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Application of the quasi-steady vector model to uplift on low-rise buildings with sloped roofs

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SUMMARY:
Wind tunnel tests have been done in Boundary Layer Wind Tunnel Laboratory of the University of Western Ontario (UWO) on four low-rise building models with gable and hip roofs at ae scale of 1:50, with slopes of 22.6^o (5:12) and 45^o (12:12), for 6 different upstream terrain conditions. Test results of a TTU building with flat roof by Wu and Kopp (2016, 2018) are used for comparison. Quasi-steady vector models are developed by a conditional-averaging technique. The findings indicate that the results for both the roof shape and the roof slope alter the performance of the QS vector model on uplift of the low-rise roofs in a complex way.

Keywords: building aerodynamics, quasi-steady theory, low-rise buildings

1. INTRODUCTION

The Quasi-Steady (QS) vector model is a tool used to account for fluctuating wind-induced pressures. It assumes that the instantaneous pressures on the building surface are functions of the instantaneous velocity magnitude and direction at a point near the building. It provides an alternative solution for wind-induced loads on structures to cover limitations of traditional wind tunnel tests.

The performance of the QS vector model on low-rise buildings has been studied for flat roofs. For example, Wu and Kopp (2019) review that the performance of the QS vector model is better in regions of flow separation compared to flow reattachment. Several studies suggest that it provides reasonably accurate predictions for some statistics of pressure coefficients, for example, probability density functions (e.g., Banks and Meroney, 2001), within the separation regions, although it tends to underestimate the peak pressure coefficients significantly (e.g., Richards and Hoxey, 2004; Wu and Kopp, 2016, 2018), with differences being greatest for small areas and point pressures. By combining the QS vector model with a separate statistical model for the body-generated turbulence, a partial-turbulence approach is proposed by Guo et al (2021) to estimate peak pressures on low-rise building with a roof, which also works particularly well for suction loads in regions with flow separation.

The applicability of the QS vector model on more complicated roofs, for example, gable and hip roofs, remains largely unknown. In this study, wind tunnel tests have been done for low-rise building models with gable and hip roofs with slopes of 22.6^o (5:12) and 45^o (12:12). Quasi-steady vector models are conducted for roof uplift, and the performance is checked to build an understanding of the effects of roof shape and slope.

2. METHODOLOGY

Tests were conducted in Boundary Layer Wind Tunnel Laboratory of the University of Western Ontario (UWO). Four low-rise building models with gable and hip roofs at the scale of 1:50 were selected for test in this study, with slopes of 22.6^o (5:12) and 45^o (12:12). The plan dimensions of the models are 11m and 10m (L×W) in equivalent full scale, with an eave height, h, of 6.7 m (typical height of 2-story house). Figure 1(b) shows the photographs of the experimental setup. In addition, data from the wind tunnel tests conducted by Wu and Kopp (2016) are used for analysis, which is for a 1/50 scale model of Texas Tech University (TTU) WERFL building with flat roof. Therefore, results from low-sloped (0^o), mid-sloped (22.6^o), and steep-sloped (45^o) roofs can be compared. The model has plan dimensions of 27.5cm×18.3cm and a height of 8cm in model scale.

The flat roof model is tested for six upstream terrain roughness conditions, summarized in Table 1, which are characterized by turbulence intensity and integral scale. Details of the terrains, as well as other details of the flat roof tests, can also be found in Wu and Kopp (2016, 2018). Three of the six terrains were selected for the tests of the sloped roofs, which are F0, O0, and S15, to represent realistic terrain conditions with different turbulence intensity.

Table 1. Characteristics of the mean streamwise velocity and turbulence, measured at model roof height (after Wu and Kopp, 2018)

Ground roughness level	Flat		Open		Suburban	
Upstream barrier height	N/A	15 in.	N/A	15 in.	N/A	15 in.
Label	F0	F15	O0	O15	S0	S15
Turbulence intensity, Iu (%)	13	14	17	17	26	27
Integral length scale ratio, Lux/H	6	13	8	11	7	12
Jensen number, H/zo	540	600	290	600	56	71

For both tests, pressure signals were sampled at 625 Hz for 19 nominal wind directions (0^o to 90^o in 5^o increments), with the sampling length of 180s for the sloped roofs and 200s for the flat roof. The component velocity measurements are made by Cobra probes, synchronized with the pressure measurements, to conduct analysis for QS theory. For the flat roof test, the velocity is measured at 1 building height (1H) above the mid-point of the leading edge. When the wind is perpendicular to the wall, the measurement location is right above the separation point. For the sloped roofs, the velocity is measured at 1 eave height (h) above the mid-point of the ridge (shown in figure 1(a)), which is at 2 times of the mean roof height (2H). This is consistent with the flat roof test as the roof height being taken as a reference dimension.

The quasi-steady coefficients, $Cp(\theta, \beta)$, is a function dependent on the instantaneous θ and β, which is obtained through the conditional-averaging technique developed by in Wu and Kopp (2018). Details of the steps of obtaining QS functions can be found in Guo et al. (2021). The effects of both wind azimuth and elevation angles are included. The QS-predicted pressure coefficients, Cp_{QS}, can then be calculated as:

$$Cp_{QS} = \frac{V(t)^2 Cp(\theta, \beta)}{\bar{u}^2} \tag{1}$$

Where $V(t)$, θ and β denotes the magnitude, azimuth, and elevation angles of the velocity vector, respectively, and $\bar{u}$ is the reference velocity.

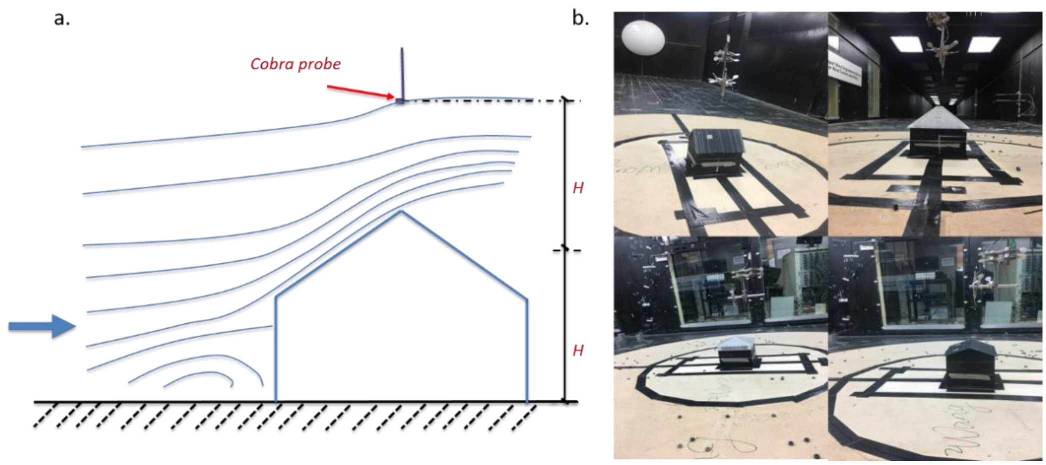

Figure 1. Schematic sketch of the mean flow field of 12:12 gable roof, and the location of the cobra probe measurement. (b) Photographs of the experimental setup

The performance of the QS vector model is evaluated by comparison between the measured (Cp_m) and the model-predicted (Cp_{QS}) pressure time series, which is achieved through 2 major aspects: i) the correlation between two signals, and ii) the level of fluctuation energy that can be accounted for by the model. Several parameters are used in the analysis and will be introduced in the next section.

3. PRELIMINARY RESULTS AND CONCLUSIONS (UP TO DATE)

Define the zero time lag correlation coefficient between Cp_m and Cp_{QS}:

$$Corr_{QS,m} = \frac{Cov(Cp_{QS}, Cp_m)}{\sigma_{Cp_{QS}} \sigma_{Cp_m}} \tag{2}$$

where $Corr_{QS,m}$ denotes the correlation coefficient, $Cov(Cp_{QS}, Cp_m)$ is the covariance between Cp_m and Cp_{QS}. σ_{Cp_m} and $\sigma_{Cp_{QS}}$ are the standard deviations, respectively. The zero time lag correlation coefficient is an overall measurement of the linear dependence between two signals. The magnitude of the function varies between 0 and 1 and should be equal to unity if the QS assumption holds perfectly. A higher magnitude of correlation implies a better correlation between Cp_m and Cp_{QS} time series, and therefore, a better performance of the QS vector model.

Figure 2 shows the $Corr_{QS,m}$ for whole-roof uplift for nominal wind directions from 0^{o} to 90^{o}, for all five roof shapes in the O0 and S15 terrain. The correlations in the S15 terrain are generally higher than the O0 terrain, indicating that the QS vector model works better for upstream conditions with higher turbulence level. Comparing the results of different roof shapes in the S15 terrain, the model works best for the flat roof, where the magnitude of the correlation coefficients varies from 0.65 to 0.8, which is the highest among five shapes, with relatively small change due to wind directions. The 5:12 hip roof is the second best, with the function ranges from 0.6~0.7, also with relatively small difference as the nominal wind direction changes. For both gable roofs, the correlations are low at 0^o and increases with the nominal azimuth increasing, with the highest values of 0.65~0.7 at 90^o. As for the 12:12 hip roof, the correlations are good at 0^o and 90^o but less good for the oblique direction (45^o).

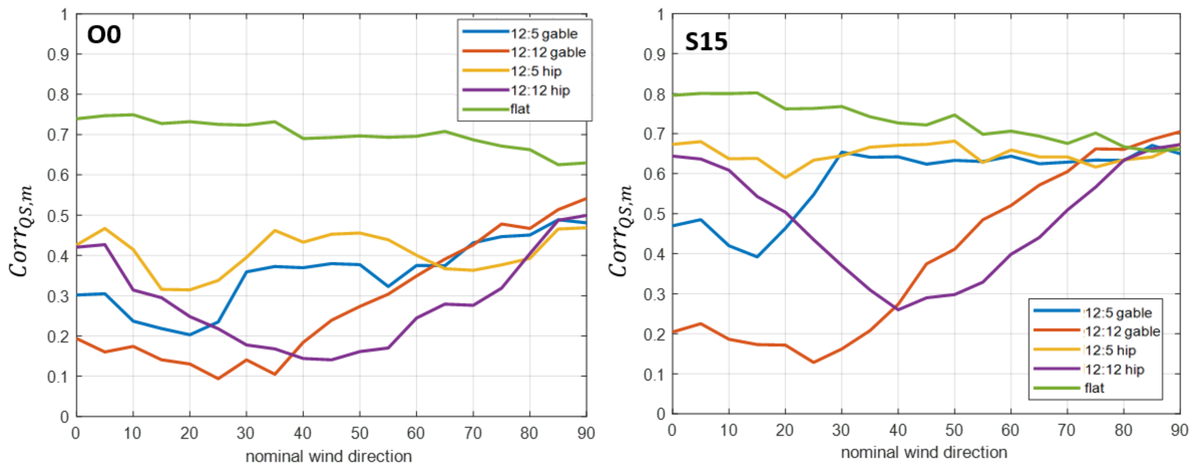

Figure 2. $Corr_{QS,m}$ of the whole-roof uplift of all five roofs for different nominal wind directions in the (a) O0 and (b) S15 terrains.

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