# Structural Collapse from Snow Loads

*By Michael O'Rourke, Ph.D., P.E.*

Every winter brings with it a unique collection of snow related building collapses. Although each collapse is different – different structural engineer, different contractor – there are certain elements, roof geometry being one, that are similar and that can be used to categorize the collapses.

This article presents such a categorization based upon roof collapse case histories from the author's forensic consulting practice. The hope is that an improved understanding of the circumstances that have led to structural performance problems in the past will result in fewer collapses and headaches for structural engineers in the future.

Although there are exceptions, it is generally the case that snow related roof collapses are due to larger than average loads on a small portion of roof, as opposed to nominally uniform loads over the whole roof. As evidenced by the percentages in *Table 1*, the most common of these "larger than average" snow loads are drift loads of one kind or another, and to a much lesser extent, sliding snow loads or ice dams at the eave of a roof.

## Drift Loads

Three elements are needed for drift formations; a source of driftable snow, wind speed sufficient to cause transport of driftable snow (typically 10 MPH or so), and finally, a geometric irregularity (region of aerodynamic shade) where the transported snow can settle "out of the wind".

### *Roof Steps*

One such geometric irregularity is a roof step as shown in *Figure 1*. A leeward step drift results from wind that blows from left to right, and hence snow on the upper level roof is the snow source for leeward roof step drifts. Wind streamlines running parallel to the upper level roof separate from the building at the roof step and reattach at some point downwind on the lower level roof. The space between the roof step and the reattachment point is the region of aerodynamic shade where the drift forms. Typically, the slopes of these drifts are approximately one vertical to four horizontal, which is roughly the average angle of repose of drifted snow. If the drift grows large enough to reach the level of the upper roof, additional growth occurs at the toe of the drift, decreasing the slope of the drift surcharge. As per the current provisions of the American Society of Civil Engineers (ASCE) *Minimum Design Loads for Buildings and Other Structures*, ASCE 7-05, the drift is assumed to be streamlined, that is, the whole area of aerodynamic shade is filled when the drift has a one vertical to eight horizontal slope.

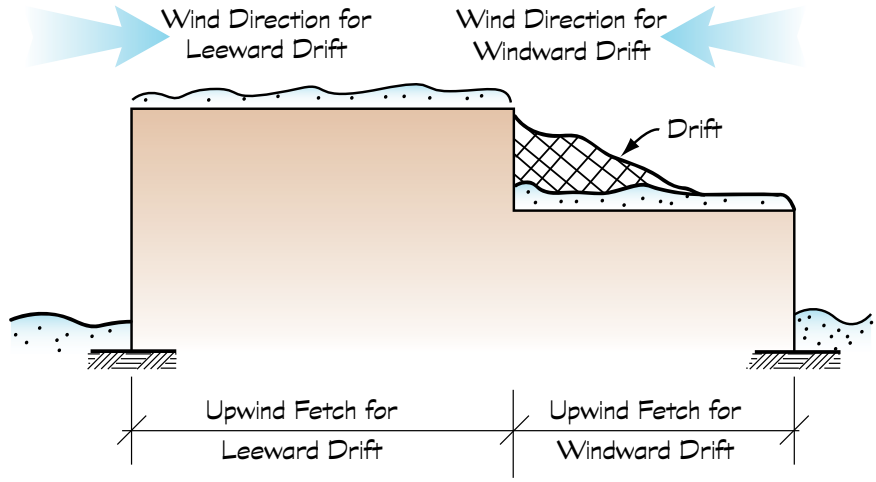


*Figure1: Roof Step Drift.*

If the wind blows from right to left, as shown in *Figure 1*, a windward roof step drift can form. In that case, the lower level roof is the snow source.

As one might expect, the potential size of a roof step drift is a function of the amount of snow in the source area, and the inherent windiness at the site in winter time. For example, the Dakotas are particularly windy in the winter while some parts of the Pacific Northwest are not. For quite a while, the size of the drift surcharge in ASCE 7 has been a function of the size of the snow source as characterized by the upwind fetch distance and the ground snow load. Currently, the drift surcharge required in ASCE 7-05 is not a function of the windiness of the region, which would require an additional map.

Note that not all the snow that is transported from the snow source settles in, or is trapped at, the geometric irregularity. For a leeward roof step, the "trapping efficiency" is approximately 50% based upon water flume studies and back calculations from case histories. Because of this, a parapet wall atop the upper level roof at a roof step will not prevent formation of a leeward snow drift on the lower level roof. That is, even when the drift upwind from the parapet wall is only partially full, some of the transported snow from the upper level snow source will blow over the parapet wall. The snow which blows by the parapet wall is then "available" for leeward drift formation at the roof step.

As shown in *Table 1*, roof step drifts are a common cause of snow related structural performance problems, accounting for over 20% (12 of 54) of the case histories in the author's forensic practice.

*Table 1: Frequency of predominant roof snow loads from author's forensic consulting practice.*

| Category | Number | Percentage |
|---|---|---|
| Roof Step Drift | 12 | 22% |
| Parapet Wall Drift | 6 | 11% |
| Gable Roof Drift | 12 | 22% |
| Combined Drift | 8 | 15% |
| Open Air & Freezer Building | 8 | 15% |
| Sliding Show | 1 | 2% |
| Ice Dams | 4 | 8% |
| Odd Balls | 3 | 5% |
| **Total** | 54 | 100% |

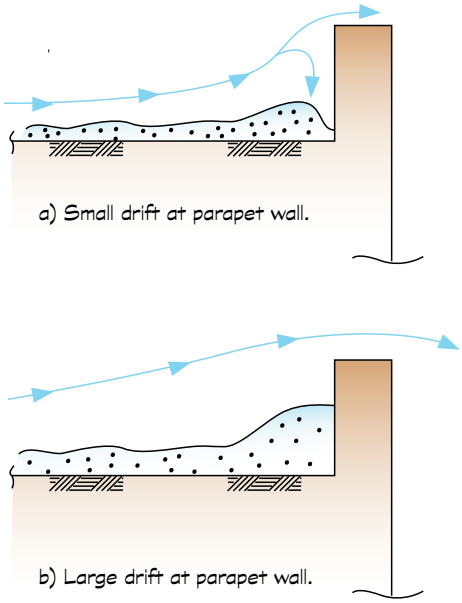


*Figure 2: Parapet Wall Drifts.*

### Parapet Walls

Parapet walls are another geometric irregularity where snow drifts form. By their nature, the drifts at parapets are windward drifts, since they form upwind of the geometric irregularity. The snow source area typically extends from the parapet wall all the way back to the opposite roof edge.

As shown in *Figure 2*, when the parapet wall drift is small, the wind streamlines impinging upon the wall itself are either turned upward and flow over the wall, or are curved downwards and create a vortex adjacent to the wall. The vortex results in a triangular drift surcharge, with the peak load at some distance from the wall. As the drift grows, the direction of the wind streamlines apparently rotate upwards, and the downward flow and vortex lessens. This causes the area immediately adjacent to the wall to fill, and the shape of the windward drift surcharge morphs into the classic right triangle shape assumed in ASCE 7-05. This same process also applies for windward drifts at roof steps.

Hence, for a particularly tall wall, it is possible that the area immediately adjacent to the wall does not fill-in eventually. In that case, one is left with a drift surcharge with a maximum load at some distance from the wall as opposed to the right triangular shape with the peak drift load at the wall. This non-right triangular shape, sometimes referred to as quadrilateral shape, has been observed in roof snow surveys. However, it has not played a role in any of the windward drifts (parapet walls or roof step), as shown in *Table 1*. That is, all the windward drifts in the author's forensic files have had the peak loads at or quite near the wall.

In relation to drifts that have led to problems, large parapet wall drifts tend to occur on large roofs. This is due to two factors. First, by their nature, large roofs have large upwind fetch distances and large snow source areas. Secondly, large roofs tend to have tall parapet wall heights, and hence large areas are available for drift formation. Tall parapets often result from a uniform elevation for the top of the wall, in combination with a sloping roof surface. A uniform elevation of the top of the parapet is an esthetic consideration, and sometimes is required by local codes.

For the six parapet wall drift cases shown in *Table 1*, the roofs ranged in size from 160 feet to 470 feet in the parallel wind direction, and 100 feet to 350 feet in the cross-wind direction. The parapet wall height ranged from 3 feet to 7 feet.

## Gable Roofs

The break in slope at the ridge of a gable roof is a geometric irregularity where drifts may form. These drifts are leeward in nature, forming downwind from the irregularity (*Figure 3*). As such, the length of the snow source is characterized by the eave-to-ridge distance upwind from the ridge. Based upon observations, the top surface of the gable roof drift is nominally flat and the drift nominally has a triangular shape. *Figure 3a* is the typical observed shape. *Figure 3b* is the idealized right triangular shape, while *Figure 3c* is the "designer friendly" uniform surcharge used in ASCE 7-05.

Water flume tests suggest that the trapping efficiency at the ridge is comparable to that of a leeward roof step. Hence, one would assume that the size or cross-sectional area of a gable roof drift would be nominally the same as a roof step drift if the upwind fetch distances are the same. The current ASCE 7-05 provisions for a gable roof drift (a.k.a. the unbalanced load on a gable roof) are based on the application of this "equal area" concept to the idealized right triangular shape shown in *Figure 3b*. The design depth of the "designer friendly" surcharge shown in *Figure 3c* is taken as half the peak value for the idealized right triangle shape. The horizontal extent of the design surcharge (*Figure 3c*) is such that its center of gravity matches that of the idealized triangle (*Figure 3b*).

In order for the gable drift to form, there needs to be enough of a geometric irregularity so that wind streamlines detach at the ridge and reattach at some point downwind. The space between the detachment and reattachment points is the aerodynamic shade region where the drift forms. Case history experience suggests that drifts form only on gable roofs with slopes of ½ on 12 (2.39 degrees) or larger. That is, the total angular change from the upsloping windward side to the downsloping leeward sides needs to be larger than approximately 4.8° degrees for drifts to form. This is consistent with observations of Venturi tubes which suggest that the angle between the flat region to the sloping region should be no more than approximately 4 degrees if one wants to avoid separation.

The current ASCE 7 provisions have adopted this limit. That is, one need not consider unbalanced loads on gable roofs with slopes less than ½ on 12. These roofs are flat enough such that drifts do not form. At the other end of the spectrum, the ASCE 7-05 provisions exempt very steep roofs (70 degrees or larger)

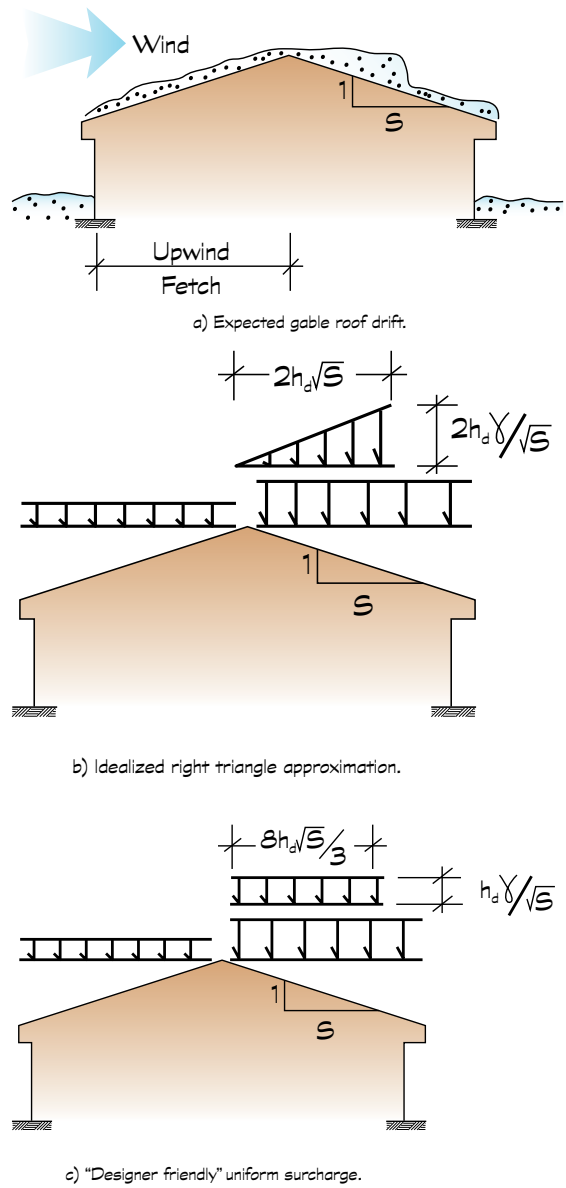


*Figure 3: Gable Roof Drifts.*

from unbalanced load requirements. That is, these roofs are viewed as steep enough such that any snow will simply slide off. It seems that this upper bound, which has been in ASCE 7 for the past 20 years, is based upon the slope coefficient $C_s$. Irrespective of the slipperiness or thermal condition of the roof, $C_s$ is zero for roof slopes of 70 degrees or larger. However recent observations by a group of structural engineers in the Lake Tahoe region indicate that drifts do not form on gable roofs with slopes steeper than 6 on 12 or 7 on 12. This suggests a maximum angle of response for drifted snow is 26 degrees or 30 degrees. There is evidence from the observed geometry of roof step drifts that supports these Lake Tahoe observations.

At first blush this seems to be at odds with the slope coefficient value quoted above. However, these two views regarding the angle of repose for snow can both be correct. The slope coefficient $C_s$ (implied maximum angle of repose = 70 degrees) applies to balanced (non drifted snow), while the 6 on 12 or 7 on 12 limit (implied angle of repose of 26 degrees to 30 degrees) applies to drifted snow.

The dominant transport mechanism for drifting snow is saltation – snow particles bouncing along the snow surface, dislodging other particles along the way. It seems reasonable that as saltating snow particles bounce across the surface they become more rounded. This process would result in sharp cornered undrifted snow particles with a high angle of repose, in comparison to the more rounded drifted particles with correspondingly lower angle of repose. A reduction in the current 70 degrees upper bound slope for gable roof drifts is currently under consideration by the ASCE 7 snow group.

## Combined Drifts

This category consists of case histories where the drift was due to two mechanisms. An example is a parapet wall, say at a north end wall of a gable roof with a north-south ridgeline. One gets a "pure" parapet wall drift for wind out of the south, and a "pure" gable roof drift for wind out of the east or west. The drift adjacent to the parapet wall for wind out of the southeast or southwest is classified herein as a combined drift – in this case, part parapet wall drift and part gable drift. As shown in *Table 1 (page 42)*, this grouping accounts for approximately 15% of the author's forensic case histories.



## Open Air and Freezer Building

These case histories are the exception, in that the collapse was due to nominally uniform loads across the whole roof. Some of these structures were open air, an example being a composting facility with a roof and columns, but no walls. Others were freezer or cold room buildings, an example being an apple storage facility where the air temperature below the roof insulation layer was intentionally kept below freezing.

In many of these cases, the roof snow load was larger than the ground snow load. For the four case histories with reasonably good information, the ratio of nominally uniform roof snow load to the ground snow load ranged from 1.12 to 1.64, with an average of 1.40.

This probably strikes engineers familiar with the ASCE 7 provisions as odd. That is, ASCE 7 provides a formula for determining the balanced snow load on a roof. Using the largest possible values for the exposure factor ($C_e$ = 1.2 sheltered in Terrain B) and the thermal factor ($C_t$ = 1.2 unheated) the balanced roof snow load is nominally the same as the ground snow load 0.7 (1.2)(1.2) = 1.01. This seems reasonable in that, absent wind and internal building heat, the uniform roof snow load should be close to the ground snow load.

The difference is due to the reduction in ground snow load by heat flow up from the warm earth. Note that this effect is not present for open air and freezer buildings. That is, for this select group of facilities there is cold air below the roof snow, not the warmer earth. Unfortunately, this category of structure is not currently covered by the ASCE 7 provisions. The unheated building category in ASCE 7 envisions a building with walls which, like the ground snow, is subject to heat flux up from the earth.

## Sliding Snow

Since its first edition in 1988, ASCE 7 has had provisions for sliding snow – additional load on a lower level roof due to snow which has slid from a sloped upper level roof. Hence, one would think it would be a fairly common cause of roof performance problems. Oddly enough, only one of the author's 54 case histories involved sliding snow. It is unclear why there are so few cases; possibly the dollar loss associated with sliding load collapses are not large enough to trigger a lawsuit and a forensic investigation.

## Ice Dams

Ice dams can form at the eaves when the roof insulation R-value is low, the interior temperature is high, the roof snowpack is deep and the outside temperature is below freezing. For such cases, snow at the bottom of the roof snowpack melts and some of the meltwater freezes at the cold eave. The ice dam thickness at the eave for some of the case histories was up to six inches for relatively large eave-to-ridge distances of 100 feet or so.

## Odd Balls

The forensic case history database has a few unusual cases. In one, a fire hose was used to remove roof snow from a school bus garage. Unfortunately the facility collapsed during the snow removal operation, due in part to the extra weight of the water.

## Rain-on-Snow and Other Factors

The various categories in *Table 1* are the predominant roof snow loads at the time of collapse. However, often times there were other factors which contributed to the collapse. For example, in one of the roof step case histories, roof ballast (12 to 14 psf) was not considered in the original design. In a couple of the parapet wall case histories, there were also blocked roof drains/scuppers. Similarly, rain-on-snow was a contributing factor in approximately 10% of the case histories. The calculated load due to rain-on-snow surcharge was typically in the 4 to 5 psf range. It was the straw that broke the camel's back.

## Conclusions

Drifting of one kind or another accounts for 70% of the case histories in *Table 1*. Clearly these are not areas where the structural engineer should look to economize – "design with a sharp pencil". Similarly, an extra bit of conservatism may be warranted for open air and freezer buildings.▪

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