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PARAMETRIC SIMULATION OF ROOF STRUCTURAL SNOW LOADS

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ABSTRACT

While the National Building Code of Canada (NBCC) provides engineers with suitable snow loading guidelines for structural design, the strict application of the code may not lead to an optimized structural design. Generalizations have been made to ensure the applicability of the code to the majority of potential structures within Canada, which result in conservative estimates in certain situations. In particular, the interaction between region-specific prevailing wind directionality, climate and roof orientation are not accounted for. However, the development of advanced physical and numerical snow simulation approaches allows for the investigation of building-specific variables that affect snow loading. The Finite Area Element (FAE) process simulates the hour-by-hour accumulation and depletion of snow on a specific building design. This tool provides detailed quantification of the probabilistic snow loading accounting for region-specific long term meteorological conditions and building-specific variables such as roof size, exposure to prevailing winds, thermal capacity and local aerodynamics. While providing a detailed assessment of the snow loads, a full FAE assessment can be both time consuming and relatively costly for many applications. This parametric analysis approach has been developed using a variety of simple building geometries to provide an approach to assess the relative impacts of many of the key variables needed to inform a design. This paper describes the physical and numerical models used for the parametric simulation of snow loads, and discusses their application to structures within Canada.

Keywords: Snow Load, Snowdrift, Wind Tunnel, Wind

1. INTRODUCTION

Snow loading guidelines are provided in many building codes and standards, and are meant to be conservative to cover a wide range of possible design scenarios. Alternative methods for characterizing design snow loads for a specific building geometry and meteorological climate are accepted by most building codes and standards, for example the National Building Code of Canada (NBCC) and the America Society of Civil Engineers (ASCE) standard. Such methods include the use of water flume wind and snow simulations and wind tunnel based finite area element modelling, which have been shown to provide reliable snow load estimates (Gamble 1992 and Irwin 1983).

Of the snow loads recommended by the NBCC, roof surcharge snow loads tend to be the most significant and have a large impact on the overall design of the structural system. This paper investigates the relationship between roof step orientation of a typical building and the local meteorological climate to provide snow load reduction coefficients that can be reliably applied to reduce roof step snow surcharge loads.

2. PARAMETRIC ROOF STEP SIMULATION MODEL

2.1 Model Description

The dependence of snow surcharges on both meteorological climate and building orientation was analyzed using three typical building models featuring roof steps of 3 m, 9 m and 30 m height. Each model has identically sized large upper and lower roofs, as shown in Figure 1. The effect of building orientation was evaluated by rotating each building for 16 equally incremented compass directions relative to the meteorological climate. The geometry and intent of this model is similar to the scale model building used by Tsuchiya et al, 2002.

Three corresponding numerical FAE models were created to simulate the hour-by-hour deposition, drifting, and melting of snow and absorption of rain and melt water into a snow pack within a grid system that divides the roof into a large number of finite areas. 1:300 physical scale models of the three roof step models were instrumented and tested within a boundary layer wind tunnel using a standard suburban wind velocity and turbulence profile to obtain the required aerodynamic flow patterns. Entire winters were simulated on an hour-by-hour basis, including the cumulative effects of successive storms, drifting events and melting periods. Specific methodology and applications of the FAE method are described in: Irwin and Gamble 1988 and Gamble et al. 1992.

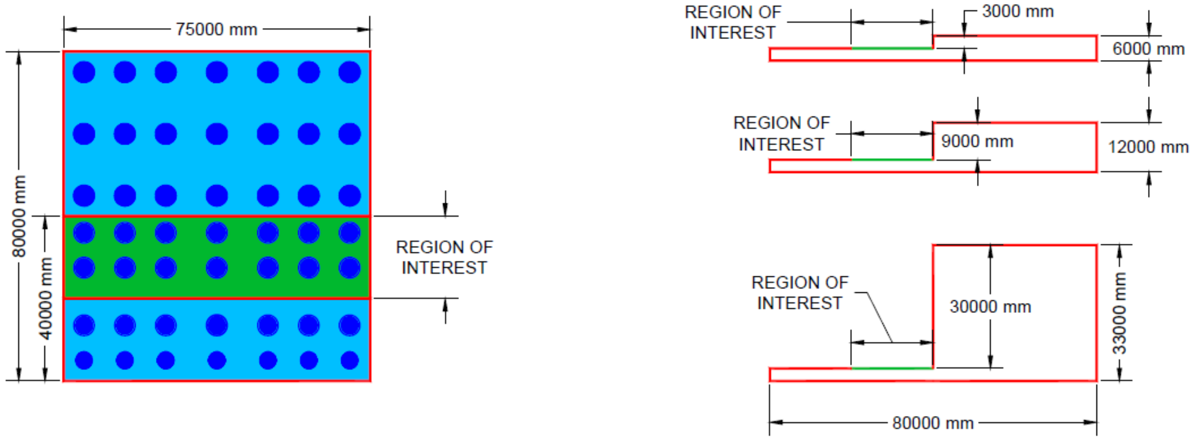

Figure 1: Plan and elevation views of the parametric model buildings. Dimensions are given in full-scale millimeters. Dark blue circles indicate the location of wind tunnel sensors.

2.2 Directional Sensitivity of Building Orientation to Meteorological Climate

Meteorological data from 25 cities across Canada were processed using the three roof step FAE models for each of the 16 equally incremented building orientations for a total of 1200 unique snow load design scenarios. The area averaged snow load within the roof step was determined on an hour-by-hour basis and used to determine each peak annual maxima within the meteorological data set under investigation, and the 1 in 50 year mean recurrence snow load derived using a Fisher-Tippet Type 1 fit. This simulation and analysis process was completed for each of the 16 building orientations and for each roof step height. The building orientation which exhibited the largest load was used to normalize each of the remaining test orientations. The normalized snow load values were plotted to determine the relative sensitivity of the building to the climate. For comparison purposes, key examples of representative meteorological climates are presented, including London, Toronto, Quebec City and Vancouver.

The left image in Figure 2 presents the normalized snow load for each of the 16 building orientations investigated based on meteorological data recorded at London International Airport for each of the three building roof step heights. Each cardinal direction presented represents the direction in which the roof step is facing; for example, a data point for the north direction corresponds to a north facing roof step, where the lower roof is on the north side and upper roof on the south side of the step. The right image presents the directional distribution of frequency of winds (blowing from) from October through May for the same meteorological data.

It is apparent that roof steps facing towards the northeast through southeast directions are most heavily loaded with snow. However, roof steps oriented facing towards the south-southeast through north directions are not likely to accumulate as large of a snow load, and large reductions to building code recommendations may be applicable. This is expected to be primarily due to the lack of winds of significant strength and low frequency from the north through northeast and southeast through southwest directions as indicated in the wind rose in Figure 2.

These simulations reveal that roof steps of greater heights result in greater reductions in snow accumulations for westerly facing roof steps. The trends in the data remain similar for other building orientations. This is due to strong westerly winds downwashing from the exposed building roof step face and scouring snow from the lower roof. Increasing the height of the step increases the strength of this downwashing and scouring wind flow.

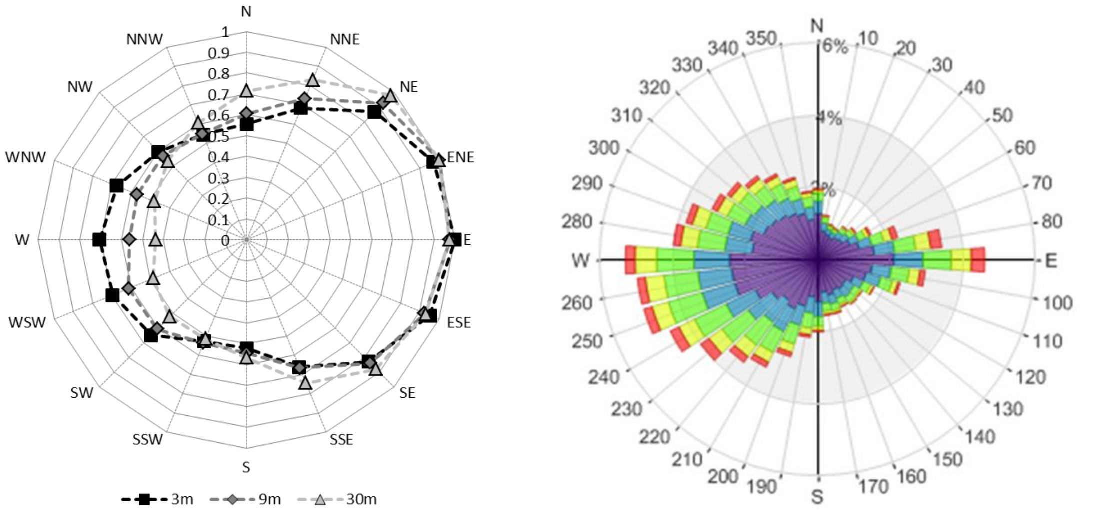

Figure 2: Left: Load reduction factors due to building orientation and meteorological climate sensitivity. Illustrated are buildings with 3 m, 9 m and 30 m roof step heights. Right: Directional distribution (%) of winter winds (blowing from) from October through May. Data recorded at London International Airport from 1953 through 2009.

A distinctly different trend in sensitivity to buiding orientation was observed for the meteorological climate in Toronto. As shown in Figure 3, the meteorological climate around Toronto resulted in a more uniform distribution of strong winds over the course of the winter and a therefore more uniform snow load within roof step zones. This results in less sensitivity of building orientation to the climate and lower directionality reduction factors. However, reductions of up to 60% are seen for roof steps facing towards the north. Similar to what was observed in the London meteorological data set, higher roof steps result in a reduced windward snow accumulation on the lower roof. However, these snow load reductions are somewhat limited as the relatively infrequent winds from the east are responsible for the redistribution of snow from the upper roof into the roof step region.

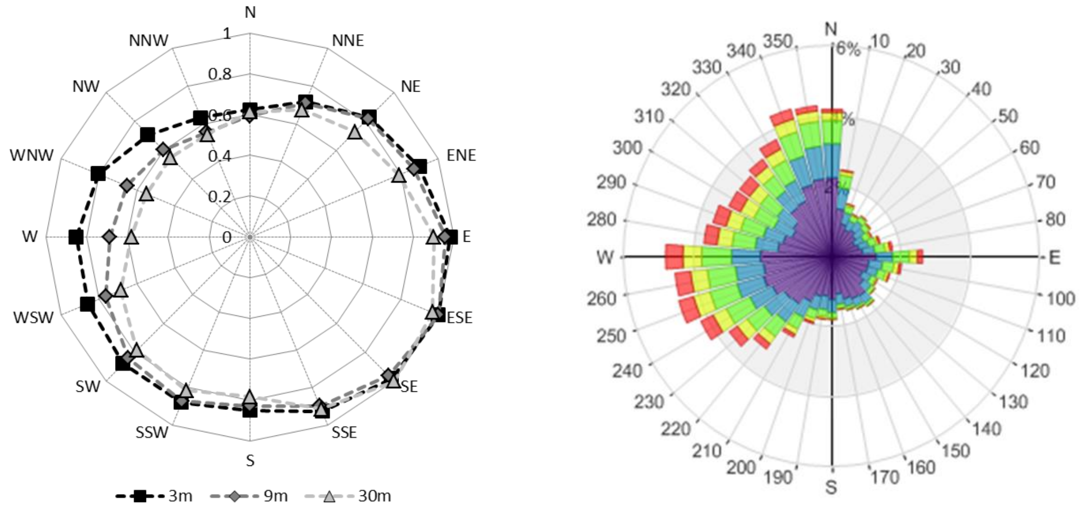

Figure 3: Left: Load reduction factors due to building orientation and meteorological climate sensitivity. Data recorded at Toronto International Airport from 1953 through 2015.

Upon reviewing wind data from a region with a highly directional wind climate such as that found at Quebec City International Airport (right image in Figure 4), a designer may assume that large reduction ratios would occur for roof steps that are not aligned in directions downwind of prevailing wind directions. However, the interactions between wind speed, frequency and a snow pack cannot be simplistically reviewed in this fashion as evidenced by the results of the parametric simulation for data from Quebec City International Airport (see left image in Figure 4). A comparison between the Quebec City and London wind data sets indicate that greater reductions should be present for Quebec City; however this is not necessarily the case as even relatively infrequent directions still contribute to a large amount of snow scour and subsequent deposition on the lower roof surface. This is a due to the relationship between the driftable state, availability of snow to drift, and the movement of snow with wind speed.

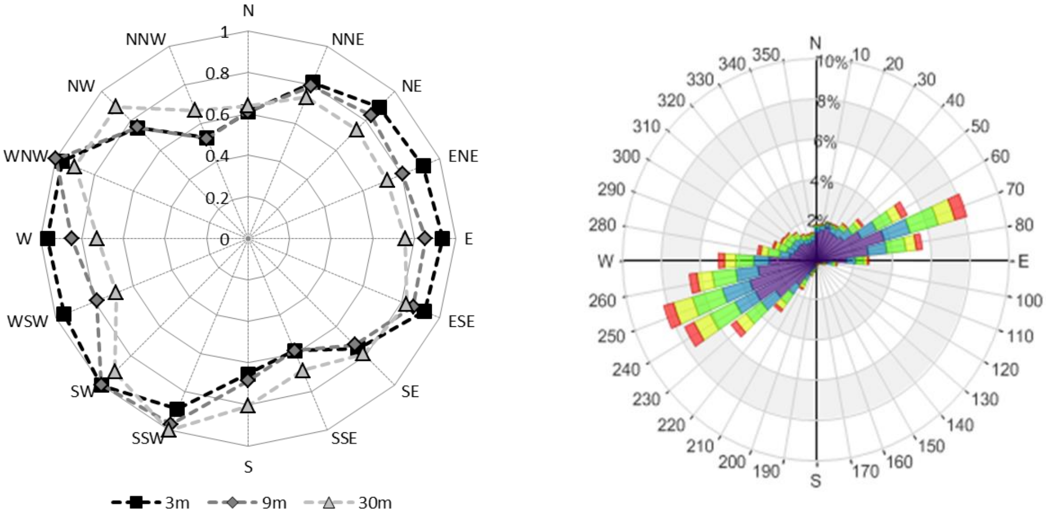

Figure 4: Left: Load reduction factors due to building orientation and meteorological climate sensitivity. Data recorded at Quebec City International Airport from 1953 through 2014.

A disconnect between prevailing wind directionality and the resulting load sensitivity is apparent when meteorological data from Vancouver International Airport was reviewed (Figure 5). This is due to the relatively low frequency of strong winds during the winter, snowfall events consisting of wet snow with low driftability and the relatively short period of time that snow is present on the roof due to frequent melting periods. As a result, reduction factors based on building orientations are likely to be limited, as is the likelihood for large roof step surcharges.

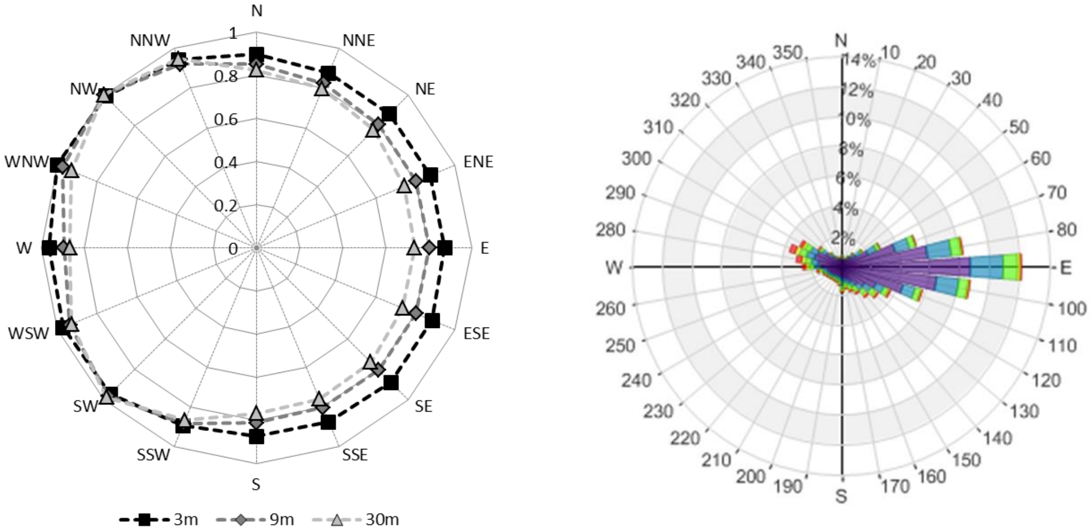

Figure 5: Left: Load reduction factors due to building orientation and meteorological climate sensitivity. Data recorded at Vancouver International Airport from 1953 through 2012.

3. APPLICATION

The following sections illustrate the application of step surcharge reduction factors previously determined to a model with complex geometry that is representative of features that are encountered in practise. Illustrated below are NBCC code calculations and loads parametrically modified using reduction factors obtained for Toronto and Quebec City. Lastly, the loads derived using the parametric analysis are compared against load derived using the detailed FAE simulation process.

The Snow Accumulation and Precipitation Calibration Experiment (SPACE) model, as illustrated in Figure 6, features complex but common geometries that allow for evaluation of building aerodynamics and snow simulation methods. Key building geometries have been included in the geometric design of the building such as a mechanical penthouse on a projecting tower, multiple roof steps and a large central arched roof. A detailed description and resulting water flume snow drifting simulations of the SPACE model can be seen in Brooks et al, 2015.

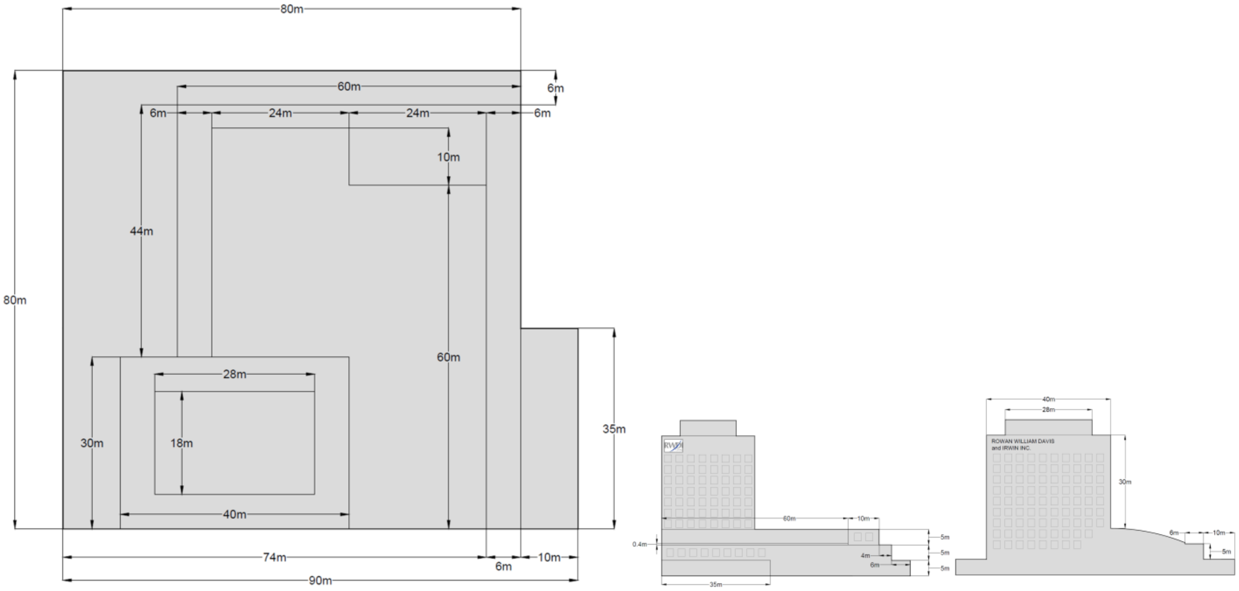

Figure 6: Plan and elevation views of the SPACE model building. Dimensions are provided in full-scale meters (Brooks et al 2015).

3.1 Comparison of NBCC Recommended and Parametrically Modified Design Snow Loads

Figure 7 illustrates the three-dimensional distribution of snow as recommended by the NBCC (left) and as modified by the reduction factors determined using the simplified building roof step model and the FAE (right). These loads are the 1 in 50 year mean recurrence snow loads based on meteorological data from Toronto, Ontario. The height of the snow accumulation is based on an NBCC recommended density of 3.0 kN/m^3. Any abrupt changes in the geometry of the NBCC recommended snow loads have been smoothed through interpolation during modelling.

The roof snow loads shown in Figures 7 and 8 illustrate where differences in the volume of snow within roof step zones are present between code and those parametrically modified. As can be seen, some of the wind directions have seen appreciable reductions in depth, where others oriented in more sensitive directions relative to the meteorological climate remained unfactored.

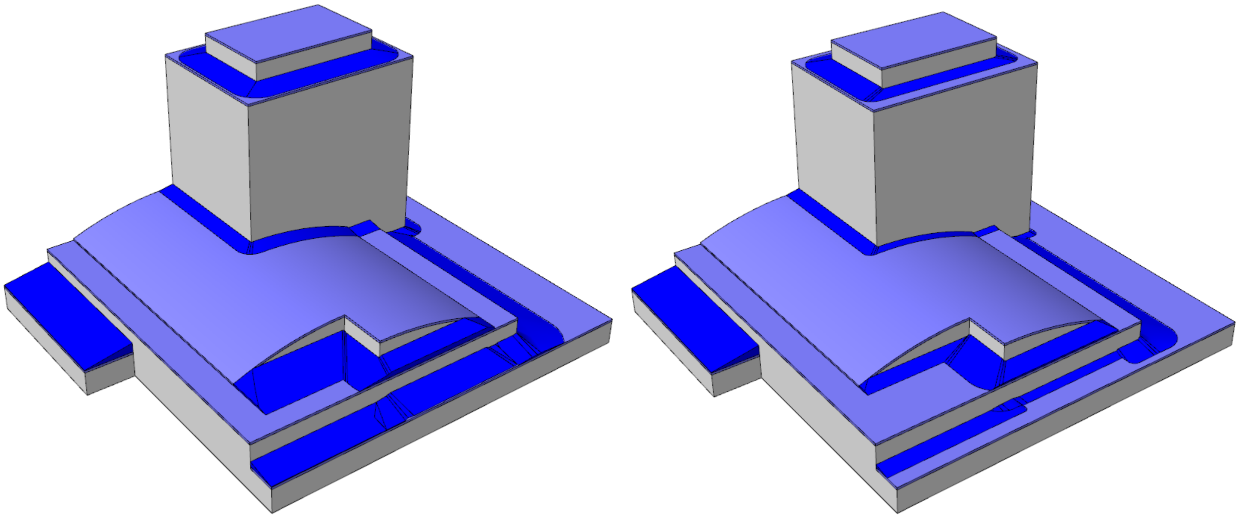

Figure 7: Left: Three dimensional representation of 1 in 50 year design snow loads as recommended by the NBCC. Right: NBCC recommendations factored using roof step surcharge reduction relationships derived using the simplified building roof step model. Presented snow loads are based on meteorological data from Toronto, Ontario.

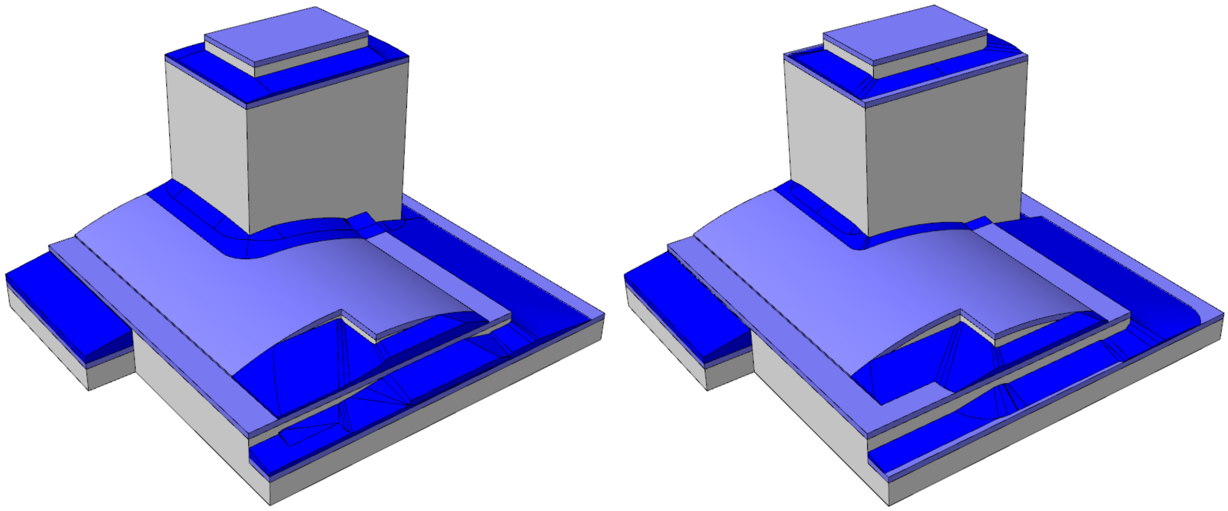

Figure 8: Left: Three dimensional representation of 1 in 50 year design snow loads as recommended by the NBCC. Right: NBCC recommendations factored using roof step surcharge reduction relationships derived using the simplified building roof step model. Presented snow loads are based on meteorological data from Quebec City, Quebec.

3.2 Comparison of Parametrically Modified Snow Loads and FAE Snow Loads

Since the building roof step parametric model is representative of a simple building roof step geometry in isolation, a detailed FAE simulation of the SPACE model was conducted to compare the loads recommended by the parametrically modified NBCC loads to a current, state of the art analysis method.

Using the FAE simulation method required detailed wind flow velocity information. This information was obtained through the boundary layer wind tunnel testing of a 1:300 scale model (left image in Figure 9). Velocity data (magnitude and direction) were measured with a high degree of spatial resolution using 253 surface velocity vector (SVV) sensors, as described in Gamble et al 1992 (right image in Figure 9). A standard suburban wind and turbulence profile was used.

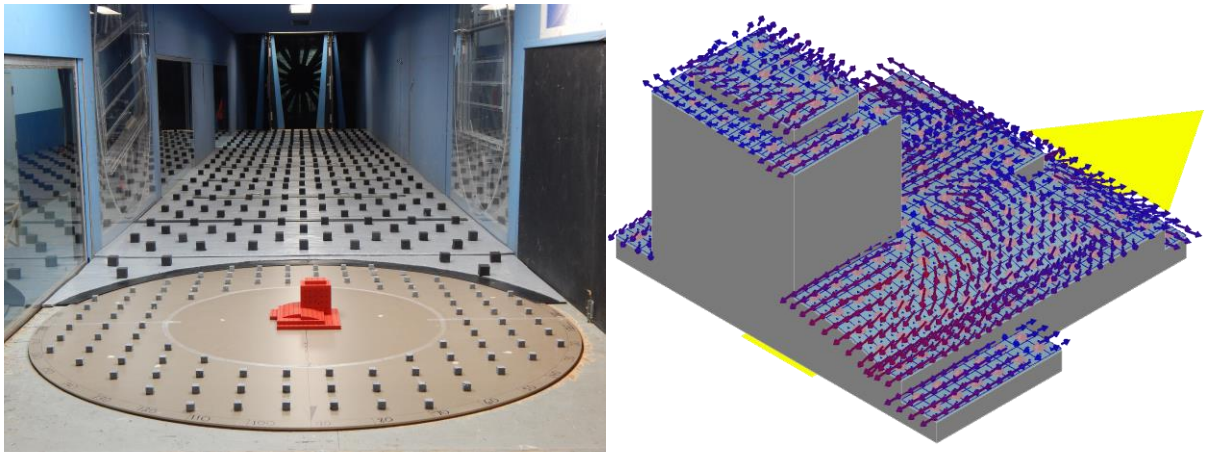

Figure 9: Photograph of the SPACE wind tunnel model within a boundary layer wind tunnel (left) and example of measured wind velocity vectors for winds from the north (right).

As can be seen in Figures 10 and 11, the parametrically modified code loads appear larger than those derived using the detailed FAE simulation process. This indicates that the code loads, and resulting parametrically modified roof step loads do provide a degree of conservatism, as is desirable for a method that does not relay on detailed physical and numerical modelling.

The total snow load on the building including area averaged and roof step surcharges was calculated for each analysis method for a building located in both Toronto and Quebec City based on an assumed snow density of 3 kN/m^3, and is presented in Table 1. The difference in total snow load for each of the analysis methods is also provided for comparison purposes.

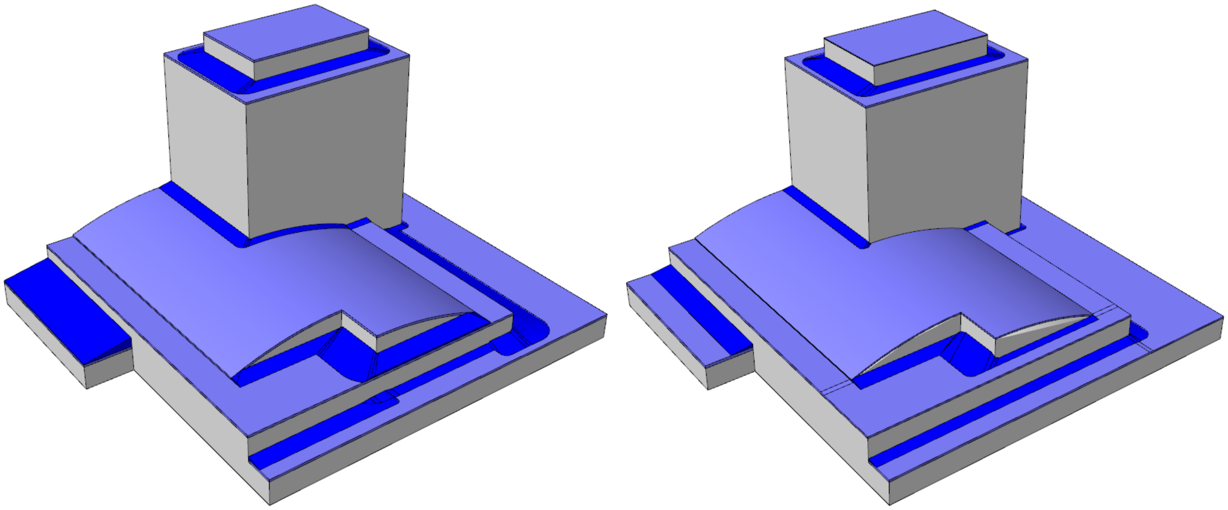

Figure 10: Left: NBCC recommendations factored using the reduction factor relationships derived using the simplified building roof step model. Right: Snow loads derived using the detailed FAE simulation process. Presented snow loads are based on meteorological data from Toronto, Ontario.

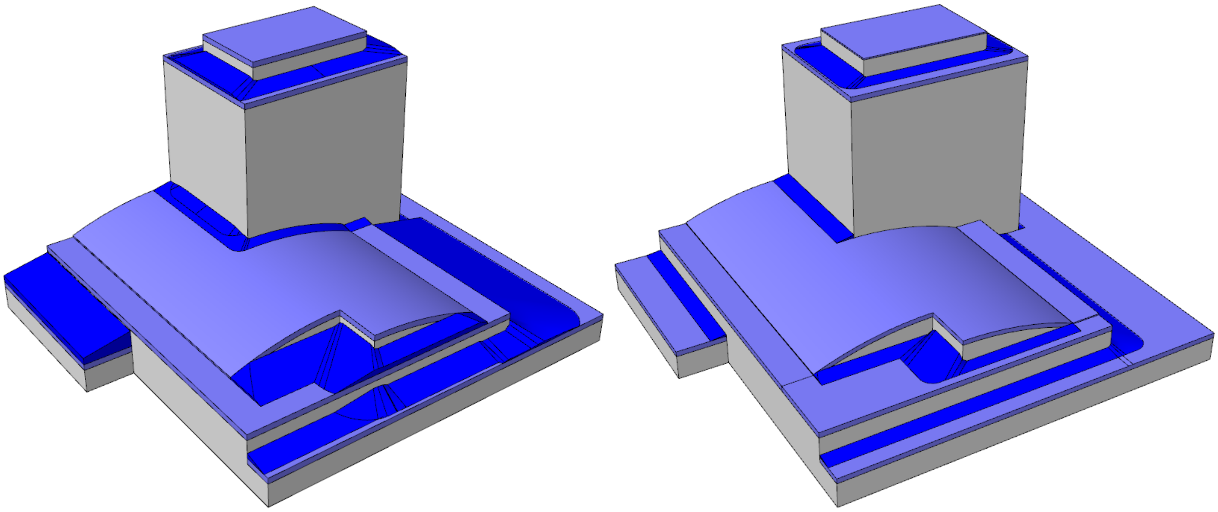

Figure 11: Left: NBCC recommendations factored using the reduction factor relationships derived using the simplified building roof step model. Right: Snow loads derived using the detailed FAE simulation process. Presented snow loads are based on meteorological data from Quebec City, Quebec.

Table 1: Total Area Averaged and Step Surcharge Snow Load

	NBCC Code Snow Load (kN)	Parametric NBCC Snow Load (kN)	FAE Snow Load (kN)
Toronto	15490	13264	8612
Quebec City	39881	35523	21273

4. SUMMARY OF FINDINGS

A parametric simulation of snow accumulation and depletion was conducted for 25 sites across Canada using simple roof step model geometries with heights of 3 m, 9m and 30 m. The resulting directional sensitivities of roof step orientation to structural snow loads were demonstrated using different meteorological data sets. Conclusions drawn from this work include:

1. The strict application of NBCC recommended roof step surcharge snow loads are often conservative, depending on the meteorological climate, because there are often directional sensitivities due prevailing wind directions and other climatic factors.
2. Parametric reduction factors applied to roof step surcharge loads, as illustrated within this paper, allow designers to refine the predicted code design snow loads to allow for a more efficient structural system.
3. A comparison of NBCC and parametrically adjusted loads to FAE simulated snow loads on a detailed building indicates that, for the example geometry and climates investigated in this paper, the parametric refinement method does include conservatism as is desirable for a method that does not rely on detailed physical and numerical modelling.

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