AVALANCHES OF SNOW FROM ROOFS OF BUILDINGS[1]

Jonathan Paine and Lee Bruch[2]

Many of the principles learned from studying snow on mountainous terrain can be applied to snow on roofs of buildings. This understanding can be used to design better buildings for snow country.

We human beings are a funny species. We expend large amounts of energy, time, and money in finding ways of avoiding the hazards of avalanches in the natural environment. Then we cluster people in towns in the mountains, sometimes in the paths of potential avalanches. And often we fill the towns with buildings whose roofs catch large amounts of snow, roofs which precariously perch the snow high above people's heads, and which periodically avalanche it into occupied spaces.

This paper is about the principles of the design of roofs to avoid problems and hazards in areas of heavy snowfall. Most importantly for this conference, our hope is to encourage and assist a dialogue between the building design industry and snow scientists.

Most building designers do little work in snow country and are oblivious of the pitfalls involved in dealing with snow. Those designers that are aware of the problems are faced with a lack of information published in formats that are accessible to them and usable by them. Often they must rely purely on intuition.

Building designers are already faced with a complex task in designing a building. They usually can not afford to take the time to research and understand the complex bodies of knowledge of snow science.

Snow scientists could be of great help. They could produce "rules of thumb" and easy to use summaries of existing knowledge in formats usable by building designers; they could adapt existing knowledge to answer the specific needs of building designers; and where necessary, they could perform new research.

OVERVIEW: BUILDING IN SNOW COUNTRY

Many of the special considerations of building in snow country fall into three categories:

1. Structural Considerations

Snow can weigh a lot. Because most people know that and because the weight of snow involves safety in a very obvious way, there is a relatively good amount of literature on the subject and building designers tend to address the more obvious structural considerations. There are a number of less obvious considerations, including the effect of drifting; the accumulation of unusually heavy weights in roof valleys, behind obstructions, and on roofs subject to dumping from roofs above; and the effects of unequal loads. Although these topics are interesting and need discussion, we will leave these to be addressed in another paper.

2. Leaks

Snow has the nasty habit of accumulating, sitting around for some time, and gradually melting. The meltwater is the source of considerable headaches. Because designers inexperienced in snow country often ignore the special considerations that melting snow demands, many buildings in snow country tend to leak. Although some leaks can be traced to faults in materials or workmanship, many leaks are due to the basic design of the building. As we will point out repeatedly throughout this paper, some building shapes and designs create

[1]Paper presented at the International Snow Science Workshop, Lake Tahoe, California, October 22-25, 1986.

[2]Jonathan Paine: Structural Engineer and Consultant on buildings in snow country; principal of Snow Country Consultants, Whistler, B.C., Canada.

Lee Bruch: Architect and consultant on buildings in snow country; with the Urban Design Group, Vancouver, B.C., Canada.

situations where it is difficult if not impossible to avoid future problems. Other shapes, because of their intrinsic nature, avoid problems or make their solution easier.

The problem of leaks in buildings is a lengthy topic. We will leave it to be addressed another time.

3. Movement of Snow

Another habit of snow is that it accumulates, undergoes change, and given a chance, moves and falls. This is the topic of this paper.

The tendency for snow to avalanche from the roofs of buildings is frequently overlooked by building designers. But the importance of such avalanches should not be overlooked.

Snow falling from a height can be extremely dangerous. If it falls after it has been sitting on a roof for a number of weeks and has turned to ice, or if it falls from high enough, it can kill. Even falling from a low roof its impact can seriously injure someone, as a number of successful lawsuits can testify.

Snow falling can also do considerable damage to property. Every year in Whistler several cars sustain thousands of dollars of damage when hit by snow falling from roofs. The trajectory of snow shooting from a roof can carry it to an adjacent building. If it doesn't destroy an unlucky porch or smash through a window, the tremendous sound of the impact will at least unnerve the occupants. Falling snow can also ruin improperly placed landscaping or signage or can easily disconnect improperly placed electric or phone lines.

The forces of snow sliding along the roof of a building can also do considerable damage. We are all familiar with the way glaciers can carve into mountains. Similarly, in the valleys where two roof slopes meet the abrasion of the snow can cause considerable damage to the roofs. Snow can also do considerable damage to obstructions in its path; it can knock chimneys off and bend or shear off plumbing vents.

At the very least, snow dumping from improperly designed roofs can create maintenance and snow removal problems.

A couple of examples give an indication of what can happen.

The Sun Valley newspaper, The Mountain Express, several years ago carried a picture of a team of avalanche probers searching through a large snowslide from the roof of Sun Valley's ice rink. Luckily they found no victims.

At the conference center in Whistler a snowpack about 5 feet deep was held on the roof by large glu lam beams. The snow sheared right through the beams. There was an adjacent underground parking garage. Luckily extra shoring was added to it before the slide so that it wouldn't collapse. Luckily the beams could be heard cracking for three hours before the avalanche; no one was caught under it.

With proper forethought, snow shedding can be designed to be problem free. Indeed, if roofs are designed to shed snow safely into planned areas, the results can be attractive and exciting to watch.

The remainder of this paper deals with the methods and calculations necessary to successfully plan for shedding snow.

PRINCIPLES

There are many factors which affect snow on roofs. These factors are often interrelated in complex ways. These factors determine whether snow will remain relatively static, whether it will gradually creep, or whether it will suddenly avalanche.

Building designers do not need to know all of the the theory involved; we can leave that to snow scientists. But we do need to simplify some of the principles and apply them to our field in order to predict the action of snow on roofs we are designing.

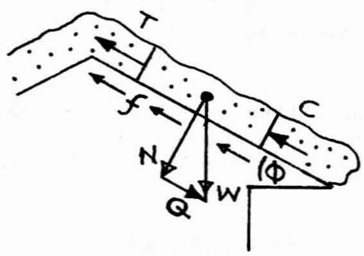
The amount of snow to be expected on a roof depends upon a number of factors: geographic location, wind exposure, solar exposure, shape of the roof, weather patterns, and amount of heat lost from the building. The snow is subject to redistribution on the roof due to drifting, sliding, melting, and refreezing of water.

The predicted snow load is based on the ground snow load as established by building inspectors and by the building codes. In some instances snow scientists must be called in to estimate probable amounts of snow.

Once the predicted snow load is known the tendency for movement and its forces can be analyzed. First, we will look at snow in a static condition, then the dynamics during movement, and finally, the resulting trajectory and impact after it leaves the roof.

Snow on Roofs: Static Condition

As in any mass, snow on a sloping roof is affected by a combination of factors.



W = Weight
N = Normal force = W cos Ø
Q = Sliding or shear force = W sin Ø

The forces which resist sliding are:

T = tension in the snow from the peak or a block of snow which is anchored for some reason.

C = compression. This would be from snow frozen to the unheated overhang or from a snow retainer or other obstruction.

f = friction between the snow mass and roof slope.

V = shear resistance along the sides of the snow mass from adjacent anchors or from a block of snow which is anchored for some reason.

When the sum of these forces (T + C + f + V) is more than Q avalanching does not occur, though a plastic flow of slow movement may occur, often resulting in snow cantilevering beyond the eaves of roofs with very low slopes.

The magnitude of the sliding and resisting forces are affected by several factors:

Slope. As the slope increases the sliding force Q increases. Although not much empirical analysis exists, from casual observation it seems that the roofs most prone to dangerous avalanching are between 16° and 60° in slope. Sliding is not as likely on roofs with less slope. Snow does not tend to accumulate to dangerous depths on steeper roofs. CAUTION: the above observations also depend on the many other factors which are listed below. It should be noted that these dangerous slopes correspond to the most common roof slopes.

Roughness. As the coefficient of friction between the roof and the snow increases, the force of Q required to cause sliding increases. Note that the coefficient of friction of the roof is the coefficient of friction of its material after it has been modified to account for the effects of the profile of the roofing, fastenings, and flashings; all of which increase the effective coefficient of friction. For example, our casual observations indicate that sliding does not occur on metal roofs until the slope is about 14°. This corresponds with a calculated coefficient of friction of $\mu = .25$ if tension and compression forces are absent. This is greater than the coefficient of friction to be expected on smooth, flat metal. Further research in examining this topic would be valuable.

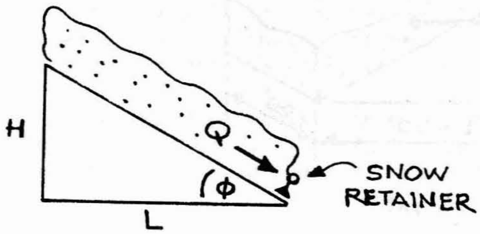
$$f = \mu N = \mu W \cos \emptyset$$

Temperature. The temperature at the snow/roof interface drastically affects the ability of snow to slide. Snow at cold eaves often bonds or freezes to the surface, decreasing the tendency to slide. The water from melting can tend to lubricate the surface, increasing the tendency to slide.

Melting can occur because of external sources such as solar radiation or ambient air temperature, or from heat loss from the building. Heat losses from the building depend upon the amount of insulation and the effectiveness of ventilation of the roof space. The amount of snow on the roof can also affect melting: even in cold climates the insulating effect of deep snow can be great enough to enable melting at the roof surface with even minimal amounts of heat loss from the building.

Obstructions. Even a small obstruction can hold back a wedge of snow far wider than the obstruction. The shearing forces can be tremendous. This is particularly important at snow retainers, dormers, and chimneys.

The shearing force can be calculated per the following example. (It would be wise to assume the coefficient of friction at zero since rain or meltwater often lubricate the surface.)



Shearing Force = Q
Snow Load = W
$Q = W \sin \emptyset$

If snow load = 100 psf, H = 10', L = 20', and
$\emptyset$ = 26.6°, W = 2000 pounds per linear foot
Q = 895 pounds per linear foot

Snow on Roofs: Dynamic Conditions

When a mass of snow breaks loose and begins to move down a roof slope, it tends to accelerate. This acceleration is hindered by the friction at the roof surface:

$$\boxed{a = g (\sin \emptyset - \mu \cos \emptyset)}$$

where

g = acceleration due to gravity
μ = coefficient of friction

(This assumes no loss of energy due to air friction or due to internal forces within the snow mass, which is probably safe for the limited lengths of most roof surfaces).

As the snow accelerates down the slope it imparts a lateral force to the building. For most buildings there are three types of lateral forces that govern the structural design: wind, earthquake, and snow-induced forces. In snow country, for small to medium sized buildings, the snow-induced forces due to acceleration can be several times greater than the earthquake induced forces.

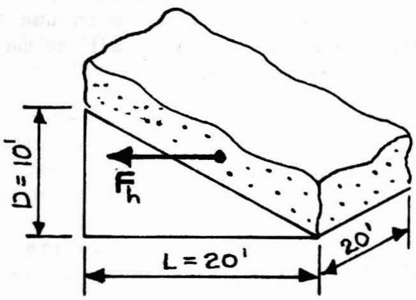
This horizontal acceleration $a_h = a \cos \phi$. After adjusting the acceleration for friction, we get:

$$\boxed{a_h = g\,(\sin \phi \cos \phi - \mu \cos^2 \phi)}$$

Therefore the horizontal or lateral force (F_h) is:

$$\boxed{F_h = Wg\,(\sin \phi \cos \phi - \mu \cos^2 \phi)}$$

Example:



Snow Load = 100 psf

$\therefore W = 40$ k

$g = 32$ ft/sec^2

the lateral force F_h is:

if $\mu = 0$ $F_h = 16$k

if $\mu = .25$ $F_h = 8$ k

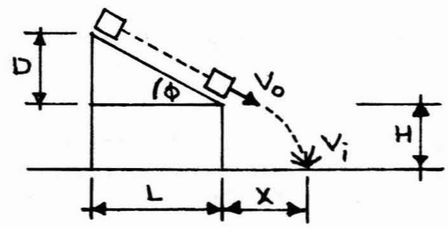
Note how a change in the coefficient of friction drastically changes the lateral load. Also, as snow begins to fall off of the roof the weight of remaining snow diminishes, so the lateral load also diminishes.

Snow on Roofs: Trajectories

The trajectory of snow sliding off a roof defines a danger zone. The building layout and the surrounding site must be designed to keep people away from these zones. To accomplish this successfully the designer must be able to calculate the trajectory.

The trajectory depends on the velocity of the snow as it leaves the building's eaves. This will inevitably vary tremendously. Wet snow may dribble off and fall straight down. A chunk of ice speeding down the roof or a sudden release of a large snowpack will approach the theoretical maximum trajectory.

We will ignore the effects of air friction and will assume the linear acceleration of snow. This will ease the calculations, on the size of most roofs it will not significantly alter the results, and at worst it gives us a slightly conservative result.



t = drop time

g = acceleration due to gravity

v_i = impact velocity

v_o = original velocity at roof edge

Velocity (v_o):

With no friction loss considered: $v_o = \sqrt{2g\,D}$

With friction loss: $\boxed{v_o = \sqrt{2g\,D\,\left(1 - \frac{\mu}{\tan \phi}\right)}}$

Trajectories:

$$H = \left(v_o \sin \phi + \frac{gt}{2}\right) t$$

$$H = v_o t \sin \phi + \frac{gt^2}{2}$$

$$\frac{g}{2}(t^2) + v_o \sin \phi\,(t) - H = 0$$

Solving for t:

$$t = \frac{-\,v_o \sin \phi \pm \sqrt{v_o^2 \sin^2 \phi + 4\,\frac{gH}{2}}}{g}$$

$$\boxed{t = \frac{1}{g}\sqrt{v_o^{\,2} \sin^2 \phi + 2gH} - \frac{v_o \sin \phi}{g}}$$

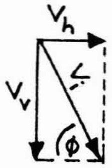
Solving for the danger zone x:

$$\boxed{x = v_o \cos \phi\; t}$$

Rearranging:

$$\boxed{x = \frac{v_o^{\,2} \sin \phi \cos \phi}{g}\left(\sqrt{1 + \frac{2gH}{v_o^2 \sin^2 \phi}} - 1\right)}$$

Impact Velocity (v_i). The impact velocity can now be calculated. Eventually, with the help of snow scientists in determining the dissipation of energy upon impact for various snow conditions, and with the impact velocity, we hope to be able to understand the forces resulting on impact. This is obviously important to designers when designing roofs subject to serious impact from above.



ϕ = angle of impact

$$v_H = v_o \cos \phi$$

$$v_v = v_o \sin \phi + gt$$

$$\boxed{v_i = \sqrt{v_H^2 + v_v^2}}$$

Example. For a roof with a rise (D) = 10', a run (R) = 20', coefficient of friction (μ) = .25, g = 32 ft/sec., and a drop of 12':

v_o = 17.9 ft/sec
t = .65 sec
x = 10.4 feet
v_i = 33 ft/sec (23 miles per hour)

Of course, instead of going through all the above calculations, it is easy for a child to determine the maximum trajectory: release a ball from the top of the slope and observe the impact location.

SOLUTIONS

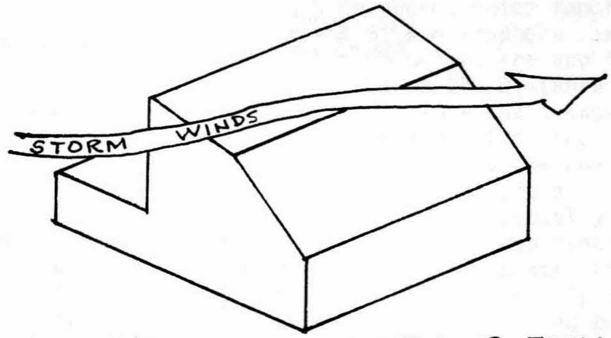
Ideally roofs should be planned so snow behaves predictably and moves where it will cause no danger or damage. Snow dump areas for all parts of the roof, even small parts, should be carefully located. Even a piece of a roof only a foot or two square or a small obstruction can retain snow that eventually turns to ice and which can become a deadly projectile. If dormers or intersecting roofs are used, the designer should understand that snow can easily hang up in the valleys and turn to ice, even on extremely steep roofs.

The basic building form should be designed to shed snow away from people or should be flat to avoid the problem.

Snow retainers can be used on roofs to prevent snow slides, but they are best used only with caution. If they are used, it should be only on low slopes; if the roof is very steeply pitched, a snowpack could shear off over the top of the retainer.

Other possible strategies include the use of heat cables to melt the snow (very expensive and troublesome; not recommended) or the use of lower or flat roofs to deflect or catch falling snow.

A strategy we used at Pika's, Whistler Mountain's mountaintop restaurant, involved using wind stripping to help control snow accumulation. We oriented the building in relation to consistent storm winds and bent the roof into two slopes to conform to the wind flow and to manage the snow that did accumulate.



PIKA'S RESTAURANT BUILDING FORM

The best solutions are obtained when the basic design of the building accommodates the principles of snow. Some building shapes and concepts make it difficult, if not impossible, to avoid problems. Other shapes, by their intrinsic nature, avoid problems or make their solution easier.

The snow scientist can play an important role in assisting building designers to produce better buildings for snow country. We invite your input.

REFERENCES

D.M. Grey and B.H. Male, eds. 1981. Handbook of Snow, Principles, Process & Use. Pergamon Press, NY.

Taylor, D.A. 1985. "Sliding Snow on Sloping Roofs," Canadian Building Digest, National Research Council of Canada.