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Snow Loads on Roofs

Charges de neige sur les toits

Schneelasten auf Dächer

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SUMMARY

This paper examines various properties of roof snow loads with emphasis on their variability and the reliability of snow load estimates used for design. A greater sensitivity to the action of climatic and meteorological variables and the influence of the roof aerodynamics tend to result in a variability higher than that found for ground snow loads. Situations, where the combined snow and wind loadings can become significant are identified and discussed.

RESUME

L'article présente quelques propriétés des charges de neige sur les toits, leur variation et la fiabilité des prédictions utilisées pour le projet. L'influence des conditions climatiques et météorologiques ainsi que l'influence de la forme aérodynamique du toit sont plus grandes que pour les charges de neige sur le sol. Des cas sont présentés où la combinaison de la charge de neige et de vent devient déterminante.

ZUSAMMENFASSUNG

Dieser Artikel stellt Betrachtungen an über verschiedene Eigenarten von Schneelasten auf Dächer, mit Betonung auf die Variabilität der Schneelasten und die Zuverlässigkeit von Abschätzungen für die Berechnung der Tragkonstruktion. Die Einflüsse auf die Variabilität der Schneelasten durch klimatische und meteorologische Parameter und durch die Aerodynamik des Daches sind grösser, als auf dem Erdboden festgestellt werden kann. Es werden Situationen genannt und erläutert, bei denen Kombinationen von Schnee- und Windlasten massgebend werden können.

1. INTRODUCTION

Accumulations of snow can impose significant loads on buildings and structures located in cold climates. The practical importance of these loads increases for longer span roof systems as used in stadiums, arenas, skating rinks, hangars etc. and generally for buildings and structures where the roof system represents a major portion of the construction cost. Snow loads, like other environmental loads, exhibit marked variability. Not only are there large regional variations due to climatic differences but within each region considerable variations occur from roof to roof and from winter to winter. While specified design snow loads have tended to be conservative, there is ample evidence in the literature (1,2) to demonstrate the dangers which can arise from an inadequate provision.

The complications which result due to large differences in the aerodynamic, thermal, and structural characteristics of roofs are compounded by the variability of climatic effects. Design snow loads contained in most building codes are based on annual extreme ground loads, expected to be exceeded with some acceptably small probability level. While suitable for conventional buildings and structures, loads arrived at from the cumulative effects of snowfalls over some period of time are not necessarily suited for structures designed not to accumulate snow. For example, snow melting systems are commonly used to maintain air-supported roofs or skylights clear of snow. For these types of structures there is on average no snow accumulation and the extreme loading tends to be dominated by effects resulting from single extreme storms. The diversity of possible structural systems, many with unusual requirements and sensitivities to snow imposed loads, also complicates the specification of design loads with clear implications on their overall reliability.

2. CURRENT PRACTICE

Roof snow loads currently specified in most building codes (1,2) are based on measurements of ground snow depth. In this approach L_r, the design snow load on the roof is expressed as,

$$L_r = C_s L_g \tag{1}$$

where L_g is the snow load on the ground estimated for a selected return period and C_s is a snow load coefficient which relates the roof snow load to that on the ground. In Canada (1), L_g for a particular location is taken as the 30-year return period annual maximum ground snow depth converted to a load using a specific gravity of 0.192. The load corresponding to the maximum recorded 24-hour rainfall for the month during which the ground snow depth tends to reach a maximum is added to this value. Values of C_s contained in codes are based on empirical information and are selected to allow for reductions of the roof snow deposit due to the action of wind and slide-off and local increases in snow accumulation due to drift formation and in some cases the transfer of snow from higher to lower roofs by sliding. Some codes (2) also contains a factor which allows for heat losses from the building.

Although snow deposits on roofs and on the ground are influenced by the same meteorological and climatic processes, there are important differences in the details of the snow load formation (3,4,5). Generally, while the ground snow depth does represent a good measure of the snowfall and its persistence over the course of winter, it does not necessarily provide a reliable measure of snow loads formed on roofs. Despite these difficulties, the simplicity of the approach described by equation (1) is attractive, particularly since relationships between ground and roof snow loads have been improved and calibrated by extensive full-scale observation programs (6,7,8,9,10,11).

3. ALTERNATIVE METHODS

3.1 Overview

Physical scaled model tests in wind tunnels or water flumes can be used to provide information on snow deposition on roofs during particular snow storms (3,4). Unlike extreme winds effects which are caused by single events or storms, the formation of extreme snow loads, accept in relatively mild winter climates, tends to be formed by an accumulation of snow over a period of time. As a result, the magnitude of the maximum roof snow load depends on the time history of individual snowfalls and complex interaction of meteorological factors which can act to reduce, modify and, in some cases, increase snow deposits. In such situations the formation of extreme snow loads is clearly more difficult without a representative physical model. A mass balance approach has been developed to describe the snow accumulation process in terms of its basic meteorological and climatic parameters (3,4,12). In this approach, the roof snow load is taken as the running sum of incremental loads due to individual snowfalls and the depletion of the roof snow load by wind action and thermal ablation. Physical model tests are used to provide information on the deposition of snow during particular snowfalls and the depletion of the roof snow deposit by drifting. Wind is the dominate factor influencing both the magnitude and the distribution of snow deposits on roofs. During calm conditions the snow accumulation tends to be uniformly distributed with modifications due to slide-off from inclined surfaces. In the presence of wind the deposition of new snow on roofs tends to be non-uniform and snow depositions are further modified by drifting.

The influence of thermal effects are more difficult to address in physical model studies and must rely on mathematical and numerical modelling. Relatively simple approaches, using the air temperature as an index, are possible to estimate the ablation of snow due to melting and the inhibiting effects of surface melting and refreezing on the drifting action of wind.

3.2 Numerical Simulation of Snow Load Formation

A Monte Carlo computer simulation technique has been developed (3,4,12) to simulate, on a day-by-day basis, the history of the snow load on particular roofs. Repeating this simulation over a large number of winters, provides statistical information on snow load extremes required in design. Suitable statistical models of such climatic variables as the depth and water equivalent of the daily snowfall, the wind speed and wind direction, and the atmospheric temperature used in the simulation are given elsewhere (3,4,12).

A Weibull distribution has been found to provide a good statistical model of daily snowfall depths S. Here the probability of exceeding a particular value of S during a particular month denoted by t and in the general form including the dependence of the daily snowfall on the direction of the wind during a snow storm is of the form,

$$P\,(>S,t,\theta) \;=\; m\,(t,\theta)\, exp - \;\{S/C\,(t,\theta)\}^{K\,(t,\theta)} \qquad (2)$$

Here $P\,(>S,t,\theta)$ is the probability of exceeding a daily snowfall depth of S during month t and during wind conditions with a wind direction θ, and $m\,(t,\theta)$ is the expectation of snowfall during month t and $C(t,\theta)$ and $K(t,\theta)$ are Weibull parameters for the same month and wind direction. The parameter K generally is less than 1.0 and does not vary significantly over the course of the winter. The parameter C is a measure of the magnitude of the snowfall. The expectation m provides a measure of the length of the snowfall season and tends to peak near mid-winter. All three parameters tend to vary regionally. Either continuous or sector-by-sector variations of the parameters can be used. Typical probability distributions of the daily snowfall during snow storms associated with different wind directions are indicated in Figure 1. The distribution for Ottawa includes the entire winter, that for Chicago is for the month of January. The probability of exceeding a particular snowfall amount varies markedly with wind direction. This is not unexpected as the local snowfall tends to be highly sensitive to the local geography. The pronounced easterly lobe for Chicago reflects the influence of Lake Michigan.

The water equivalent of new snow used in the Monte Carlo simulation so far has been based on the analysis of daily precipitation data. A summary of the mean water equivalent of new snow and its dependence on the average daily air temperature is given in Figure 2. The average water equivalent is approximately around .1 with coefficients of variation, depending on location, ranging in the order of 20 to 50%.

3.3 Relationship Between Roof and Ground Loads

Snow loads on roofs on average tend to be significantly lower than those on the ground. Nevertheless, in certain circumstances larger than ground snow loads can be experienced on roofs. Figure 3 provides a summary of the daily roof snow load expressed as a ratio of the corresponding ground load. These results are from a Monte Carlo simulation for exposed flat roofs. The average value of L_r/L_g or the roof snow load coefficient C_s, on a daily basis, is seen to be of the order of 0.3 and less. The variability of L_r/L_g for one of the stations is shown for ground snow loads which corresponds to about .5 and .9 of the 30-year extreme value. The distributions are highly skewed and C_s, on a day-to-day basis, occasionally exceeds 1.0 (see the histogram given for $L_g/L_g\,(30) = 0.5$). This is consistent with available field observations which suggests that the roof snow load can in certain circumstances exceed that on the ground.

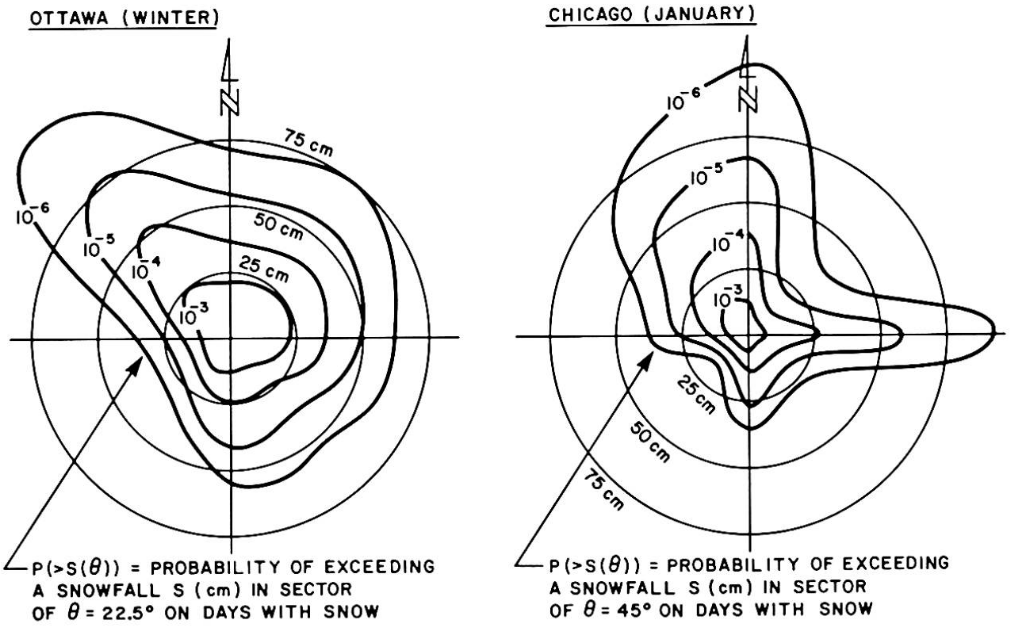

Fig. 1 **Probability Distribution of Daily Snowfall During Wind Conditions Associated With Differnt Wind Directions**

General trends observed for annual maxima, obtained from a Monte Carlo simulation for exposed flat roofs, are as follows:

i) Annual maximum roof and ground snow loads rarely occur on the same day.
ii) Maximum roof load tends to be well below those on the ground.
iii) The correlation between the annual maximum roof and ground snow loads tends to be small. Typical correlation coefficients using a linear relationship tend to be generally less than .5 which is consistent with full-scale observations.
iv) The relationship between the extreme roof and ground snow loads is influenced by the statistical properties of local snowfall, air temperature, wind speed and wind

direction climates. Extreme roof snow loads tend to be least in comparison with those on the ground for locations with well-below-freezing temperatures and where the ground snow load represents the accumulation of a large number of relatively small snowfalls. The ratio of roof-to-ground snow loads on the other hand tends to be largest for relatively warm winter climates where a few events dominate the entire winter snowfall.

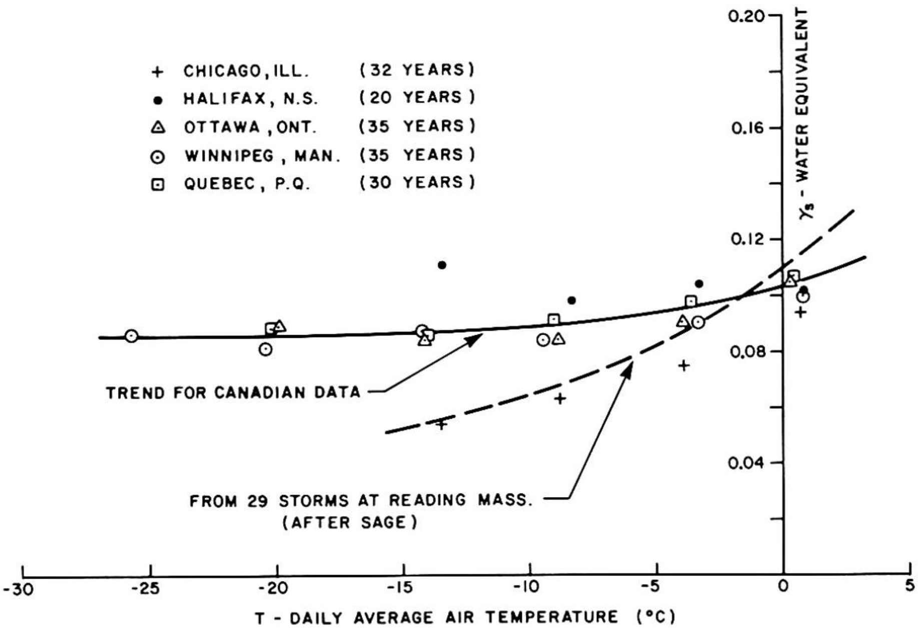

Fig. 2 Mean Water Equivalent of New Snow and Its Dependence on Temperature

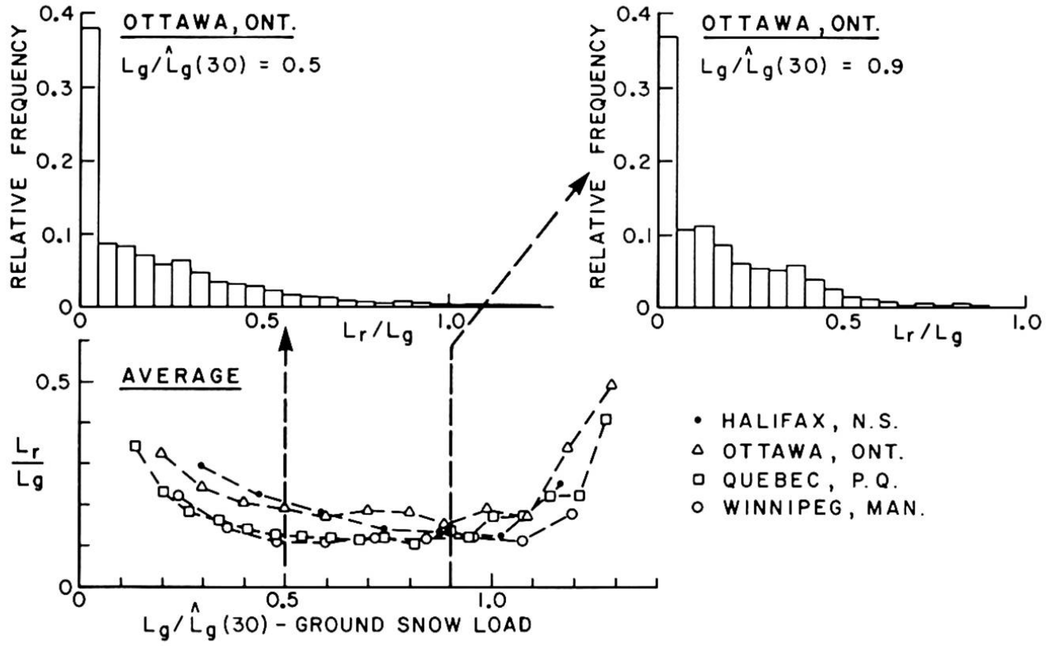

Fig. 3 Ratio of Daily Roof Snow Load to the Ground Loads; From Monte Carlo Simulation for Exposed Flat Roofs

4. VARIABILITY

The variability of roof snow loads is consistently greater than that of the ground snow load. This is illustrated by the results of Monte Carlo simulations of extreme loads on the ground and on flat roofs, seen in Fig. 4. A Type I extreme value distribution is used to fit the extremes. To improve the comparison, the annual extremes have been normalized by their respective modal value. The coefficients of variation of the annual maximum ground and roof snow loads are respectively about 0.26 and 0.57. Coefficients of variation of the annual and lifetime extreme ground and roof snow loads are shown in Table 1 for 4 locations. The individual annual extremes in this analysis are taken to be independent and the lifetime M is taken as 30 years. Large differences in the coefficients of variation are seen particularly for the annual extremes.

Treating the roof snow load coefficient C_S in equation 1 as an independent random variable, provides an estimate of its coefficient of variation in terms of V_{L_r} and V_{L_g} (see equation 3). A load factor, defined as the ratio of the design roof snow loads to its 30-year expected value can be expressed as shown in equation 4. Values of the coefficient of variation of C_S and the load factor γ are given in Table 2 for exposed flat roofs based on a lifetime of 30 years. The values of C_S are in the order of 15 percent and the load factors are comparable to the value of 1.5 specified for limit states design in the Canadian National Building Code (1). A greater variability and hence larger values of γ are expected for more complex roof shapes.

$$V_{C_S} \simeq (V_{L_r}^{\;2} - V_{L_g}^{\;2})^{\frac{1}{2}} \tag{3}$$

$$\gamma = \frac{L_{r_{design}}}{L_{r_{expected}}} = exp\,(1.65\ V_{L_r}) \tag{4}$$

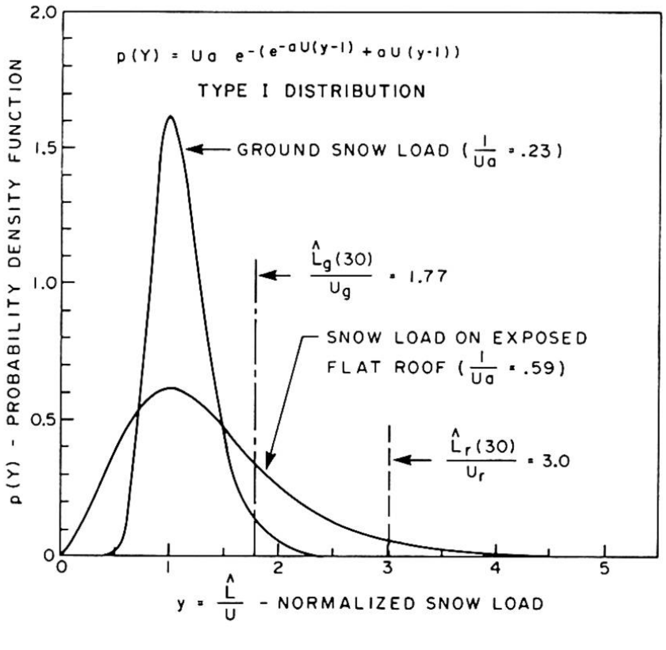

Fig. 5 **Typical Extreme Value Distributions of Ground and Roof Snow Loads; From Monte Carlo Simulation for Exposed Flat Roofs**

4.1 Duration of Snow Loads

The simulated time histories of snow loads allow an analysis of the duration associated with particular load magnitudes. In this case the duration is taken as the uninterrupted dwell time associated with a particular exceedance of a load level. As a first approximation, the duration of a particular snow load level can be taken to follow an exponential distribution as given in equation 5. Here a is a parameter of the distribution equal to its mean value and its standard deviation. Estimates of the duration of ground and roof snow loads corresponding to their respective 30-year return period values were estimated for exposed flat roofs at several locations. As one would anticipate, the durations of roof snow loads tend to be well below those of the ground loads. For the Halifax, Ottawa, Quebec City and Winnipeg areas, the average durations of the 30-year return period ground snow loads are found to be 18, 14, 13 and 33 days, respectively. The corresponding durations of the 30-year roof snow load, however, were found to be about 9, 10, 10 and 19 days respectively. A shorter exposure to the design load is seen to be a distinct advantage.

$$P(> T) = e^{-aT} \tag{5}$$

4.2 Joint Action of Snow and Wind Loads

Available climatic information indicates that occurrences of extreme wind and snow loads can be treated as statistically independent events. As a result, it is reasonable to use a joint action or load combination factor in situations of combined loading. This allows for the reduced likelihood of a simultaneous occurrence of an extreme wind and snow load. A value of 0.75 for this factor as used by NBC (1), is not inappropriate.

Generally wind and snow loads on roofs tend to act in opposite directions and some aerodynamic insight is required to identify situations where these loads can be additive. Some schematic representations of combined snow and wind loads are shown in Fig. 5. While cases ii) and iii) would normally be recognized, the possibility of experiencing positive or downward acting wind pressures on low roofs adjacent to a taller building tends to be overlooked. This can be an important load case as large snow drift deposits can accumulate near changes in elevation. Finally, the combined action of snow and wind tends to accentuate load non-uniformities and can be important for structures sensitive to unbalanced loadings.

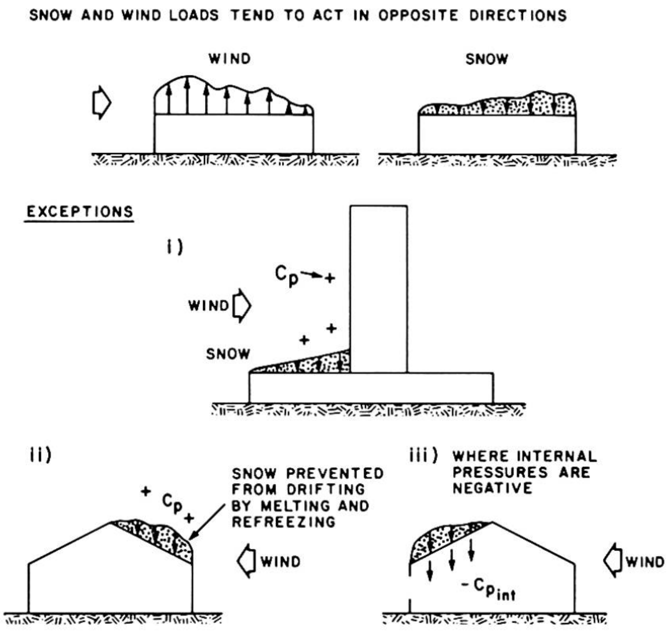

Fig. 5 Combined Snow and Wind Loads on Roofs

5. CONCLUSIONS

The emergence of new types of structural forms for longer-span roof systems necessitates a review of existing snow load design procedures which may not be fully suited for these new systems. An alternative design approach, using a Monte Carlo simulation of the winter climate, has been used to examine the characteristics of snow loads on flat roofs located in cold and moderately cold winter climates. Statistical descriptions of the various meteorological variables, required in the computer simulation are generally available. This, combined with a growing body of full-scale data is expected to lead to improvements in the reliability of design snow loads.

TABLE 1
Coefficients of Variation of Simulated Annual and Lifetime Extreme Snow Loads on Exposed Flat Roofs at Several Locations

	Annual Extremes		Lifetime Extremes (M = 30)	
Station	V_{L_r}	V_{L_g}	$(V_{L_r})_M$	$(V_{L_g})_M$
Halifax, N.S.	0.65	0.55	0.24	0.21
Ottawa, Ont.	0.54	0.34	0.22	0.18
Quebec City, P.O.	0.51	0.30	0.21	0.16
Winnipeg, Man.	0.58	0.31	0.23	0.17

TABLE 2
Coefficients of Variation of C_S and Load Factors for Lifetime Extreme Roof Snow Loads; Exposed Flat Roofs (M = 30 Years)

Station	V_{C_S}	Load Factor γ
Halifax, N.S.	.12	1.49
Ottawa, Ont.	.13	1.44
Quebec City, P.Q.	.14	1.41
Winnipeg, Man.	.15	1.46

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