Effect of low-rise building geometry on tornado-induced loads

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Challenges to quantify tornado-induced loads:

- Lack of research facilities capable of determining tornado-induced loads (pressures, forces, etc.)
- Absence of full-scale data
- Lack of interest in tornado-resistant design

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1. Because the tornado is occasional and has destructive capacity.
2. This is the direct result of the first limitation. Because of this, we can hardly understand the real structure of the tornado wind field.
3. Because people used to believe that tornado resistent design is impossible.

How to overcome these challenges:

- Iowa State University (ISU) tornado simulator
- Full-scale data from several recent tornados
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1. This tornado simulator is capable of creating a simulated tornado, which can travel relative to a building model.
2. There is a research team named VORTEX, and it uses Doppler Radar On Wheels to chase the tornado.
3. Input the pressures into the FEA model, the real damage of full-scale building can be replicated.

Maximum horizontal wind speed

Fact 1: Around 90% of all tornados are rated F2 or less

Fact 2: Maximum velocity of F2 tornado is 74 m/s

Fact 3: Design wind speed ranges from 63 m/s to 80 m/s (ASCE 7-10, 2010)

Fact 4: Maximum horizontal velocity of the tornado generated by ISU Simulator is 11.7 m/s

Choose target full-scale wind speed to be 74 m/s

Velocity scale $\lambda_v = 11.7/74 = 1/6.3$

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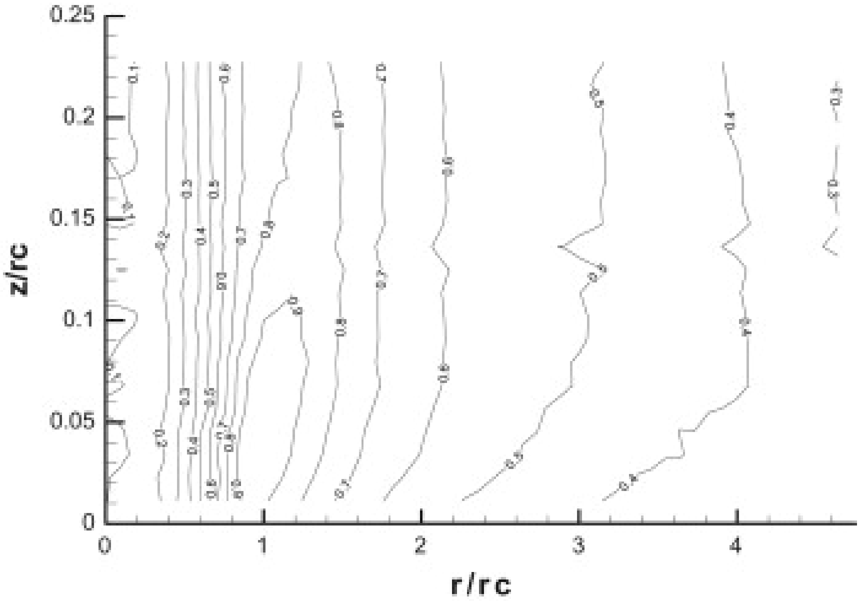
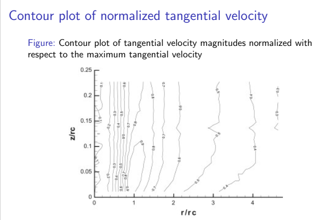
1. It's Fujita scale to measure the intensity of tornado.
2. We can find that the Maximum vvelocity of F2 tornado is the same order of magnitude with the design wind. So it is possible for tornado resistent design.

Contour plot of normalized tangential velocity

Figure: Contour plot of tangential velocity magnitudes normalized with respect to the maximum tangential velocity





This is the contour plot of normalized tangential velocity of ISU simulated tornado. r_c is core radius, it will be defined later.

Tornado vortex diameter

Definition

Radius of the core r_c: radius of the maximum wind near the ground

- Fact 1: r_c of F2 tornado is between 45 to 225 m
- Fact 2: r_c of simulated tornado is 0.56 m

Choose r_c of target full-scale tornado to be 56 m

Length scale is 1 : 100

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Choose r_c of target full-scale tornado to be 56 m
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It is found that the damage to building may occur withein a diameter, so the radius of the core is important.

Swirl ratio: definition

Definition

Swirl ratio S:

$$S = \frac{\pi V_{\theta\max} r_c^2}{Q}$$

r_c: core radius

$V_{\theta\max}$: maximum tangential wind speed

Q: inflow rate of the vortex measured at $r = r_c$

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Swirl ratio is an important parameter, because vortex structure is related to the swirl ratio.

How to choose swirl ratio

Fact 1: Data from full-scale tornados indicates $S \geqslant 2.0$

Fact 2: Best fit of full-scale data with numerical simulation when $S \geqslant 2.0$

Choose the swirl ratio S to be 2.6

How to choose swirl ratio

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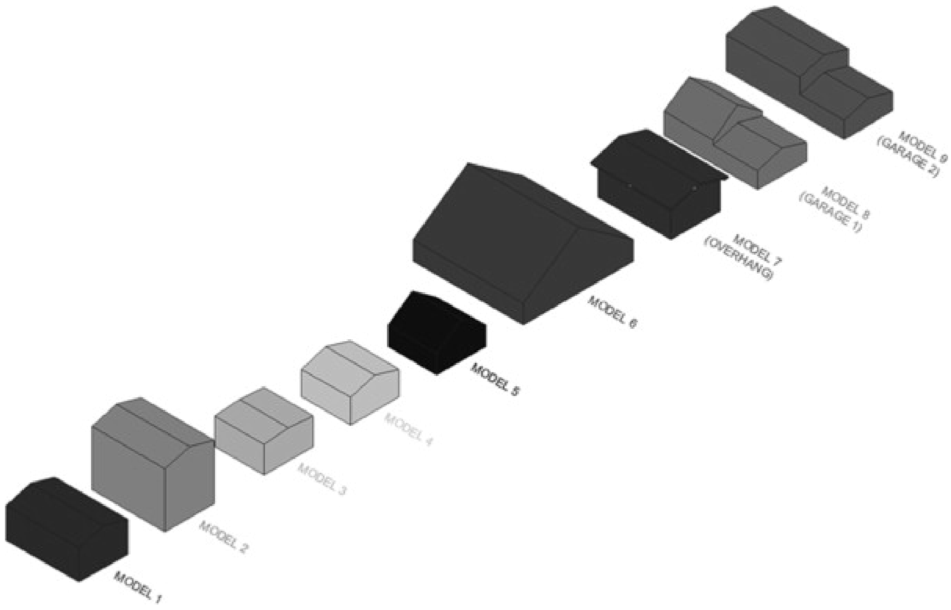
The ISU tornado simulator has vane to generate shear wind. Change the vane angle, the swirl ratio can be varied.

Building models



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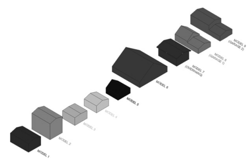
└Model description, instruments, conventions
└Building models
└Building models

Building models



These nine building models have varying roof pitched, eave heights, aspect ratio and so on. We can see the true dimension in this page.

Model dimensions

Model	Roof pitch, θ (deg)	Width, B (mm)	Length, L (mm)	Eave height, h_e (mm)	Roof ridge height, h_t (mm)	Mean roof height, h (mm)	L/B	h/L
1	15.95	98	146	60	74	67	1.5	0.46
2	15.95	98	146	110	124	117	1.5	0.80
3	4.6	98	98	53	57	55	1.0	0.56
4	15.95	98	98	48	62	55	1.0	0.56
5	35.5	98	98	37	72	55	1.0	0.56
6	35.5	221	221	37	114	76	1.0	0.34
7 (Overhang)	15.95	98	146	60	74	67	1.5	0.46
8 (Garage 1)[a]	35.5[b]	98	187	37	72	55	1.9	0.29
9 (Garage 2)[a]	15.95[b]	98	235	60	74	67	2.4	0.29

[a] Dimensions of "garage" addition were B=98 mm, L=89 mm, h_e=33 mm, and h_t=47 mm.
[b] Roof pitch of "house" part of model. Roof pitch of "garage" addition was 15.95°.

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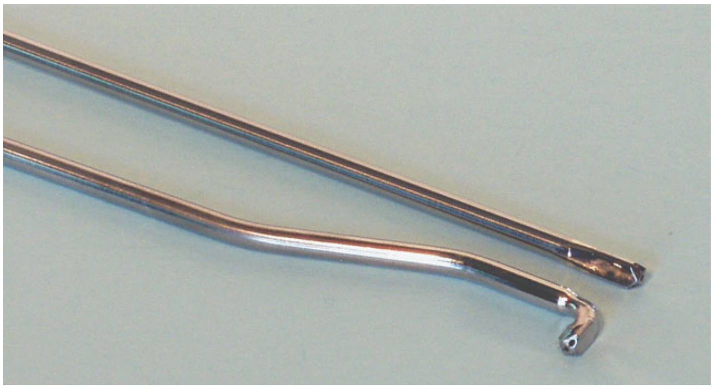
Model dimensions

This page lists the dimensions of the building models, which is real scaled version of the common full-scale buildings.

Wind velocity measurement: Cobra probe



Measurement points

horizontally spaced at 50.8 mm
vertically spaced at 6.35 mm

Pressure measurement: ZOC33/64Px pressure transducer

Measurement frequency: 390 Hz

Procedure

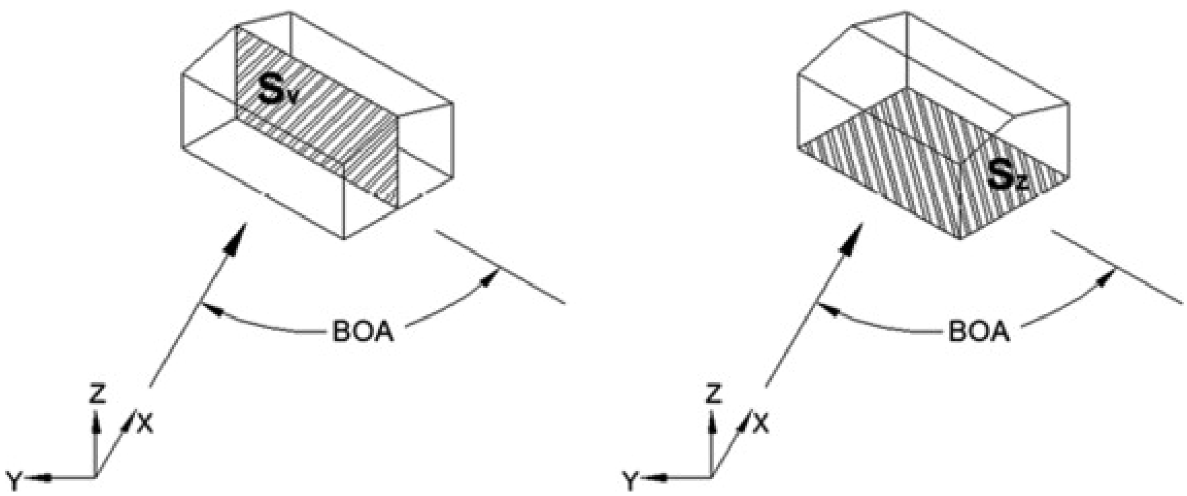
- For each test case the pressure were recorded 10 times
- Calculate the peak pressure as the average of the peak pressures from each of the 10 runs
- Change the BOA from 0° to 90° with a step size of 15°

Definition

BOA: the orientation of the building with respect to the direction of translation of the tornado

BOA & Areas used to compute force coefficients

Figure: Building orientation angle (BOA) with respect to the tornado translation axis (X) and areas (S_v, S_z) used to normalize force coefficients



Calculation of force coefficients

$$C_{Fx} = \frac{F_x}{(1/2)\rho V_H^2 S_v} \tag{1}$$

$$C_{Fy} = \frac{F_y}{(1/2)\rho V_H^2 S_v} \tag{2}$$

$$C_{Fz} = \frac{F_z}{(1/2)\rho V_H^2 S_z} \tag{3}$$

$$C_{Fxy} = \sqrt{C_{Fx}^2 + C_{Fy}^2} \tag{4}$$

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The equations used to calculate the force coefficients are given as the following equations.

The effect of eave height: Models

Fact 1: Difference between Model 1 & 2 was eave heights h_e

Fact 2: Model 1: $h_e = 60\,\mathrm{mm}$
Model 2: $h_e = 110\,\mathrm{mm}$

The effect of eave height: Models

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Fact 2: Model 1: $h_e = 60\,\mathrm{mm}$
Model 2: $h_e = 110\,\mathrm{mm}$

We can see that the eave height of Model 2 is almost two times of Model 1.

The effect of eave height: Peak pressures

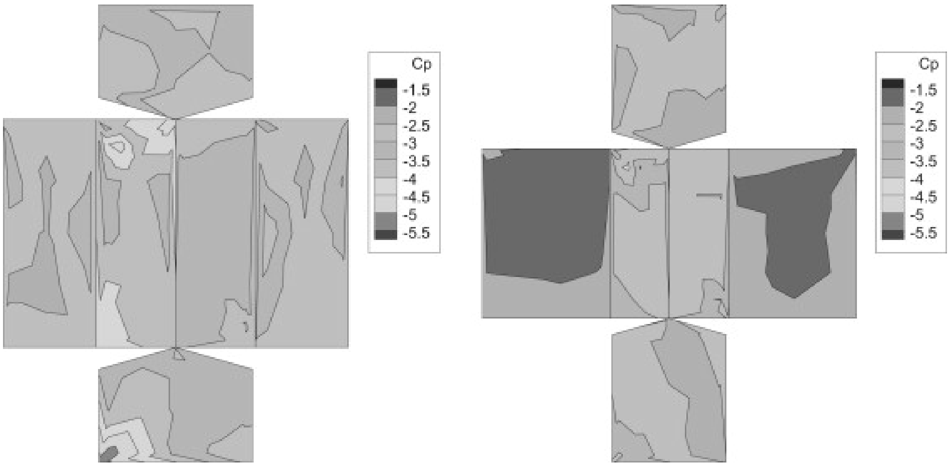

Figure: Peak pressure contours for Model 1 (left) & 2 (right), BOA=30°

- Peak pressure contours of Model 1 & 2 are similar
- Magnitudes of peak pressure: Model 1 > Model 2

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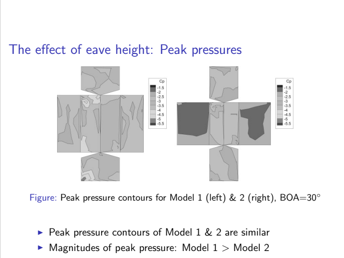
└The effect of eave height: Peak pressures



The peak pressures on Model 1 are significantly higher.

The effect of eave height: Vertical force coefficient

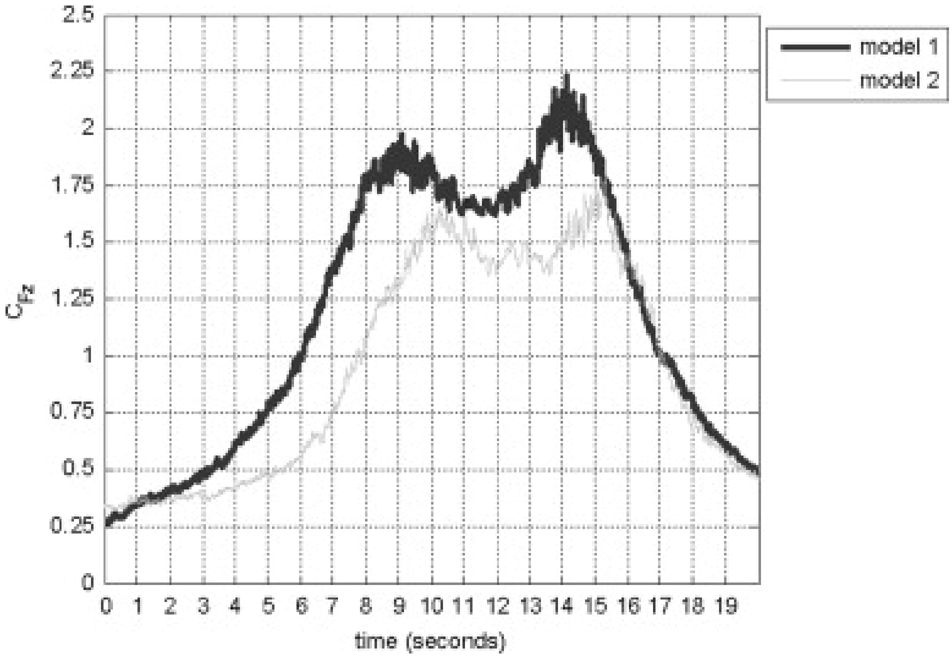
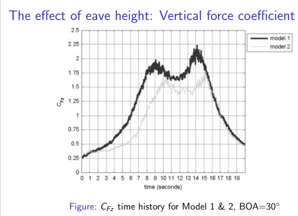


Figure: C_{Fz} time history for Model 1 & 2, BOA=30°



From this picture, we can easily find that the magnitudes of vertical force coefficient of Model 1 is higher than Model 2. Vertical force coefficient is used to determine the uplift force.

The effect of eave height: XY force coefficient

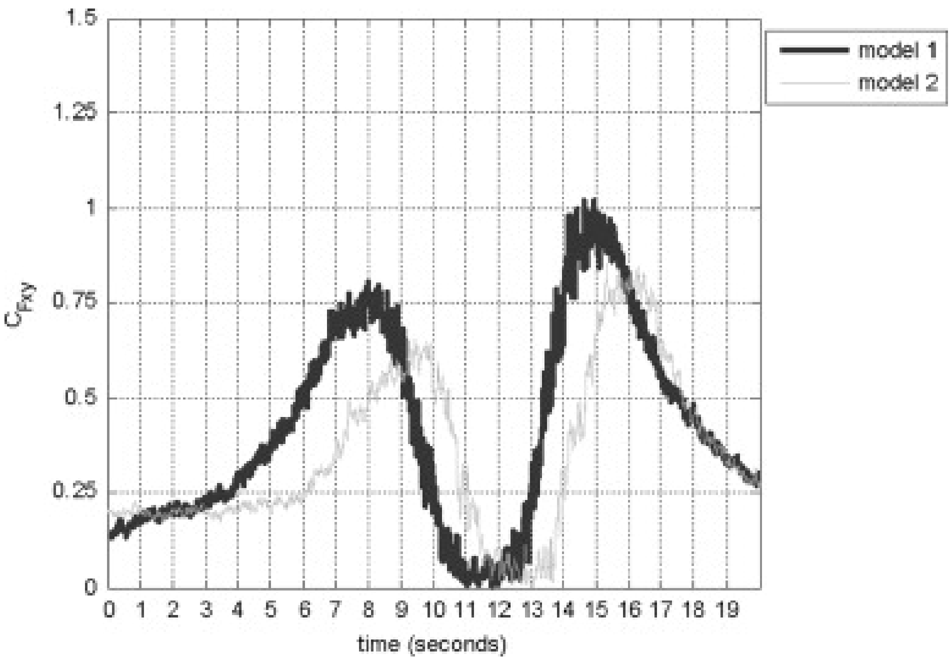
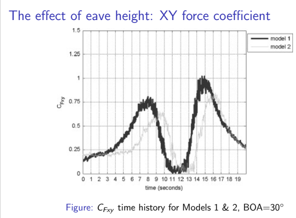


Figure: C_{Fxy} time history for Models 1 & 2, BOA=30°



From this picture, we can find that Model 1 and Model 2 have similar C_{Fxy} time history.

The effect of roof pitch: Models

Fact 1: Difference between Model 3, 4 & 5 was roof pitch θ

Fact 2: Model 3: $\theta = 4.6^\circ$
Model 4: $\theta = 15.95^\circ$
Model 5: $\theta = 35.5^\circ$

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All three models have the same mean roof height, the same plan dimensions, and the same aspect ratios.

The effect of roof pitch: Peak pressures

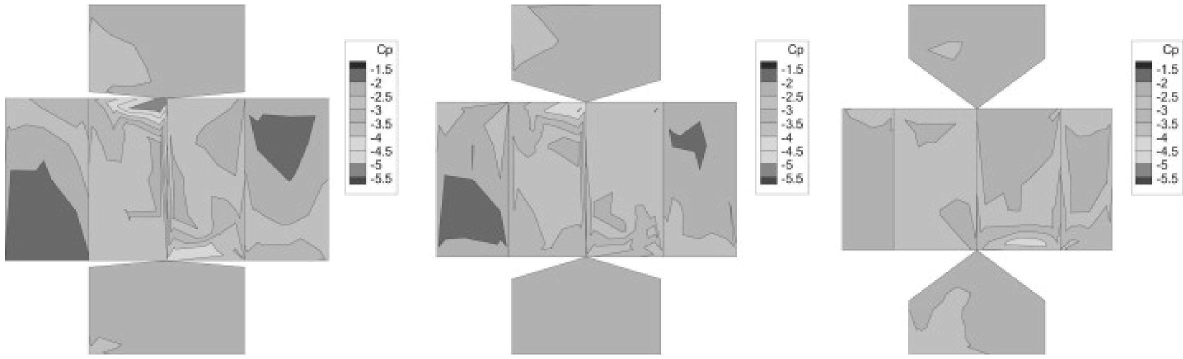

Figure: Peak pressure contours for Model 3 (left), 4 (center) & 5 (right), BOA=45°

- As $\theta \uparrow$, peak pressure magnitudes for the roof $\downarrow$
- As $\theta \uparrow$, peak pressure magnitudes for the wall $\uparrow$

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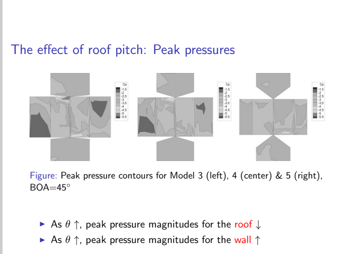


1. A clear trend occurs in the average peak pressures, as the roof slope increases the peak pressure magnitudes for the roof decrease
2. However, as the roof slope increases the peak pressure magnitudes for the wall increases.

The effect of roof pitch: Vertical force coefficient

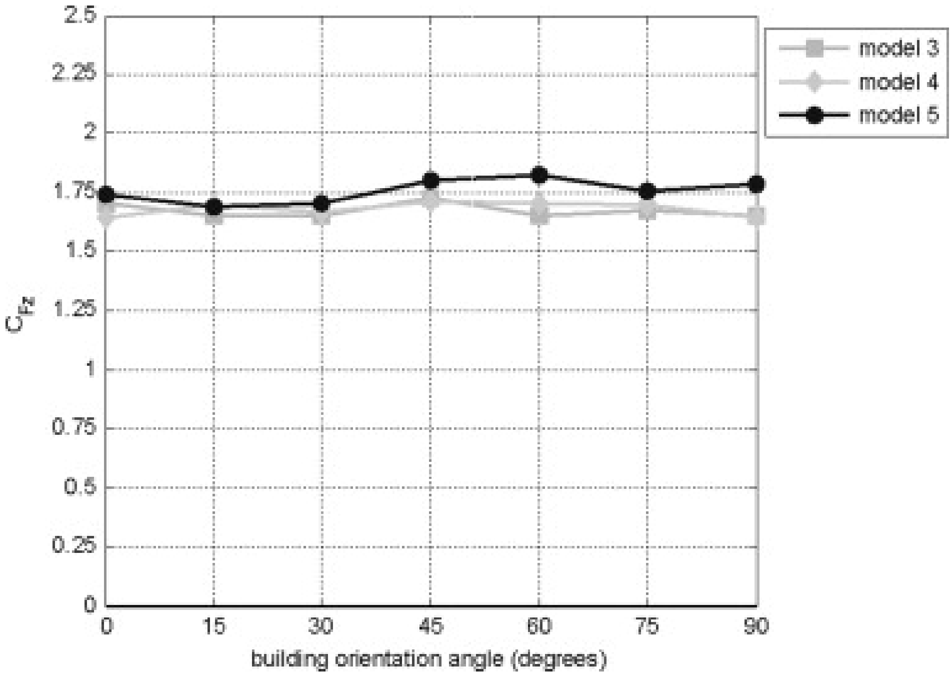
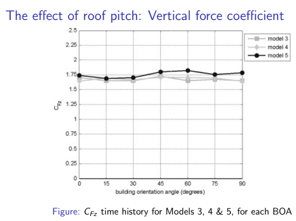


Figure: C_{Fz} time history for Models 3, 4 & 5, for each BOA



We can find that the vertical force coefficient does not change much when the building orientation angle changes.

The effect of roof pitch: Vertical force coefficient

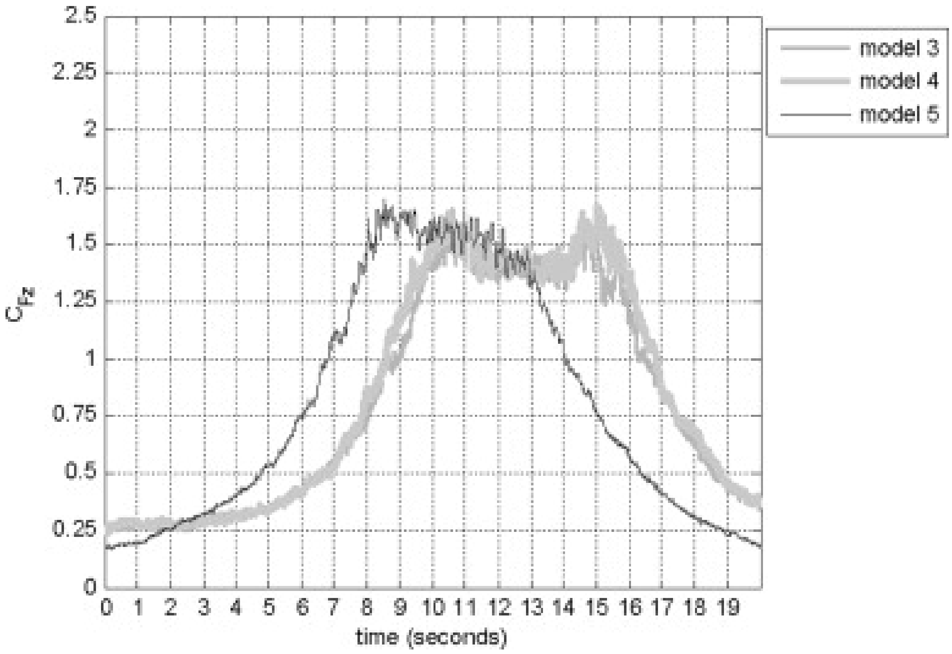


Figure: C_{Fz} time history for Models 3, 4 & 5, BOA=30°

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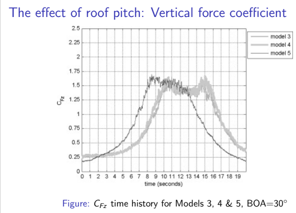

The vertical force coefficient time history of these three models are almost same with respect to shape and magtitudes as well, the clear difference is in the time when the model experienced the peak value.


Thank
You