Flow around the cube

Eurocode

Eurocode is the source for wind load regulations in Europe.

Wind tunnel measurements

The measurement setup is described in Wind Load Simulation using CFD and BENCHMARK FOR SELF-ACCREDITATION

Simulations

We have used OpenFOAM for simulating the flow. Since wind speeds are much lower than the speed of sound we have chosen an incompressible simulation.

After several simulations with different meshes and turbulence models we chose a fairly coarse mesh with 1466764 cells modelling the full setup. This mesh captures the dynamics while still computationally feasible. The meshing was done with snappyHexMesh

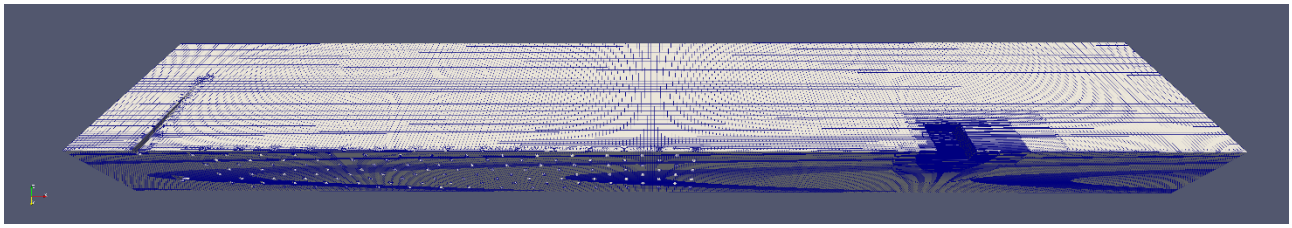

Figure 1 Computational mesh modelling the full flow area of the wind tunnel. Half the mesh is seen from below

For the turbulence model, we have chosen k-ω SST IDDES a modern industry standard turbulence model that handles a broad range of flows. It is a type of turbulence model that switches between different sub models. Away from walls a large eddy simulation is used with a k-ε in free flow and k-ω nearer to the wall. Close to the wall a RANS model is used which also has different sub models for the boundary layer.

The mean value of the simulation is very close to the measurements in the all the simulations we have made. The errors are in the peak values.

There are different sources for the peak error and we investigate some of them

- Compressibility: Since the model is scaled down in the wind tunnel a scaling effect is expected. We have made a compressible simulation on the same mesh. The biggest pressure gradients are at the corners and edges and we investigate if compressibility has an effect.
- Mesh resolution: We made a mesh that is refined at the edges with 1634392 cells. The location where the difference between measurement and simulation is greatest is near the corners and edges.
- Wall effects: We use a different variant of the same turbulence model k-ω SST DES which is an older version with a different modelling of the boundary layer and LES switching. It has a slightly different behaviour of the small eddies near the wall which gives rise to different eddy development in the two models

Wind profile

The roughness section of the wind tunnel is designed to a terrain category II turbulence.

In Figure 2 the simulated wind profile is fitted to an Atmospheric Boundary Layer (ABL). The wind profile matches the ABL to just over 0.1 m which correspond to the height of the cube.

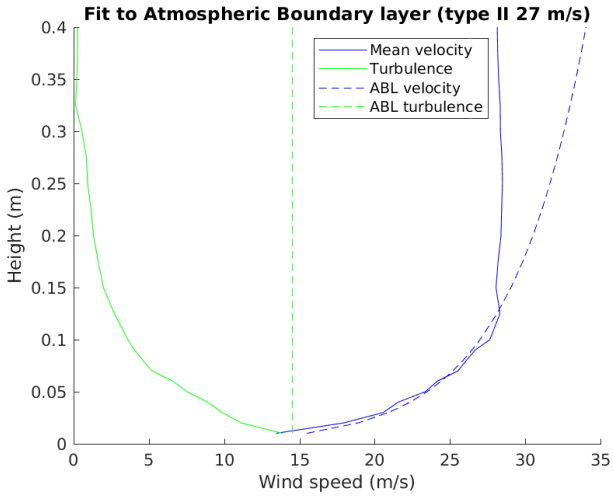

Figure 2 Fit to Atmospheric boundary layer. Terrain category 2 mean wind speed 27 m/s

Stream lines in wind tunnel

Before putting the model into the wind tunnel a mixture of oil and paint in applied to the model. The paint will follow the flow and visualize the mean stream lines.

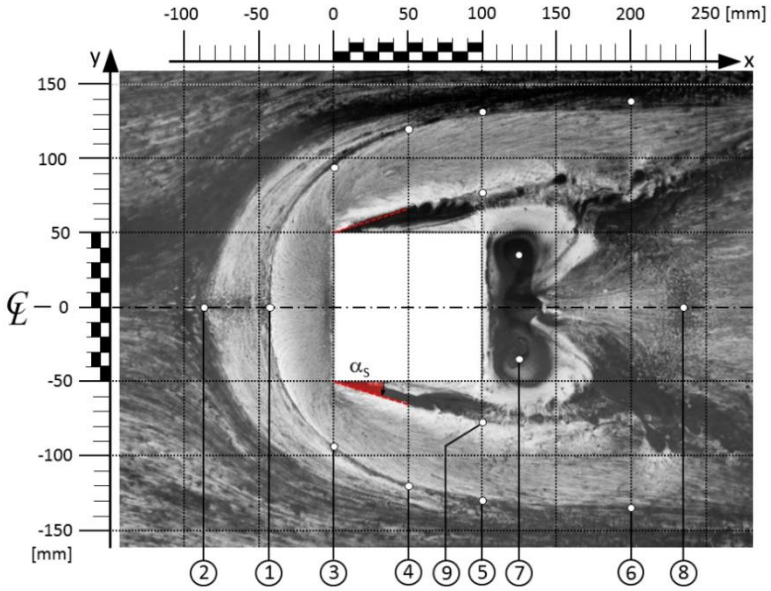

Figure 3 Flow around cube in wind tunnel

Table 1 Streamline markers

marker	Description of marker	Position	
		x/h	y/h
①	Depth of primary horseshoe vortex (HV1) at CL	-0.43	0
②	Outer border of secondary horseshoe vortex (HV2) at CL	-0.87	0
③	Lateral position of HV1 border line at cube front	0	±0.93

④	Lateral position of HV1 border line at mid cube depth	0.50	±1.20
⑤	Lateral position of HV1 border line at cube rear	1.00	±1.30
⑥	Lateral position of HV1 border line at two cube distances from front	2.00	±1.35
⑦	Center of vertical recirculation vortex in wake zone	1.25	±0.35
⑧	Floor stagnation point (SP3) in wake zone behind cube	2.36	0
α_S	Separation angle of side shear flows to cube sides	17°	

Stream lines in simulation

Since the deposition is a cumulative effect it is challenging to capture the exact values from mean values.

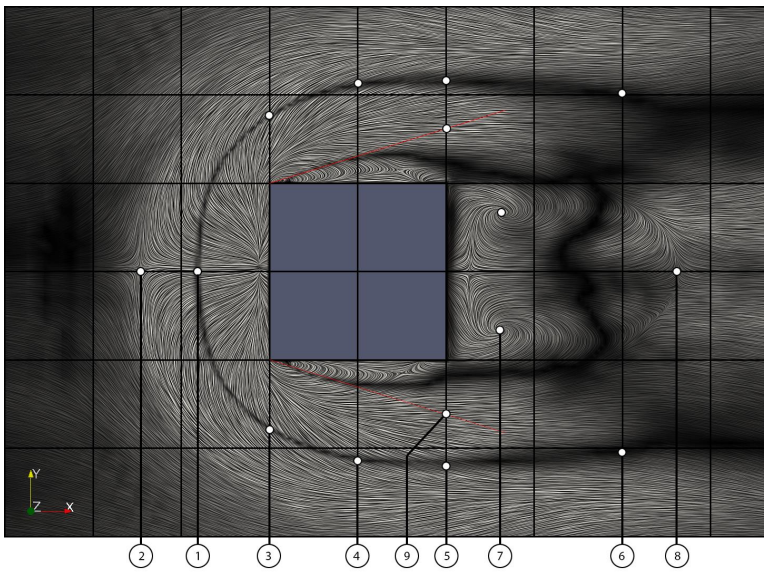

Figure 4 Flow around the cube in simulation

The visualization in Figure 4 is composed of two elements.

The fine lines are stream lines of the velocity projected to a plane a small distance from the surface.

The bigger dark features are where the normal component of the velocity is low $|U_z| < \varepsilon$. It is an estimate of the actual effect giving the main horseshoe feature: when two vortices meet head on they will bring paint to the meeting point, but these vortices are unstable and the effect is only partly captured in mean field. In mean field, the flow coming in is pressed over the cube and give $U_z > 0$ and the backflow give rise to $U_z < 0$ some distance to the surface, so where they meet $|U_z| = 0$. This approximation works well at marker 1 but it quite off at marker 4-6.

Comparing simulation and wind tunnel

Comparing the flow around the cube in wind tunnel and simulation, it is found that all the same same features are present (marker 1-9).

Marker 2 is a little too close to the cube, but I am not sure it is actually located at the saddle point in Figure 3.

The wake is getting narrow downstream in the simulation which might be because the method for detection the main features are not reliable in that range (marker 4-6).

Wind load

The wind load is the pressure difference between p on the structure and a refence free stream pressure p_0. To make results more reusable they are usually given as pressure coefficients c given as the relation to a reference pressure in free stream at the height of the building.

$$c = \frac{p - p_0}{p_b}$$
$$p_b = \frac{1}{2}\rho U_{ref}^2$$
$$U_{ref} = \bar{U}(h = h_{building})$$

We have measured and simulated the pressure at 133 different locations in the front, top and back on the cube, as illustrated in Figure 5.

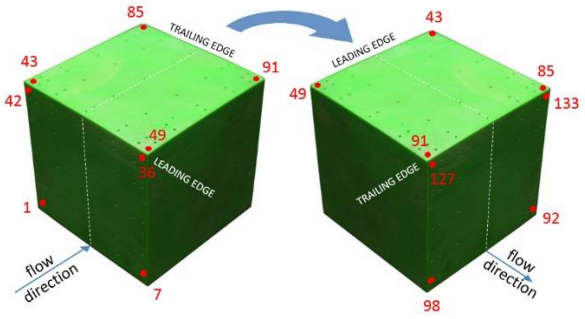

Figure 5 Positions of pressure taps

Mean pressure

The mean pressure coefficient is given as $c_m = \frac{\bar{p}}{p_b}$. In Figure 6 the mean pressure coefficient for simulation and wind tunnel measurement is shown on the front, top and back.

The Mean pressure coefficient in the simulation is very close to the wind tunnel measurement. In all the simulations we made the mean pressure is close to the wind tunnel measurements whereas the peak pressures differs much more.

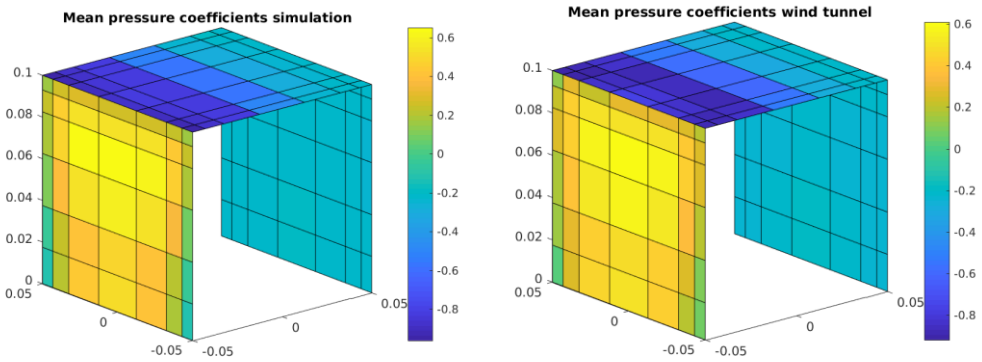

Figure 6 Mean pressure coefficients in simulation and wind tunnel

Peak pressure

The peak pressure values are given as the 78% quantile of the maxima over 10 minutes. The 10-minute maxima are distributed as the Gumbel distribution $f_g(x) = \frac{1}{\sigma} e^{-(z-e^{-z})}, z = \frac{x-\mu}{\sigma}$.

For getting a 5% confidence for the 78% quantile around 30 periods are needed, which is very long to simulate. Instead we convert the criteria to peak over threshold which is the maximum peak values of peaks distanced by more than the correlation length and it is distributed as the exponential distribution

$$f_e(x) = \frac{1}{\lambda} e^{\frac{-x}{\lambda}}$$

With the cumulative distribution function

$$F_e(x) = \int_0^x \frac{1}{\lambda} e^{\frac{-t}{\lambda}} dt = 1 - e^{\frac{-x}{\lambda}}$$

and inverse cumulative distribution function

$$F_e^{-1}(p) = -\lambda \ln(1-p)$$

If there are n_0 peaks in over a threshold x_0 in a 10-minute interval $t_0 = 600s$, then the 78% quantile $x_{78\%}$ is given as the smallest value where the probability is 78% for all n_0 values being smaller or the value where with the probability

$$p = 1 - \frac{1 - 0.78}{n_0}$$

and is found from

$$x_{78\%} = F_e^{-1}\left(1 - \frac{0.22}{n_0}\right)$$

This scales with simulation length t_s having n_s peaks over threshold in during the simulation as

$$x_{78\%} = F_e^{-1}\left(1 - \frac{0.22 t_s}{n_s t_0}\right)$$

The measured and simulated peak and mean values are compared in Figure 7.

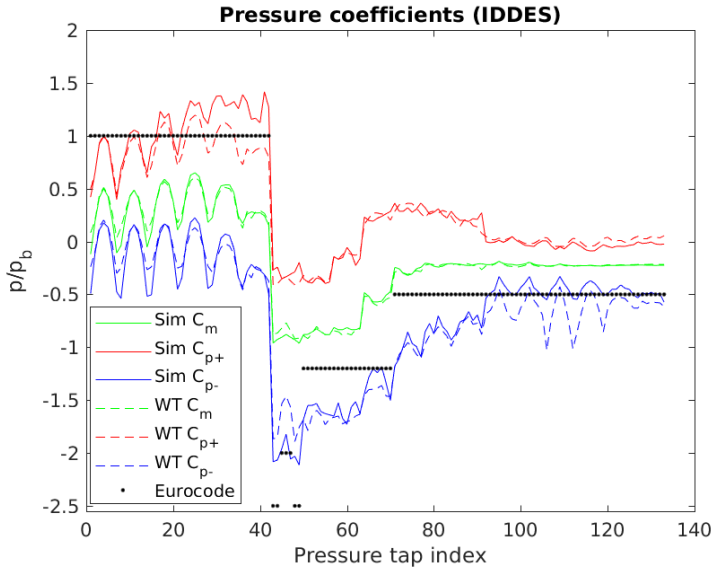

Figure 7 Comparison of measured (WT) and simulated (Sim) wind pressure. C_m is mean pressure coefficient, C_{p+} is max peak pressure coefficient and C_{p-} is min peak pressure coefficient, Eurocode is the values calculated from Eurocode.

Eurocode

Eurocode is the European standard for buildings which includes wind load. The wind load on standard shapes is defined in zones with either min or max pressure (max on the surface facing the wind and min on the remaining surfaces) In Figure 8 the wind load in the zones from Eurocode on front, top, and back are shown. The values in Eurocode are consensus values from experience.

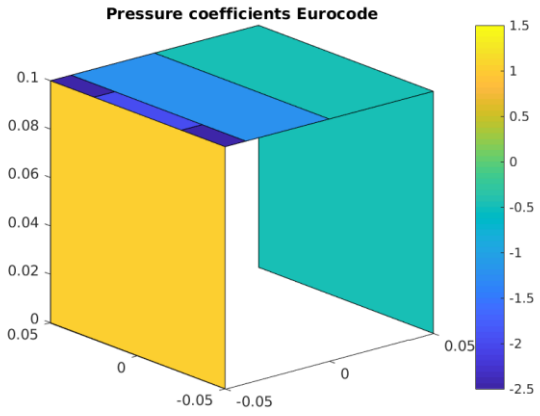

Figure 8 Pressure coefficients from Eurocode

With the corresponding min and max from Figure 7 the resulting wind load for the simulation shown in Figure 9

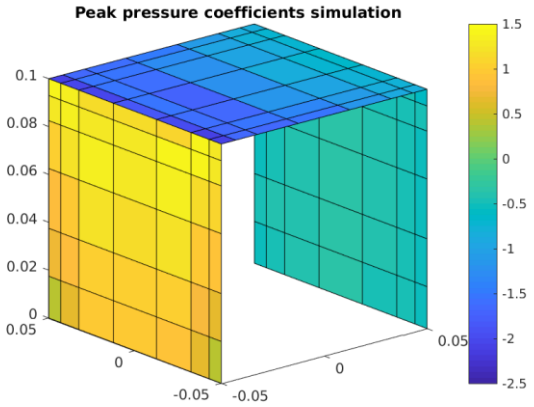

Figure 9 Pressure coefficients from simulation

and wind tunnel is shown in Figure 10

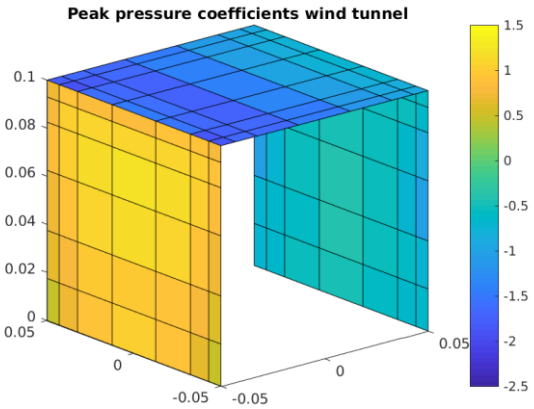

Figure 10 Pressure coefficients from wind tunnel

Error analysis

Simple comparison with wind tunnel

Plotting the maximum difference of the peak pressure coefficients (Figure 11) shows where the simulation differs from the measurements. The locations where errors are biggest are on the top leading edge where the pressure gradients are highest and the flow changes.

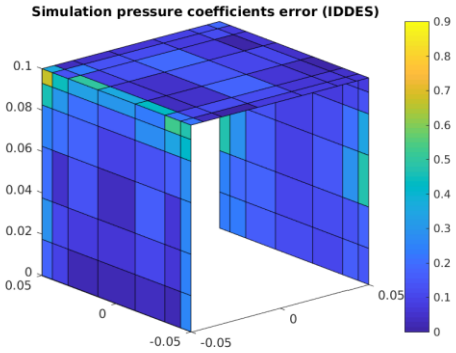

Figure 11 Peak pressure coefficient difference between measurement and simulation.

Fitting error

We have used Matlab to fit the extreme values. The function expfit is used for fitting to the exponential distribution and explike and expinv is used for estimating the 95% confidence interval.

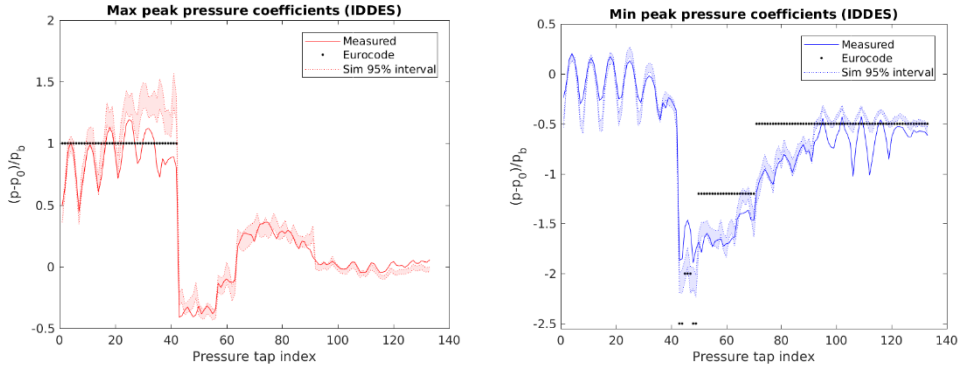

Figure 12 Confidence intervals for max peak pressure coefficients

In Figure 12 the confidence interval for max and min peaks are shown. The difference between simulation and measurement is close to the 95% confidence interval in most areas. The areas where the difference is greater are the same that has a large difference in the direct comparison (Figure 11).

Compare to Eurocode

The pressure coefficients are related to the refence free stream pressure p_0. The simulation data are fitted to have the same p_0 as the wind tunnel. The Eurocode values has been determined from experience by a range of people so a p_0 is not defined in the same way.

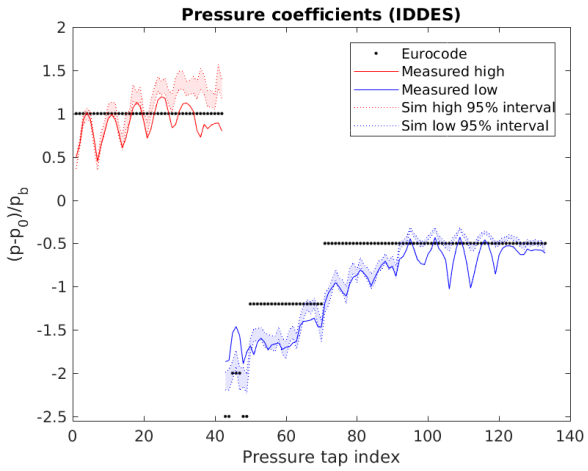

Figure 13 Comparison of pressure coefficients at the pressure taps

In Figure 13 the pressure coefficients are compared for Eurocode, simulation and wind tunnel.

The low pressures in the corners of the leading edge are more significant in the simulation than in the wind tunnel. The difference in pressure coefficient at the corner between tap 42 and 43 is close to Eurocode whereas the wind tunnel 30% smaller.

Compare to compressible simulation

An error source in the wind tunnel is scaling effects where compressibility gets too high. So, we have made a compressible simulation on the same mesh.

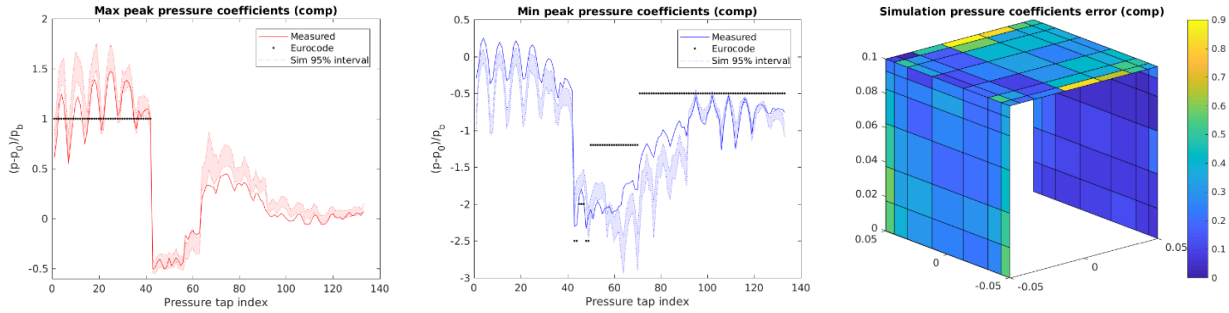

Figure 14 Comparison of compressible simulation to Eurocode and wind tunnel

It is seen in Figure 14 that the compressible simulation generally has larger errors than the incompressible simulation. A compressible simulation solves more equations in additional sub iterations and is less stable than an incompressible simulation so a greater error is expected overall due to numerical errors.

On the top leading edge (tap 36-49) where there was a significant difference in the incompressible simulation. There is a better agreement between the wind tunnel and the compressible simulation on. So, compressibility can explain the difference at the top leading edge between wind tunnel and Eurocode.

Compare to refined mesh

We have refined the mesh for the incompressible simulation at the edges to get a better resolution where there is a peak in wind speed and pressure gradient.

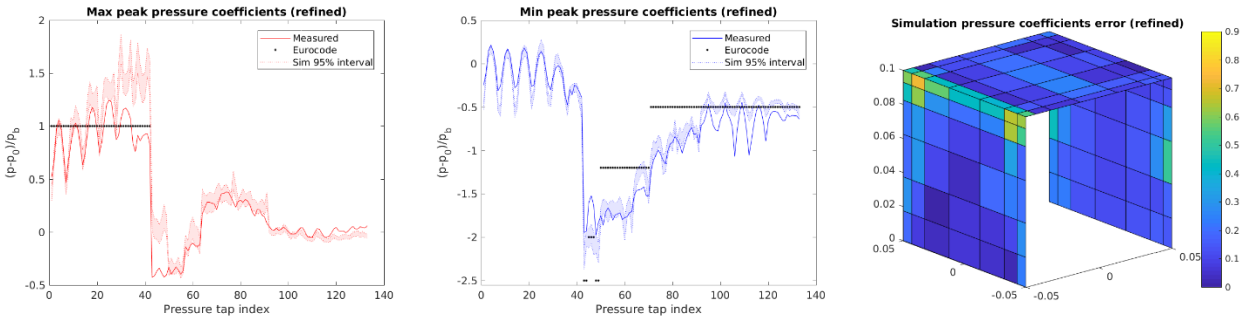

Figure 15 Comparison of refined mesh to Eurocode and wind tunnel

In Figure 15 it is seen that the difference at the top leading edge is getting more significant with refining the mesh. Simulations are dependent on the mesh and finer meshes does normally give more correct results. So, given that we haven't generated a bad mesh these results support that the incompressible simulation is more correct than the wind tunnel in this region because of a compressible scaling effect.

Compare to alternative wall turbulence model

To estimate effect of selection of turbulence model we have run a simulation that has a slightly greater damping of eddies.

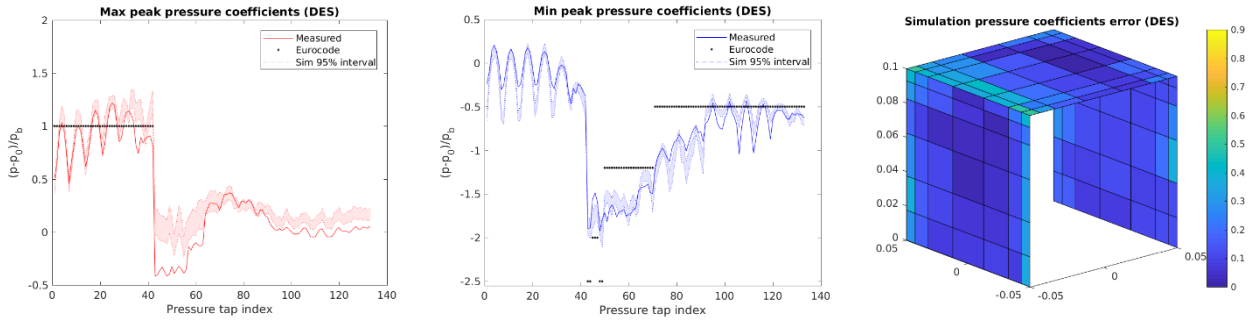

Figure 16 Comparison of alternative turbulence mode DES to Eurocode and wind tunnel

In Figure 16 shows that the extra damping has the biggest effect on the top leading edge. This adds the findings that the top leading edge is most difficult zone to simulate so extra attention should be made to these kinds of zones.

Error size

The differences between pressure coefficient c_p wind tunnel measurements and incompressible simulation with k-ω SST IDDES turbulence model with refined mesh are close to the 95% confidence interval in most areas.

In the areas, away from the leading edge and a smaller area on the back we find that the error in the peak pressure coefficients are of the order 0.2 for the incompressible simulation.

In the areas with greater difference between incompressible simulation and measurements in wind tunnel such as at the top leading edge, the difference between incompressible simulation and measurements in wind tunnel is generally smaller. So, it is most likely because of a compressible scaling effect. This would make CFD more valid for wind load estimation than wind tunnel in this kind of region.

Convergence

For wind load analysis in practice the correct values are not known so the error must be estimated. We will use different methods for estimating the error and compare them until a satisfying precision is achieved.

- Meshing
    - Refinement level
    - Meshing algorithm/software
- Turbulence model
- Solvers

The primary method will usually be to gradually refine the mesh after each simulated period and see is the result converges to a value. The advantage of this method is that integrates well into a design process, where you will start to address the bigger problems in the beginning.

Correlation analysis

We have done correlation analysis on the incompressible k-ω SST IDDES simulation. The correlation analysis for the other simulations are similar and are not included here.

There are different zones where the pressures have similar behavior. These zones can be identified from a correlation analysis.

We have chosen look at strictly spatial correlation. A more detailed correlation analysis can be made by including a time shift (in the order of distance/velocity) in the signals but will give a 3D correlation matrix that is difficult to visualize.

The correlation $\rho_{i,j}$ between the time dependent pressure at two pressure taps i and j is given by

$$\rho_{i,j} = \frac{\int_0^{t_s}(p_i(t)-\mu_i)(p_j(t)-\mu_j)dt}{t_s\sigma_i\sigma_j}, \mu_i = \frac{1}{t_s}\int_0^{t_s} p_i(t)dt\,, \sigma_i = \sqrt{\frac{1}{t_s}\int_0^{t_s}(p_i(t)-\mu_i)^2 dt}$$

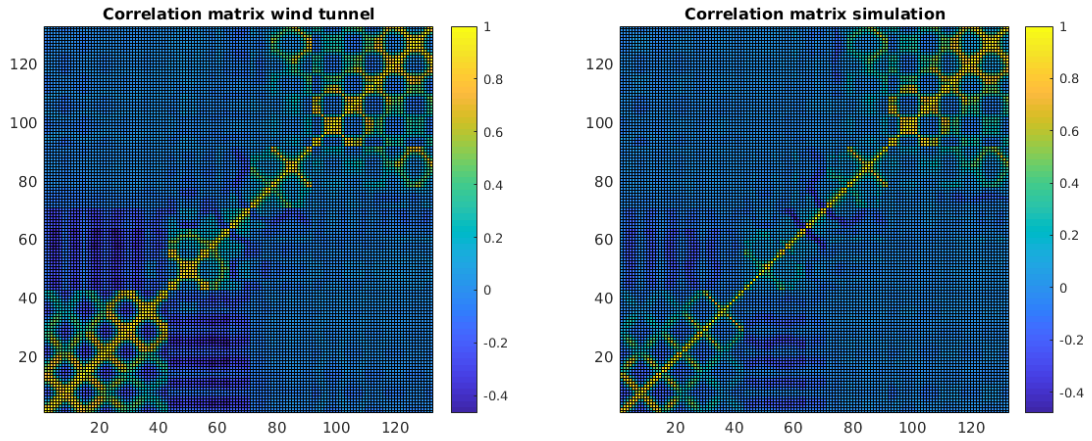

Figure 17 Correlation matrix for measurements and simulation. The yellow and green areas indicate a positive correlation and the blue areas indicate a negative correlation

The yellow and green colors in the correlation matrix visualization in Figure 17 indicates positive correlation and the blue colors indicate negative correlation. The matrix shows 4 major zones:

- The front (1-42): A correlated area (crosshatch pattern)
- Front of top (43-70): A smaller correlated area, that has negative correlation with the front (blue bands)
- Back of top (71-91): After reattachment of the flow there is a correlated area uncorrelated to the front of the top
- The Back (92-133): In the back is a correlated area with shorter correlation length (larger blue holes in the crosshatch)

The zones are the same in measurement and simulation, there are generally weaker correlations in the simulation. This is probably because the mesh is getting coarser away from the surface and the eddies will deteriorate quicker in the coarse mesh.

Conclusion

Compressible effects are important for making simulations of the peak pressures in a wind tunnel particular at corners with large pressure gradients. So, for simulating wind tunnels compressible simulations should be used.

Wind tunnel measurements are approximation of real world buildings and the compressible effect are error sources that underestimates the actual loads on buildings. A further study will be done to give a better estimate of the error.

Eurocode has pressure coefficients that are in better agreement with the incompressible simulation, which indicates that the compressible effects are not significant for real building.

Incompressible simulations are numerically better behaved than compressible simulations and incompressible simulation gives a safer overestimate of peak pressures. So, incompressible simulations should be used for simulation wind loads on buildings.

The turbulence model is important for estimating the peak pressures and k-ω SST IDDES is an industry standard turbulence model that gives good predictions.