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Comparison of full-scale and LES-predicted peak pressures on the Space Needle

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SUMMARY:
The estimation of peak wind pressures on tall buildings is of fundamental importance for cladding design. We aim to compare full-scale pressure measurements with reduced-scale experimental and computational model results to assess uncertainty in the model estimates. This abstract presents an initial comparison of full-scale measurements on the Space Needle in Seattle to results from 1:200 scale large-eddy simulations of the building. A sensor was selected that can make meaningful C_p measurements at windspeeds as low as 10 m/s and a custom sensing mote was designed for long-term deployment on tall buildings. The results from an initial deployment of 4 motes mounted on the building's sloped roof show some similarities in C_p statistics, but the LES results generally reveal more turbulence in the pressure signal, with higher $C_{p,rms}$ values and more negative $C'_{p,min}$ values.

Keywords: peak pressures, full-scale measurements, large-eddy simulations

1. INTRODUCTION

The cost of damage to buildings and infrastructure due to global extreme weather is estimated to be \$150 billion annually (Bienert, 2014), with a significant portion due to wind events (Walker, 2003). Improving our understanding and modeling of wind loads on buildings will enable resilient design to alleviate damage.

Currently, cladding loads are estimated using data derived from reduced-scale wind tunnel testing. Two limitations of this method are potential scaling effects due to Reynolds number disparity and the limited spatial resolution of results. Regarding the former, previous studies have compared wind loads measured at full- and model-scale on low-rise structures and consistently found peak pressures to be underestimated at the wind tunnel scale (Morrison et al., 2013; Richardson et al., 1997; Tieleman et al., 1996) - an alarming finding.

On larger high-rise buildings there is a lack of data comparing full- and model-scale loads. One experiment in the 1970s involved taking full scale measurements at 32 locations on a 57-floor Toronto skyscraper (Dalgliesh et al., 1980). Although this data shows some agreement between full- and model-scale measurements for both mean and peak pressures, it is limited because the use of differential sensors meant changes in the building's internal pressure made measurements more uncertain. Additionally, sampling at 2 Hz meant they were not able to detect peaks due to smaller scale turbulence.

The use of computational fluid dynamics (CFD) may offer a solution to these limitations: the resolution is limited only by the computational grid, and the simulations can be performed at full-scale to obviate disparities due to scaling. Despite these potential benefits, CFD is currently not a widely accepted approach for calculating wind loads.

We aim to compare full-scale pressure measurements with reduced-scale experimental and computational model results to assess uncertainty in the model estimates and compare the predictive capability of experimental and computational tools. Our intent is for the results to advance the capabilities of CFD for predicting wind loading on tall buildings, a step toward unlocking a potentially valuable tool for design engineers.

The first building chosen for this comparison is the Space Needle in Seattle, WA. This building was selected because it is a tall building with a dominant wind direction for which there are only low-rise buildings upstream, minimizing difficulties modeling interference effects from surrounding buildings.

2. METHODS
2.1. Full-Scale Measurements
Unlike in Dalgliesh et al., 1980, we used absolute pressure sensors to preclude uncertainties associated with fluctuating internal building pressure (this is however replaced with an uncertainty due to the more slowly changing barometric reference measurement). A series of wind tunnel tests were performed to identify an absolute sensor capable of reliably measuring C_p on a building at relatively low windspeeds ($U > 10$ m/s), and then a custom environmental sensing 'mote' was designed to house, power, and log data from sensors.

The data presented here is from a preliminary deployment of motes on the Space Needle between May and June 2022. In December 2022, 21 motes were installed on the building's roof. The positions of the motes of both deployments are shown in Figure 1, and an image of one of the sensors is shown in Figure 2.
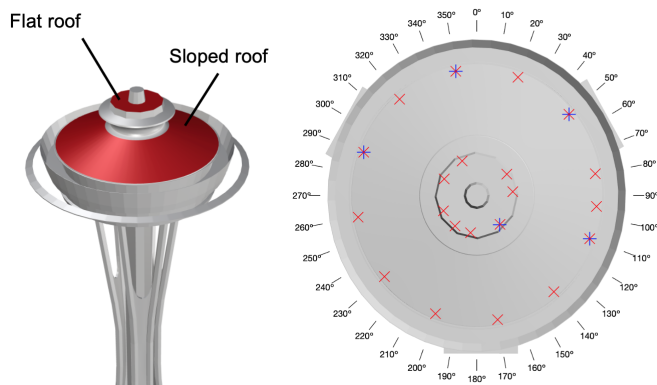
Figure 1. Positions of motes on the Space Needle flat and sloped roofs. Blue markers indicate positions for the initial deployment, red markers indicate positions for the ongoing deployment.
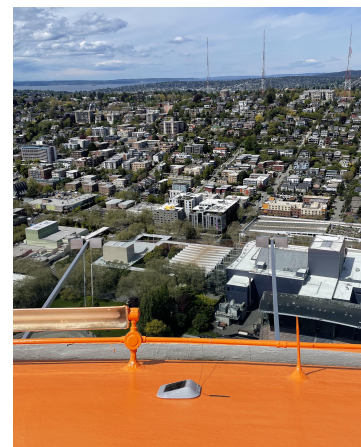
Figure 2. Mote mounted on the sloped roof of the Space Needle.

The reference windspeed with which to calculate C_p was measured by an anemometer mounted at the top of the building. Because the flow measured at this point is affected by the building geometry, the LES results were used to determine a scale factor and angle offset that relates the anemometer position wind characteristics to freestream at the same height. The scale factor was measured to be $U_{anem}/U_{freestream} = 1.43$ and the angle offset $\Delta\theta = 3.2°$. The full-scale reference wind speed measurements were corrected accordingly.

Because it is challenging to obtain a reliable and precise barometric pressure measurement, P_{ref}, we focus our analysis on the turbulence content in the pressure measurements. Hence, we calculate and present C'_p statistics instead of the usual C_p statistics, with C'_p given by: Eq. 1.

$$C'_p(t) = \frac{P(t) - \overline{P}}{\frac{1}{2}\rho U^2} \tag{1}$$

where $\overline{P}$ is the 10 minute moving mean of the fluctuating pressure $P(t)$, ρ is the density, and U is the windspeed at building height.

2.2. Large-eddy simulations
The simulations or performed with CharLES, a large-eddy simulation (LES) code developed by Cascade Technologies, Inc. (*CharLES* 2022). Initial work has focused on simulations at 1:200 model scale. At this scale, the Space Needle is 1 m tall. The domain extends 18.6 m downstream, 9.2 m upstream, 6.9 m laterally either side of the building, and is 5.5 m tall. All upstream and immediately downstream buildings are included in the domain. Results are presented for a mesh with a smallest cell size of 0.8 mm and 16.1 million control volumes.

3. RESULTS
3.1. LES Results
Figure 3 shows top-down views of the Space Needle roof with contours corresponding to $C_{p,mean}$, $C_{p,rms}$, and $C_{p,min}$.
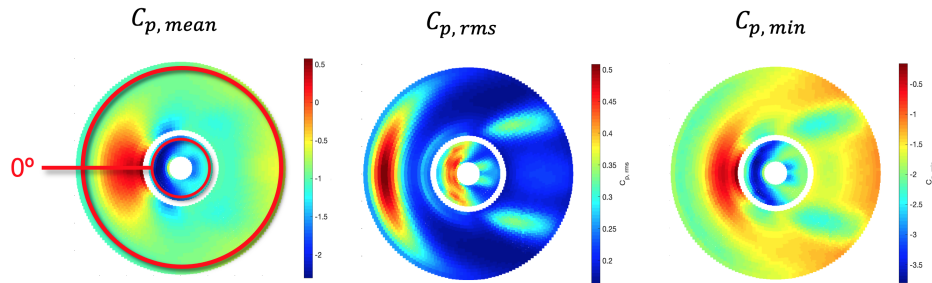

Figure 3. C_p contours on the sloped (outer ring) and flat (inner ring) roofs. The wind direction is marked by $0°$.

3.2. LES and Full-Scale Results Comparison
Figure 4 compares the LES results from a single simulation with the full-scale measurements obtained from 4 motes. Although measuring at only 4 points, we can effectively measure C'_p statistics over a large portion of the perimeter by plotting as a function of wind direction, taking advantage of the building's rotational symmetry. The simulations and measurements show some similar trends

along the perimeter of the sloped roof, but the LES results generally reveal more turbulence in the pressure signal, with higher $C_{p,rms}$ values and more negative $C'_{p,min}$ values. Ongoing analysis is investigating potential reasons for these discrepancies, including differences in the sampling rates for both data sets, differences in freestream turbulence intensities, and inaccuracies in the freestream velocity scaling factor.
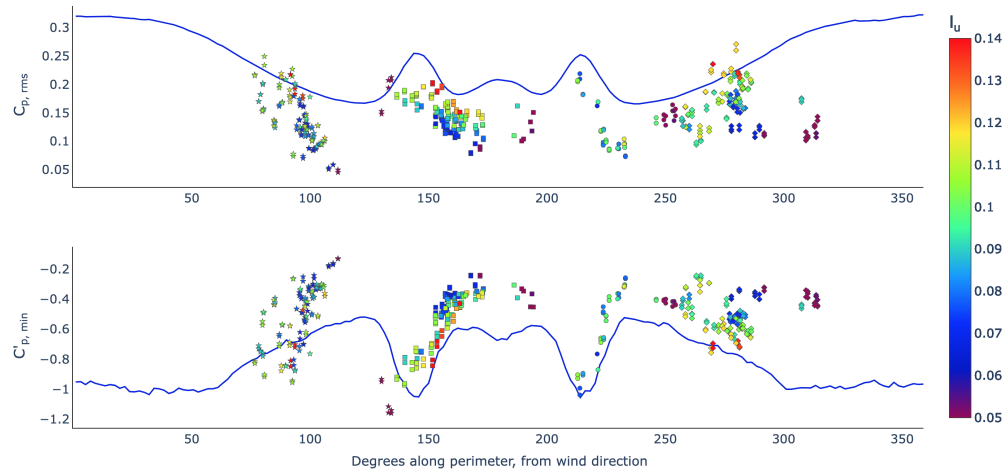
Figure 4. Comparison between full-scale and LES $C'_{p,min}$ and $C_{p,rms}$ along the perimeter of the sloped roof. Marker shape corresponds to mote and marker/line color corresponds to turbulence intensity I_u measured by the roof anemometer, or at the equivalent position in the LES.

4. CONCLUSIONS

Initial comparison of full-scale measurements and LES results shows a similar trend in $C'_{p,min}$ values along parts of the building's perimeter, but the LES appears to have consistently higher turbulence levels. In ongoing work we are gathering data from the 21 motes currently installed on the building to add more datapoints to Figure 4, and we are analyzing the data to identify the main reasons for the observed discrepancies. Future work will also focus on running the large-eddy simulation at full-scale.

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