A Wind-Tunnel Study of a Cubic Rooftop AC Unit on a Low Building

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Abstract

A wind-tunnel test was conducted to determine gust wind loads on simple cubic rooftop equipment installed on a low building at a scale of 1:50. Pressure distributions were simultaneously measured on four sidewall and top surfaces to provide mean and peak area-averaged pressures, lateral forces, uplift and overturning moments. The largest lateral peak force coefficient measured was 2.13 based on a 3-second gust reference pressure at the roof height. This implies a gust effect factor of 1.64 if the baseline force coefficient of 1.3, as given in the current ASCE standard, is used.

Introduction

Wind loads on low buildings are recognized as a hazard that requires continuous acquisition of knowledge for effective mitigation. The current U.S. standard, ASCE 7-98, provides detailed wind design loads for structural systems as a whole, and for structural components such as roofs and walls including local cladding pressures. Wind loads on rooftop appurtenances, on the other hand, are not addressed specifically. However, a provision to provide for design loads on appurtenances such as air-conditioning units in the next edition of the standard, ASCE 7-00, is being considered by the ASCE 7 Task Committee on Wind Loads. If the proposal is accepted, the current guidelines for chimneys and tanks will be expanded to include rooftop equipment with a recommendation to adopt a higher gust effect factor (> 0.85), say 1.1 or higher. Use of a higher gust effect factor is easily justified because of the relatively small size of typical rooftop equipment that tends to result in high area-averaged peak pressures. In addition, the equipment may be located in an accelerated flow zone near a roof edge, thus warranting a higher gust effect factor. Any particular value of a gust effect factor, however, is not yet defined largely due to lack of research or wind-tunnel studies on rooftop equipment.

A wind-tunnel study was initiated in an effort to obtain realistic values of gust effect factors for simple rooftop equipment. This paper presents the results of the wind-tunnel study on a simple cubic rooftop equipment.

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Some Field Observations on Failure of Rooftop Equipment

Around Christmas time of 1997, Typhoon Paka hit the Territory of Guam. Typhoon Paka registered 140-mph sustained and 190-mph gust wind speeds, and caused $250 million of damage to the local homeowners and businesses. Tom Smith of TLSmith Consulting Inc. was one of the team members who surveyed the aftermath of the typhoon. Prior to the wind-tunnel test, the authors contacted Smith to learn typical failure mechanisms of rooftop equipment through his field observations.

On the modes of failure of rooftop equipment, Smith noted:

> *"Blow-off of equipment (fans, HVAC units, relief air hoods) from curbs or support stands is very common. I expect this is primarily related to overturning rather than uplift, although I am sure the two work together to cause the damage. On smaller pieces of equipment, fasteners (typically screws) used to attach the equipment to the curb/stand fail either due to pullout or shear off. Also, sometimes small metal straps are attached to the stand and the equipment and these sometimes fail in tension.*
>
> *On larger pieces of equipment (e.g., a few hundred to over a thousand pounds), it is common for the equipment to have no provision for uplift resistance other than the dead load of the equipment itself. In very high winds, even extremely large and heavy units can be thrown from their curbs/stands."*

On failures of exterior panels, he observed:

> *"With fans, it is common for the fan cowling to blow off, while the remainder of the fan unit remains attached to the curb… The problem is that the fastener is too weak (usually rivets are used), or in some cases, the metal through which the fastener is placed is torn.*
>
> *Sometimes access panels (doors) on the HVAC units are blown off -- these can cut the roof membrane, break glass and injure people."*

Based on these field observations, specific load effects to be evaluated by the wind-tunnel study were identified. The load effects of interest included: 1) area-averaged pressures on the exterior panels, 2) integrated lateral and uplift forces, and 3) overturning moment.

Wind-Tunnel Test

The wind–tunnel test was conducted in the Meteorological Wind Tunnel at Colorado State University (CSU), Fort Collins, Colorado. A nominal open-country boundary layer was simulated. The wind-tunnel model was designed to represent a 4x4x4 ft air conditioner unit placed flush on top of a 1:50 scale model of the Texas Tech University (TTU) field site building. Figure 1 is a photograph of the wind-tunnel model, and a drawing showing the various locations of the model rooftop equipment tested.

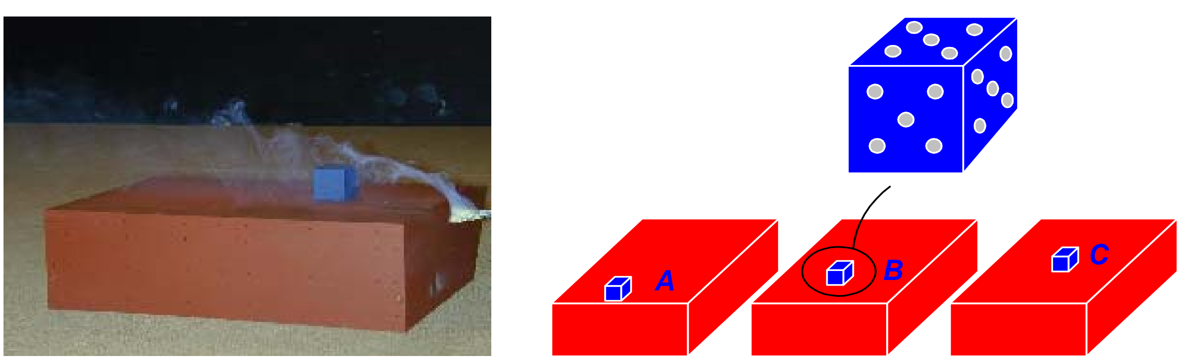

Figure 1: Wind-Tunnel Model

A total of 25 pressure taps was installed on four sidewall and top surfaces of the cubic model. Pressures at all locations were measured simultaneously at a rate of 500 samples per second for 16 seconds. The test run was repeated 8 times to obtain accurate statistical measures of the mean, RMS, and peaks by ensemble averaging. The time series of the pressure data were saved in electronic files to later calculate the above mentioned load effects of interest. The cubic model was tested at three different positions on the base building roof centerline with wind directions varying from 0 to 180 degrees at 10-degree increments.

Analysis Methods

By combining individual point pressures with appropriate weight factors, the area-averaged panel pressures, total lateral force, uplift, and overturning moment were computed. For calculation of the overturning moment, the contributions due to both lateral and vertical forces associated with the pressures, were included. Unless otherwise noted, all the results on the overturning moments presented here were evaluated at the center point of the cube bottom. These load effects were then normalized into a coefficient form using the mean dynamic pressure, Q, measured at the height of the base building as follows:

Panel Pressure Coefficient: $C_p = \dfrac{P}{Q}$ Lateral Force Coefficient: $C_F = \dfrac{F}{QDH}$

Uplift Coefficient: $C_{Fz} = \dfrac{Fz}{QD^2}$ Overturning Moment Coefficient: $C_M = \dfrac{M}{QDH^2}$

Here, P, F, Fz, and M represent the pressure, lateral force, uplift, and moment at the bottom of the rooftop model, respectively. The weight W is not included in the Fz and M coefficients. The height and width of the rooftop model were specified as H and D, and for the cubic model discussed in this paper $H = D$. The lateral force and overturning moment were computed in two orthogonal directions, designated as X and Y, as shown in Figure 2.

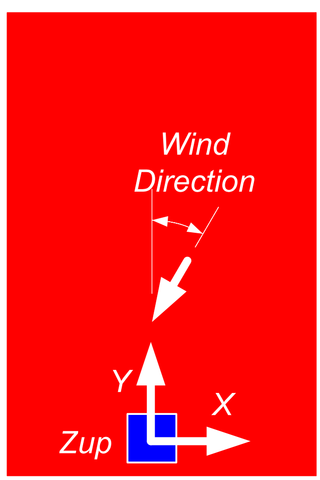

Figure 2: Definition of Coordinate System

Results and Discussion

Area-Averaged Panel Pressure

Figure 3 shows the area-averaged pressure coefficients for all 5 exposed surfaces with the cube positioned at the edge of the base building. The mean pressures are plotted with a line, and the maximum and minimum pressures are plotted with square symbols and a line. These plots are color-coded to correspond to the surface shown in the expanded view of the rooftop cube.

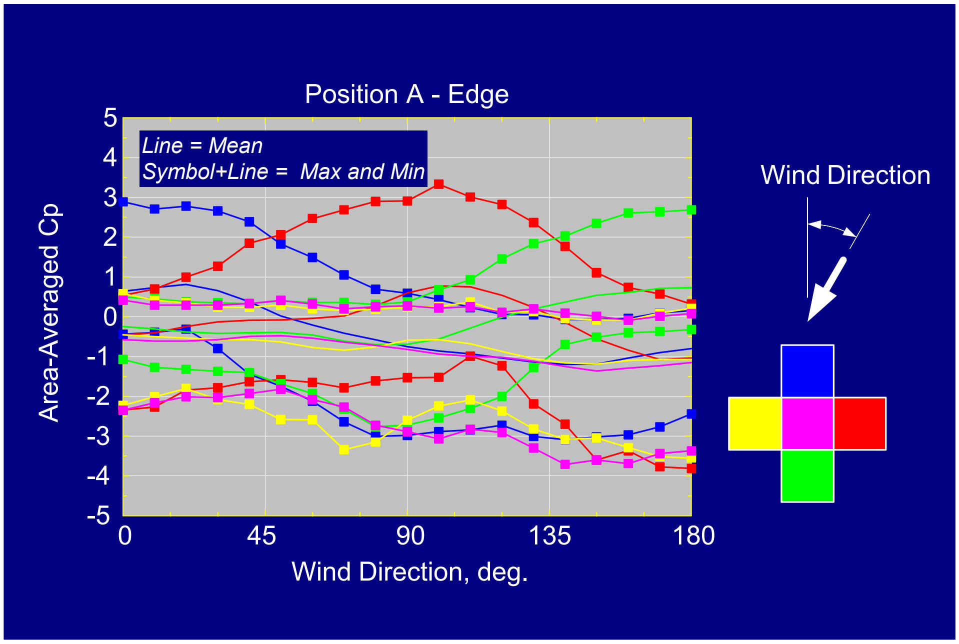

Figure 3: Area-Averaged Panel Pressure Coefficients

It can be seen that the largest positive panel pressure occurred on the red-coded sidewall surface at a wind direction of 100 degrees, where the wind approached almost perpendicular to the surface. The largest negative pressure was recorded also on the red-coded surface at a wind direction of 180 degrees, and was similar in magnitude to the largest suction on the top (purple-coded) surface.

The largest negative pressure coefficient on the sidewall surface was –3.81, or equivalently –1.65 if the 3-second gust pressure at the roof height had been used to obtain the coefficient. It is interesting to note that the gust-based coefficient of –1.65 is comparable to the design cladding uplift pressure GCp (= -1.66) in ASCE 7-98 for the roof edge of a flat building with a similar effective area (approximately 16 ft^2).

The largest positive mean pressure coefficient on the sidewall surfaces was 0.78 (on the red-coded surface at 100 degrees), similar to a wall pressure of 0.8 specified in ASCE 7-98. The peak positive sidewall surface pressure, however, was 3.3 (or 1.43 on a 3-second gust basis), nearly 50% higher than the code cladding pressure for a wall edge.

Table 1 summarizes the peak area-averaged surface pressure coefficients on the rooftop cube for the three different positions tested.

Table 1: Peak Area-Averaged Surface Pressure Coefficients

Position	Sidewall Surface		Top Surface	
	Max	Min	Max	Min
A (edge)	3.3	-3.8	0.4	-3.7
B (intermediate)	3.0	-3.4	0.3	-3.6
C (center)	2.7	-2.6	0.4	-2.6

The results indicate that the worst surface pressure occurs when the rooftop cube is placed at the edge of the roof of the base building, due probably to a locally accelerated flow. The peak pressure decreases as the cube is moved toward the center of the base building.

Lateral Force, Uplift, and Overturning Moment

Figure 4 shows the lateral force and uplift with the cubic model placed at the edge of the base building.

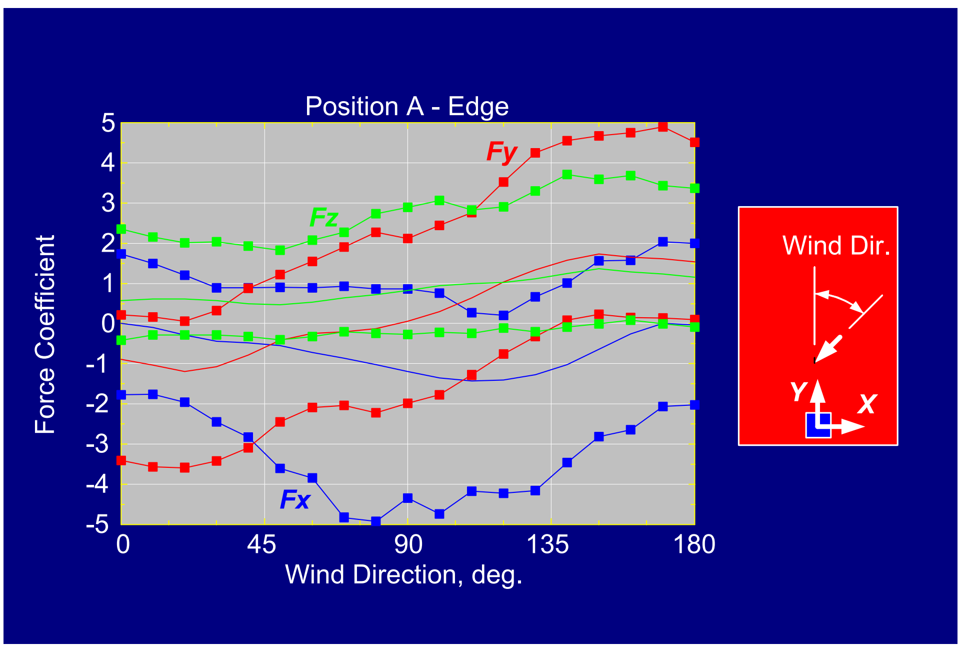

Figure 4: Lateral Force and Uplift Coefficients

The largest peak lateral force coefficient, disregarding the sign, was 4.93 in the X-direction, and 4.90 in the Y-direction. Both were observed when the wind was nearly normal to the vertical surfaces of the cubic rooftop model. These worst lateral force coefficients were considerably higher than the maximum uplift of 3.71 occurring when the wind approached diagonally with respect to the orientation of the cubic model. Note that the uplift force here is identical to the area-averaged surface pressure on the top surface of the cubic model discussed above, except for the sign convention.

On a 3-second gust reference pressure basis, the maximum lateral force and uplift coefficients can be converted as 2.13 and 1.61, respectively. Using the baseline lateral force coefficient of 1.3 as specified in ASCE 7-98, the gust effect factor for the rooftop cube results in 1.63. This is much higher than a nominal value of 0.85. This is partly because the cubic model was placed at the edge of the base building roof where the approach flow is accelerated. In addition, it is suspected that the pressure fluctuations on the opposing surfaces of the cube are highly correlated due to the relatively small size of the cube compared to the size of the base building, which dictates the flow structure around the rooftop cube. Accordingly, the results of the wind-tunnel test confirm the anticipated use of a higher gust effect factor as suggested by the ASCE 7 Task Committee on Wind Loads. Somewhat higher uplift should be expected if rooftop equipment is raised above the roof of the base building due to additional pressure acting on the bottom surface of the equipment.

The overturning moment of the cubic model is illustrated in Figure 5 for the same cube position.

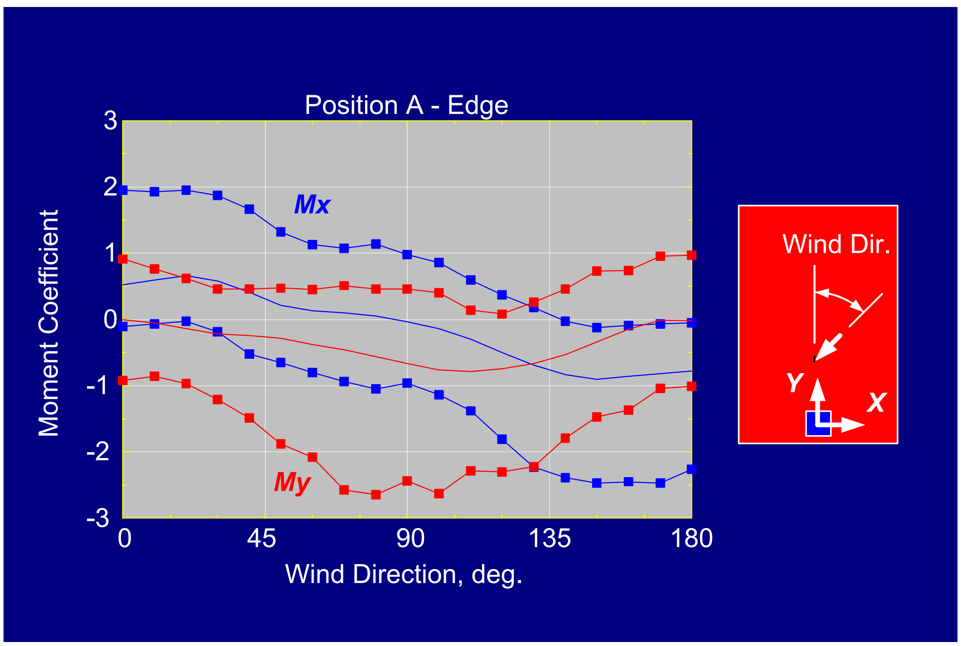

Figure 5: Overturning Moment Coefficient

It should be noted that the occurrence of the largest overturning moments about the X and Y axes coincides with the largest Y and X lateral forces, respectively, which were found to be the major contributors to the overturning moment. This implies, in turn, that the effectiveness of the uplift is relatively small compared to that of the lateral forces. In other words, the center of pressure on the top surface of the cube is located close to the plan center of the cube where the overturning moments were calculated in this paper. However, it is important to note that in actuality, the overturning moment for rooftop equipment might be evaluated at the trailing edge of the equipment as the center of rotation rather than at their geometric center. Thus, for elongated rooftop equipment, the uplift could cause a considerable contribution to the total overturning moment as well as to the lateral forces.

The lateral force, uplift, and overturning moment coefficients are summarized in Table 2 for the structural design of cubic rooftop equipment.

Table 2: Absolute Maximum of Force and Moment Coefficients

Position	Lateral Force	Uplift (+ upward)	Overturning Moment
A (edge)	4.9	3.7	2.7
B (intermediate)	4.7	3.6	2.6
C (center)	4.3	2.6	2.4

Similar to the area-averaged surface pressures, the worst force and moment occurred when the rooftop cube was placed near the edge of the roof of the base building.

Correlation of Lateral Force, Uplift, and Overturning Moment

Table 2 explicitly specifies the lateral force, uplift, and overturning moment coefficients, and can be used for a basic design of support for cubic rooftop equipment. But this is somewhat insufficient, as far as the overturning moment is concerned because the design overturning moment may have to be determined at various points of rotation depending on the configuration of the support. The point of rotation may not be necessarily at the center of the equipment base as assumed in Table 2. Alternatively, the overturning moment may be implicitly obtained by a combination of the two force components if the effective centers of pressure are known. For example, the moment about the Y axis due to the lateral force in the X direction and the uplift can be expressed by:

$$M_y = hF_x + cF_z \tag{1}$$

where h and c represent the effective arm lengths associated with the lateral force and uplift, respectively, about the point at which the overturning moment must be evaluated. This concept is illustrated in Figure 6.

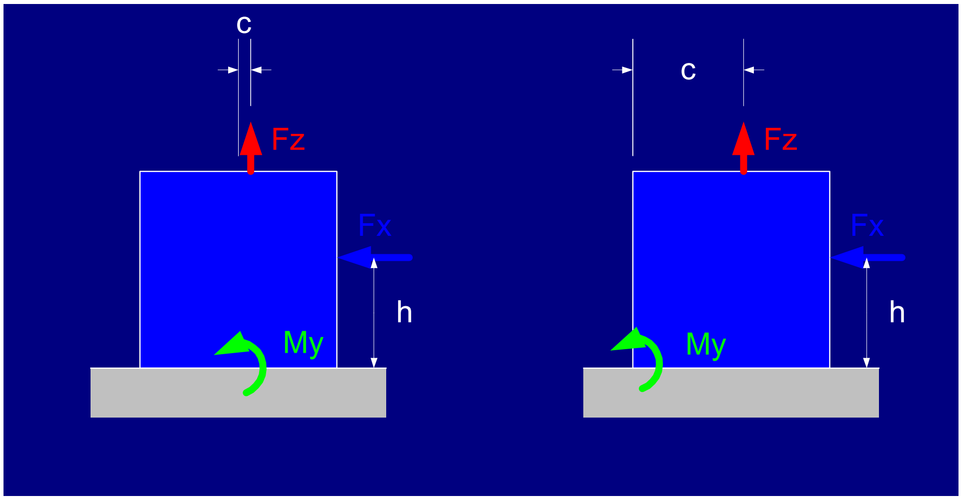

Figure 6: Overturning Moment as Combination of Moments by Aerodynamic Forces

Note that, for the sake of discussion, the parameters in Equation (1) are in engineering units, rather than coefficients. In this example, the overturning moment is evaluated at the center and the trailing edge of the rooftop cube bottom surface. As far as implementing Equation (1) for a code type application, it would be most convenient if the maximum lateral force and uplift, thus the design forces, can be assumed to occur simultaneously to produce the maximum overturning moment. To test this assumption, the correlation between the lateral forces and uplift was computed for the cubic model positioned at the edge of the base building roof. The result of the analysis is shown in Figure 7.

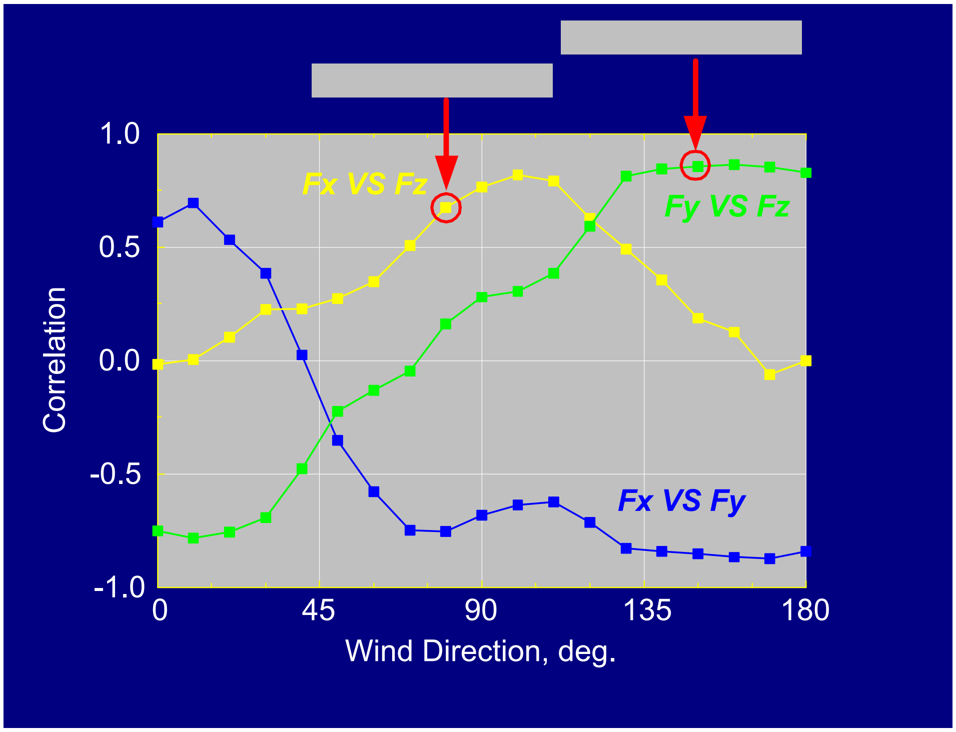

Figure 7: Correlation between Lateral Forces and Uplift

As seen in this figure, the correlation between the two forces contributing to the overturning moment is high when the resulting overturning moment is maximum. Thus, it can be concluded that the maximum lateral force, uplift, and the overturning moment occur nearly simultaneously.

In order to use Equation (1) for estimating the design overturning moment, it is also necessary to specify the effective locations of the lateral force and uplift, represented by the parameters h and c. The estimated location by the wind-tunnel results varied from 49 to 53% of the cube height measured vertically from the bottom of the cube for the lateral force depending on the wind direction. For the uplift, it varied from 0 to 6% of the cube width measured horizontally from the center of the cube. Nominal averages for the lateral force and uplift were 52% and 4%, respectively.

With the assumption of simultaneous action of the lateral force and uplift, along with the nominal effective arm lengths determined, Table 2 can be revised as follows:

Table 3: Absolute Maximum of Forces and Moment - Revised

Position	Lateral Force	Uplift (+ upward)	Moment Measured	Moment Calculated	%Diff.
A (edge)	4.9	3.7	2.65	2.70	+1.7%
B (intermediate)	4.7	3.6	2.56	2.59	+1.1%
C (center)	4.3	2.6	2.39	2.34	-2.1%

It is evident that Equation (1) adequately predicts the directly measured design overturning moment, even disregarding the actual correlations among the contributing forces. Strictly speaking, the data given in Table 3 (and Table 2) are applicable only to cubic rooftop equipment of a similar size as tested in the wind tunnel presented here. Further wind-tunnel tests for a variety of shapes and sizes are necessary for a sound code implementation.

Conclusions

Based on the wind-tunnel study for the cubic rooftop equipment, the following conclusions can be made:

- Gust effect factor for lateral force can be much larger than that for the base structure.
- Lateral force and uplift are well correlated when the overturning moment is large.
- Design overturning moments can be estimated from a combination of maximum lateral force and uplift.
- Overturning moments are an important load effect leading to failure of rooftop equipment (based on field observations).

Acknowledgement

The wind-tunnel study presented in this paper was conducted as part of the CSU/TTU Cooperative Program in Wind Engineering supported by the National Science Foundation Grant CMS-9411147. The authors sincerely thank Tom Smith of TLSmith, Inc. for his guidance and valuable comments.

References

American Society of Civil Engineers (1998), *Minimum Design Loads for Buildings and Structures*, ASCE Standard ASCE 7-98, New York.

Personal Communication with Tom L. Smith.