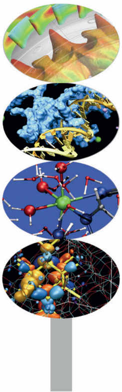
HPC enabling of OpenFOAM® for CFD applications



LES for wind loads assessment on a low-rise building

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SuperComputing Applications and Innovation
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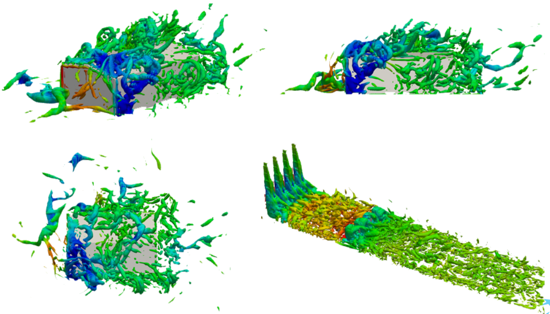
Introduction

- The **correct and safe design** of low-rise structures subjected to wind actions requires a **realistic estimate of wind loads.**
- The turbulent flow around bluff bodies appears to be very complex and **research work is still necessary to obtain an accurate assessment of unsteady forces** acting on them.
- Engineers are interested also in design procedures: **effects in terms of internal forces are needed**.



Introduction

In this contribution

- Large Eddy Simulations are performed to study **wind effects around a low rise building**;
- the turbulence characteristics of the atmospheric boundary layer are simulated by introducing a **synthetically generated fluctuating velocity field**;
- results are firstly analyzed in terms of **pressure distributions on the building** and systematically compared with experimental data;
- finally, starting from both simulated and measured pressure fields, a structural analysis is performed and a **comparison in terms of internal forces on structural elements** is provided;

Wind tunnel setup

- Experiments carried out at the **Boundary Layer Wind Tunnel of the Tokyo Polytechnic University** in Japan.
- The length scale was set at 1 : 100, while the velocity scale was set at 1 : 3, so the resulting time scale was 3 : 100.

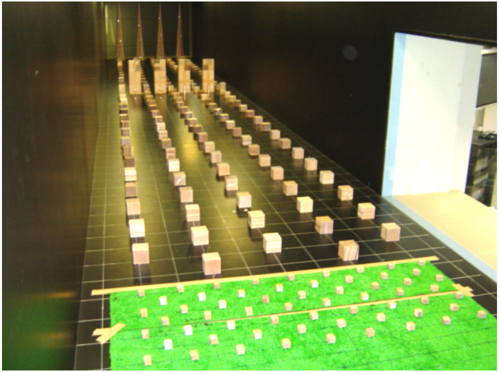


Figure 1: Wind tunnel upwind fetch.

Test models geometry

- The present contribution is focused on a **low-rise building with gabled roof without eaves**.
- The considered geometry is characterized by $H_0/B = 2:4$, $D/B = 3:2$ and $\beta = 9.4°$.
- In experiments the length scale was $1:100$, leading to a model with $B = 160\ mm$, $D = 240\ mm$ and $H_0 = 80\ mm$.

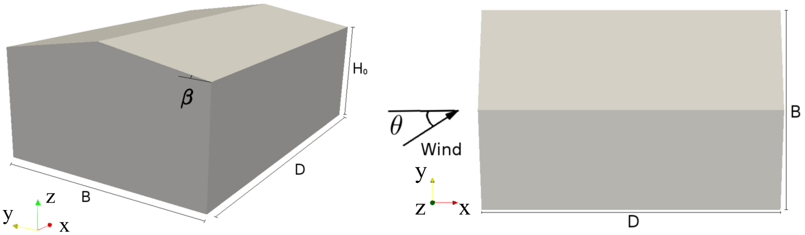


Figure 2: Geometry of the low-rise building.

Wind field

The wind field reproduced in the wind tunnel corresponded to that of **terrain category III** according to the Architectural Institute of Japan reference standards [1].

Mean wind velocity

$$U(z) = 1.7 \left(\frac{z}{Z_G} \right)^{\alpha} U_{ref}, \qquad Z_b < z \leqslant Z_G, \qquad (1)$$

$$U(z) = 1.7 \left(\frac{Z_b}{Z_G} \right)^{\alpha} U_{ref}, \qquad z \leqslant Z_b, \qquad (2)$$

Terrain Cat.	Z_G [m]	Z_B [m]	α	U_{ref} $[m/s]$
III	450	10	0.2	22

Table 1: Parameters of the mean wind velocity profile.

Wind field

The arrangement of **roughness blocks** placed upstream the model was designed to reproduce, together with the mean profile, also the **turbulence intensity profile** below reported:

Wind turbulence intensity

$$I(z) = 0.1 \left(\frac{z}{Z_G} \right)^{-\alpha - 0.05}, \qquad Z_b < z \leqslant Z_G, \tag{3}$$

$$I(z) = 0.1 \left(\frac{Z_b}{Z_G} \right)^{-\alpha - 0.05}, \qquad z \leqslant Z_b. \tag{4}$$

At the reference height of 0.1 m in the wind tunnel, corresponding to 10 m in full scale, the along-wind turbulence intensity was equal to **26%**.

Measurements setups

- Experiments were conducted for **7 wind directions**, starting from $\theta = 0^\circ$ to $\theta = 90^\circ$ with a step of $\Delta\theta = 15^\circ$.
- The model was equipped with **384 pressure taps** that acquired synchronously at a frequency of 500 *Hz*.
- The duration of each test was equal to **18 seconds**, corresponding to **10 minutes in full scale**.

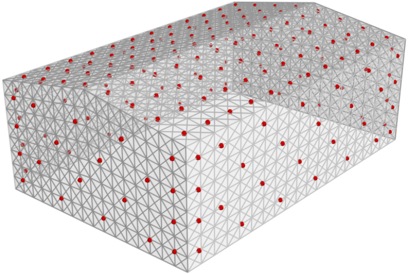


Figure 3: Position of the pressure taps in experiments.

Overview of OpenFOAM

Domain and Boundaries

- **Three rows of roughness blocks** are included in the domain.
- In order to avoid boundary conditions effects on the solution, the outflow boundary is placed $37.5H_0$ behind the building, while the distance from inflow boundary is set equal to $25H_0$ [6].

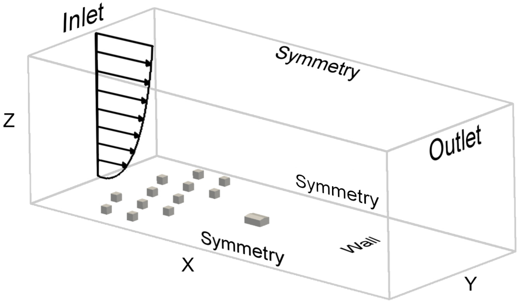


Figure 4: Computational domain adopted for the numerical study.

- $\Delta_x/H_0 = 62.5$
- $\Delta_y/H_0 = 27.5$
- $\Delta_z/H_0 = 22.5$

Domain and Boundaries

- The **mean velocity profile is imposed** at the inlet boundary.
- In order to accurately reproduce the turbulent Atmospheric Boundary Layer (ABL) features, **the fluctuating part of the velocity field is generated by means of the Modified Discretizing and Synthesizing Random Flow Generator** (MDSRFG) method.
- Fluctuations are introduced in a plane immediately after the inlet boundary.

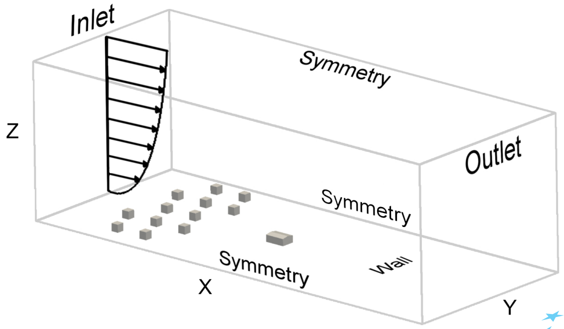


Figure 5: Computational domain adopted for the numerical study.

Mesh

- Close to the wall, a structured mesh has been adopted: $\delta_x/H_0 = \delta_y/H_0 = 1.5e-3$, $\delta_z/H_0 = 1.3 \times 10^{-4}$.
- Upwind the model, the mesh sizing is coarsened up to $\delta_x/H_0 = \delta_y/H_0 = \delta_z/H_0 = 2.5 \times 10^{-2}$ and then **kept constant until the inlet boundary is reached**, in order to propagate turbulent fluctuations.
- The resulting mesh counts about 8×10^6 finite volumes.

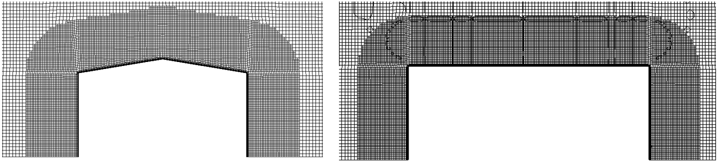


Figure 6: Mesh adopted for LES: frontal and lateral views.

Numerical Setup

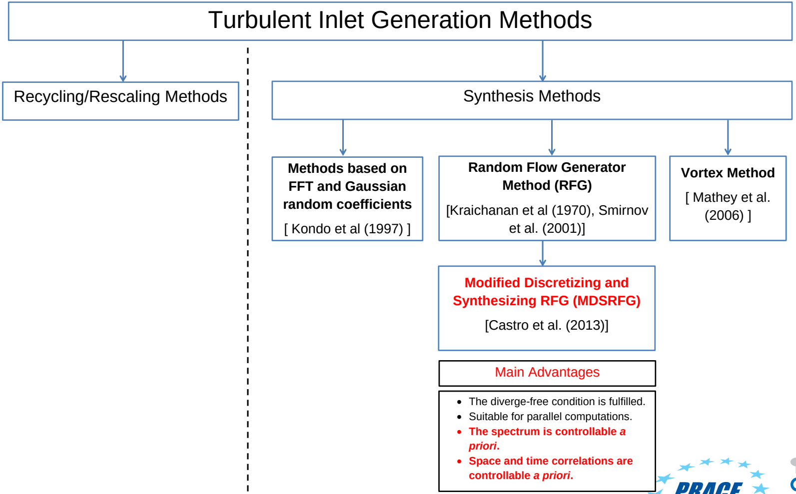
- The **Smagorinsky-Lilly sub-grid model** [4] with in addition the **transport equation of the sub-grid turbulent kinetic energy** has been adopted;
- pressure-velocity coupling is obtained by using the **PISO** algorithm;
- the time integration is performed with the **implicit second-order Backward scheme**;
- centered second-order differentiation scheme is adopted for diffusive terms;
- the Linear Upwind Stabilized Transport (**LUST**) scheme is adopted for the advective term;
- the adopted non-dimensional time step (based on H_0 and U_{ref}) is $\Delta t^* = 8.0 \times 10^{-3}$;
- the maximum *Courant* number obtained is $Co = 2.4$;
- the mean y^+ obtained is 2.3.

CINECA & *OpenFOAM®*

- All the simulations have been performed by using the open source **Finite Volume software** *OpenFOAM®* .
- A preliminary scalability test suggest to run cases on **80 CPUs**.
- All the analysis are performed at the **CINECA Galileo cluster**.
- Each simulation required about 2.5×10^4 CPU hours.

Turbulent inlet

In this contribution, fluctuations are generated by means of the MDSRFG method, that belongs to the family of **synthesis methods**.



Target spectra

The fluctuation field is generated by assuming as a target the von Kármán spectra:

$$S_u(f) = \frac{4(I_u U_{ref})^2 (L_u/U_{ref})}{[1 + 70.8(fL_u/U_{ref})^2]^{5/6}}, \tag{5}$$

$$S_v(f) = \frac{4(I_v U_{ref})^2 (L_v/U_{ref})[1 + 188.4(2fL_v/U_{ref})^2]}{[1 + 70.8(fL_v/U_{ref})^2]^{11/6}}, \tag{6}$$

$$S_w(f) = \frac{4(I_w U_{ref})^2 (L_w/U_{ref})[1 + 188.4(2fL_w/U_{ref})^2]}{[1 + 70.8(fL_w/U_{ref})^2]^{11/6}}. \tag{7}$$

According to experimental measurements, $I_u = 0.26$, while $I_v = 0.75 I_u = 0.195$ and $I_w = 0.5 I_u = 0.13$.

LES of the wind tunnel

- Since the experimental measure of the **turbulence length scale** is not reported in the aerodynamic database for low-rise buildings of TPU [5], in order to estimate it a **LES of the wind tunnel including the upstream arrangements of roughness blocks** has been performed.

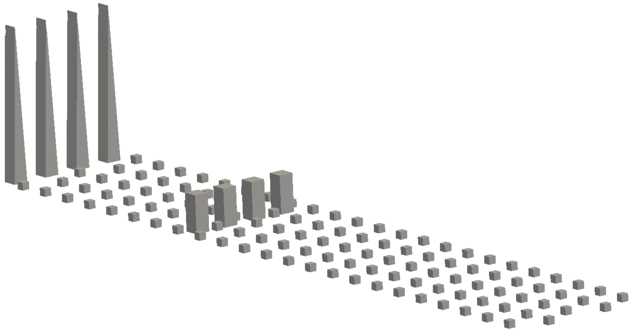


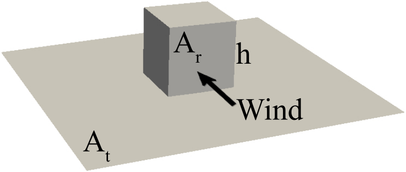
Figure 7: LES of the fetch as reported by the wind tunnel setup: three-dimensional view of the wind tunnel.

LES of the wind tunnel

- Theoretical estimation of the roughness length [3]:

$$z_0 = 0.5h\frac{A_r}{A_t}, \tag{8}$$

where z_0 is the roughness length [2], A_r is the area of the element normal to the wind direction and A_t is the ground area per roughness element.



Roughness check

✓ A good agreement between the estimated z_0 of the fetch and that of the reference terrain category is achieved.

LES of the wind tunnel

- The numerical analysis and the sub-grid model adopted are the same as previously described;
- boundaries are compliant with wind tunnel condition (all walls but inlet and outlet patches);
- velocity profiles are sampled in a plane located where the model will be placed afterwards.

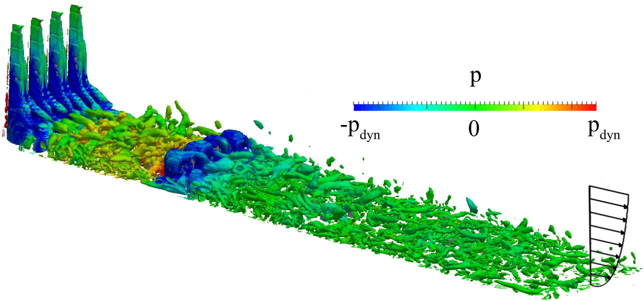


Figure 8: LES: iso-contour of Q coloured by pressure.

Profiles comparison

- The estimated along wind turbulence length is equal to $L_{uu}/H_0 = 4.38$;
- the **synthetic fluctuation field has been generated by means of the MDSRFG method** using as an input the length so estimated together with the target spectra;
- **the upstream arrangements of obstacles has been removed**, exception made for the first three rows, and fluctuations are introduced in the computational domain;
- a comparison between the LES of the wind tunnel, the LES with the synthetic inlet and the experimental measurements in terms of turbulence characteristics has been performed.

Profiles comparison

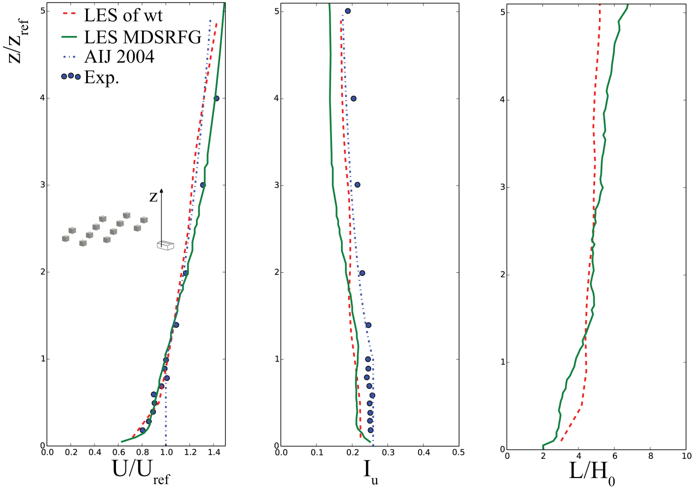


Figure 9: Wind velocity profiles measured in the wind tunnel: average (a), turbulence intensity (b) and turbulence length (c) profiles.

Inflow validation

Inflow characteristics check

- ✓ A **good agreement between experimental measurements and data obtained from LES** with synthetic inlet is observed.
- ✓ **The lower part of the ABL is of major interest for the low-rise buildings and it results to be well represented** by simulations. The three rows of blocks explicitly taken into account in LES are important to accurately reproduce this region, since in the roughness sub-layer velocity profiles are **deeply affected by the geometry of the roughness elements**.

Spectra comparison

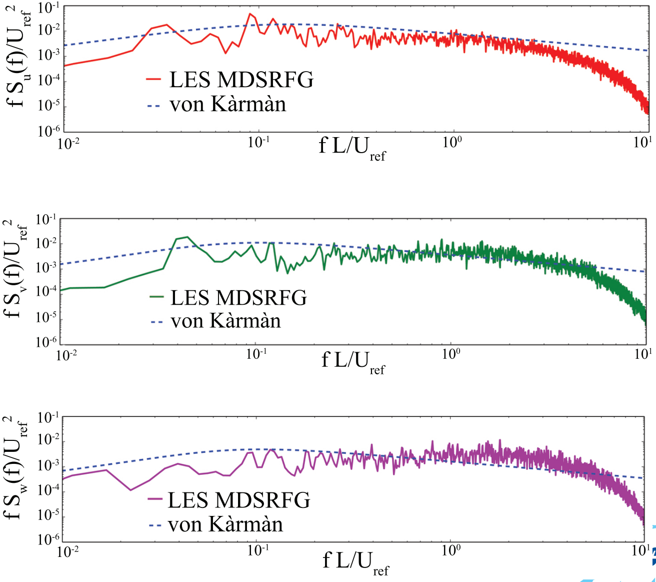
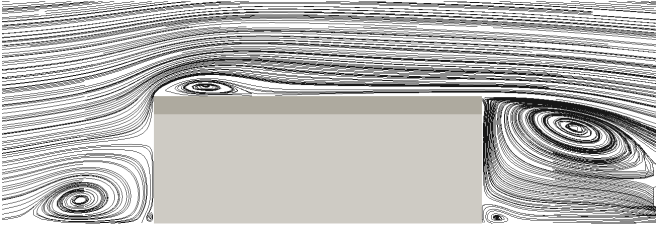
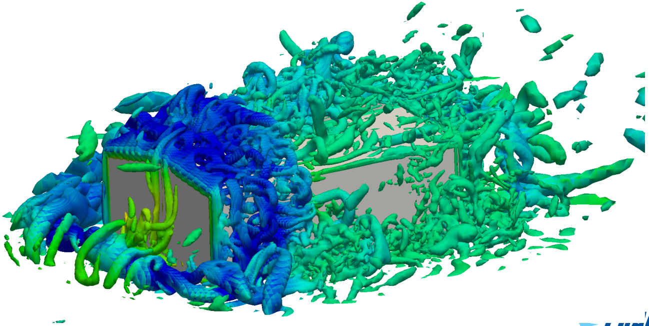


Figure 10: Spectra of the velocity time series obtained from LES

Overview of OpenFOAM

Flow topology





Pressure distributions

The statistics of the pressure coefficient C_p are plotted along three different curvilinear abscissae as showed by Fig. 11.

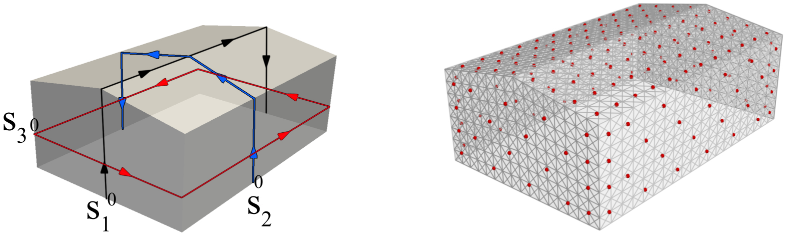
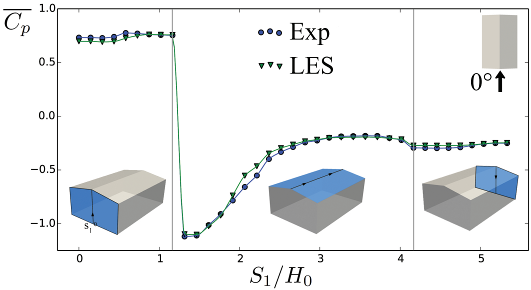
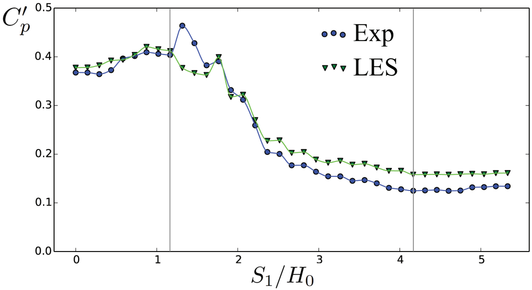


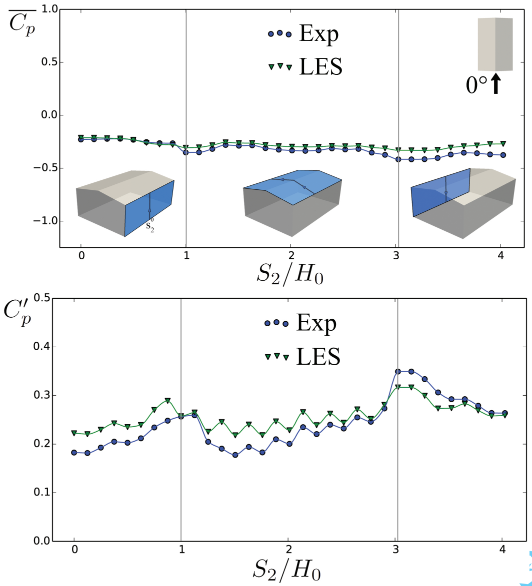
Figure 11: View of curvilinear abscissae adopted for plotting the pressure coefficient statistics (a) and position of pressure probes according to the experimental setup (b).

0°: C_p statistics along S_1

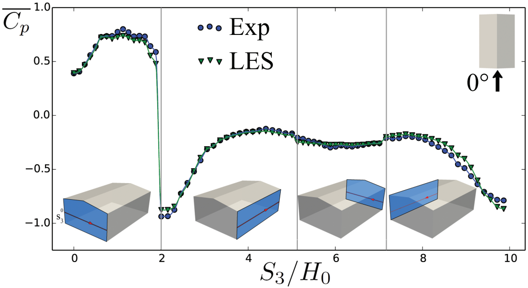


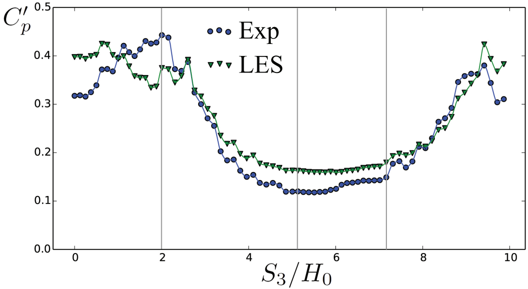


0°: C_p statistics along S_2

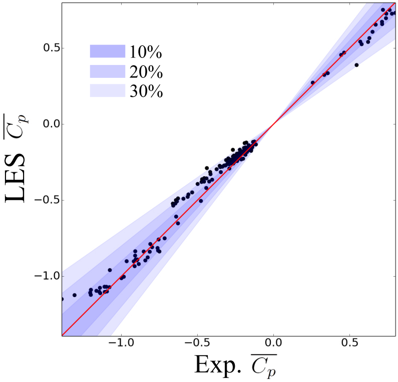


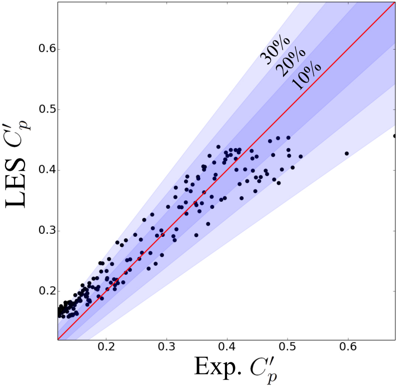
0°: C_p statistics along S_3





0°: Overall C_p statistics





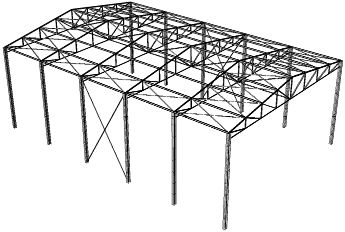
Tolerance	Average	Standard Deviation
10%	56%	36%
20%	89%	68%
30%	98%	90%

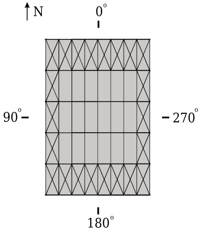
Table 2: Percentage of points in each tolerance range.

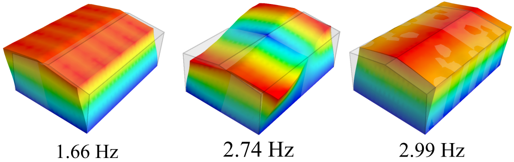
Overview of OpenFOAM

Assessment of wind loads

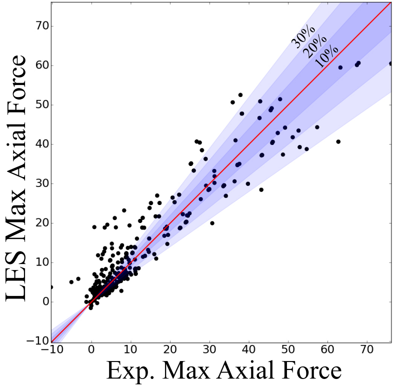
Starting from both simulated and experimental pressure fields, a structural analysis has been performed.

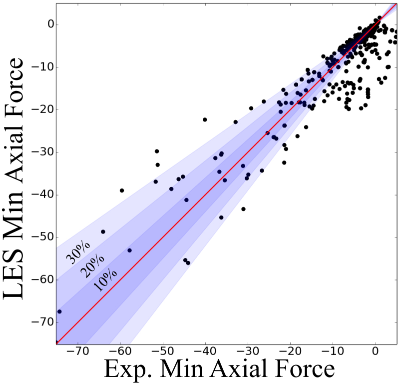






Effects envelops





Summary

- ✓ A LES of the empty wind tunnel has been performed in order to obtain the parameters to use as an input for the synthetic inflow generator method.
- ✓ A **good agreement between experimental measurements and data obtained from LES with synthetic inlet** is observed.
- ✓ The simulated turbulent ABL is used for LES of the flow field around a low-rise building at 0° angle of attack.
- ✓ Results in terms of **pressure coefficient statistics show to be in good agreement with experimental outcomes**.
- ✓ Aiming at studying wind loading effects on the structure, starting from both simulated and experimental pressure fields, a **structural analysis has been performed**.
- ✓ A satisfactory agreement between numerical and experimental assessment of internal actions can be considered achieved.

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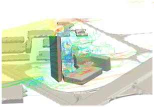

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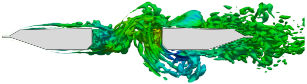

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