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COMBINED PROBABILITIES OF PEAK WIND AND SNOW LOAD EVENTS

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ABSTRACT

The National Building Code of Canada 2010 (NBCC) defines several loading combination scenarios for use in structural design. Appropriate combination factors are provided based on the probability of failure due to the simultaneous occurrence of the specified loads. Load Combination Cases 3 and 4 of Table 4.1.3.2.A include the combination of wind and snow loads, which are transient in nature. The recommended combination factors are intended to provide a uniform degree of reliability for design. However, in reality, the probability of the simultaneous loading due to wind and snow depends on the local meteorological climate. This probability can be more accurately simulated through the Finite Area Element (FAE) process, which studies the hour-by-hour accumulation and depletion of snow based on historical meteorological records. It takes into account variables such as wind speed and direction, temperature, humidity, water retention in a snow pack and many others. In the present work, the accumulation and depletion of snow on a modelled ground patch and the corresponding wind speeds were computed on an hourly basis to determine the correlation of wind and snow loads. Using this process, this paper investigates the interaction between wind and snow loads for 25 distinct regions in Canada, for both ground and roof snow loads.

Keywords: Wind Load, Snow Load, Load Combination, Wind Tunnel, Snowdrift

1. INTRODUCTION

The National Building Code of Canada 2010 (NBCC) defines several loading combination scenarios for use in structural design. These factors are provided based on the probability of failure due to the simultaneous occurrence of the specified loads, and are intended to be conservative enough to reliably encompass a variety of loading scenarios that are expected to be encountered in practise. Load Combination Cases 3 and 4 of Table 4.1.3.2.A include the combination of wind and snow loads, which are transient in nature and depend on the regional meteorological climate. The load combination factors themselves, however, are the same across all regions.

This paper investigates the possibility that the simultaneous loading of wind and snow would depend on the local meteorological climate and the wind exposure of the surface carrying the loads. This is done through the use of sophisticated snow and wind load simulation tools, which are used to model climate-specific loads for various loading scenarios on a building. Typically wind and snow loads are calculated independently, but by modelling them simultaneously, it is expected that a great deal of refinement in the predicted loads can be provided to create a more efficient and reliable structure.

2. METHODOLOGY

Estimates of the snow loads for 25 locations across Canada were determined using the Finite Area Element (FAE) method, and were combined with the hourly wind data as measured at local meteorological stations. The FAE method simulates 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. Entire winters are 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). Both ground snow loads and roof snow loads for a generic building were modelled using this method, and then analysed alongside the wind pressures for the same areas. These techniques are described below.

2.1 Ground Snow Simulation

First, an isolated patch of ground for each region was simulated by using a single grid element with the FAE method. To do this, the FAE simulation requires detailed hourly and daily meteorological data including wind speed and direction, dry bulb temperature, rainfall, snowfall and cloud cover. The resulting time series of hour by hour accumulation and depletion of snow was recorded for the entire period of record, which encompassed between 30 and 60 years of data, depending on the availability of data for each meteorological station. The peak annual snow load maxima were plotted, and a Fisher-Tippet Type 1 fit was used to determine the 1 in 50 year mean recurrence snow load.

2.2 Roof Snow Load Simulation

In addition to simulating ground snow, the effect of snow loading on a typical commercial building with large upper and lower roofs and a step height of 3 metres was parametrically assessed. A 1:300 scale model of this building was tested within a boundary layer wind tunnel using a standard suburban wind and turbulence profile to determine wind velocities at various points on the building surface for drifting purposes. The orientation of the building was evaluated for 16 equally incremented compass directions. This allowed for the investigation into the effects of local climate, wind directionality and step orientations on snow accumulation and depletion. Further descriptions of this parametric roof step model can be found in: Dale et al, 2014, Dale et al, 2015. The geometry and intent of this model is similar to the scale model building used by Tsuchiya et al, 2002 for review of snow modelling tools on a generic building roof step.

The FAE simulation method was then used to determine the area averaged snow loads on the upper roof and the step region of the lower roof on an hour-by-hour basis, as well as the peak 1 in 50 year mean recurrence snow load value as determined using the peak annual maxima and a Fisher-Tippet Type 1 fit. One building orientation was selected for each meteorological station, which corresponded to the roof's maximum sensitivity to the region's prevailing winds and climate. This was selected based on the ratio of upper roof area averaged snow load to the lower roof area averaged snow load; a larger ratio indicates that the upper roof is generally more scoured of snow compared to the lower roof. This also tends to result in a more significant lower roof accumulation.

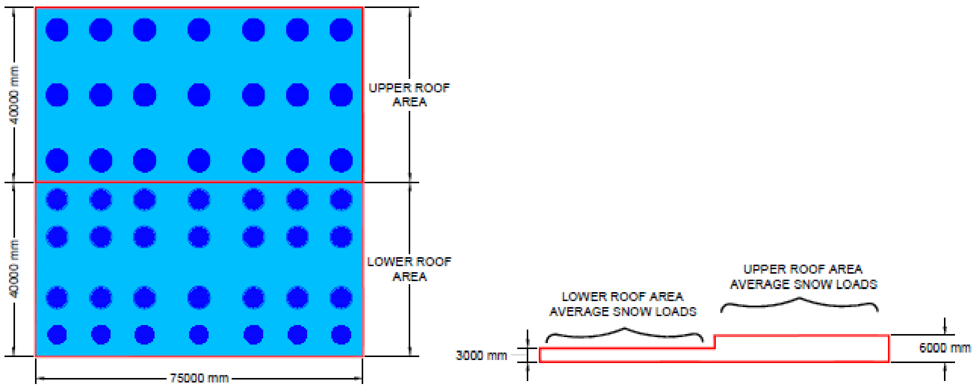

Figure 1: Plan and elevation views of the parametric model building. Dimensions are given in full-scale millimeters. Wind tunnel sensor locations indicated by the dark blue circles.

2.3 Wind Pressure

Hourly wind speed records from each of the 25 meteorological sites within Canada were analyzed to determine the expected 1 in 50 year mean recurrence wind speed using a Fisher-Tippet Type III fit. The hourly records and the 1 in 50 year wind speed were converted to equivalent wind pressures using Equation 1, where P is pressure, ρ is the density of air, and V is the wind speed.

[1] $P = \frac{1}{2}\rho V^2$

For the purposes of comparison, the wind loads on the building roofs were considered the same as those at the ground for ease of analysis and to highlight the effects of variable snow load effects. Future work will include specific roof wind loads for the geometry of the reference building.

2.4 Combining the Data

For each of the ground, upper roof and step region scenarios, the hourly snow loads were normalized to the scenario-specific 1 in 50 year snow load value and the hourly wind pressures were normalized to the site-specific 1 in 50 year wind load value. Thus, the hour by hour normalized snow loads and wind pressures can be plotted against each other referenced to an equivalent return period.

3. COMBINED WIND AND SNOW LOAD FACTORS

3.1 Ground Snow Simulation – All Meteorological Stations

Figure 2 presents the normalized snow loads versus normalized wind pressures including data for all 25 unique meteorological sites within Canada. Each data point within the plot corresponds to the simulated wind and snow load at one hour within the time series, for a total of 1227 years and 10 748 520 hours.

To allow for the direct comparison of wind and snow loads, the combination factors recommended within the NBCC were factored from the ultimate limit state design (Equation 2 and 3) to a limit state value equivalent to 1 in 50 year mean recurrence interval (Equations 4 and 5):

[2] Ultimate State Design: $1.5\,S+0.4W$

[3] Ultimate State Design: $1.4\,W+0.5S$

[4] Limit State Design: $1.0S +0.285W$

[5] Limit State Design: $1.0W +0.33S$

Each of these loading combination factors have been overlaid on Figure 2. As can be seen, a number of data points for both wind and snow loads lie beyond a value of 1, indicating a mean recurrence interval beyond the 1 in 50 year return period. This is expected for a data set consisting of a long period of record with some events above the desired return period. Noting that the plot in Figure 2 contains in excess of ten million points, the data reveals that only a small number of simulated events fall outside the point recommendations provided by the NBCC. This implies that the code provides a reliable, conservative estimate of the joint probabilities, as one would expect from a code intended for use by the engineering community at large.

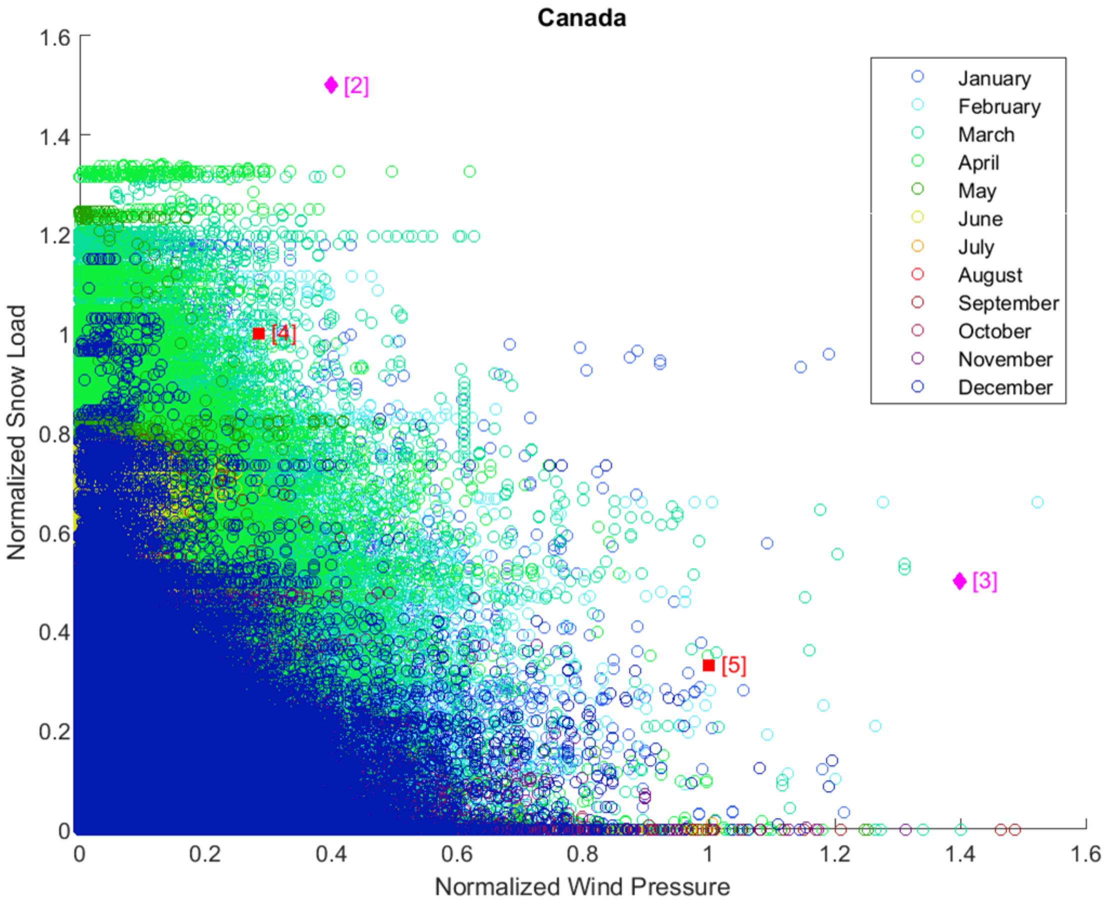

Figure 2: Normalized snow load vs. normalized wind load for 25 meteorological stations across Canada.

This time series approach to tracking the snow accumulation with a corresponding wind load allows us to see how these variables interplay. For example, one may assume that the point of greatest interest is the largest value within the desired return period. However, this may not necessarily be the case, as the net load effect on an actual structure of these coincident factors depends on a multitude of variables such as wind direction, geometry of the building and the distribution of snow which is the result of the preceding meteorological events. Thus, a load combination maximizing a particular load effect could be any combination of wind and snow within a range appropriately described by a function that encompasses data points corresponding to the desired return period. Determining this function is challenging, but may be notionally described by a function that encompasses all but say 2% of the data points within the normalized return period, thus corresponding to approximately the 50 year mean recurrence period. Future work is recommended to further refine the interpretation of this data to a more usable generalized format over the time series approach currently used by the authors.

3.2 Meteorological Climate and Load Case Specific Combinations

Hourly time series of load combinations are presented for three cities within Canada: Halifax, Toronto and Vancouver. These cities were selected because they have different meteorological climates which produced different trends in the presented data.

3.2.1 Combined Load Factors - Halifax Meteorological Climate

Normalized ground snow loads and coincident normalized wind loads using meteorological data recorded at Shearwater Airport in Halifax from 1953 through 2006 can be seen in Figure 3. Each data point corresponds to a single hour of time within the period of record. The corresponding peak annual maxima and Fisher-Tippet Type 1 fit can be seen in Figure 4, which was used to calculate the 1 in 50 year snow load. As can be seen within the data, the peak snow loads typically occur in April, however many of the peak wind loads that occurred simultaneously with moderately high snow loads occur early to mid-winter. In fact, some of the highest wind load events occurred during the winter in January and February. Review of the distribution of the data within Figure 3 indicates that the general trends in the data are similar to those presented in Figure 2.

A dramatic shift in the simulated wind and snow load values becomes evident when values are derived on a building geometry and load case specific basis using the parametric building model previously described. Figures 5a and 5b present data from the exposed upper roof of the building, and as a result is generally well exposed to wind and subsequent snow scour. Figures 6a and 6b present data from the lower roof of the building including the roof step region, where snow from the upper roof is typically redistributed.

The comparison between the exposed and sheltered roof steps indicates a significant shift in combined wind and snow factors, in addition to a shift in time as to when they typically occur. For example, combined factors typically peak in February and March on the exposed roof step. This is evident by the lack of peak snow load events later in spring as is commonly seen within Canada, and due to the extreme event that is beyond the 1 in 50 year mean recurrence interval that appears in the extreme value fit (Figure 5b) that is not present within the ground snow simulation, nor within the sheltered roof scenario. This indicates that the Halifax region is susceptible to significant single snowfall events.

In the sheltered scenario, accumulations typically build over a prolonged period of time and peak late in the winter, typically in March and April. As snow is present for a longer period of time there is a greater probability of a coincident high wind speed event, leading to a significantly higher shift in the combined wind and snow load factors when compared to the exposed roof scenario.

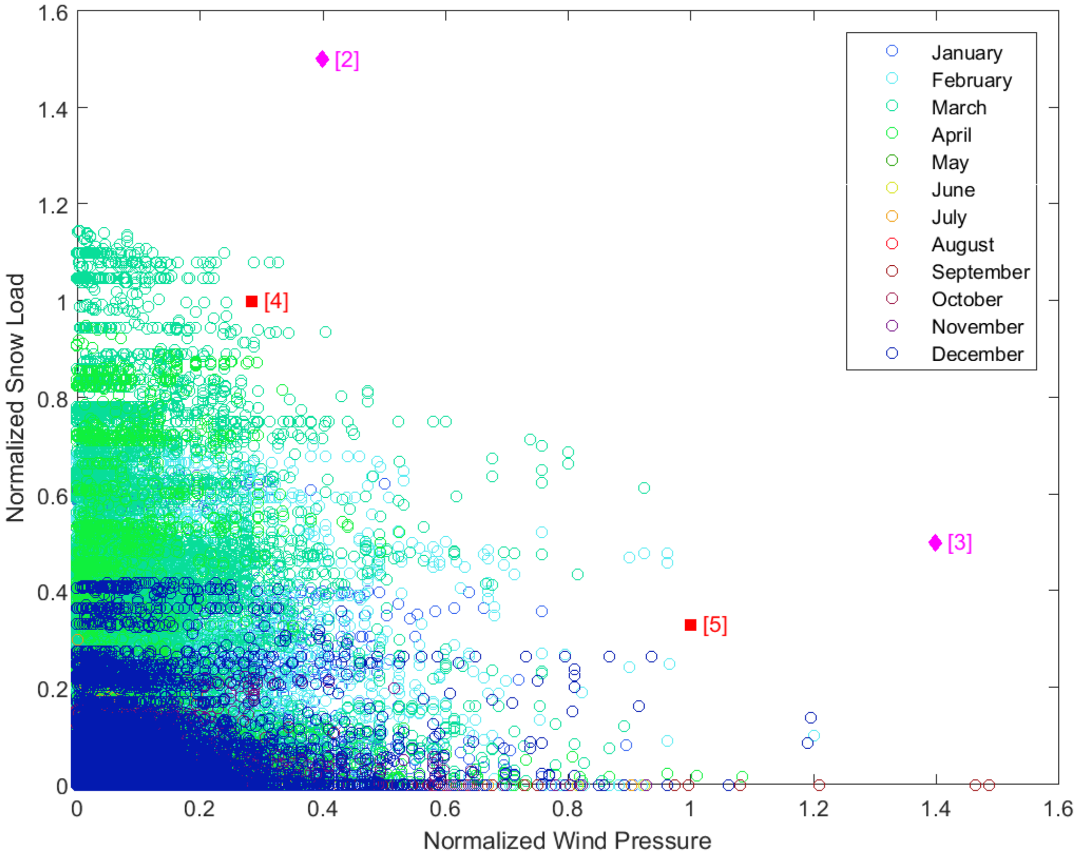

Figure 3: Normalized snow load vs. normalized wind load as recorded at Shearwater Airport in Halifax from 1953 through 2006.

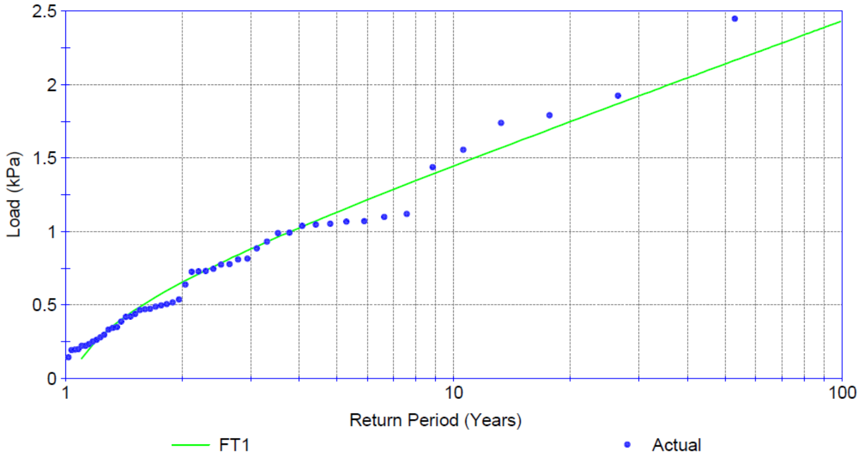

Figure 4: Annual ground snow load maxima for Shearwater Airport from 1953 through 2006 using a Fisher-Tippet Type 1 fit.

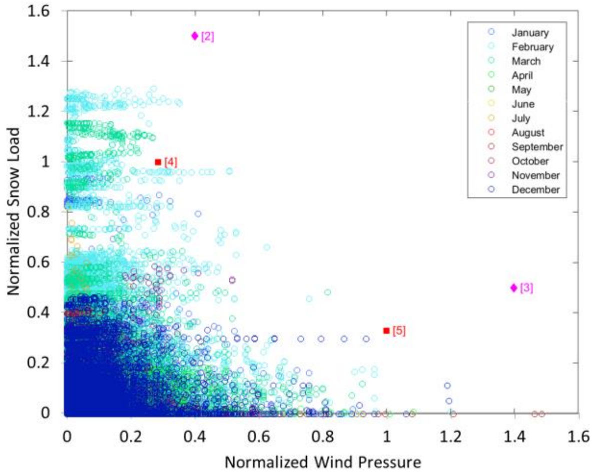

Figure 5a: Hour-by-hour area averaged roof snow loads for an exposed roof

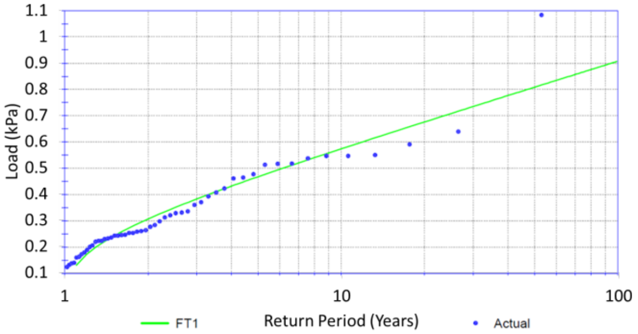

Figure 5b: Corresponding annual maxima for Shearwater Airport from 1953 through 2006 using a Fisher-Tippet Type 1 fit

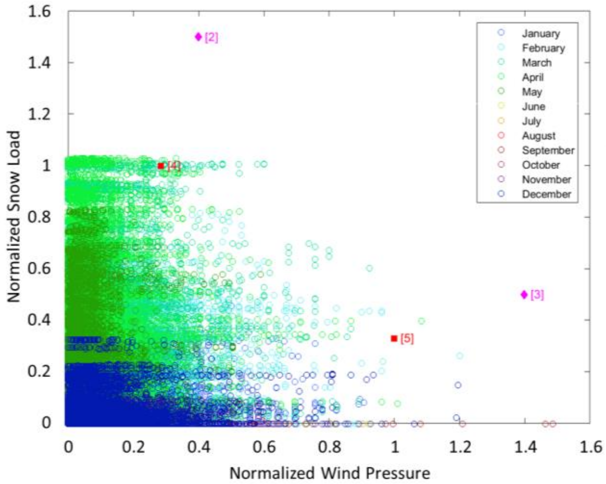

Figure 6a: Hour-by-hour area averaged snow loads for a sheltered roof

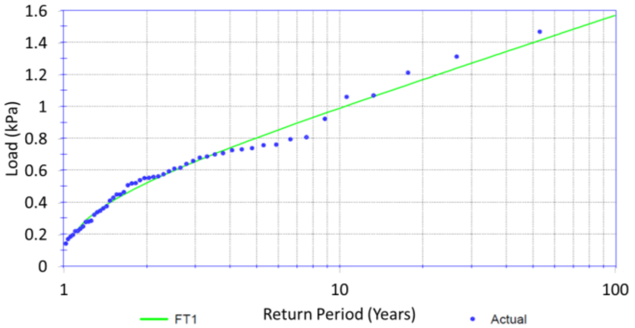

Figure 6b: Corresponding annual maxima for Shearwater Airport from 1953 through 2006 using a Fisher-Tippet Type 1 fit

3.2.2 Combined Load Factors - Toronto Meteorological Climate

Load combination factors simulated using 62 years of meteorological data (1953 through 2015) from Pearson International Airport in Toronto illustrate a trend observed within the larger data set of locations analyzed. As seen in the Halifax data, a distinct shift in the data is seen between the ground snow, and the exposed and sheltered roof loading scenarios. Unlike within the Halifax dataset, the seasonal distribution of peak snow load and wind data points are more uniformly distributed. This indicates that the Toronto meteorological climate may be less prone to significant single event snow accumulations, or there is less wind and resulting snow scour, indicating a lower exposure factor on upper roof surfaces or a combination of both.

Similar to the data presented in Figures 5a and 6a, the data plotted within Figures 8a and 8b indicate a greater frequency of significant snow accumulation present on the lower sheltered roof throughout the winter as there is an upward shift in the coincident wind load data compared to the exposed roof.

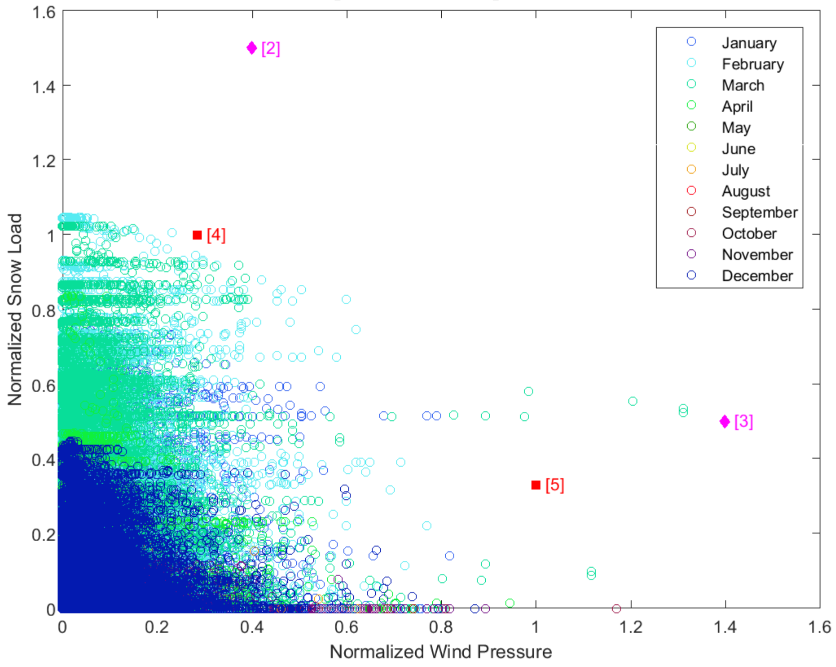

Figure 7: Normalized snow load vs. normalized wind load as recorded at Pearson International Airport in Toronto from 1953 through 2015.

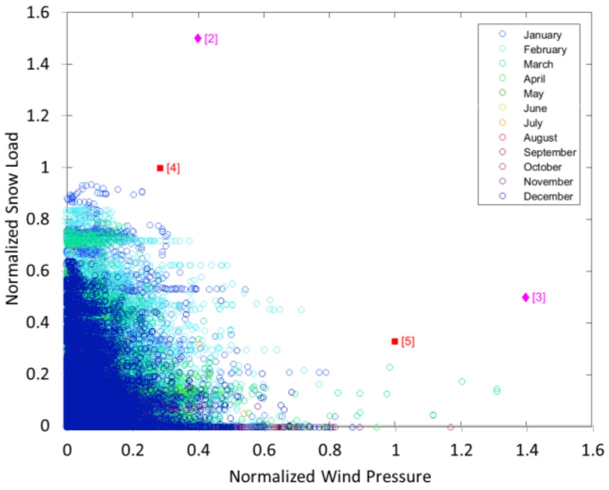

Figure 8a: Simulated area averaged exposed roof snow

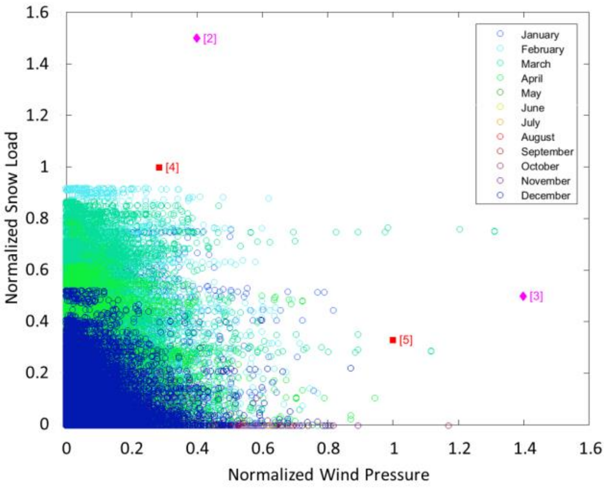

Figure 8b: Sheltered roof snow load

3.2.3 Combined Load Factors – Vancouver Meteorological Climate

Review of data from Vancouver International Airport from 1953 through 2012 indicates that load combination factors within the NBCC may contain a great deal of conservatism. The trends in these figures are the result of the meteorological climate of Vancouver where peak snow loads are often the result of a single snowfall event. The limited difference between the distribution of wind and snow load data points in the exposed and sheltered roof cases indicates that this climate is not as conducive to snow drifting and redistribution as those previously described. This is the result of the warmer, wet climate of Vancouver leading to snowfall which is less susceptible to drifting, and due to cyclical ambient air temperature that tend to melt accumulations relatively soon after the precipitation event. These typical meteorological characteristics will limit the probability that a wind event of significance will occur when snow is present. In these scenarios, significant reductions in the load combination factors recommended by the NBCC are possible.

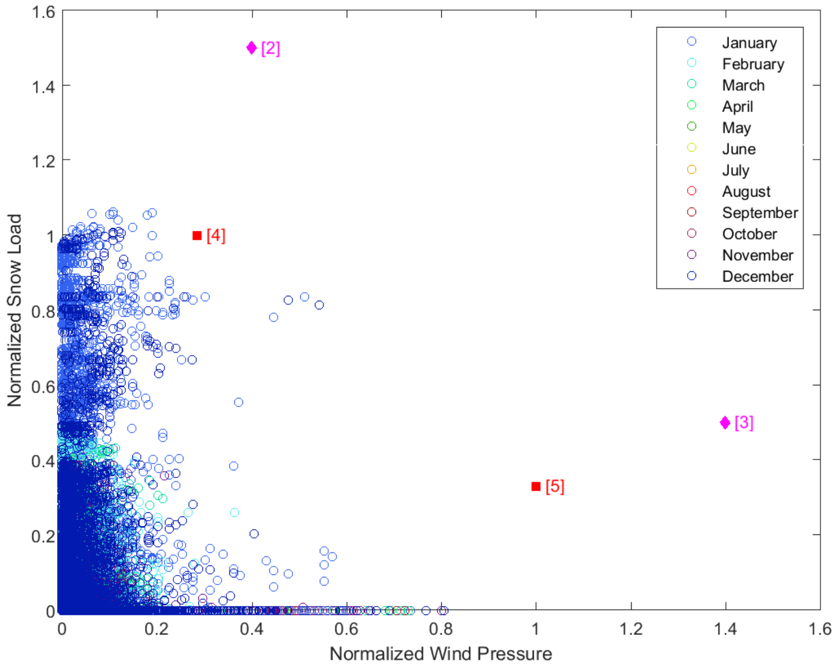

Figure 9: Normalized snow load vs. normalized wind load as recorded at Vancouver International Airport from 1953 through 2012.

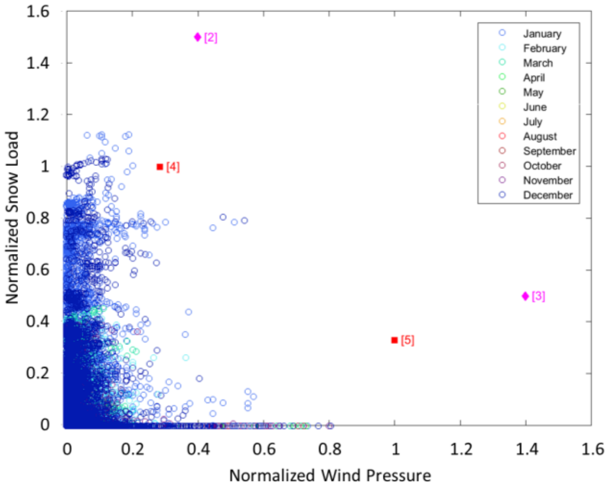

Figure 10a – Simulated area averaged exposed roof snow load

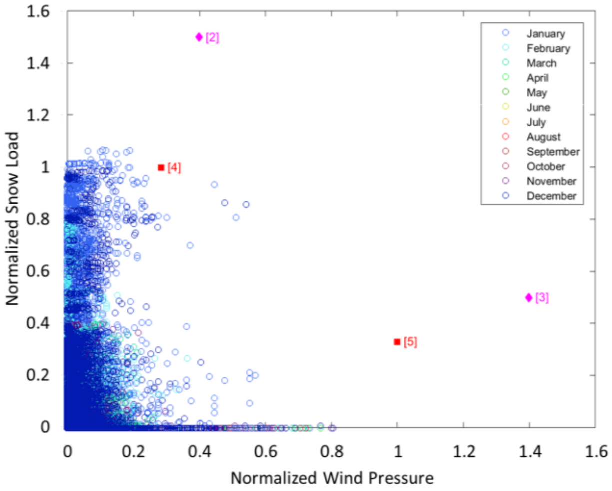

Figure 10b – Sheltered roof snow load

4. SUMMARY OF FINDINGS

As described within this paper, the simulation of the hour by hour accumulation and depletion of snow load on a ground snow patch and roof allows for the detailed analysis of combined snow and wind load probabilities. The conclusions drawn from this work include:

1. The combined probabilites of a peak snow and wind load are dependent on the meteorological climate of a site as evidenced by the wide range of snow and wind load data points between simulations illustrated for Halifax, Toronto and Vancouver meteorological data sets.
2. Wind and snow load combination factors are influenced by the building geometry. Differences in these factors are the result of building specific variables such as geometry, but also the interaction of these variables to the meteorological climate and are therefore not considered mutually independent. As seen when comparing the Halifax and Toronto meterological data sets, combination factors for the exposed upper roof are a funciton of the climate, as some loading scenarios become more sensitive to specific climatic conditions, such as large single snowfall event snow loads.
3. The NBCC recommended load combination factors are likely conservative for some meteorological climates such as Vancouver.
4. In addition, the NBCC recommended load combination factors may be conservative for a number of building load cases, such as on exposed roof surfaces. Additional investigation into the load effect of the combined wind and snow loads may be required to investigate the reliability of the combination factors for load cases where snow is present over greater periods of time.
5. Advance analysis techniques, such as what were used within this paper can be used to better understand the interconnected relationships between the variables of snow load, wind loads, building geometry and meteorological climate.

5. RECOMMENDATIONS FOR FUTURE WORK

Determining the net effect of coincident wind and snow loads for generic or building and site specific application is not a simple process. Future work by the authors and by the engineering community should be undertaken to further investigate these combination factors. Topics of investigation include:

1. Simulation and statistical models for snow and wind load combination functions to better reflect the wide range of load design scenarios that can occur. This should include further research into assigning appropirate probabilities to the data, including methods for reconciling the differences between a peak annual snow load and an hourly event wind load, for example.
2. Develop climate-specific snow load combination factors for use along with the current ground snow and wind load values presented within the NBCC.
3. Develop generic building applicable refinements to the snow and wind load combination factors by investigating varaiables such as wind exposure and roof size/geometry.
4. To provide refinements to building load case specific wind loads, specific wind loads should be determined and applied, as the wind loads presented within have been simplistically modelled for the purposes of comparison of trends.

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