SNOW LOADS ON STRUCTURES*

Michael J. O'Rourke

Rensselaer Polytechnic Institute
Troy, N.Y. 12181

ABSTRACT

Fairly sophisticated procedures exist for determining, in a statistical manner, the maximum snow load on the ground for a particular area. However, from a structural engineering viewpoint, the snow load on the roof is the important design parameter. The roof snow load can be related to the ground snow load through a ground to roof conversion factor. This conversion factor is a function of the geometric and thermal properties of the roof itself as well as the wind and thermal environment in which the roof is located.

This paper describes a two winter study of roof snow loads in New York State. Thermal, geometric, and metrological variables are analyzed to determine their effect upon the ground to roof conversion factor. Also typical roof drifting patterns are illustrated. Finally, descriptions of the partial collapse of two structures and the total collapse of one structure due to roof snow are presented.

MAXIMUM GROUND SNOW LOAD

The starting point for determining the roof snow load is obviously quantification of the ground snow. The maximum ground snow depth expected for a particular location in the next 10, 20 or 50 years is, by its very nature, a probabilistic quantity. Taking a statistical set of annual maxima of recorded snow depths for a particular location and fitting that data with a Gumbel (Fisher-Tippett type 1) or some other extreme value distribution, the probability that the maximum ground snow depth will exceed a particular value in a period of N years may be calculated. In this sense, the determination of the expected ground snow depth is similar to determination of the expected wind speed for a particular structure. For any reasonable design value there is a small probability that that value will be exceeded during the lifetime of the structure.

Ghiocel and Lungu (1975) have used a Gumbel extreme value distribution to fit the maximum annual snowfall depths recorded in Bucharest between 1922 and 1970. Boyd (1961) has used the annual maximum ground snow depth for over 200 locations in Canada recorded from 1941 thru 1959 to obtain the maximum ground snow depth with a 30 year return period. Tobiasson and Redfield (1973) use a log-normal distribution as well as a conversion density which will be discussed subsequently to calculate the 5, 10, 25, 30, 50 and 100 year return period ground snow loads for 137 locations in the state of Alaska. The 25 and 50 year return period load is that load which has a 0.04 and 0.02 probability of being exceeded in any particular year.

Isyumov and Davenport (1974) have taken a different approach by developing a computer model for predicting snow throughout a winter season. A statistical description of the various meterological variables such as wind speed and direction, air temperature, and snowfall is required as input. A digital simulation technique is then used to generate a snow depth and load history for an entire winter. Repeating the technique, a set of

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simulated annual maximum snow loads can be easily developed.

For procedures which fit annual ground depths with an extreme value distribution to obtain return periods for ground depth, a density is then required to calculate return periods for ground snow load. Ghiocel and Lungu (1975) and Anderson (1965) as well as others have noted that the density in a snow pack is a function of depth, and that compression, melting, evaporation and run off causes an increase in snow density with time. Ghiocel and Lungu (1975), Boyd (1961) and Anderson (1965) have proposed using an average snow density for calculation of the maximum ground snow load. Noting that the maximum ground snow load and the maximum ground depth often occur at different times during the winter, Tobiasson and Redfield (1973) propose using a conversion density. This conversion density is neither the maximum snow density nor the density corresponding to the maximum snow depth but a density which when multiplied by the maximum depth yields the maximum ground load.

CONVERSION FACTOR

Once the ground snow load has been determined, a ground to roof conversion factor is needed to determine the roof load. For the purposes of this paper, the ground to roof conversion factor C_f is defined as follows:

$$C_f = \frac{\gamma_r h_r A_r}{\gamma_g h_g} \qquad (1)$$

where h_r and h_g are the average roof and ground depths, γ_r and γ_g are the average roof and ground densities and A_r is the percentage of the roof covered by snow. For a gabled roof with one side bare and a uniform depth of 8 inches (20.3 cm) on the other side, h_r is taken as 8 inches (20.3 cm) and $A_r = 0.5$.

In building codes such as the American National Standards Institute (1972) and National Building Code of Canada (1970), as well as in other studies on roof snow loads Boyd (1961), Ghiocel and Lungu (1975), Isyumov and Davenport (1974), Lutes (1970), Lutes and Schriever (1971), O'Rourke (Feb. 1977), Schriever et. al (1967) and Tobiasson and Redfield (1973), one can find mentioned the main parameters which effect the ground to roof conversion factor. These parameters are;

1. Exposure of the roof to wind (i.e. sheltered, windswept, etc.).
2. Wind speed during and after snowfalls.
3. Parapets, roof slopes, multi-level roofs.
4. Roof insulation for heated structures.
5. Air temperature and amount of sunshine.

The effects of some of these parameters upon the ground to roof conversion factor have been investigated by the author in a two winter study of structures in New York State. Twenty-one structures were used in the 1975-76 study while 51 structures were investigated in the 1976-77 study. The structures studied included classroom buildings on the RPI campus, residential structures in the Albany area, summer camps in the Adriondacks Mts. at North Hudson, and U.S. Army facilities at Fort Drum. Both heated and unheated structures were considered. For the heated structures, the R value for the roof insulation (resistance to heat flow) was experimentally measured or estimated from construction drawings. Roof slope ranged from 0° (flat roofs) to 60°. Also, each of the buildings were classified by the data gatherer (RPI graduate students) as either windswept, semi-sheltered or sheltered. Meterological variables such as snowfall depth and daily wind speed were also recorded when available. A more detailed description of the structures is found in other reports, O'Rourke (1976 and July 1977).

WIND EFFECTS

Wind action can redistribute and/or remove a substantial portion of a roof's snow. Because of this, the roof's wind environment is one of the most important parameters affecting the ground to roof conversion factor. This effect is dramatically illustrated by the 18 structures at North Hudson, NY. On one day during the 1976-77 winter, 11 of the structures which were exposed to the west-southwest winds coming off an adjacent pond had no snow on their roofs while the 7 remaining structures had an average conversion factor of 0.82. All the structures at North Hudson were unheated and within a tenth of a mile of each other. Since they all had similar ranges of roof slope, and none had parapets, the difference in conversion factor can only be attributed to wind effects.

The effect of wind has been noted by others and is considered by some codes. For instances, Lutes (1970) reports the following ratios between roof and ground snow loads;

Well sheltered	0.9
Unobstructed	0.6
Well exposed	0.3

Both the 1970 Canadian National Building Code (1970) and the American National Standard Institute Code (1972) recommend a basic conversion factor of 0.8 for sheltered roofs. This value is reduced by 25% for roofs fully exposed to high velocity wind (i.e. $C_f = 0.6$). A similar reduction of approximately 25% for wind swept structures is recommended by Tobiasson and Redfield (1973) for structures in Alaska.

There are two elements which determine the ability of wind to remove snow from a roof. The first is the exposure of the roof to wind (i.e. windswept, semi-sheltered or sheltered). The wind exposure ratings are functions of the relative location of the roof with respect to trees and other wind breaks. It should be noted that these ratings are subjective measures. Two individuals could classify the same structure differently. The second element comprising the wind environment is the wind speed in the general area of the structure during the winter season.

Ghiocel and Lungu (1975) cite work done in Russia which indicates the following relationship between conversion factor and wind speed

$$C_f = 1.24 - 0.13\,\bar{V} \qquad (2)$$

where $\bar{V}$ is the average winter wind velocity, in meters per second. Using the 1975-76 and 1976-77 data mentioned previously, the following relationships have been developed which take into account both the structure's exposure rating and wind speed:

$$C_f = \frac{\sum_{i=1}^{n} g_i - s \cdot \sigma_w}{\sum_{i=1}^{n} g_i} \qquad (3)$$

where g_i is the depth of the i^{th} snowfall in the series, n is the number of snowfalls in the series, σ_w is a wind parameter and s is the snow removal rate which is a function of the structure's exposure rating. The above relationship assumes that the snow removal rate, s, is independent of snow depth and that the ground and roof densities can be taken as equal. The second of these assumptions is quite accurate for unheated structures but on the unconservative side for heated structures. That is, eqn. 3 assumes that the ratio γ_r/γ_g equals 1.0 while γ_r/γ_g averages 0.98 for unheated structures and 1.20 for heated structures.

A number of different meterological variables were considered for use as the wind parameters σ_w in equation 3. The sum of the daily average wind speed measured from the start of the snowfall series was chosen although the sum of the daily fastest mile speeds also correlated well with the data.

A linear regression line (least squares line) was calculated for eqn. (3) using data for heated structures in the Albany area with roof slope less than 30°. Wind and snowfall data for the Albany County Airport were used to determine σ_w and Σg_i. An average of the conversion factors for all structures in the Albany area with the same exposure rating was used for C_f. From the least squares line the snow removal rate, s, for various exposures was calculated. For the windswept exposure rating, the snow removal rate was 0.064 inch/mph (0.101 cm. hr/Km) while the value for a semi-sheltered exposure was 0.030 inch/mph.

(0.047 cm. hr/Km).

It should be noted that while the correlation between the average conversion factor and the wind and snowfall parameters recorded at the Airport was good (correlation coefficient = 0.93 for windswept and 0.81 for semi-sheltered), there was relatively wide variation in the individual conversion factors which went to make up the average. This difference between the average and individual conversion factors may be due to variations in roof R-values or differences between average daily wind at an individual structure and the wind recorded at an airport up to 10 miles (16 Km) away.

SLOPE EFFECTS

Intuitively, the slope of the roof should have an effect upon the conversion factor; the larger the slope, the smaller the conversion factor. However, an analysis of the 1975-76 and 1976-77 data does not yield a concise relationship. All the sloped roofs had regular shingles and all but one of the roofs had slopes less than 30°. In this range of roof slope, the effect of slope upon the conversion factor is small for shingled roofs. Data for the Fort Drum structures are representative. Four of the unheated structures at Fort Drum were considered to be semi-sheltered by data gatherers. Of these four structures, 2 had flat roofs, while the other 2 had roof slopes of 27°. The average of the conversion factors for the flat roofs was 0.78 while the average of the conversion factors for the sloped roofs was 0.71. This slight difference may well be due to minor variations in the wind exposure as opposed to slope effects.

The one roof with a slope greater than 30° is a portion of the RPI Chapel roof which had a slope of 60°. There was no accumulation on the 60° portion of that roof during both winters. Although there were no structures with roof slopes in the 30° to 60° range, the data do tend to confirm the roof slope provisions of the National Building Code of Canada (1970) and the American National Structures Institute (1972) codes. Both codes allow no reduction in the basic conversion factor for slopes less than 30°, a straight line reduction between 30° and 60° and a conversion factor of 0.0 for slopes of 60° or greater.

THERMAL EFFECTS

The conversion factor for a structure is affected by its roof's R-value or resistance to heat flow. If the structure is heated, and has a low R-value, thermal energy can flow through the roof causing the roof snow to melt and hence reduce the conversion factor. If, on the other hand, a heated structure has a heavily insulated roof, (i.e. high R-value) then less thermal energy can flow through the roof and less roof snow can melt. During the 1976-77 winter, two structures on the RPI campus were instrumented to determine experimentally the R-value for these roofs. The procedure used to experimentally measure the R-value was developed by the US Army Cold Regions Research and Engineering Lab. The measured R-value for the 2 structures which were both classified as windswept, as well as the conversion factor for the 1975-76 and 1976-77 winters are presented in Table 1.

Data Gathering Date	Science Center $R = 5.4 \frac{°F.hr.ft^2}{BTU}$	Burdett Hall $R = 9.47 \frac{°F.hr.ft^2}{BTU}$
12/24/75	0.45	0.71
2/4/76	0.24	0.41
3/17/76	0.28	0.91
1/11/77	0.68	0.81
1/25/77	0.29	0.45
2/24/77	0.38	0.51

Table 1: Conversion Factors vs. Roof R-value

Notice that an increase in R-values from 5.14 to 9.47 corresponds to an increase of approximately 0.15 in the conversion factor (i.e., 0.38 + 0.15 ≈ 0.51).

A roof's resistance to heat flow affects the conversion factor only when there exists a temperature difference between the two sides of the roof. If the structure is unheated, melting of snow due to heat flow through the roof is not possible and one would expect higher conversion factors for unheated structures as compared to heated ones. Quantification of this effect requires a comparison of conversion factors for structures which are similar in all aspects except that one is heated while the other is unheated. Unfortunately, insufficient data exists from the two winter study to make such a comparison. It should be noted, however, that Tobiasson and Redfield (1973) suggest a 30% increase in the basic conversion for unheated structures.

DRIFTING

The total load on the roof is easily calculated knowing the conversion factors, ground depth and ground density. However, the structural design of a roof's system requires knowledge of the distribution of the load as well as its total magnitude. In general, if the winds during and after a snowfall are mild, or if the roof is sheltered from the wind, the distribution of the snow on the roof will be essentially uniform. This situation is illustrated by the photograph shown in Figure 1 which was taken at Fort Drum during the 1976-77 winter. However, if the roof is exposed to relatively strong winds, drifting or redistribution of the roof snow may occur.

Figure 1 Uniform Snow Load

One type of drifting occurs on roofs with parapet walls or on structures with roofs at different elevations. A typical example of drifting due to roofs at different elevations was observed during the 1976-77 winter. For this structure, the average roof and ground depths were 4 and 8 inches (10.2 and 20.3 cm) respectively. But the roof snow depth was 36 inches (91.4 cm) at the wall between the two roofs of elevation of 20 and 25 ft. (6.1 and 7.6 m). An example of drifting due to parapet walls was also observed during the 1976-77 winter. This roof had an 18 inch (45 cm) parapet wall around its perimeter. On the day the readings were taken, the average ground depth was 8 inches (20.3 cm). On the roof, the average snow depth around the perimeter averaged 15 inches (38.1 cm) while the depth at the center of the roof was approximately 4 inches (10.2 cm).

A second type of drifting can occur due to aerodynamic shading of the leeward side of a gabled roof. This general phenomenon is illustrated by the photograph shown in

Figure 2 taken at Fort Drum during the 1976-77 winter. When a strong wind blows parallel to the ridge, it can remove most or all of the snow from the roof. However, if the wind blows perpendicular to the ridge, the windward side is unloaded while additional load is placed on the leeward side. This effect was noted for three structures during the 1975-76 winter. In all three cases, the windward side was completely unburdened of its load, while the leeward side was characterized by a uniform distribution of approximately 70% of the ground depth plus a triangular distribution, zero at the eave and equal to the average ground depth at the ridge. This wind induced redistribution of roof snow was noted by Lorenzen (Aug. 1970 and Dec. 1970) in his investigation of the collapse of farm structures in upstate New York and also by the Canadian case histories studies, Lutes and Schriever (1971) and Schriever (1967). This general effect is also taken into consideration by the present Canadian and ANSI codes.

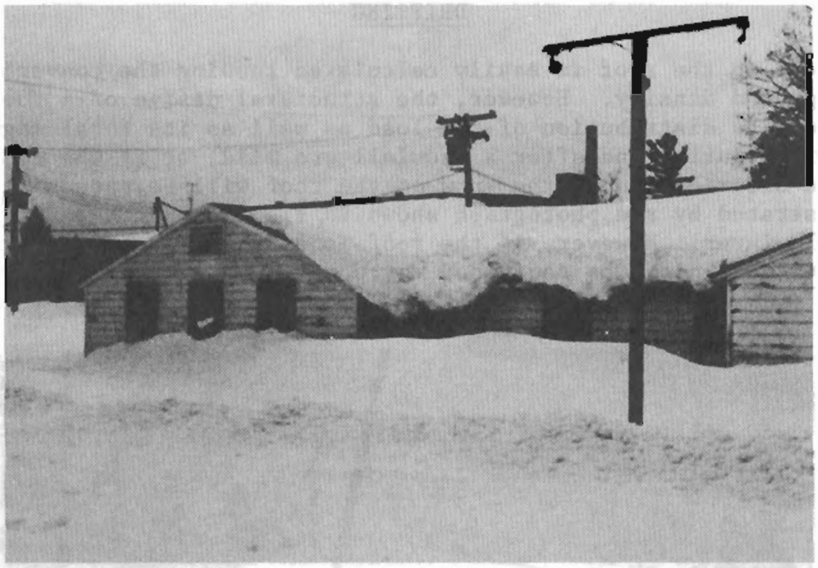

Figure 2 Nonuniform Snow Load

STRUCTURAL COLLAPSE DUE TO SNOW

A few structural failures due to snow and ice effects were observed at Fort Drum during the 1976-77 winter. The first is shown in Figure 3. This partial collapse of a bachelors' officers' quarters (BOQ) is due to the eave icing. The eave, for approximately 20 feet (6.09 m) to the right of the photograph, collapsed. Apparently heat flow through the roof of the heated BOQ caused melting of the roof snow. This water subsequently refroze at the eave, forming a 5 inch (12.7 cm) thick ice lens which extended from the edge of the building, a distance approximately 3 feet (0.91 m). If the melted snow had been prevented from accumulating at the eave, the partial collapse could probably have been avoided.

Figure 4 shows a collapsed unheated vehicle shed at Fort Drum. When the photograph was taken, a neighboring structure had approximately 2.5 feet (0.76 m) of snow covering a 4 inch (10.2 cm) layer of ice on the roof.

As mentioned previously, wind can remove snow from a roof. This is usually desirable unless the snow subsequently lands on a lower roof. This type of behavior is shown in Figure 5. In this case, the wind came from the left of the photograph, removed snow from the gabled roof, and deposited the snow on the lower porch roof, eventually causing collapse.

Figure 3 Partial Collapse Due to Eave Icing

Figure 4 Collapsed Vehicle Shed at Fort Drum

Figure 5 Collapse of Lower Level Roof

SUMMARY AND CONCLUSIONS

Sophisticated statistical procedures exist for determining, in a probabilistic sense, ground snow loads. The ratio of roof snow load to ground snow load can be quantified by the ground-to-roof conversion factor. Snow load case histories were analyzed to determine the effects of various parameters upon the conversion factor. Wind speed, wind exposure and the roof's thermal properties are shown to have a first order effect upon the conversion factor. Roof slopes less than 30° have a second order effect for shingled roofs. Examples of structural collapse due to eave icing and snow blown onto a lower level roof have been presented.

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