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Application of LES to wind loading estimation on buildings

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Abstract

This study discusses the applicability of CFD to the estimation of wind load on buildings. As the MILT promotion projects for building standard maintenance, we performed numerical simulation based on the computational fluid dynamics (CFD) technique for the estimation of pressure distribution on two types of tall buildings consisting of an office- and a residential tall building. Large eddy simulation (LES) is adopted for the numerical model of wind turbulence. At the same time, the wind tunnel experiments are carried out for these tall buildings at three different facilities. Based on the variability of experimental data the consistency of numerical data is elucidated and the numerical validation of the provided model is accomplished.

Introduction

Recent performance of computers has made it possible to carry out the large scale computation with high resolution mesh system for actual shaped building model and to predict accurately the pressure distributions on the surface of the complex building. According to the previous technical papers (Yoshikawa and Tamura [1]), it is well known that the numerical method which uses the unstructured grid system and models the turbulent flow by sub-grid scale concept of LES can estimate the sufficiently accurate pressures enough to be used for the wind resistant design of tall buildings. This type of LES could be applied to wind flows around the complex configuration such as the actually-shaped building with various cladding parts.

In Japan, there is a building standards act which provided an order for enforcement concerning the wind resistant design. One of the orders requires the wind pressure and the wind force coefficients should be provided by the wind tunnel test. However considering above present situation concerning the accuracy of CFD technology, we have to examine the potential of this technology to generate the appropriate values for wind forces and pressures, comparable to the data obtained by the technology of wind tunnel test. Based on the current findings for accuracy of CFD approach, MILT arranged the public promotion projects for building standard maintenance (Building Standard Development Promotion Program) and in 2015 indicated the research theme on the introduction of CFD technology to the building standard for estimation of wind pressure and wind resistant design of buildings. Here this study has started with focusing on the cases of tall buildings that the performance assessment and design should be applied to. This study reviews and summarizes the results and the knowledge obtained by this project activity in 2015 (Tamura et al. [2]).

With regard to this project, the working group (WG) on CFD wind resistant design of tall buildings was established. The members of this WG, who mainly investigate the CFD performance and availability on the wind load estimation, are shown as follows:

Tetsuro TAMURA(Chair), Hidenori KAWAI(Secretary), Makoto TSUBOKURA, Hiroto KATAOKA, Yoshiyuki ONO, Koji KONDO, Yoshiaki ITOH, Hirotoshi KIKUCHI, Tsuyoshi NOZU, Hiroshi TERAZAKI, Ryohei NAKAMURA, Kazuo Ohtake, Hideyuki TANAKA, Keisuke YOSHIE, Hitomitsu KIKITSU, Yasuo OKUDA

As a model of object building, two types of office- and residential tall buildings are selected. Both of tall buildings are artificially made considering aspects of the recent actually existing buildings and represented using the CAD data. Experimental and numerical models are made using the CAD data. This study firstly discusses the statistical meanings on the variability of the experimental data obtained by the wind tunnel tests at different facilities. Based on these data, the computational condition about wind direction where the drastic characteristics are observed on aerodynamic forces is determined.

The comparison of the experimental data with the numerical data which are obtained by LES was carried out and the numerical validation has been achieved. Concerning the extreme situation for aerodynamic characteristics the physical mechanism is elucidated analyzing the flow structures represented by the flow visualization technique.

Problem Formulation –Wind Flow around a Tall Building-

This study takes into consideration wind flows around a tall building with actual shape. Two types of tall buildings are examined for the aerodynamic characteristics to obtain the required data in the process of wind resistant design. These target tall buildings are artificially made utilizing the CAD data and have same height of 128m (Fig. 1). One is the residential tall building with three types of corner shape consisting of right angled, chamfered and double-recessed corners at three different parts in the vertical direction. Balcony is surrounded at four walls of the residential building. The other target is the office tall building with the crown wall at the top and the commercial facility in the piloti at the bottom. Its vertical walls have the eaves at each story. The surrounding buildings are also artificially made and used in the same manner for these two target buildings.

Validation data obtained by wind tunnel experiments

This study plans to perform the wind tunnel experiments at three different facilities. The same model is used for all wind tunnel experiments in order to minimize the difference of experimental conditions. The variability of the experimental data is discussed and the validation data were extracted to check the accuracy of the numerical data. Also, taking into consideration the peak pressures or maximum wind force, the wind direction is determined for numerical simulation.

The inflow condition of the wind velocity profiles is given as roughness category III of AIJ Recommendations for Loads on Buildings (AIJ, [3]). The surrounding buildings are modeled in the diameter range of 800m. Model scale ratio is set to 1/400. Design wind speed is set to 44.9m/sec at building height equivalent to 50 year return period. Data sampling frequency is equal to 1000Hz for both of pressure and velocity measurements.

For the pressure experiment the averaging time is 0.005 sec (the number of moving averaging: 5) based on the TVL method. The number of ensemble averaging based on 10 minutes data is set to 9. The wind direction is changed at 5 degree pitch and 72 wind directions measurements are conducted.

Experimental results

This chapter discusses the variability of experimental data obtained by various wind tunnel facilities. This project employs three different wind tunnels at technical research institutes which have been mainly utilized to obtain the data for wind resistant design of tall building to be actually planned to be constructed. By the conventional manner three institutes carry out the wind tunnel tests under same experimental conditions using the same model. It means the measurement points are completely coincident.

Figure 2 shows the correlation of experimental data on peak pressures with and without the surrounding buildings obtained by 3 different wind tunnel facilities. Based on the facility A, the correlations of B and C are very high even for the peak values which usually tend to be unstable. We should note the consistency of the experimental data are realized under the conditions that mean wind velocity and turbulent intensity of the approaching wind flow are almost same but the turbulent integral length scales are slightly different among the three wind tunnel tests.

LES for wind pressures on the tall building

This chapter discusses the accuracy of numerical results obtained by the CFD technique, comparing with the experimental data which have been settled by the detailed examination at the previous chapter. This study employs the LES technique because the unsteady simulation is required for wind load estimation. We can check whether the present LES model generates the sufficiently appropriate numerical results comparable to the wind tunnel experimental data.

Numerical model and method

The numerical model around the target building in the urban district is reproduced by the CAD data with the same geometry as experimental model. Also, the mesh systems are generated using the unstructured grid system (Fig. 3). Details of the balcony on the residential building and the crown wall at top of the office building can be reproduced evidently. Figure 4 shows inflow conditions of the wind velocity profiles and the spectrum of velocity fluctuation generated by the Synthetic Eddy Method (SEM) method proposed by Jarrin [4]. The simulated wind velocity profiles are reasonably

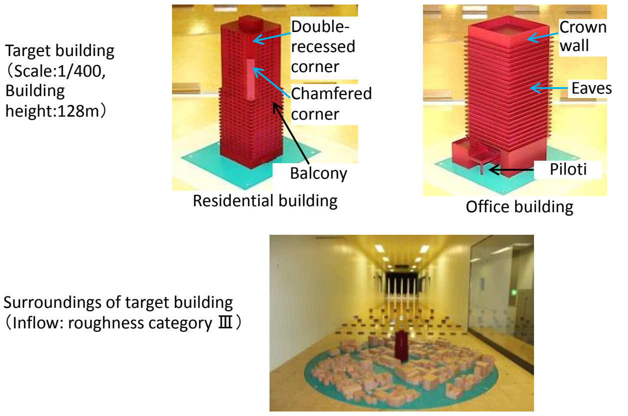
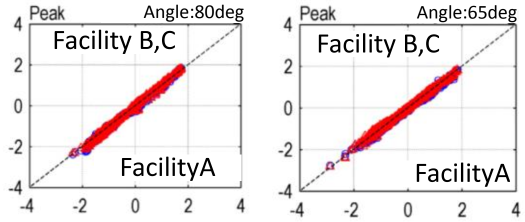
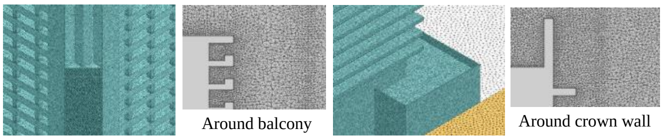


Figure 1 Target building and surrounding buildings



(a) Residential building with surrounding buildings (b) Office building with surrounding buildings

Figure 2. Correlation of experimental data on peak pressures by 3 different wind tunnel facilities.



(a)Residential building (b)Office building

Figure 3. Mesh division

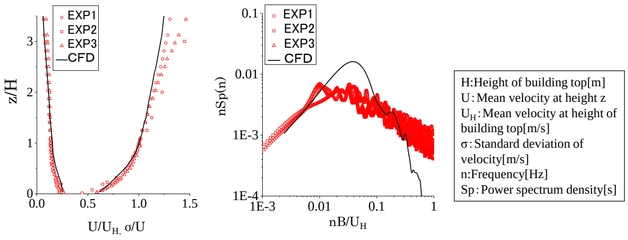
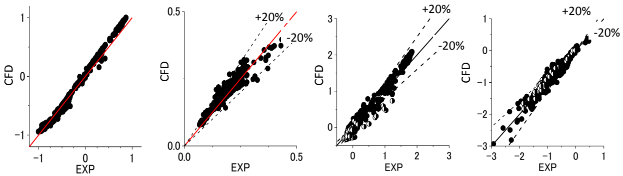
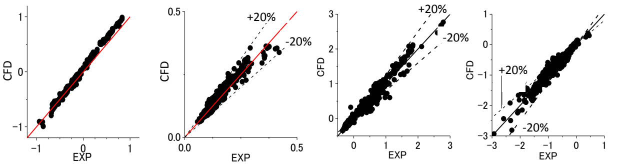


Figure 4. Inflow condition made by SEM method and comparison with experimental results



(a)Averaged wind pressure coefficient (Residential building)
(b)Fluctuating wind pressure coefficient (Residential building)
(c)Maximum peak wind pressure coefficient (Residential building)
(d)Minimum peak wind pressure coefficient (Residential building)



(a)Averaged wind pressure coefficient (Office building)
(b)Fluctuating wind pressure coefficient (Office building)
(c)Maximum peak wind pressure coefficient (Office building)
(d)Minimum peak wind pressure coefficient (Office building)

Figure 5. Correlation between CFD (LES) and experimental data in office building and residential building

in good agreement with the experimental data. The obtained spectrum energy shows some difference from experimental data in lower and higher frequency regions, but agrees with experiment near the natural frequency estimated by conventional tall buildings.

Concerning the numerical method, Front Flow Red (FFR) is employed for LES of wind around tall building. In this code, we solve the incompressible Navier-Stokes equation and the continuity equation, and use the unstructured grid system formulated with second order accuracy by vertex-centered definition. For time integration the implicit Euler scheme is used and the very small blending with upwind scheme is applied. For numerical algorithm the SMAC method is used. Concerning the Sub-grid Scale modeling of LES, this code uses the standard Smagorinsky model with Van-Driest type of damping function near the wall.

Numerical results –Comparison with experimental data

In order to elucidate the consistency between LES and the experimental data, this chapter carries out the comparison about the time averaged, fluctuating, maximum peak and minimum peak wind pressure at the all measurement points on the residential and office tall buildings. Figure 5 displays the correlations between CFD data obtained by LES and experimental data in the residential tall building. Time averaged data are completely consistent with each other. The fluctuating and peak values show agreement within 20%. Larger minimum negative values, which are important from safety point of view, do not scatter so much. Figure 5 displays the correlation between LES data and experimental data in the office tall building. The results of this case have almost the same tendency with the residential case.

Physical mechanism of peak forces and pressures

This chapter discusses the consistency of details of the wind forces or pressures on the cladding part such as crown wall, eaves, chamfered corner and balcony wall at special angle determined by the experimental data (Figs. 6, 7, 8 and 9). Almost aerodynamic values are sufficiently in good agreement with experimental data. Very large peak wind forces or very low negative peak pressures appear at the specified point shown by red circle. Even these extreme values also can be quantitatively simulated to the experimental data.

By using the flow visualization technique, the physical mechanism for the drastic values of the aerodynamic forces and pressures on the complex tall building has been elucidated. Figure 10 depicts the instantaneous streamlines and pressure contours for the office tall building at wind direction 65 degree. Higher force at the leeward crown wall is produced by the separating and overhanging flows. At the end of eave we can find the very local vortex which generates the local suction, and between two eaves the rotating flow occurs which generates the higher pressure. Accordingly the upward wind force is generated. Figure 11 illustrates the instantaneous streamlines and pressure contours around the residential tall building at wind direction 80 degree. In the case of a square cylinder, the local suction occurs at the windward corner. But for the cylinder with the chamfered corner the local suction occurs at the leeward corner because the flow separated from the first corner is going close to the chamfered surface. The flow entering the balcony generates the swirl flow inside and this swirl flow attacks to the wall at the end of the balcony. As a result, the higher wind force is generated at the balcony near the corner of the square building.

Numerical results using the practical model for LES

This chapter shows the numerical results obtained by reasonably small-sized LES with the feasible mesh number used. On the other hand the previous chapter shows the computed results with sufficiently high accuracy as a champion data with 200M meshes. In order to clarify the minimum requirement for getting the accurate solutions by the LES, various kinds of simulations are

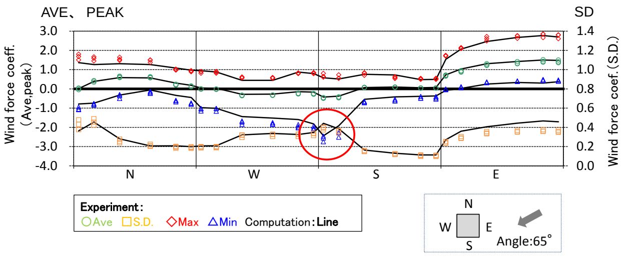


Figure 6. Wind force coefficient of crown wall(z=123m)
（Office building, angle: 65degree）

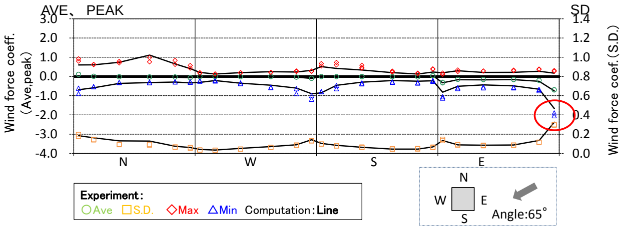


Figure 7. Wind force coefficient of eaves (z=113.5m)
(Office building, angle: 65degree）

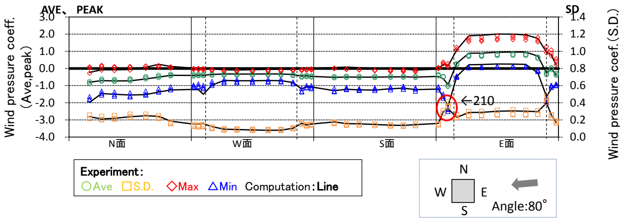


Figure 8. Wind pressure coefficient of 26th floor wall (z=94.2m)
（Residential building, angle: 80degree）

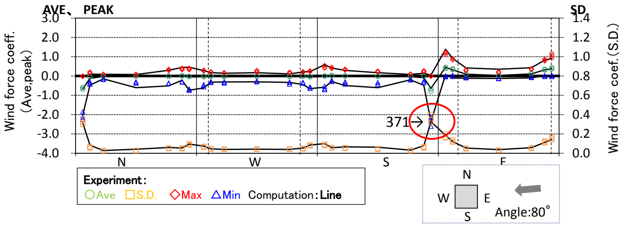


Figure 9. Wind force coefficient of balcony(z=40.7m)
（Residential building, angle: 80degree）

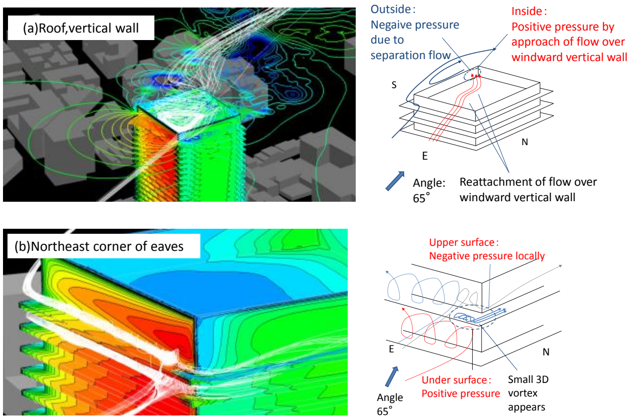


Figure 10.Mechanism of peak force and pressure（Office building, angle: 65degree）

carried out by various designers or engineers. Table 1 shows the computational conditions of the practical LES by various research groups. Almost research groups employ 50M for a number of meshes. For the mesh size, 0.3-0.4m is set in the parallel direction to the wall and 0.04-0.1m in the normal direction to the wall.

Figure 12 shows the horizontal distribution of maximum and minimum peak wind pressure coefficients for office building with angle of attack of 65 degree. The results by 5 research groups with the champion data by 200M meshes and 3 experimental data are included in the figure. The results of small-sized LES are a little bit scattered but almost show reasonable agreement to the experimental and the champion data. Figure 12 shows the horizontal distribution of maximum and minimum peak wind pressure coefficients for residential building with angle of attack of 80 degree. The previous papers show that the pressure on the leeward chamfered corner indicates the negative peak values. The results of 5 research groups are largely scattered and some of them do not agree with the experimental and champion data.

Conclusions

Based on the project on the CFD applicability to the wind load estimation, the-state-of-the-art in LES technology is discussed, comparing with experimental data which was also obtained very carefully. It can be said that at least the level as a predictive method has reached the same level as wind tunnel test. In the near future, LES can be used for the actual wind resistant design of tall buildings in cities. In February 2017 the “Practical guide of CFD for wind resistant design” was published at AIJ.

Acknowledgments

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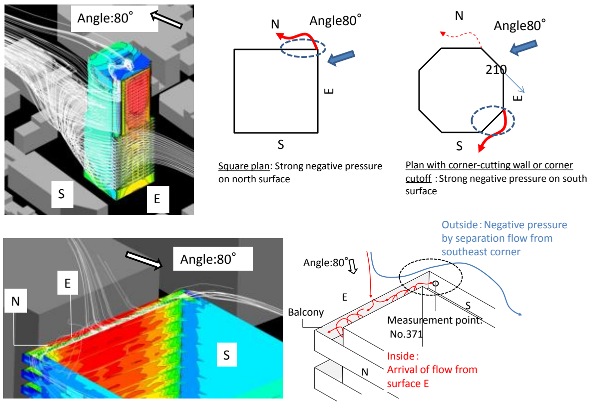
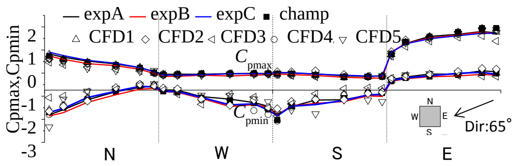


Figure 11.Mechanism of peak force and pressure（Residential building, angle: 80degree）

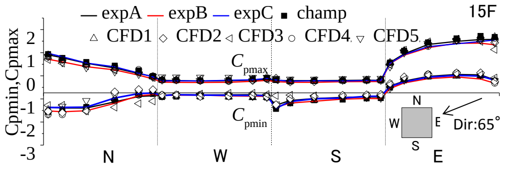
Table 1. Computational conditions of the practical LES for various research groups

		Group1	Group2 CFD1	Group3 CFD2	Group4 CFD3	Group5 CFD4	Group6 CFD5
Analysis code		FFR1	SCRYU	OF1	OF2	Self	Self
Grid system		Unstructured					Structured
Definition of physical quantity		Vertex center		Cell center		Vertex center	-------
Cell shape		Tetra	Tetra	Hex	Hex	Tetra	Cartesian
Numerical viscosity		10～20%	GammerLimiter	20～50%*1	TVD	5%	None
SGS model		SM Cs=0.1	SM Cs=0.15	SM Cs=0.12*2	SM Cs=0.2	CSM	SM Cs=0.12
Grid Number(million)		31~65	59~65	48	17~43	43~66	79~97
Spatial resolution	Horizontal	0.2	0.4	0.3	0.4	0.2~0.4	0.215~0.54
	Corner	0.3～0.4	0.4	0.3	0.4	0.2～0.4	0.215
	Vertical direction to wall	0.04	0.08	0.04	0.4	0.06~0.1	0.215
	Boundary layer mesh	○	○	○	×	○	----
	Vertical	0.2	0.4	0.3	0.4	0.2~0.4	0.215~0.54
	Surrounding building	3.0	0.8	0.8	1.6～6.4	3.5~4	0.215~8.6

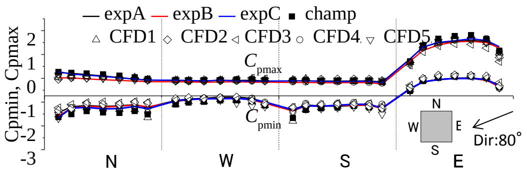
FFR1: Frontflow/Red, FFR2 : Frontflow/Red(HPC edition), OF1 : OpenFOAM（Helyx &v1606） Kajima Corp. Edition, OF2 : OpenFOAM v1.7.1, Fluent : ANSYS Fluent R17.2, STAR-CCM+: STAR-CCM+ Ver11.06,SM:Smagorinsky model, CSM : Coherent Structure Smagorinsky Model *1 Sweby Type limiter, *2 Also calculated in WALE model(Cw=0.39)



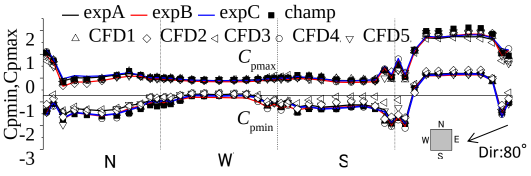
Crown wall (Office building)



15F wall (Office building)



16F wall(Residential building)



30F wall (Chamfered corner, Residential building)

Figure 12. Horizontal distribution of wind pressure coefficients for residential building (angle: 80 degree).