Prediction of Snow Loading on Large Snow Roofs

S.L. GAMBLE, W.W. KOCHANSKI AND P.A. IRWIN
Rowan Williams Davies and Irwin, Inc.
650 Woodlawn Road West
Guelph, Ontario N1K 1B8, Canada

ABSTRACT

The application of a finite area element (FAE) computer snow accumulation simulation technique to provide insight into the magnitude of snow loading on roofs with dimensions greater than 75 metres is discussed. The intent of this work, which was funded by the Canadian National Research Council, was to provide information on which extensions to the Canadian National Building Code could be based. The work indicated that as the roof size increased the peak snow loading on flat roofs approaches the ground snow load. The roof size at which peak loading equals the ground load was found to be dependent on the level of exposure to wind. Some results for roof step loads are also presented.

INTRODUCTION

The National Building Code of Canada (NBCC) provides minimum design loads for roofs. The load provisions try to allow, in a simplified generic way, for a number of factors. These include: the effects of climatic differences in the various regions of Canada, as indicated by ground snow load; the removal of snow from roofs by wind action; the unbalanced, or nonuniform, snowloads that are caused by snow drifting; the reductions or increases in snow loads that occur due to sliding of snow on sloped roofs; and the added load caused by rain absorbed by the snowpack.

Historically the snow loads in the NBCC have been based on statistical analysis of field observations made on a variety of roofs (e.g. Schriever, 1967). Because snow loads depend on so many cumulative factors (snowfall, drifting for different wind directions and speeds, melting, rainfall etc.), and because of analytical and modelling difficulties, this approach has been preferred to analytical methods or to scale model tests. A major disadvantage of this approach is that the process of acquiring the necessary field data is laborious, taking many years and an inevitable result is that there remain many gaps in the data. This has created substantial difficulties for those endeavouring to develop improvements to the code's snow load provisions.

In recent years, as a result of continuing efforts to develop better analytical, computational and model test methods, there have been some significant advances made in these areas (eg. Gamble 1991). These advances are significant enough to make these types of methods a useful supplement to the field data approach in that they hold out the promise of filling in many of the gaps in the field data. In particular, the Finite Area Element (FAE) method (Irwin 1988) has been developed. In this approach computational methods are used to simulate snowfall, snow drifting and melting in a time history fashion on the roof of concern.

A study, funded by the National Research Council of Canada, was carried out in which the FAE method was used to examine the effect of roof size on the 30 year return period snow loads. Attention focused on flat, square planform roofs ranging from 10m to 500m side lengths. Current code provisions are based on field observations on roofs of less than 75m length. The primary objective of the study was to provide a means of extrapolating beyond the 75m limit. A further objective was to provide some guidance on how snow loads in a roof step increase with the size of the upper level roof.

FACTORS AFFECTING THE ACCUMULATION OF SNOW ON A ROOF

The initial arrival of snow on a roof is the result of snow that falls during snowstorms. After or during a snowfall the snow is frequently redistributed by wind action and, depending on wind direction and how roof shape influences the wind flow patterns over it, heavy buildups can occur in some areas while others are scoured clear. In some areas significant increases in load occur when rainfall soaks into an existing snowpack.

Snowdrifting, through a process called saltation, is considered to be the greatest cause of mass transfer from one area of a roof to another. The rate of snow mass transfer depends on the local wind velocity just above the snow surface. Once the drift rate and drift direction is known then variations in snow load over the roof can, in principle, be predicted as a function of time.

Decreases in snow load occur during periods of melting. The melting of snow is a complex phenomenon affected by air temperature, wind, direct short wave solar radiation, indirect radiation, long wave radiation and latent heat transfer.

The groundwork for this simulation approach was laid out by Isyumov (1971) for estimating roof loading although redistribution of the snow through drifting was not accounted for and melting of the snow pack was incorporated in a simplified manner. The present technique discussed in this paper incorporates a drifting mass flux expression derived from the work of Dyunin (1963) and Kiobayashi (1973) and a detailed heat balance on the snow pack based on the approach laid out in the ASHRAE Fundamentals Handbook (1985) which includes the effects of air temperature, wind speed, building internal temperature, roof insulation, snow pack age and direct and indirect solar radiation transfer.

PREDICTION OF SNOW ACCUMULATION ON A ROOF

In order to predict the snow accumulation on a roof, a **Finite Area Element** model of the drifting on the roof surface is set up. The entire FAE approach is described in greater detail by Irwin (1988). However, a brief explanation of the major steps involved follows.

Essentially a roof is divided into elemental areas by a grid system as shown in Figure 1. A typical area element is illustrated in Figure 2. From the predicted wind velocities at a height of 1m (full scale) above the roof at the four corners of each elemental area, the snowdrift fluxes across the four sides of the element are computed. Thus, for a given time interval, which is generally selected to be one hour, the increase or decrease in the mass of snow in each elemental area, as a result of drifting, can be computed.

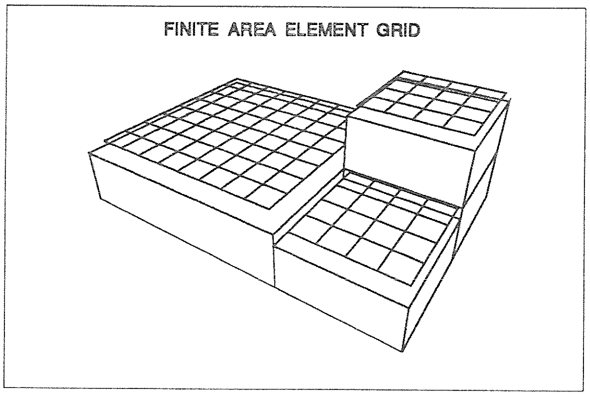

Figure 1: Orthogonal Grid System

From meteorological records for snow fall, the amount of snow falling onto an element in a given one-hour interval can be estimated. Likewise, meteorological records for temperature, when combined with solar radiation data and building heat loss data, determine the melting rate for the snow in the element. By stepping through the meteorological data in one-hour intervals, the increase in snow load as a result of snowfall, the redistribution of load by drifting, and the reductions in load from melting, can be evaluated in a detailed manner for all elements comprising the

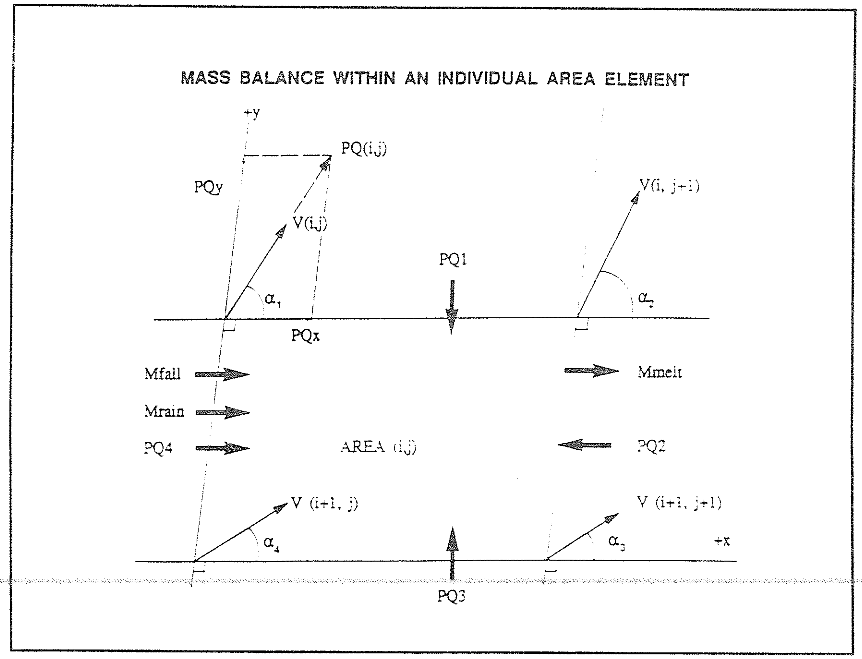

Figure 2: FAE Element

grid. For data such as snow fall which are often not recorded hourly, less frequent measurements are interpolated to give hourly estimates based on light, medium or heavy flags or evenly distributed over the interim period if flags are not available. Since the peak loading on a roof in any year is generally the result of the entire sequence of events leading up to that point in time, this interpolation is expected to be insignificant to the final result.

The entire history of events in each element is computed for the number of years of meteorological records available for the study city. Critical load conditions, such as maximum overall snow load on a roof of the structure or maximum snow load in each elemental area (bay), can then be examined in detail.

APPLICATION OF METHODOLOGY TO STUDY EFFECT OF ROOF SIZE

To study the effect of roof size on the accumulation of snow, five different square roof sizes were selected with side lengths ranging from 10m to 500m assumed to be at a height of 10m above the ground. An orthogonal grid system with varying area element size was laid out for each of the 5 different roof sizes. Large, low rise, flat roof structures are generally supported at variable spacing by columns. Typically, for very large roofs, a roof bay supported by columns, spaced 20m apart, appears to be common. For the purposes of this study, the 20m x 20m bay size was selected as being typical for a given roof size. Smaller bay sizes were also evaluated.

The roof structures were evaluated as if they were located in an open and a suburban exposure. Local wind speeds near the roof surface were assumed to be uniform over the entire roof. In this way a large buildup of snow in any element could not be attributed to changes in velocity (i.e. such as the creation of a dead air zone) and thus leaving roof size as the primary consideration.

Montreal, Quebec and Edmonton, Alberta were the select cities for these studies. Montreal was picked for its generally high snowfall in a temperate climate, while Edmonton was selected as having moderate snowfall in a generally cold climate. For each city, 33 years of meteorological data records were available. These data bases were used to create one-hour records of mean gradient wind speed, wind direction, air temperature, snowfall, rainfall, cloud cover and cloud opacity.

In order to provide a calibration of the computer simulation on the different roofs for each city, a ground snow load case was run to compare with the ground snow load value provided by the 1990 National Building Code of Canada (1990 NBCC).

For the City of Montreal, the 1990 NBCC specifies a 30 year ground snow load of 2.2 kPa with a rain load of 0.4 kPa. It should be noted that the computer simulation includes the effect of rain and also meltwater retained within the snowpack. The inputs to the computer program were set up to calculate the accumulation of snow on a horizontal piece of ground with no drifting effects (i.e. wind speed equal to zero). The amount of liquid water that was allowed to remain within the snow pack was adjusted until the 30 year predicted ground snow load matched that stated by the NBCC for Montreal. The results, presented in Figure 3, show an extreme value plot of 33 years of simulation for Montreal and predicts the 30 year ground snow load to be 2.6 kPa. Through this calibration procedure, the appropriate water retention factor was found to be an additional 60% of the solid water mass.

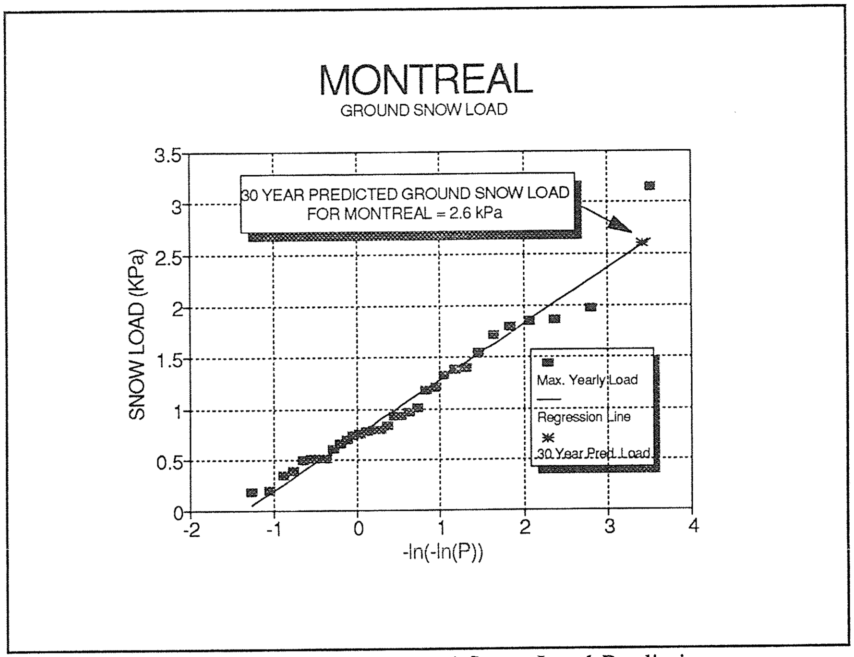

Figure 3: Montreal Ground Snow Load Prediction

For the City of Edmonton, the 1990 NBCC specifies a 30 year ground snow load of 1.6 kPa with a rain load of 0.1 kPa. The results for Edmonton are also presented in Figure 4. This figure shows an extreme value plot of 33 years of simulation and predicts the 30 year ground snow load to be 1.7 kPa. It was found that results for Edmonton were relatively insensitive to the assumption regarding how much liquid water the snowpack can retain.

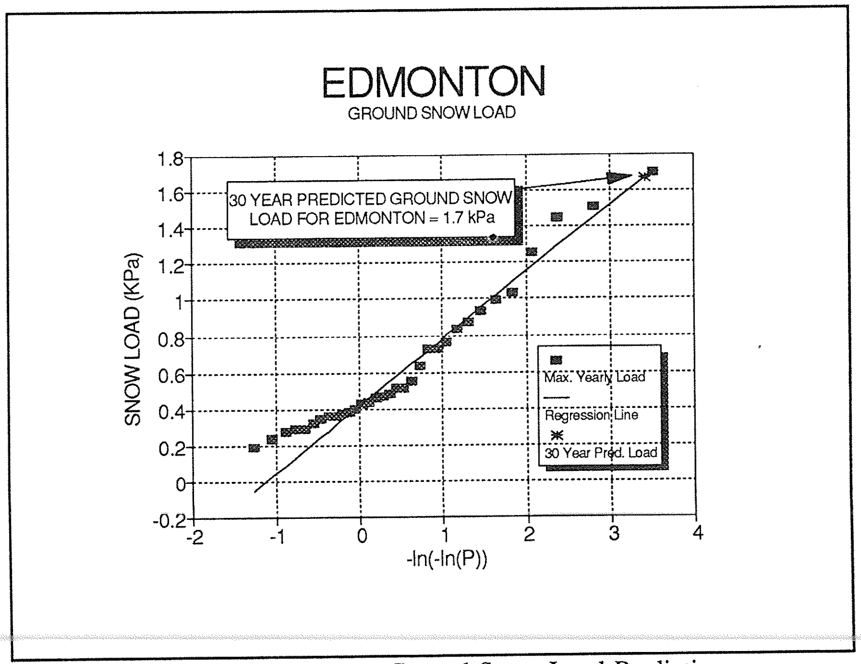

Figure 4: Edmonton Ground Snow Load Prediction

RESULTS OF ANALYSIS

The computer simulation steps through the meteorological data beginning at September 1 of each year and ending at May 31 of the following year determining the total quantity of snow on the roof at each hour. The computer stores the data for each hour which results in a time history of the snow load on the roof for the year. For illustrative purposes, the time history data of the snow load on the 100m x 100m roof (element size of 20m x 20m) was plotted for several winters.

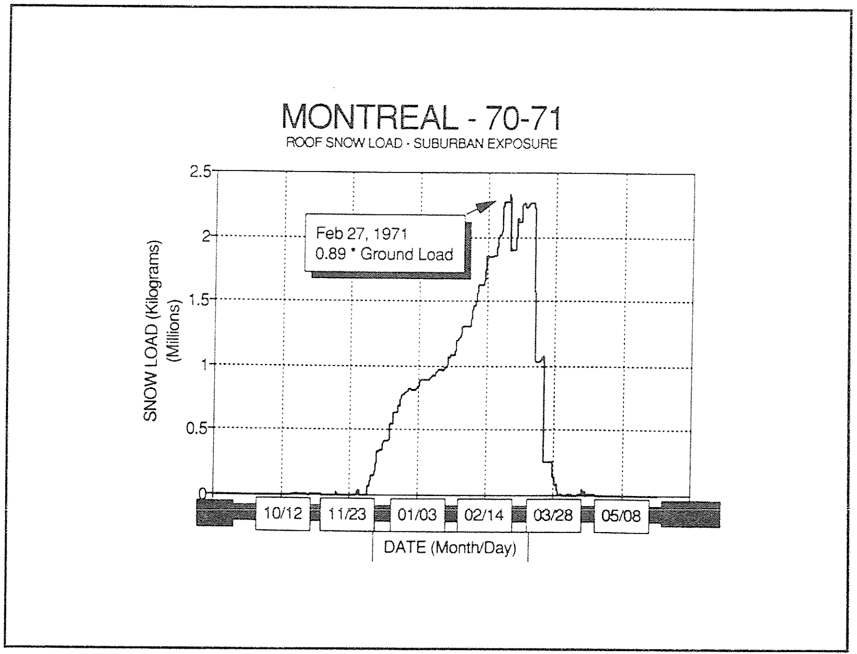

Figure 5: Time History - Overall Roof Snow Load - 100m x 100m Roof

For Montreal, time histories for the winters of 1970-71 and 1973-74 (suburban exposure) are shown in Figures 5 and 6. On the plot in Figure 5, there are a number of consecutive snowfalls starting around the beginning of December 1970 occurring on a continuous basis resulting in a constant accumulation of snow on the roof until a maximum is reached on February 27, 1971. The winter of 1973-74, shown in Figure 6, shows moderate accumulations and subsequent depletions of snow typical of an average winter.

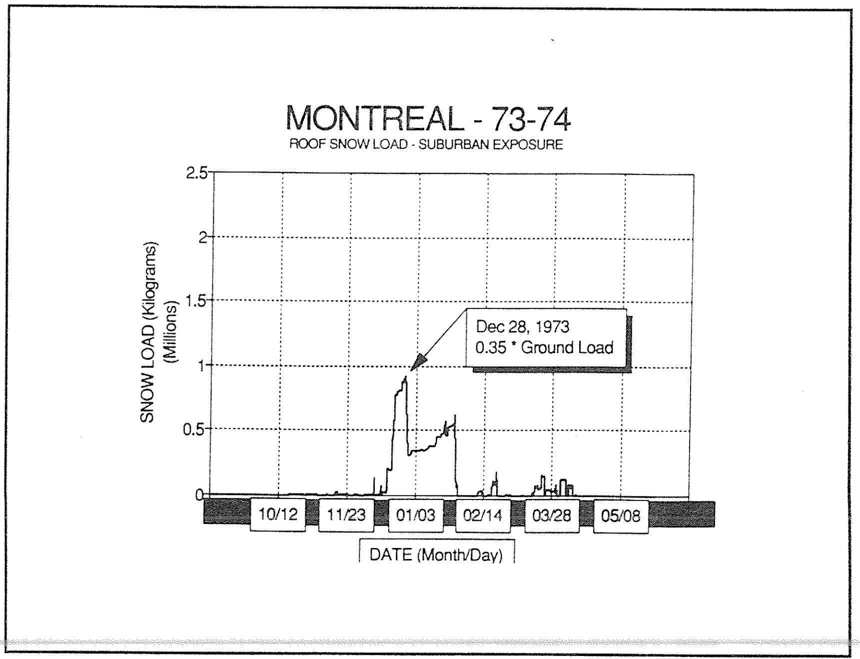

Figure 6: Time History - Overall Roof Snow Load - 100m x 100m Roof

For Edmonton the winter of 1973-74 (suburban exposure) was chosen for illustration. In Figure 7, representing the overall roof snow accumulation, snow began to fall around the middle of November 1973. Possibly because it was a cold winter, subsequent snowfalls kept building up the accumulation of snow on the roof until a maximum was reached on February 6, 1974. Almost immediately following, a warming trend reduced the snow accumulation significantly over a short period of time. A similar time history plot is shown in Figure 8 for the individual roof element with the highest accumulation of snow during the winter of 1973-74.

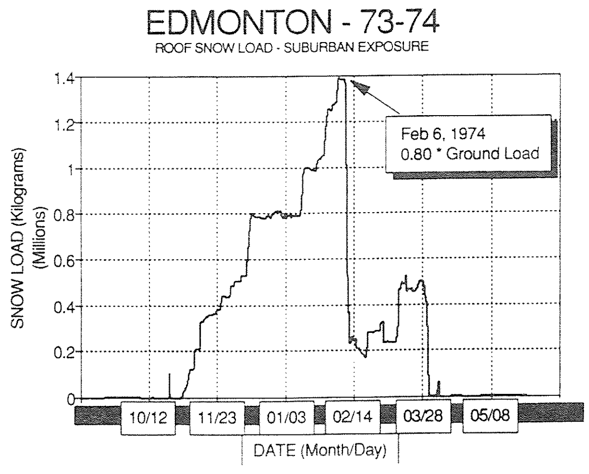

Figure 7: Time History - Overall Roof Snow Load - 100m x 100m Roof

As the snow drifts across a roof each of the area elements experiences either increasing or decreasing snow load. This is highly dependent on the wind speed given in the hourly meteorological records. With wind blowing from one direction the snow will tend to drift towards the downwind end of the roof. As the wind then shifts to another direction the snow begins to drift in that direction. This therefore creates an uneven distribution of snow on the roof at any particular instant in time.

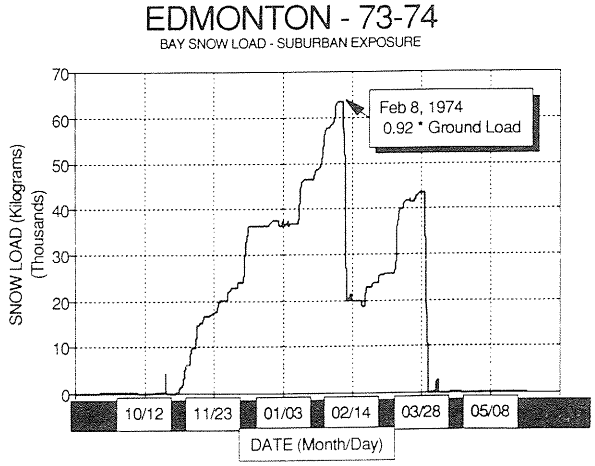

Figure 8: Time History - Snow Load on 20m Bay - 100m x 100m Roof

INTERPRETATION OF RESULTS

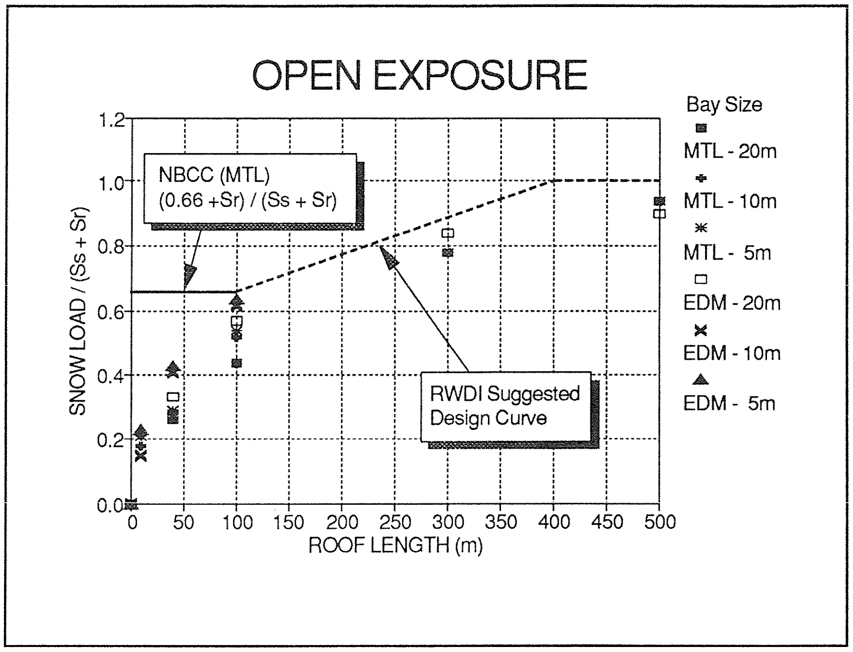

Figure 9: Recommended Design Snow Load Comparison

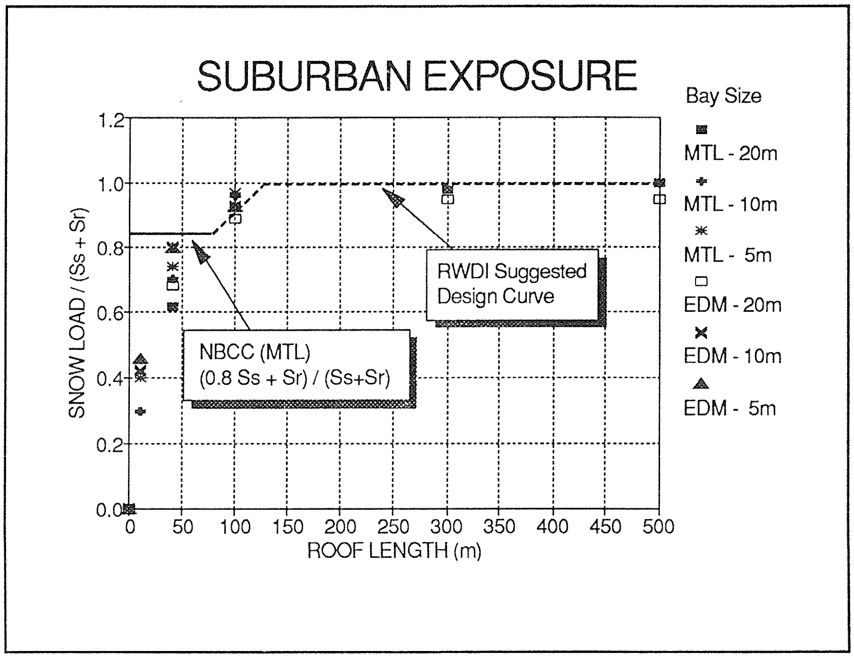

Figure 10: Recommended Design Snow Load Comparison

Montreal and Edmonton are two cities with substantially different climates. Where Montreal is a city with moderate temperatures and heavy snowfall, Edmonton is a city with a cold climate and less snowfall. Yet some parallels can be drawn between the cities when it comes to predicting snow load on roof structures. The computer simulation predicted substantially higher snow loads on a typical 20m x 20m roof bay in Montreal than in Edmonton. However, after these snow loads have been normalized by dividing by the ground snow load, $S_o = S_s + S_r$, for their respective cities, the results for both cities are very similar. When the normalized snow loads for both cities are plotted on one graph, one can see this pattern. This is shown in Figure 9 for the open and suburban exposures. Results for a variety of bay sizes from 5m to 20m are included. Generally, the results up to a 75m long roof are below the 1990 NBCC recommended snow load values for the suburban exposure. However, for roof sizes greater than 75m, the snow load on a roof increases until, when the roof length is 125m, it is close to ground load. For an open exposure, the results indicate that for a roof under 100m or so in length the 1990 NBCC snow load value is adequate. Thereafter the roof bay snow load gradually approaches the ground snow load.

In Figure 10 an upper bound envelope has been drawn on the plots for the purpose of providing a guideline for designing roof bays on large roofs. For simplicity, the envelope has been made linear. For the suburban case, the 1990 NBCC snow load values appear adequate for roofs up to 75m in length. After that point the guideline envelope increases linearly to 1.0 corresponding to roof lengths of approximately 125m. A snow load of 1.0 times the ground snow load (S_o) is recommended for any roof size greater than 125m. For the open exposure, the 1990 NBCC recommended snow load can be used up to a roof length of 100m. After this point, the upper bound snow load increases linearly until it reaches 1.0 x S_o at a roof length of 400m. Thereafter the recommended snow load is 1.0 x S_o. For the case where there is no wind, it is recommended that the design snow load be 1.0 x S_o.

EFFECTS OF ROOF SIZE ON ROOF STEP ACCUMULATION

Embarking on a continuing investigation of the effects of roof size and roof exposure, simulations were run in which the snow from the various sizes of roofs used previously which drifted off of the roof edges was collected and examined. This produced some preliminary results which are briefly discussed.

The results are presented in Figure 11 and compared with the 1990 NBCC and the ASCE 7-88 Standard (American Society of Civil Engineers - Minimum Design Loads for Buildings and Other Structures) for step snow loads. In addition, data from an actual case study on the Jordan Marsh facility in Squantum, Massachusetts was scaled and plotted in this figure. The Jordan Marsh facility experienced considerable snow accumulation in a roof step in 1978 that eventually caused a roof failure. The peak snow load recorded at the failure point was 287 psf (13.8 kPa).

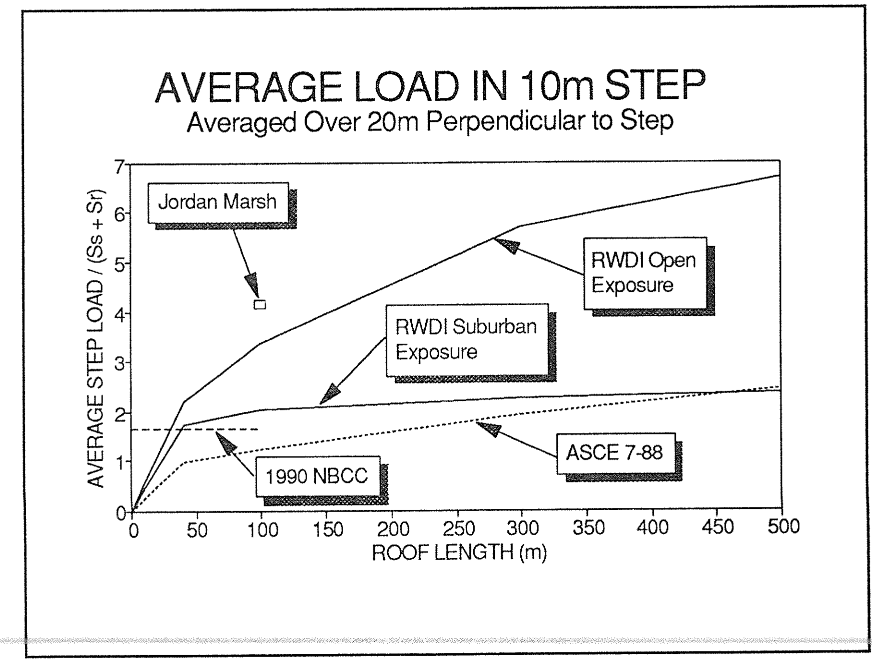

Figure 11: Step Load Comparison

Generally, the plots in Figure 11 indicate that, in suburban terrain, the results for the 1990 NBCC and the ASCE 7-88 Standard are slightly lower than that predicted by the computer simulation. Part of this may be due to the fact that all snow drifting off the roof as modelled in this simplified computer simulation collects in the step below, whereas, in reality some snow may not be captured in the step. The Jordan Marsh facility, which is set in an open terrain, located almost adjacent to a large body of water, is similar to the result of the computer simulation for an open terrain.

CONCLUSIONS AND RECOMMENDATIONS

1) As roof size increases, the 30 year predicted snow load for a roof bay approaches the ground snow load, $S_o = S_s + S_r$.

2) In a suburban exposure more snow is retained on a roof than if the roof is in an open exposure and the snow load approaches the ground snow load much more rapidly as roof size increases.

3) The 1990 NBCC calculated roof snow loads are in general agreement with or above the computer simulation results for roof lengths up to 75m. For roof sizes greater than 75m the simulation indicates that the roof snow loads on a bay are greater than the code calculated value and approaches the ground snow load, S_o, for larger roof sizes. This conclusion does not allow for heat transfer through the roof which, if included, would reduce the computer simulation loads.

4) It is recommended that the straight line envelopes in Figures 9 and 10 be used as a guideline for determining how the snow loads on roofs increase with roof size. These imply using current code provisions for roofs up to 75m and 100m long in respectively suburban and open terrain. Thereafter the load should be increased linearly until it reaches full ground load, S_o, at roof lengths of respectively 125m and 400m. Again, this conclusion would be modified if heat transfer effects are included.

5) As far as the code provisions are concerned there are several coefficients through which roof size effects could be incorporated. These are the basic roof snow load factor, C_b, the wind exposure factor, C_w, and the accumulation factor, C_a.

6) The results of a comparison of snow accumulation on a lower surface (i.e. roof step) is shown in Figure 11. This figure shows that for a roof in a suburban exposure the computer simulation results and the 1990 NBCC and ASCE 7-88 Standard results are comparable.

REFERENCES

1) ASHRAE Handbook, 1985 Fundamentals.

2) Dyunin, A.K., 1963, "Solid Flux of Snow-Bearing Air Flow", NRC Technical Translation, TT-1102, from Trudy-Transportno-Energicheskoko Institute.

3) Gamble, S.L., Kochanski, W.W., Irwin, P.A., 1991, "Finite Area Element Snow Loading Prediction - Applications and Advancements", Proceedings International Conference on Wind Engineering, London, Ontario, Canada - July - In Preparation

4) Irwin, P.A., Gamble, S.L., 1988, "Predicting Snow Loading on the Toronto SkyDome", Proceedings of First International Conference on Snow Engineering, Santa Barbara, California, July.

5) Isyumov, N., 1971, "An Approach to the Prediction of Snow Loads", Ph.D. Thesis, Faculty of Graduate Studies, University of Western Ontario, London, Ontario, Canada.

6) Kobayashi, D., 1973, "Studies of Snow Transport in Low-Level Drifting Snow", Institute of Low Temperature Science, Sapporo, Japan, Seriesa, January.

7) Shriever, W.R., Faucher, Y., Lutes, D.A., 1967, "Snow Accumulations in Canada Case Histories: I", National Research Council of Canada, Division of Building Research, Technical Paper No. 237, January.