

Developments toward a Performance-Based Methodology for Design and Assessment of Buildings Subjected to Snow Loads

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Abstract: The authors have developed a framework for performance-based design and assessment of buildings subjected to snow loads. This paper describes how probabilistic assessments of structural performance under snow loads can be obtained. These assessments rely on probabilistic models linking the intensity and distribution of roof snow loads with their likelihood of occurrence, and accounting for weather, site and building factors. The evaluation of roof deflections and structural damage is illustrated using a case study roof failure that occurred in Copper Mountain, Colorado. The paper also examines why certain types of buildings are particularly vulnerable to snow-induced failure and the conditions that trigger building closure and evacuation.

1. Introduction: This paper summarizes recent research efforts to develop an innovative framework for performance-based design and assessment of buildings subjected to extreme snow loads. Data from past U.S. snowstorms shows that structural failure under heavy snow loads can have significant socio-economic impacts, requiring costly repairs, interrupting business, damaging building contents and potentially endangering life safety. Performance-based methods can improve snow engineering by enabling explicit consideration of the possible consequences of snow-induced damage, including risks of collapse, repairs, and building closure, in decisions about structural design. Performance-based snow engineering may be particularly relevant to improving design and safety of buildings with high occupancy or high-value contents, such as sports arenas, theaters, or manufacturing facilities, a number of which have failed in the past. The methodology also provides a mechanism for improving snow design through evaluation of the consistency of current design practice and building code provisions.

Performance-based snow engineering is a significant departure from current methods of snow design and assessment, in that it accounts directly for uncertainty

in loading, design, and structural behavior in order to predict the likelihood of damage, failure, and building closure. Quantification of building performance requires sophisticated nonlinear simulation models, capable of capturing strength and stiffness deterioration until the onset of collapse under extreme loading, and Monte Carlo statistical algorithms for incorporating dominant sources of uncertainty. Collapse and structural damage limit states can be evaluated from analytical predictions of structural response. To predict the impact of snow loads on business interruption and downtime, we evaluate the factors triggering evacuation and closure of buildings loaded with snow and the impact of these closures on business interruption and downtime.

This paper presents selected aspects of ongoing research related to the development of a performance-based methodology for structures subjected to large snow loads. The theoretical framework for performance-based snow engineering is outlined in Section 2. Section 3 describes research efforts to characterize the types of structures that are particularly vulnerable to extreme snow loads and the impacts of these failures. Models to predict snow loads on roofs of vulnerable structures are the focus of Section 4. These roof snow load models provide input into structural analyses and simulation models that can be used to assess the risk of snow-induced damage, collapse or building closure. The load models and performance limit states are illustrated through the assessment of a case study condominium structure in Colorado, described in Section 5. Finally, Section 6 reports early stage efforts to quantify the impacts of snow-induced failure on building downtime and business interruption, as well as the conditions triggering building closure.

2. Performance-Based Engineering for Extreme Snow Loads:

Performance-based engineering is a methodology for the design and assessment of engineered facilities, which ensures that building performance under normal and extreme loads meets the

needs of owners, occupants, and the public [1]. Metrics of building performance are probabilistic and expressed in terms of potential consequences, such as collapse (*e.g.* What is the likelihood the structure will collapse due to snow in the next 50 years?), economic losses (*e.g.* What is the likelihood the cost of repairing structural damage due to snow loads will exceed \$X?) or downtime (*e.g.* What is the probability that snow-induced structural damage will interrupt business for more than Y days?). The link between performance metrics and decisions about structural design and assessment distinguishes performance-based methods from conventional prescriptive design methods. In this context, a building owner could choose to invest in a stronger or more redundant roof system, on the basis of quantifiable estimates of the reduction in future risks of structural failure or dollar-losses associated with the improved roof system. Although performance-based methods are gaining increased use in seismic and, more recently, wind engineering, applications to snow engineering have not yet been explored.

The theoretical framework for performance-based snow engineering is modular, separating hazard characterization (*e.g.* probabilistic prediction of ground snow loads, accounting for uncertain weather) and structural analysis and estimation of engineering demands due to snow loads (*e.g.* simulation of deflections and stresses in a structure subjected to extreme snow loads) from the evaluation of risks of damage, collapse, losses and other outcomes, as illustrated in Figure 1. This framework is intended to facilitate risk-informed decision-making for design and assessment of buildings subjected to snow loads through probabilistic assessment of risks of collapse, losses, and building closure.

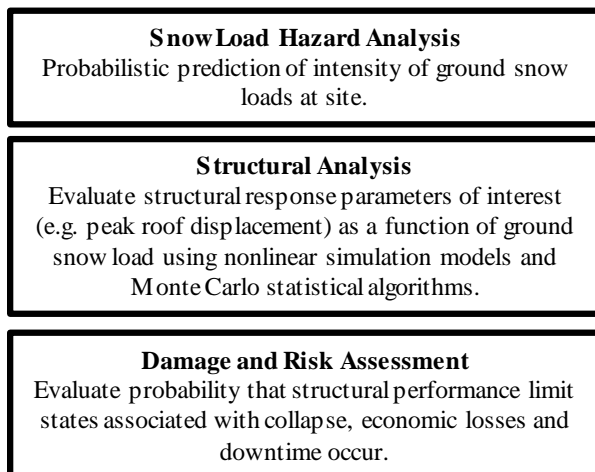


Figure 1: Framework for performance-based snow engineering.

3. Building Vulnerability to Snow Loading:

Buildings vulnerable to snow loads include high profile structures like the Hartford, Connecticut Civic Center Arena, which collapsed in 1978, as well as a number of warehouses, strip malls, and other structures whose failure does not warrant much attention, but which may have a significant impact on communities and businesses. To set the stage for probabilistic analysis and simulation of structural response, we conducted a preliminary study to identify types of buildings that may warrant future study and to classify the impacts of building failures.

3.1 Past Failures: The vulnerability of buildings subject to large snow loads was investigated through a study of past snow-related building failure and damage trends in the U.S. and abroad. A total of 1,029 snow-related U.S. building failure incidents and 91 international building failure incidents were identified over the past 30 years through two newspaper archive databases: LexisNexis Academic and Factiva [2,3]. Reporting in the selected articles covered descriptions of snow and weather events, effects on city systems and infrastructure, and damage to buildings and other structures. Once the database was generated, incidents of snow-induced building damage and failure were classified by structural system, building activity, building age, incident type (*i.e.* collapse, damage etc.), and physical and socioeconomic impacts. The data gathered was intended to identify the types of buildings that may be particularly vulnerable to snow-induced failure. A complete description of the database generated and key findings are available in [4].

Findings from the snow-failure incident database revealed patterns of building failure, damage, and vulnerability due to extreme snow loads. Warehouses, factories, and commercial buildings were the building activities most affected by large snow loads. In general, incidents involving commercial buildings were much more prevalent than those involving residential construction, with an incident rate (per structure) roughly 200 times higher. When examined state by state, New York, New Hampshire, and Massachusetts had the largest number of incidents, comprising 30% of the total number of incidents. To account for variation in population and building stock in different states, incident counts were normalized by the total population or buildings in each state (from U.S. census data). This data show that, in normalized terms, Maine and North Dakota have elevated vulnerability compared to other states. In terms of construction type, timber, lightweight metal, and steel buildings were particularly susceptible to snow-induced failure, comprising 37%, 19% and 18% of the total number of snow-induced failure incidents, respectively. Air-inflated structures were also

found to be particularly vulnerable. Snow damage and failure incidents in buildings were commonly attributed to rain-on-snow mixes and building problems, specifically design flaws and age-related deterioration. Even so, the large number of incidents reported for buildings constructed within the last 10 years (16% of the total number of incidents), serves to indicate that not only older, potentially deteriorated structures are vulnerable; certain buildings designed according to modern code provisions may also be susceptible to building damage under large snow loads.

Impacts of these snow-induced building failure incidents have been largely economic, especially in the U.S. In the incident database generated repair costs reached as much as \$200 million for some high value structures or buildings with expensive contents. The costs of business interruption were also significant, with damaged buildings closed for an average of four months after failure. Although the database included 19 fatalities and 146 injuries associated with the U.S. incidents, the public safety risk is lower than that of international incidents, for which the 91 database incidents included a total of 293 fatalities.

In addition to the snow-failure incident database that was generated, we also interviewed a group of sixteen structural engineers, representatives of local fire departments, building managers and insurers about snow design and risk factors related to snow-induced building failure [5]. Each interviewee was asked a set of questions about snow design, emergency response and post-damage repair and rebuilding. Interview responses show considerable agreement with the findings in [4]. In particular, many respondents commented on age and the elevated risk posed by older structures designed according to outdated building codes. With regard to newer structures, the interviewees identified several factors which make structures particularly vulnerable to snow loads, including flat roofs, lightweight metal roof systems, and roofs with widely-spaced joists. Other types of structures also mentioned as being particularly susceptible to snow loads include multi-level roofs that allow drifts to form on the lower roof structure, wood-framed residential buildings and temporary structures.

Some of the interviewees provided information about specific case studies of snow-related building failures they had encountered in their careers, mostly from Colorado's March 2003 blizzard. This snowstorm caused severe structural damage or collapse in hundreds of structures, and left thousands of buildings with repairable distress to structural or aesthetic elements. According to an investigative report [6], structural damage resulted primarily from inadequate design or construction; buildings designed and constructed in

agreement with current code requirements generally performed well. Failures were observed under a variety of loading conditions, including both uniform and drifted snow, localized loads due to snow melting and ponding, and build-up of snow loads and associated impact forces from snow sliding off upper roofs.

3.2 Archetype Vulnerable Buildings: On the basis of these observations, lightweight metal buildings have been selected for further study within the performance-based snow engineering framework. These types of structures are popular in commercial and industrial applications such as strip malls, warehouses, and manufacturing facilities. Lightweight metal buildings may be particularly vulnerable under snow loading due to their large live to dead load ratios. This risk is particularly apparent in cases of snow drifting, where snow accumulates around roof obstructions (*i.e.* mechanical equipment, parapets) or on lower level roofs, resulting in non-uniform and sometimes highly amplified snow loads on portions of the roof (Figure 2).

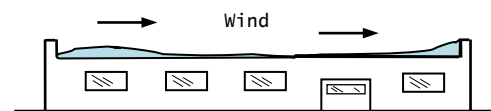


Figure 2: Building elevation depicting the effects of snow drifting around roof obstructions on a flat roof.

While lightweight metal buildings can be constructed of either cold-formed or hot-rolled steel, a combination of the two is most often used. Typical design elements and dimensions of lightweight metal buildings are shown in Figure 3. Roof framing generally consists of steel joists, joist girders, lightweight metal decking, and diaphragm supports; wall systems are typically a combination of reinforced masonry and cold-formed steel sections. These buildings have open floor plans with evenly spaced columns and moderate ceiling height. This system offers a number of advantages over other types of construction, including high strength-to-weight ratios and relative ease of design and installation. Because joists and girders are relatively light weight, load demands on other building elements, such as foundations, columns, and walls, are reduced, thereby reducing overall construction costs [7].

Future work will examine the vulnerability associated with the response of lightweight metal buildings to non-uniform snow loading. In this study, we will vary key design and loading parameters to examine the impact of design and weather conditions on the overall integrity and associated vulnerability of the structural system. The design parameters to be considered include, but are not limited to, building geometry (length, width, height), joist and girder spacing, roof

obstructions (parapets, mechanical equipment), roof material type, connection design, and snow loading environments (by region).

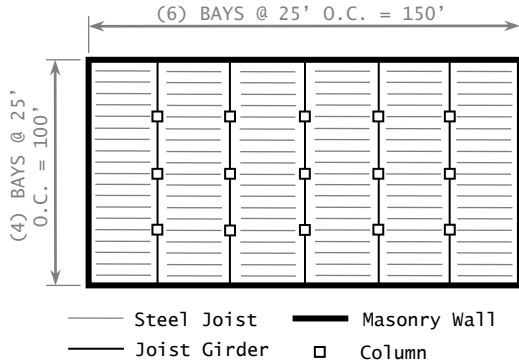


Figure 3: Plan view of a typical lightweight metal building. These typical buildings will provide the basis for a probabilistic examination of risks of snow-induced damage and failure in buildings.

4. Probabilistic Snow Load Models: A critical component of the performance-based procedure for design and assessment of buildings subjected to large snow loads is a probabilistic model for roof snow loads. The proposed roof snow load models describe the possible intensities and distributions of snow loads on buildings, as well as the probability with which each loading scenario will occur. Our approach to modeling roof snow loads consists of predicting ground snow loads through ground snow hazard curves and probabilistically relating ground to roof snow loads through an empirical model.

4.1 Ground Snow Hazard: Site-specific weather data, accounting for weather patterns, site location, elevation and snow density, is incorporated in a ground snow hazard curve, which describes the mean annual frequency of exceeding the ground snow load of specified intensity. The development of these curves has been illustrated by Lee and Rosowsky in [8] and accounts for the uncertainty in snow load intensity with geography and season. Ground snow hazard curves can be constructed for any location where sufficient historical weather data is available.

4.2 Roof Snow Loads: In this study, we develop a model for predicting roof snow loads from ground snow loads. The model consists of two parts: (1) a prediction of uniform snow loading on a roof, and (2) a prediction of whether snow will drift and, if so, the size and location of the drift(s). This load model has been developed using measured roof load data from the U.S. Army Corps of Engineers Cold Region Research and Engineering Laboratory (CRREL) [9]. The CRREL

dataset includes 467 roof and ground snow load measurements for 199 structures across the U.S., collected over a three-year period. The uniform roof snow load model is described here. The drift model is similar.

The relationship between ground and roof snow loads on a particular day depends on a variety of factors, including wind and exposure of the building, the thermal characteristics of the structure, roof material and slope, and the magnitude of the ground snow load. The proposed model takes on the functional form:

$$RSL = K_e * K_t * K_{sm} * K_{gs} * GSL \quad (1)$$

where RSL is the model prediction of the roof snow load (in psf or other consistent units), GSL is the ground snow load, K_e is the factor relating to building exposure, K_t is the factor relating to building thermal properties and insulation, K_{sm} relates to the roof slope and roofing material and K_{gs} relates to the amplitude of the ground snow load. The model was developed sequentially, *i.e.* the value of K_e determined from CRREL data for RSL and GSL , then K_t determined from RSL , GSL and K_e , etc. Each factor is a function of different building and weather characteristics and is assumed to follow a lognormal distribution.

Table 1 reports the conversion factors for Equation (1) that best fit the CRREL data. The exposure rating, K_e , varies between 0.47 (for windswept buildings) and 0.74 (for fully-sheltered buildings). The thermal characteristics of the building are critical, with a smaller conversion factor, K_t , for heated structures (compared to unheated structures) due to snowmelt. Roof slope and material also have an influence on the roof snow load. As roof slope increases, snow slides off metal and other slippery roof surfaces, resulting in a decreased K_{sm} factor. However, roof slope does not appear to be critical for shingle or other non-slippery roof materials. Lastly, we examined whether the magnitude of ground snow loads had an impact on the conversion between ground and roof snow loads. Results show that the conversion factor, K_{gs} , decreases as the ground snow load increases, *i.e.* the larger the ground snow load the greater the relative difference between the ground and roof loads. To validate the model, we apply Equation (1) and the mean conversion factors to predict roof snow loads for the CRREL buildings given ground snow loads and building properties. The mean error, quantified as the ratio of the actual to predicted roof loads (using Equation (1)), is 1.01. To evaluate if the model was biased for certain types of structures, the CRREL buildings were split into subcategories of like buildings (*e.g.* a category with windswept/heated buildings etc.). Most categories had a ratio of actual to predicted roof loads in the range of 0.94 to 1.14. However, the model does appear to under-

predict snow loads in two classes of structures: windswept, unheated shingle buildings and semi-sheltered unheated metal buildings. These categories encompassed fewer than 10% of the total 467 structures.

Table 1: Load Model Coefficients

| Factor | Description | Mean | σ_{ln} |
|----------|---------------------|----------------------------|---------------|
| K_e | Windswept roof | 0.47 | 0.72 |
| | Semi-sheltered roof | 0.59 | 0.57 |
| | Sheltered roof | 0.74 | 0.46 |
| K_t | Unheated Roof | 1.10 | 0.57 |
| | Heated Roof | 0.96 | 0.66 |
| K_{sm} | Metal (slope 0-20°) | 0.95 | 0.70 |
| | Metal (slope >20°) | 0.87 | 0.52 |
| | Shingle (any slope) | 1.01 | 0.63 |
| K_{gs} | $GSL \leq 35$ psf | $K_{gs} = -0.022GSL + 1.4$ | 0.73 |
| | $GSL > 35$ psf | 0.70 | 0.47 |

In addition to the prediction of the average roof snow loads using Equation (1), Monte Carlo simulation can be used to predict multiple realizations of the roof snow load on a particular building, accounting for uncertainties in weather conditions, snow density and building properties. In Monte Carlo simulation, a set of independent random numbers are generated to simulate values of K_e , K_t , K_{sm} , and K_{gs} on the basis of the probability distributions defined in Table 1. The simulated factors are then inputted in Equation (1) to generate one realization of RSL . In Figure 4, we predict the intensity of the uniform snow load on a metal roof with a 14° slope, a semi-sheltered exposure condition and an unheated roof (*i.e.* poorly insulated). In this scenario, the mean roof snow load is 15 psf for a ground snow load of 25 psf, indicating an average roof load that is approximately 60% of the ground snow load. For the same building properties, reducing the ground snow load to 10 psf leads to a smaller average predicted roof snow load of 8 psf. In this case, a larger percentage (80%) of the ground snow load remains on the roof, reflecting the change in the ground snow load factor, K_{gs} .

Current U.S. building codes calculate a design roof snow load of 21 psf for a design ground snow load of 25 psf [10] for the building considered in Figure 4. Note that the conversion between ground and roof snow loads in this study, which relate ground snow load *at a particular time* to roof snow load *at the same time*, are different from those used in building codes and other design documents, which relate the maximum ground snow load in a given season to the maximum roof load in the same season. Since roof and ground maxima often do not occur at the same time, the conversion

factors here are different from the ground-to-roof snow relationships in the building code. While maximum values are appropriate for building code design loads, a probabilistic performance-based engineering approach needs to consider all possible roof snow loads, not only the yearly critical values. In addition, the load models developed here provide expected-value estimates of roof snow loads, unlike building code estimations which tend to be conservative. Roof snow load models can then be combined with the probabilistic characterization of ground snow hazard to predict structural response under any level of snow load in assessing building risk.

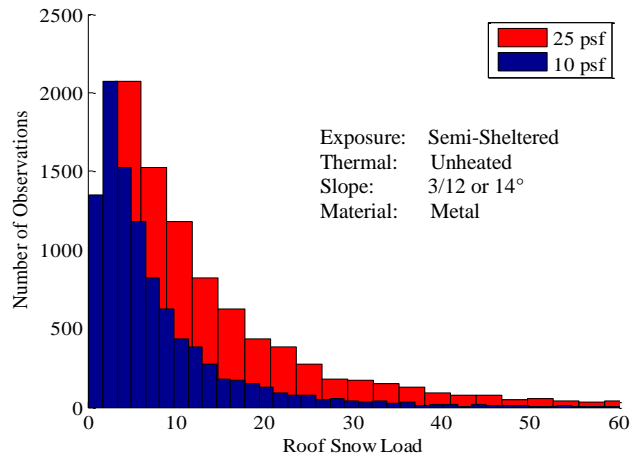


Figure 4: Monte Carlo simulations for 10,000 realizations of roof snow load, based on ground snow loads of 10 psf and 25 psf. These simulations assume uniform load (*i.e.* no drifting).

Validation, improvement, and extension of this load model are ongoing. In addition to the uniform load model presented here, we will also account for the probability of drift formation around roof obstructions and on multi-level roofs and the likely height of the drift(s). Drift load formation is a function of wind speed and direction, snow density, obstructions (*e.g.* gables, mechanical equipment, and parapets), and roof configuration (slope, multi-levels etc.). These roof snow load distributions will be modified to distinguish between buildings for which site-specific information is available, including detailed snow density and wind data, and those for which only general information is available.

5. Analysis of Case Study Building: The assessment methodology is illustrated here with analysis of a real structure that failed under large snow loads in February, 2008. This case study of an existing building is used as a preliminary demonstration and validation of the performance-based snow engineering methodology. In later parts of the project, we will systematically investigate a group of buildings with a variety of design

features to quantify the influence of particular design features with regard to the risk of snow-induced failure.

5.1 Village Square Building Failure: The case study is based on the Village Square Building located at Copper Mountain, Colorado. Village Square has six stories with condominiums on upper levels and a single-story garden level with retail outlets. In February, 2008, the garden level walkway roof was severely damaged by sliding snow and ice from the upper six-story roof.

The structural failure was investigated in March and April 2008 by Knott Laboratory, a Denver-based engineering firm. Damaged roof elements are shown in Figure 5. The majority of the bar joists supporting the walkway roof had deflected significantly (Figure 5a), and the wide flange beam supporting these joists was also visibly deformed (Figure 5b). Knott Laboratories analyzed the roof under today's building code requirements, showing that the as-built bar joists had a demand stress that exceeded the capacity by 97 percent [11]. As a result, Knott Laboratories recommended the construction of a new roof structure comprised of more closely spaced truss systems and a heavier wide-flange beam section. The construction was completed in July of 2009, approximately 15 months after the failure, at a total cost of \$350,000 [12].



Figure 5: Deflected (a) bar joists and (b) wide flange beams due to large snow loads in February 2008 [11].

5.2 Structural Analysis Model: The pre-failure Village Square Building is modeled using MIDAS Gen structural software. The simulation model consists of a 75' section of the 122' walkway roof structure, shown in Figure 6. Member sizes were obtained from a framing plan provided by [11]. The existing roof system was supported by a 16'' deep rod truss system, running at 44'' on center. Since the manufacturer of the roof trusses is unknown, the model assumes a Vulcraft 16K2 K-series (16'') trusses. The walkway roof was connected to the six-story structure by an angle section attached to the concrete framing elements, concrete-block walls or steel I-beams. In the model, a $4\frac{1}{2}'' \times 4\frac{1}{2}'' \times \frac{3}{8}''$ angle is used to support the roof truss, and is assumed to have fixed boundary conditions. The

wide-flange beam has a W16x26 section. The vertical posts are HSS 4'' x 4'' x $\frac{1}{4}''$ rectangular posts spaced at 30.5' on center. At the middlemost support in the modeled roof section, the beam is discontinuous and connected with a shear connection. The beam is continuous over the other two supporting posts. The post supports are pinned at the base, allowing for rotation between the posts and the base plate/concrete foundation connection.

All materials are modeled with linear-elastic behavior. This assumption is valid for snow loading scenarios that do not significantly stress bar joists or W- beams, but is not appropriate for predicting large deformations and buckling that may occur. The authors recognize that nonlinear models are essential for accurate prediction of the onset of failure phenomena; these advancements will be reflected in future models. The linear model is used here for illustration of the methodology and approach.

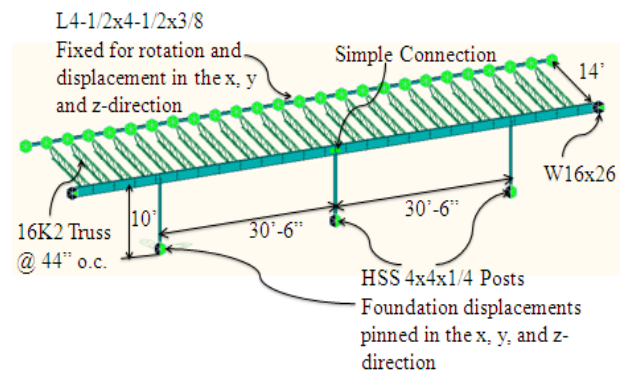


Figure 6: Existing walkway roof structure, as modeled in MIDAS.

5.3 Loading and Results: Two loading conditions are applied. First, the structure is modeled under ASCE 7-10 factored dead and snow loads [10]. In the second load case, the structure is modeled under the uniform probabilistic load models developed in Section 4.

Code Loads. The code load case consists of the dead load (D) of roofing materials, including the weight of metal roofing, plywood sheathing, wood roof framing, and metal decking, totaling 20 psf. The self-weight of the K-Series joists and other steel members is also considered. The roof snow load is calculated from a ground snow load for Copper Mountain of 90 psf [13], resulting in design roof snow load of 76 psf. These loads are combined with ASCE 7-10 provisions for sliding snow load from the upper roof structure for a total of 112 psf. The critical load combination from ASCE 7-10 is $1.2D + 1.6S$. For simplicity, wind loads are not considered.

The walkway structure is analyzed under ASCE 7-10 load requirements. A maximum deflection of 1.90” occurs at the center span of the W-flange, which exceeds the maximum allowable deflection in ASCE 7-10 of 1/360 of the span length, *i.e.* 1.0”. The deflection in the W-flange beam is associated with large deformations in the bar joists and damage to roof decking. According to data from Vulcraft’s allowable loads for trusses and metal decking, loading conditions exceed allowable loads in panels and joists [14].

Probabilistic Load Models. In the second load case, the probabilistic load models described in Section 4 are applied to the structure. In order to determine how the structural response varies with ground snow loads, ten different levels of ground snow loads varying from 10 psf to 100 psf are considered and reported in Table 2. Each ground snow load is inputted into roof load probability models to generate 10,000 realizations of the roof snow load. (Note: Figure 4 shows a histogram of realizations associated with 10 psf ground snow load). The average roof snow load for each ground load value is included in Table 2. Each loading realization is applied as a uniform load; non-uniform loads will be added as those probabilistic models are developed.

Table 2: Deflections predicted in the Village Square walkway roof for different ground snow loads.

| Ground Snow Load (psf) | Avg. Roof Load (psf) | Avg. Maximum Deflection in Beam (") |
|------------------------|----------------------|-------------------------------------|
| 10 | 8 | 0.32 |
| 20 | 13 | 0.37 |
| 30 | 15 | 0.38 |
| 40 | 19 | 0.42 |
| 50 | 24 | 0.46 |
| 60 | 28 | 0.50 |
| 70 | 33 | 0.54 |
| 80 | 37 | 0.58 |
| 90 | 42 | 0.63 |
| 100 | 48 | 0.68 |

Ten roof snow load realizations (spanning the range of possible roof snow loads from the Monte Carlo simulation) for each ground snow load level were then applied to the structure and the structural responses, including maximum deflection of the critical W-beam, were recorded. Each of these different loading scenarios leads to a different prediction of structural response, as illustrated in Figure 7. The variability in roof deflection associated with each level of ground snow load is due to uncertainties in the prediction of roof snow load. To

compute the average maximum deflection, the response under each loading realization is weighted according to its relative likelihood of occurring according to the histogram obtained from the Monte Carlo simulation model. Besides roof deflection, other structural response parameters of interest include the ratio of demand stress to yield stress in critical members.

Figure 7 shows an average maximum roof deflection of 0.63” at a ground snow load of 90 psf. The maximum roof deflection occurs in the wide-flange beam. The probability that the deflection will exceed the ASCE limit of 1/360 or 1.0” increases with larger ground snow loads. The probability of exceeding a deflection of 1.0” in the wide-flange beam can be related to ground snow load in an inverse cumulative distribution function, *i.e.* $P[\text{Deflection} > 1.0" | \text{GSL}]$. For 100 psf ground snow load, we predict an 8.4% probability that deflections in the beam exceed 1.0”, assuming a lognormal distribution. A ground snow load of 160 psf would be required for the average deflection to exceed the limit specified in ASCE. To determine the mean annual frequency of roof deflection exceeding 1.0”, the cumulative distribution function can be integrated with a ground snow hazard curve ($P[\text{GSL}]$) for case study site.

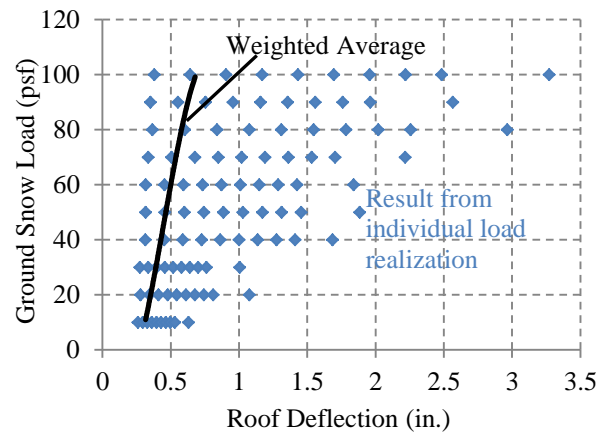


Figure 7: Prediction of maximum roof deflection as a function of ground snow load for case study structure under uniform snow loads.

6. Models for Building Closure and Downtime: Work is ongoing to develop models for predicting building closure and downtime as the result of structural damage due extreme snow loads on buildings. Downtime includes the time needed “to plan, finance and complete repairs” on damaged buildings [15]. Although difficult to quantify, the costs associated with business interruptions and downtime likely contribute significantly to the overall economic impacts of large snowstorms on buildings.

In order to understand processes and decisions related to building closure and evacuation, we asked questions about these topics during interviews with fire departments, insurers, engineers, and building managers [5]. Evacuation is typically governed by safety concerns, and the decision to evacuate may happen before or after damage occurs. Oftentimes, city fire departments respond to concerns from owners or occupants and order evacuation if a structure looks unsecure; these evacuations follow the same safety procedure used in structural fires. Once occupants have been evacuated, an engineer may be called to evaluate the stability of the structure which will be used to determine whether it is safe enough to clear snow from the roof and, in particular, the portions of the roof where it is safe to move around on.

Experts interviewed agreed that any closure of a building has a large economic impact, resulting primarily from loss in revenue. In particular, interviewees commented on difficulties for retail stores and restaurants because it may take time for the community to realize these establishments have reopened after being shut for some period of time. However, 'loss of income' clauses in insurance policies can help cover some, if not all, loss in revenue of a business. Some businesses, such as construction companies, can also benefit from snow-related building damage

Our study of past newspaper reporting of snow failures [4] was also used to quantify the likelihood a building will close after being damaged in a snowstorm and if so, the typical time period of the closure. In the U.S., 57% of buildings were closed for some period of time after the snow-related building damage or failure incident occurred. The average closure time among all incidents was just over three and a half months.

The data and information gained from the interviews will provide the basis for longer quantitative study linking building damage states, closure time and economic impacts associated with business interruption. An important part of this work will be documenting closures and repair times in buildings damaged in 2010-11 and 2011-12 winter snowstorms around the U.S. To the extent possible, downtime and closure will be directly linked to structural response limit states; for example, what magnitude of roof deflection triggers building closure?

7. Conclusions and Next Steps: This paper describes a set of research activities related to the development, illustration and validation of a performance-based design and assessment methodology for buildings potentially at risk of collapse and damage due to

extreme snow loads. A performance-based approach to snow engineering can improve our understanding about the behavior and reliability of structures subjected to extreme snow loading, thereby advancing risk-informed decisions about snow design.

Research is ongoing to improve procedures and assessments for performance-based snow engineering and the work described here reflects the current status of a multi-year study. Future work will include validation and improvement of probabilistic load models. These efforts will extend probabilistic models to account for drift formation and non-uniform snow loads, and provide the capability to incorporate site-specific weather information in order to reduce uncertainty in the loads predicted. In addition, a central part of the future research will include the development of a set of nonlinear models representing the archetypal lightweight buildings that have been shown to be particularly susceptible to snow-induced failure. The analyses will follow the same assessment procedure described here for the case study building. However, simulation models will account for nonlinear failure modes and connection failures, variation in design and detailing characteristics of buildings will be considered, and a number of limit states related to roof deflection and collapse will also be considered. The outcome of this study will be an assessment of the risk of snow-induced failure in modern code-conforming buildings in the U.S. and recommendations to improve consistency and design procedures.

8. Acknowledgments: This research is funded by the National Science Foundation Grant Number 0926680 through Division of Civil, Mechanical, and Manufacturing Innovation's Hazard Mitigation and Structural Engineering Program. This support is gratefully acknowledged.

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