PRACTICAL ENGINEERING

Holding Down the Roof

by Harris Hyman, P.E.

There's more to structural design than just making sure that a building doesn't fall down under snow loads or working loads. It also has to stay up and hold together under horizontal loads on the sides and on the roof. These loads come from two sources: wind gusts and earthquakes. If you doubt this, think back a couple of months to the evening news on central Oklahoma, or worse yet, the pictures following Hurricane Andrew.

On light wood-framed buildings of one to three stories, a little calculation shows that the wind effects are far greater than the seismic effects, at least up through seismic Zone 3. Most code officials assume that things are okay seismically if the designer takes care of the wind load. This is pretty reasonable for the Atlantic and Gulf coasts, where the winds are sometimes fierce but the earth is stable. It also seems reasonable for the Oregon and Washington coasts, where I work (although some recent seismic research suggests that it may not be quite as reasonable as we thought it was.) So, in this article, I'll ignore the earthquake loads in seismic Zone 4, and consider only wind loads.

What the Code Says

Buried in Chapter 16 of the *Uniform Building Code* are some peculiar requirements, which indicate that a roof sticking up in the wind has to be designed for both *upward* and *downward* (or inward and outward) wind pressure. That is, the wind both pushes and pulls on the roof (see Figure 1). Though this looks strange at first glance, let's wander into the physics a little.

I remember back in eighth grade when our teacher gave us a hint about how airplanes flew. He took a 2-inch strip of paper, folded it into an airfoil shape, and hung it loosely over a pencil. He then had us blow across the top surface, and hey, the thing lifted up! At that time my brain had not yet become totally poisoned in a soup of testosterone, so I was able to check with friends who built model airplanes. They verified the fundamental truth of the observations and showed that there was some real applicability. My uncles, who flew B-17s, also had a pretty clear understanding about the lifting power of moving air.

Enter the Building Researchers

About 70 years ago, while the physics boys were figuring out how airplanes flew, a few researchers turned their attention to theoretical flat planes propped up in the wind. They found that a level roof felt a suction when wind passed over it. The suction is high, 70% or more of the *stagnation pressure,* which is the pressure that a flat plane feels when it is perpendicular to the wind. The stagnation pressure (called q_s) is related to the *square* of the wind speed; as the speed increases, the pressure increases a whole lot more. This stagnation pressure is our baseline pressure, and the working pressures are related to it through relatively simple formulas.

One result of all this research is a graph called the Flachsbart curve, which plots wind pressure on the roof against the

Effect of Wind on a Roof

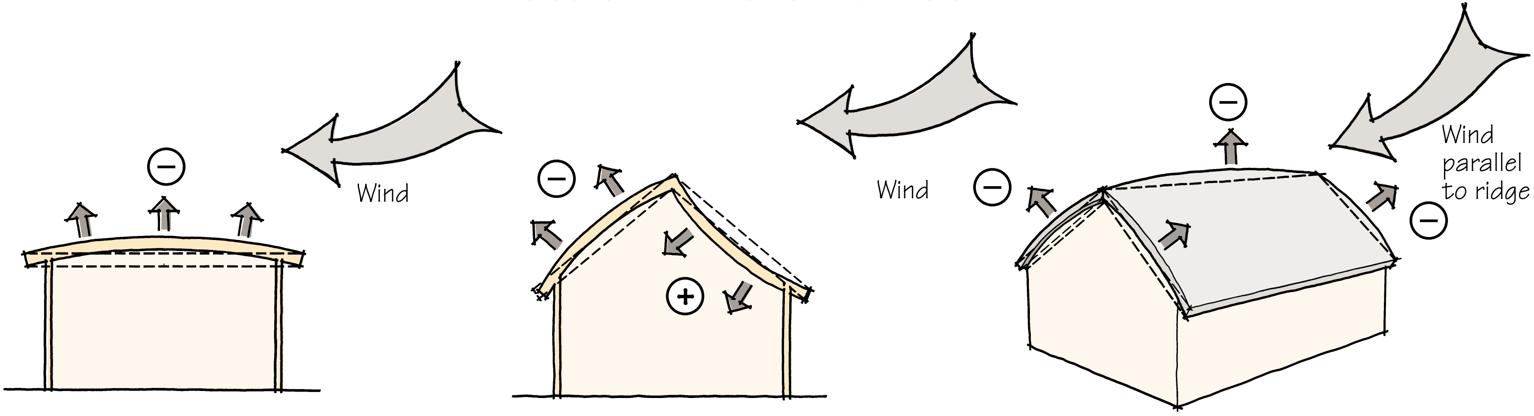

Figure 1. Wind blowing over a flat or shallow pitch roof exerts a suction, or pulling, force on the roof (left). Wind blowing perpendicular to a steep roof exerts a positive force against the windward side and a suction force on the leeward side (middle). Wind blowing parallel to the ridge line of any roof exerts a suction force on all roof surfaces (right).

Roof Pitch vs. Wind Effect

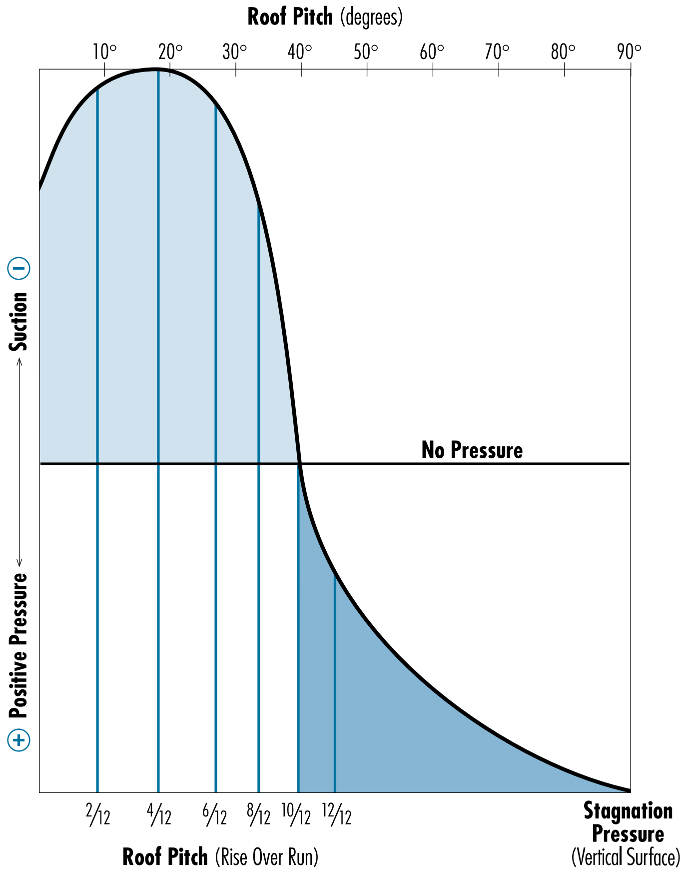

Figure 2. Based on research from the 1930s, the Flachsbart curve plots the effect of wind blowing against the pitch of a roof. At a roof pitch near 4:12, the suction force exerted by wind is greatest. At 10:12, the effect of the wind force is neutral. At pitches steeper than 10:12, the wind exerts a pushing force against the windward side of the roof. The "stagnation pressure" is reached when the wind strikes a vertical surface.

roof angle (Figure 2). As the roof tilts up from horizontal, the suction *rises* up to around a 4:12 pitch, then falls off to zero at 10:12, from which point it changes to an inward pressure. At 12:12, the pressure is about half of the stagnation pressure. Above 12:12, the inward pressure rises to the stagnation pressure. Stagnation pressures are given in Table 16-F of the *UBC* (see Table A).

Accounting for Building Shape

The research that produced the Flachsbart curve was based on a simple rectangular model with a flat roof plane. But real houses have chimneys and dormers projecting from the roof, and many buildings — particularly houses — have L-shaped plans and open porches. These are hardly simple flat surfaces floating in air. Still, the

Table A. Wind Stagnation Pressure (q_s) at Height of 33 Feet*

Basic wind speed (mph)	70	80	90	100	110	120	130
Pressure q_s (psf)	12.6	16.4	20.8	25.6	31.0	36.9	43.3

* based on UBC Table 16-F

Stagnation pressure, used in calculating design wind pressure, is the pressure of wind at a given speed against a perpendicular surface.

general research does give us a hint about how we have to design. In particular, we should note that low pitch roofs can lift right off, so we need to give some attention to holding them down as well as up.

Fast forward to the building boom of the ’50s, when the aerodynamics nerds started in again, with most of the attention being paid to wind tunnels designed to test airplanes at near the speed of sound. But in a few places, scientists began to design building research wind tunnels for 100-mph winds, a trick that was more difficult but also more useful (since there are a whole lot more houses than supersonic aircraft built every year). After a while, enough experience was developed to come up with the ancestor of *UBC* Table 16-H, the Pressure Coefficients (abbreviated C_q). These are a set of multipliers for a wide variety of building situations, for both whole buildings and components. It’s partially reproduced here (Table B), leaving out the forces on walls, which we can look at in a later article.

The pressure coefficients in the first section of the table generally follow the Flachsbart curve. With the wind perpendicular to the ridge, low-pitch roofs feel a 70% uplift. Slightly steeper roofs feel a little more, 90% uplift. At 9:12, roofs are steep enough to feel a moderate inward pressure, and at 12:12, roofs feel more severe inward pressure. But when the wind swings around to parallel the ridge, there is a lifting effect on all roofs, regardless of pitch.

Overhangs. Forces on roof elements such as overhanging eaves are somewhat stronger, because the relatively large area of wall below the eaves beats the wind to a stop and causes it to push upward on the overhang. The table simplifies the design force to 1.3 times the stagnation pressure. On a low-pitch roof over an open porch, the force goes up to 1.7 times stagnation. Where there is a discontinuity in the plane of the building, such as inside or outside corners, ridges, and rakes, the wind uplift can be as much as 2.6 times the stagnation pressure.

Height and exposure. Then there is the effect of height. Down at ground level, the unevenness of the earth slows the wind down. Up at face height, the wind begins to escape the drag of the surface and picks up some. At rooftop level, the wind escapes the drag of trees and buildings and blows a lot clearer, and at treetop altitude it begins to really move. The faster it blows, the more force it has. Here we’re assisted by another chart of coefficients, Table 16-G, which gives a multiplier, C_e, for various heights and exposures (Table C, page 107). Exposure B is urban and suburban areas, Exposure C is partially open areas like farmland, and Exposure D is wide open, like the seashore.

Table B. Pressure Coefficients (C_q) for Roofs*

Roofs on primary structures

Wind perpendicular to ridge		
	Leeward roof or flat roof	0.7 outward
Windward roof		
	Slope less than 2:12	0.7 outward
	Slope 2:12 to less than 9:12	0.9 outward or 0.3 inward
	Slope 9:12 to 12:12	0.4 inward
	Slope > 12:12	0.7 inward
Wind parallel to ridge and flat roofs		0.7 outward

Roofs on other building components

Roofs on enclosed and unenclosed structures (for example, dormers, bay windows, porches, sunrooms, etc.)		
	Slope < 7:12	1.3 outward
	Slope 7:12 to 12:12	1.3 outward or inward
Roofs on partially enclosed structures (for example, porches, breezeways, etc.)		
	Slope <2:12	1.7 outward
	Slope 2:12 to 7:12	1.6 outward or 0.8 inward
	Slope > 7:12 to 12:12	1.7 outward or inward
Areas of roofs near discontinuities, defined as corners, ridges & eaves (for example, a porch within an L, the roof over a jog in the plan)		
	Slope <2:12	2.3 upward
	Slope 2:12 to 7:12	2.6 outward
	Slope > 7:12 to 12:12	1.6 outward
	For overhangs on slopes less than 2:12:	add 0.5 to values above

* based on UBC Table 16-H

Pressure coefficients are multipliers applied to the base wind (stagnation) pressure to account for effects of slope and irregularities in the roof plan. Note that areas of roofs near corners, ridges, and eaves experience higher wind pressures. Where the word “or” is used, it means that the designer must test for the worse of the two cases, checking both inward and outward pressures, which are resisted by different parts of the structure.

Table C. Combined Height, Exposure & Gust Factor Coefficient (C_e)*

Height Above Average Level of Adjoining Ground (feet)	**Exposure B** (low — urban, suburban)	**Exposure C** (medium — farmland)	**Exposure D** (high — coastal)
0-15	0.62	1.06	1.39
20	0.67	1.13	1.45
25	0.72	1.19	1.50
30	0.76	1.23	1.54
40	0.84	1.31	1.62

* based on UBC Table 16-G

The effects of building height and location are accounted for in one multiplier, C_e.

A Worked Example

Let's work a quick example — an open porch on a house by a river. The local inspector tells us to design for 80 mph, and the river site is partially open on one side — Exposure C. The porch is 12 feet deep and the shallow-pitch rafters are 24 inches on-center, overhanging 18 inches.

Design wind pressure (*p*) is calculated by the formula:

$$p = C_e \text{ x } C_q \text{ x } q_s$$

Looking these up in Tables 16-G, 16-H and 16-F gives:

$$p = 1.06 \text{ x } 1.7 \text{ (outward) x } 16.4 \text{ psf}$$
$$= 29.6 \text{ psf upward lift}$$

The inner ends of the roof rafters are locked into the structure, but the outer ends must be held down. The connection at the rafter birdsmouth must resist the upward force on the outer half of the span plus the overhang. This area, per rafter, is:

$$A = (12 \text{ ft.}/2 + 1.5 \text{ ft.}) \text{ x } 2 \text{ ft. (o.c. spacing)}$$
$$= 15 \text{ sq. ft. per rafter.}$$

The uplift force, *P*, is:

$$P = p \text{ x } A = 29.6 \text{ psf x } 15 \text{ sq. ft.} = 443 \text{ pounds}$$

The couple or three 10-penny toenails you're used to putting in these rafters might resist about 35 pounds apiece — assuming you could get them in without splitting out the birdsmouth. A better plan [to have]: There are a lot of good metal hold-downs out there — don't forget to use them.

__Harris Hyman__ is a civil engineer in Oregon; he can be reached at hh@spiritone.com