of each zone and grid size is presented in Table 2. A number of 2 million grid cells was utilized in case 1, while case 2 had nearly 3 million grid cells. Figure 4 shows the grid discretization for case 2 (FL 27 – surrounded), with a vertical section passing along the roof of FL 27. Figure 4 shows the different zones and the prism layers used closer to the roof ridge. Polyhedral cells available in STARCCM+ was used for the meshing with coarser mesh in the outer zone (zone 1) and finer mesh at the inner zones (zone 3). It is common to carry out the meshing by using different zones. For instance, Nozu et al. 2008 successfully carried out LES simulations of wind flow across Tokyo city by meshing the computational domain in different zones. Eight prism layers with a stretching ratio of 1.05 (maximum allowable is 1.3 as per COST 2007) was used in the present study. A time step of 0.001 seconds was chosen to ensure that the Courant Friedrichs-Lewy number was less than 1 to ensure the convergence of the numerical simulation. The physical scaled duration was selected to be for 9 seconds with 8 inner iterations, using 20 processors of the High Performance Computing (HPC) facility provided by SHARCNET at Western University, Canada. In order to test the accuracy, a few simulations with varying grid size were run initially to ensure that the results were independent of the grid size.

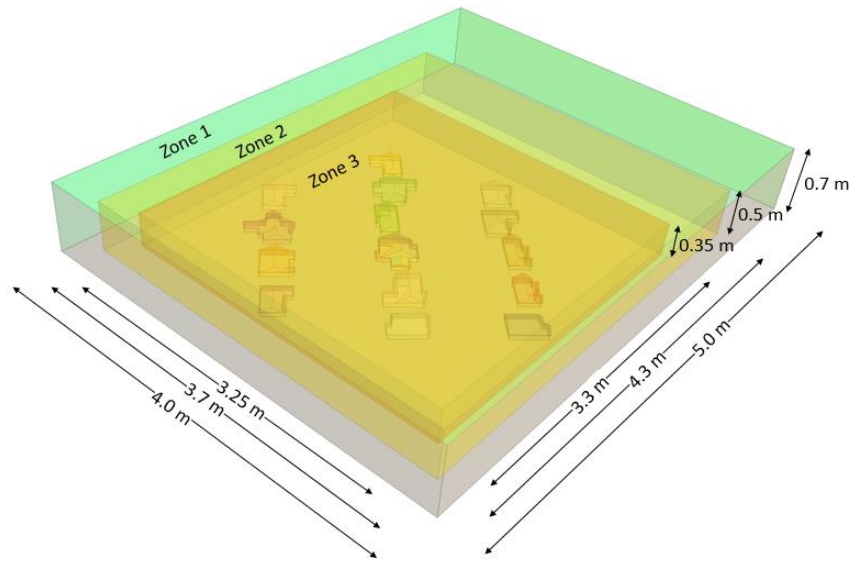


Figure 3: Zone dimensions for Case 2 (note: similar dimensions were used for case 1)

Table 2: Size of each zone for various cases

Case	Zones and their dimensions L x B x H (m)	Grid size in terms of building height (h)	Number of cells
1	Zone 1 (CD): 5 x 4 x 0.7	h/15	1953662
	Zone 2: 4.3 x 3.7 x 0.5	h/20	
	Zone 3: 3.3 x 3.25 x 0.35	h/40	
2	Zone 1 (CD): 5 x 4 x 0.7	h/15	2853700
	Zone 2: 4.3 x 3.7 x 0.5	h/20	
	Zone 3: 3.3 x 3.25 x 0.35	h/40	

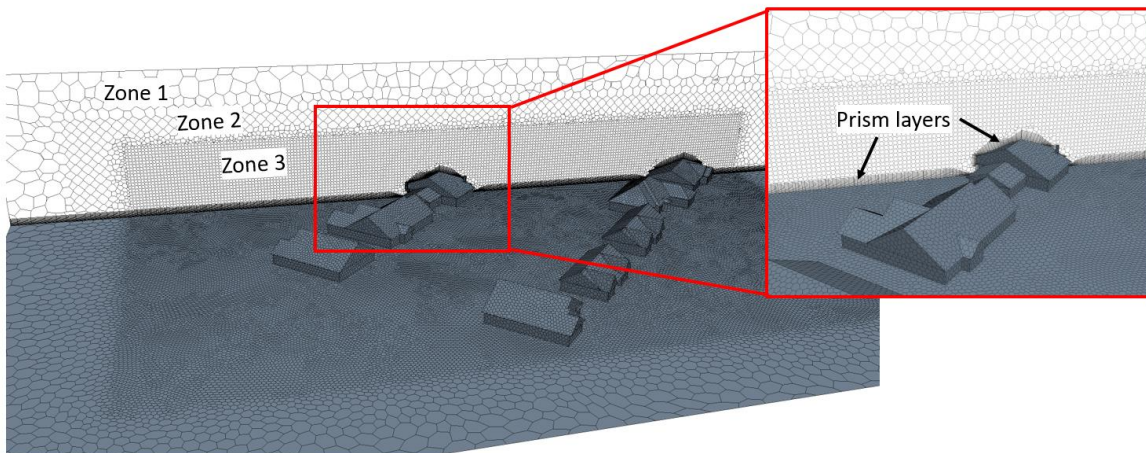


Figure 4: Grid used for FL 27 and the different zones through a vertical plane

4. RESULTS AND DISCUSSION

This section presents results for case 1 (isolated) and case 2 (effect of adjacent buildings). Figure 5 presents the instantaneous velocity streamlines around FL 27 for both cases. The velocities are nearly zero closer to the building

surface, but at the edges the velocities are somewhat higher owing to the flow separations. Also, the streamlines are very similar in both cases because in case 2 the upstream and downstream buildings are away from FL 27, and there are some interactions between FL 27 and the surrounding buildings.

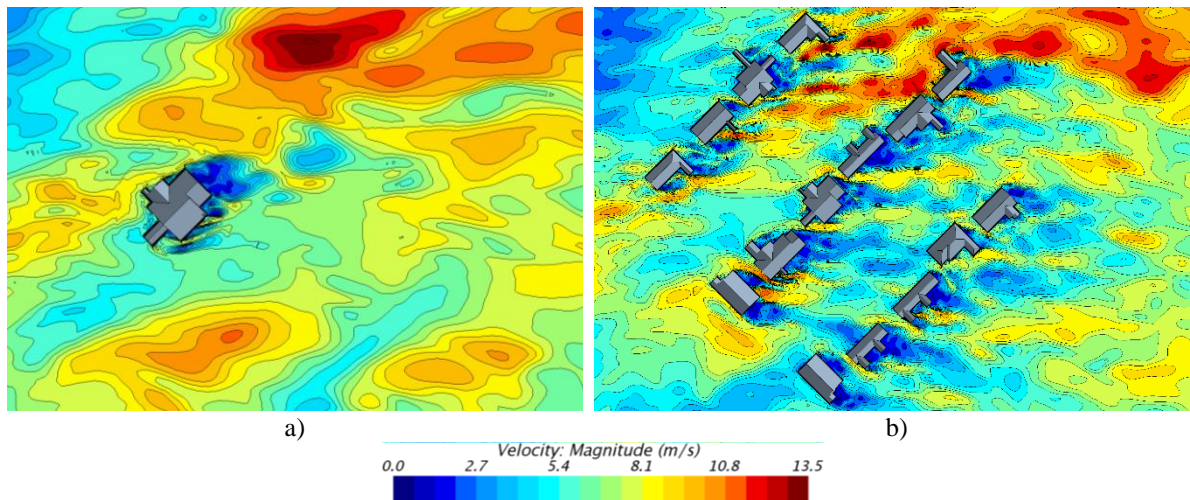


Figure 5: Instantaneous velocity streamlines (top view) at time = 6 seconds for: a) Case 1; b) Case 2

Figure 6 presents a comparison of mean C_p between LES and wind tunnel data for case 1 (FL 27 - isolated). Wind tunnel data suggest that the mean C_p values were in the range of 0.3 to -3.5, with high suction closer to the ridge (roof 'A') due to flow separations. Also, due to the wind direction there are counter rotating vortices (closer to roof 'i') which cause high suction and hence, values of -0.75 are obtained in the corners. At all the roof locations, gradually away from the ridgelines, the mean C_p values are less negative (suctions are reduced). A similar trend is observed from LES results as shown in Figure 6 (b) where the range of mean C_p values are also from 0.3 to -3.5. Excellent agreement was obtained between LES and wind tunnel data at all locations on the roof of FL 27 indicating the efficiency of LES in evaluating the wind induced pressures. The study was further extended to case 2 (FL 27 amidst adjacent buildings) as shown in Figure 7. Figure 7 (a) presents wind tunnel mean C_p values (Kopp and Gavanski 2011) on the roof of FL 27. The trends obtained from wind tunnel for case 2 are similar to those obtained from LES as shown in Figure 7 (b).

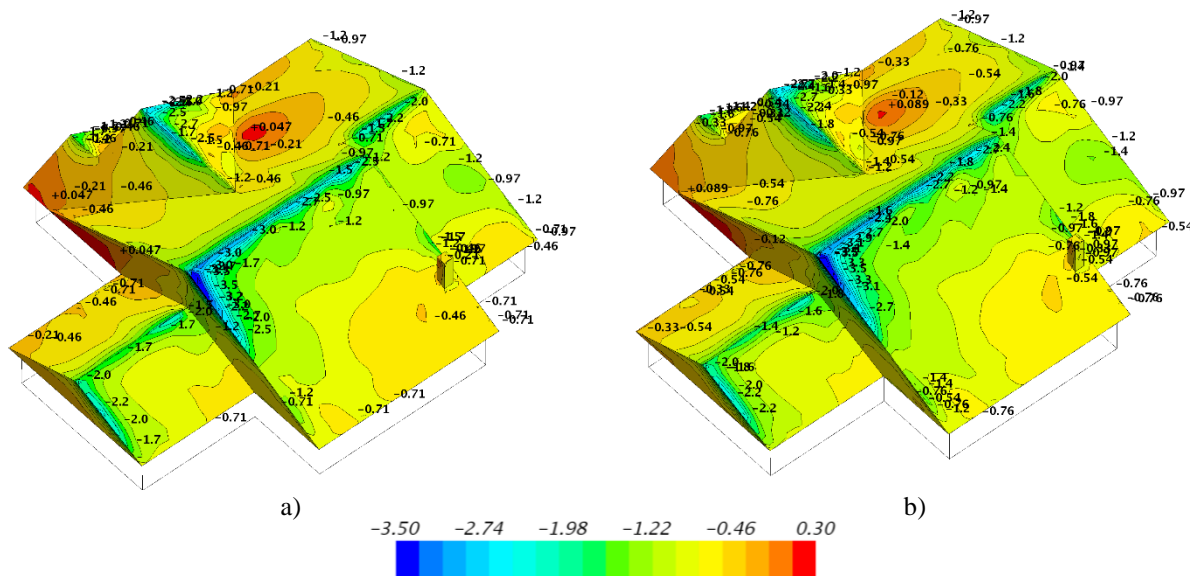


Figure 6: Mean C_p contours on the roof of FL 27 for case 1: a) Wind tunnel (Kopp and Gavanski 2011); b) LES

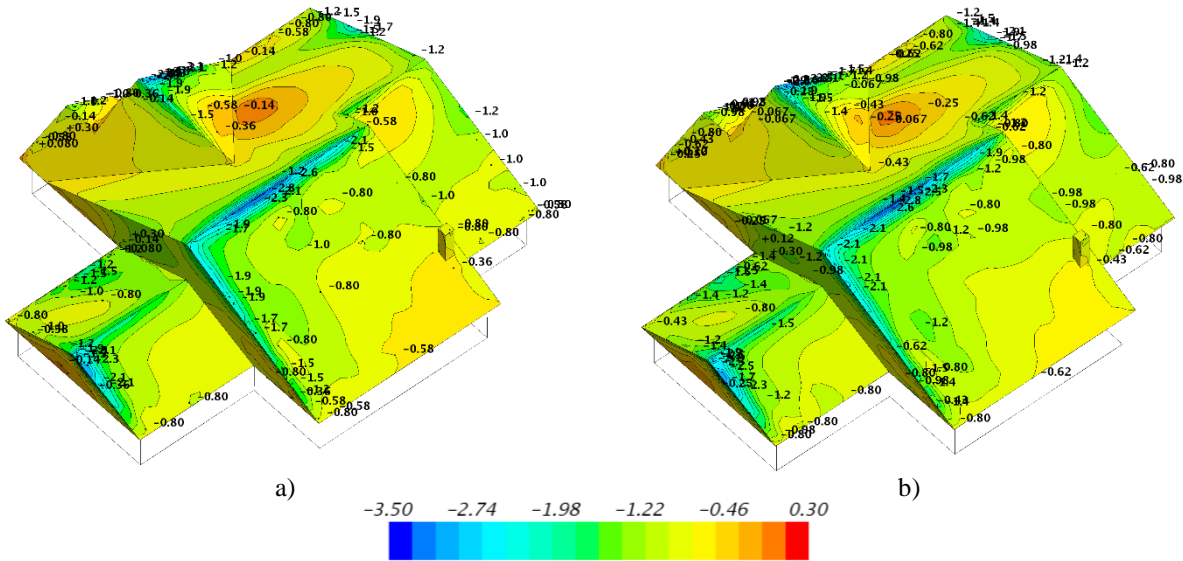


Figure 7: Mean C_p contours on the roof of FL 27 for case 2: a) Wind tunnel (adopted and modified from (after Kopp and Gavanski, 2010 -- part of NSF Grant CMMI-0928563); b) LES

Comparisons of mean C_p at individual points on the roof of FL 27 were carried out as shown in Figure 8 (a). A line ‘abc’ as shown in the Figure 1 was chosen and the LES mean and peak C_p values were extracted and compared to wind tunnel data of those corresponding points along that line. Clearly, the comparison between LES and wind tunnel for both cases 1 and 2 is excellent at almost all locations except at the ridge line where there is a slight departure in data. It may be possible to improve LES results at these locations by having a slightly finer mesh at the ridge. Similar trends were observed for peak C_p values as shown in Figure 8 (b), where matching between LES and wind tunnel data at all points was excellent except at the ridge. It is also worth noting that at the ridge (point ‘b’) the mean and peak C_p values are more negative (higher suction) for case 2 (adjacent building case) than in case 1 (isolated case). This shows that the effect of adjacent buildings can sometimes help reduce wind induced pressures on the roof as opposed to the isolated case. The general finding of this paper is that LES can be used to assess wind induced pressures on buildings with complex roof geometries, which may otherwise be difficult to model in wind tunnels. However, LES is computationally costly to generate the aerodynamic data for all wind directions. This may be improved through a greater computational speed and capacity to reduce computational time in the future.

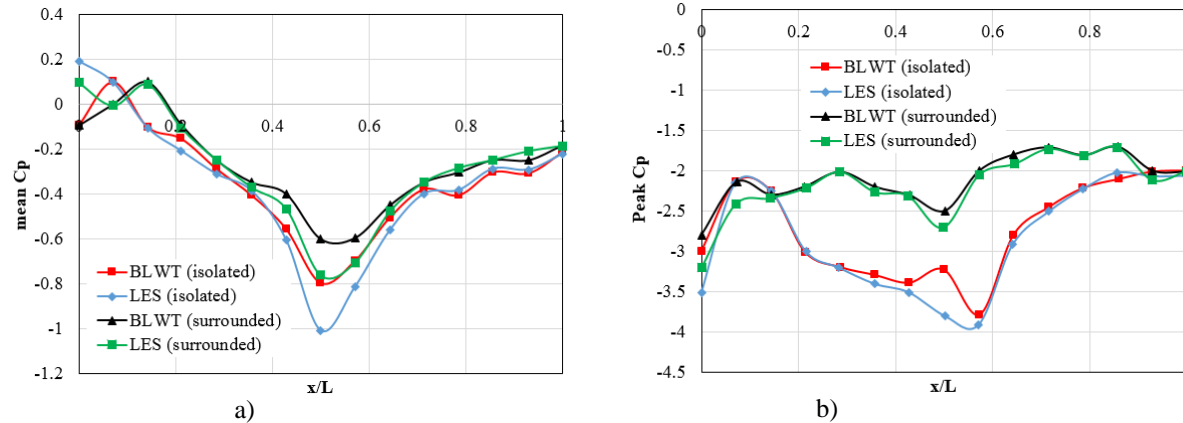


Figure 8: Comparisons between LES and wind tunnel along line ‘abc’ on the roof of FL 27: a) Mean C_p ; b) Peak C_p

5. CONCLUSIONS

This paper presented comparisons between LES and wind tunnel data for two different cases: FL 27 (case 1 - isolated) and FL 27 amidst neighbouring buildings (case 2), for a critical wind direction of 135 degrees. The mean and peak C_p values obtained from wind tunnel (Kopp and Gavanski 2011) and LES on the complex roof geometry of FL 27 for both the cases were compared. Results show excellent matching between LES and wind tunnel data at all locations on the roof, except at the ridge where there is a slight departure between LES and wind tunnel results. It is expected that a finer mesh at the ridge can improve the LES results at the ridge. The velocity streamlines provide an excellent overview of the wind flow characteristics around the buildings. In general, the performance of LES in estimating the mean and peak C_p was excellent for the cases investigated, indicating the possibility of using LES in the absence of physical modelling tools. Additional studies pertaining to the application of LES for assessing wind induced pressures on complex roof geometries in realistic urban scenarios is necessary.

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