

# A Framework for Performance-Based Design and Assessment of Buildings Subjected to Extreme Snow Loads

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**ABSTRACT:** This paper describes a framework for performance-based snow engineering that enables explicit consideration of the risks of snow-induced failure in structural design and assessment. The methodology is modular and separates hazard analysis, structural analysis, and damage assessment, from evaluation of collapse, dollar losses and life safety risks. Historic weather data are used to characterize the ground snow hazard at a particular location, accounting for the frequency of snow loads of different intensities. Roof snow loads are estimated from ground snow loads through a simulation-based probabilistic approach that accounts for sources of uncertainty, including exposure, building thermal conditions, roof material and slope, as well as wind speed and direction, temperature and moisture. The distribution of structural response parameters, such as peak roof deflection, can then be determined through nonlinear structural analyses. Key building performance metrics quantify the onset of limit states such as the risk of repair costs exceeding some critical value, building closure or downtime exceeding a specified time period, or structural collapse. The proposed framework enables inclusion of snowstorms in a multi-hazard design context.

## 1 INTRODUCTION

Large snow loads can cause significant damage to buildings and even collapse, requiring costly repairs, interrupting business, damaging building contents, and potentially threatening public safety. Snow-related damage and building closure can have significant societal and economic impacts on businesses and communities and, in some cases, lead to fatalities. High profile snow-related building failures have included the Hartford Arena in Connecticut (1978) and the C.W. Post College Theater on Long Island (1978). Moreover, a single large blizzard in January 1996 caused severe damage and collapse in buildings from Virginia to New Hampshire, including shopping malls, manufacturing facilities, supermarkets, a theater complex, and a skating rink (DeGaetano et al. 1997). A review of major U.S. newspapers reveals that building failures in snowstorms in more recent years have caused significant damage and disruption at manufacturing and retail facilities, and have also led to the closure of a number of emergency-response facilities (Geis et al. 2011). Snow loads dominate roof design in many parts of the world.

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, occu-

pants, and the public (Krawinkler and Miranda 2004). Goals for building performance can be used to inform decisions about design to reduce life-cycle costs and mitigate risks. 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 will exceed \$X?) or downtime (*e.g.*, How likely is snow-induced structural damage to interrupt business for more than Y days?). These metrics provide a feedback mechanism that links building performance assessments to decisions about structural design and rehabilitation, which distinguishes performance-based from conventional prescriptive design methods. In this context, a building owner could choose to invest in a stronger roof system to reduce future risks of structural failure or building closure due to snow loads, on the basis of quantifiable estimates of the reduction in risk. At this time, efforts to develop performance-based methods have focused primarily on seismic and, more recently, wind engineering, and potential applications to snow engineering have not yet been developed.

This paper describes an innovative framework for performance-based snow engineering that enables explicit consideration of the risks of snow-induced failure in decisions about structural design and assess-

ment. In doing so, it relies on previous research measuring and quantifying snow loads and modeling snow transport and drift formation. The performance-based framework for extreme loads utilizes these past studies to account probabilistically for the many sources of uncertainty in the magnitude and distribution of roof snow loads and their impact on structural behavior. Key sources of uncertainty affecting the magnitude and impact of snow loads on buildings include weather, *e.g.*, temperature, moisture content of snow, wind speed and direction; also important are building characteristics, *e.g.*, roof slope, roof size and building thermal properties. In addition, the framework relates design decisions to future societal impacts associated with structural damage, repair, and business interruption over the lifespan of the structure. Informed decisions for mitigating snow-related risks are particularly important for structures for which the consequences of snow-related failure are high, either because of the large number of potential building occupants (as in arenas or theaters) or because of the high costs of business interruption if the building is damaged or evacuated (as in some manufacturing facilities). Performance-based snow engineering can also advance understanding of the relationship between critical design variables and building performance for improving the consistency of code provisions and conventional design practice. The importance of considering uncertainties in snow engineering is intensified by global climate change, which has altered geographic distributions, frequencies and severities of snowstorms (U.S. CCSP 2008).

## 2 BACKGROUND

### 2.1 *Developments in Performance-Based Engineering*

The maturing field of performance-based earthquake engineering provides a prototype for the performance-based snow engineering framework. The methodology for performance-based earthquake engineering integrates knowledge and models from seismology, structural engineering, and the social sciences in a modular framework to obtain probabilistic predictions of seismic hazard, structural response, damage, economic losses, and casualties (Krawinkler and Miranda 2004; Aktan et al. 2007), as illustrated in Figure 1. The modular approach enables the propagation of key sources of uncertainty through the analysis. Evaluations of seismic performance can be used to identify structures that are particularly vulnerable to seismic risks, as the basis for evaluations of costs and benefits associated with seismic retrofits, or to justify uses of innovative technologies in design.

Recent research on performance-based earthquake engineering has included both methodology improvement and applications to specific types of structures or

retrofit solutions. For example, a project sponsored by the Federal Emergency Management Agency (FEMA) establishes a procedure whereby performance-based assessment of seismic collapse risk is used to evaluate the adequacy of U.S. earthquake code provisions for new structural systems (FEMA 2009). In addition, a large consortium of researchers has focused on development of models for prediction of economic losses and downtime (ATC 2009).

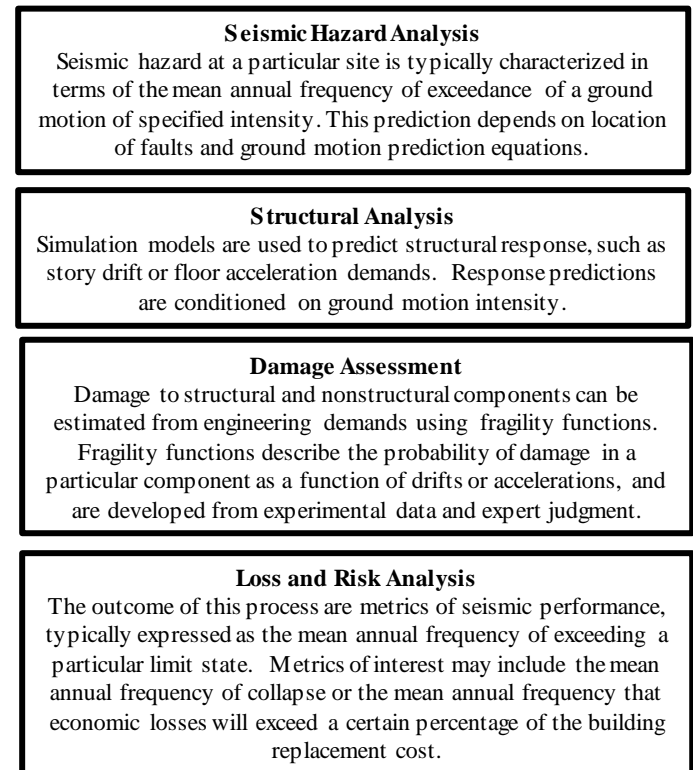


Figure 1. Methodology for performance-based earthquake engineering.

A key requirement of performance-based engineering is the ability to reliably predict structural performance under extreme loads. Computational tools have improved dramatically in recent years. As a result, some software platforms, such as *OpenSees*, now have libraries of nonlinear material models, large deformation geometric transformations, and numerical algorithms for solving systems of equations associated with dynamic analyses needed to predict structural response in highly nonlinear failure or near-failure conditions. These simulation tools can be used to predict structural behavior under extreme snow loads.

The modular framework for performance-based earthquake engineering represents an important starting point, and the performance-based snow engineering framework includes the same critical modules: hazard characterization (*e.g.*, probabilistic prediction of ground snow loads), estimation of engineering demands on the basis of robust analysis models (*e.g.*, deflections and stresses in a structure subjected to extreme snow loads), and evaluation of risk damage, collapse and other outcomes.

## 2.2 Current Snow Design Methods

According to current American code provisions, structures are designed for the ground snow load that has 2% likelihood of occurring each year,  $p_g$ . These snow loads correspond to a 50-year mean recurrence interval. Design  $p_g$  values are mapped in U.S. codes (2006 IBC or ASCE 7-05), though certain high elevation and mountainous regions require site-specific evaluations. Structural design for ground snow loads with a 50-year mean recurrence interval is consistent with European and Canadian practices.

U.S. design provisions convert ground snow load to a design roof load,  $p$ , through Equation (1):

$$p = 0.7C_e C_t C_s I p_g \quad (1)$$

The importance factor,  $I$ , is 1.0 for typical structures, and larger for hospitals and other significant structures. The exposure factor,  $C_e$ , reduces design roof loads for buildings exposed to the wind. The thermal factor,  $C_t$ , accounts for building insulation, with poorly insulated structures causing the snow to melt and thereby leading to lower values of  $C_t$  and lower roof snow loads.  $C_s$  accounts for roof slope and materials such that steeper roofs have lower design loads. For a partially-exposed structure with typical insulation and a flat roof, the design roof load is approximately 30% smaller than the ground snow load.

Additional provisions relate to drift loads, rain-on-snow surcharge and unbalanced roof loads. Drifts oftentimes occur on gables or lower roofs of buildings with multi-tiered roofs.

These prescriptive criteria have been calibrated to data relating roof snow loads to building exposure, roof slope, and other factors and empirical relationships predicting snow drift height. However, some design professionals have publicly questioned code-provided safety with comments such as, “[Snow design] codes must be modified to properly reflect the real threats to public welfare” (MacKinlay 1983). A performance-based design methodology provides a tool to evaluate and improve current design by directly evaluating the consequences of design criteria and decisions.

## 3 RECENT DEVELOPMENTS IN DESIGN AND ASSESSMENT FOR SNOW LOADS

### 3.1 Characterization of Snow Loads

Since the 1980s, a number of studies have characterized ground snow loads and the relationship between ground snow and roof loads, using measurements of snow loads on buildings (O'Rourke and Stiefel 1983; O'Rourke *et al.* 1982; Ellingwood and O'Rourke 1985; Tobiasson and Greatorex 1997). Other research has quantified snow drift height and shape as a function of building geometry and ground snow loads, using empirical data, analytical, and physical models (O'Rourke

and Auren 1997; O'Rourke *et al.* 1985; Templin and Schriever 1982). More recently, Meloysund *et al.* (2007a; 2007b) assembled data on ground snow loads, temperature, and wind speeds to re-evaluate the exposure coefficient and refine predictions of snow density as a function of weather conditions. O'Rourke *et al.* (2005) evaluated drift design provisions for gable and multi-level roofs. In addition, DeGaetano and O'Rourke (2004) used meteorological data for ground snow loads and wind speed to quantify the 50-year drift load at locations around the U.S. DeGaetano and Wilks (1999) showed how short-range weather forecasts for precipitation and temperature, together with snow water equivalent data, could be used to generate warnings that ground snow loads may exceed a particular value (*e.g.*, the snow load corresponding to a 50-year return period), thereby promoting mitigating activities to prevent roof collapse before or during a storm, such as shoveling snow from roofs.

While these data gathering and modeling efforts focused on estimating design loads, or snow loads with 50-year mean recurrence intervals, Lee and Rosowsky (2005) developed probabilistic snow models for the U.S., using available historic weather data. These models were used to develop ground snow hazard curves, which represent the annual probability of exceedance as a function of ground snow intensity.

### 3.2 Structural Assessment under Snow Loads or Multiple Hazards

Other research has examined the response of structures subjected to large snow loads. For example, Takahashi and Ellingwood (2005) assessed simply-supported steel roof systems subjected to uncertain snow loads, defining failure as the formation of the first plastic hinge. Failure was found to be more likely (*i.e.*, corresponding to a lower reliability index,  $\beta$ ) in structures with larger ratios of design snow loads to dead loads. Holicky (2007) confirmed that simply-supported roof elements designed to European codes have inconsistent reliability across roofs with different dead loads. Looking at snow loads in combination with other hazards, Lee and Rosowsky (2006) assessed the combined effect of snow and earthquakes on two single-family woodframe residential structures located in regions of moderate seismicity and moderate snow loads. That study predicted the probability a building exceeds 1% lateral drift under seismic loading, considering the possible coincidence of snow loading, finally obtaining multi-dimensional hazard fragilities as a function of snow and earthquake loads.

## 4 FRAMEWORK FOR PERFORMANCE-BASED SNOW ENGINEERING

The theoretical framework for performance-based snow engineering is modular, separating hazard analy-

sis, structural analysis, damage assessment, and loss analysis, as illustrated in Figure 2. This framework is intended to facilitate risk-informed decision-making for design and assessment of buildings subject to extreme snow loads, through probabilistic assessment of risks of collapse, losses, and building closure. Key components of each module are described in detail below, highlighting conceptual challenges that arise in the development of probabilistic assessment methods for snow engineering.

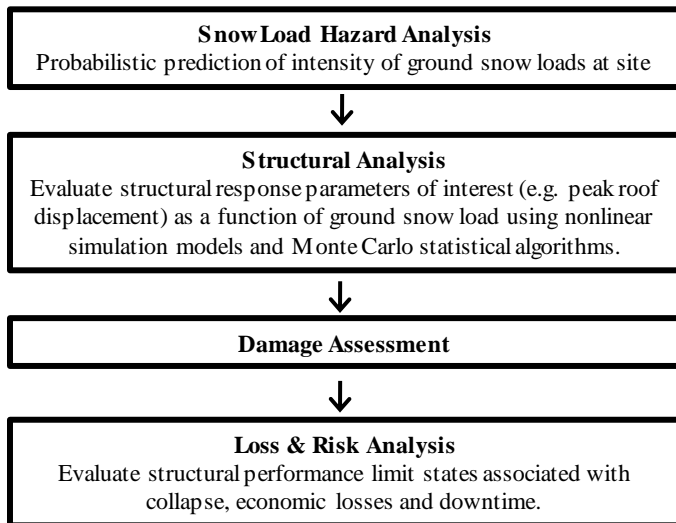


Figure 2. Framework for performance-based snow engineering.

#### 4.1 Characterization of Ground Snow Hazard

A ground snow hazard curve describes the mean annual frequency of exceeding the ground snow load of specified intensity at a particular site. Conceptually, it is analogous to a seismic hazard curve. The site-specific ground snow hazard curve is a function of weather patterns, site location and elevation, and snow density, which can vary substantially according to geography and weather conditions. Figure 3 provides an example ground snow hazard curve for a ski resort community in Copper Mountain, Colorado. Similar curves could be constructed in most of the U.S. where data is available from the National Climate Data Center and National Resource Conservation Service or anywhere similar data have been recorded. Characterization of the ground snow hazard is a crucial input to the evaluation of structural response and building performance limit states.

#### 4.2 Roof Snow Loads

In this study, roof snow loads are defined through conversion factors modifying the ground snow load on the basis of roof, exposure and weather conditions. Note that these conversion factors, 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. These maxima often occur at different times. Characterization of all roof snow loads, not only yearly maxima, allows us to combine roof snow load models with the probabilistic characterization of ground snow hazard to predict structural response under any level of snow load to assess structural risk.

Gathered data comparing snow loads on the ground to those on buildings (O'Rourke *et al.* 1983) show that these conversion factors can vary from approximately 0.04 (implying the roof snow load is only 4% of the ground snow load) to more than 2 (implying that the roof snow load is at least double the ground snow load) (Jackson 2010). Typical ground to roof conversion factors at any particular time are about 0.60, implying that roof snow loads are approximately 60% of that on the ground at any given time.

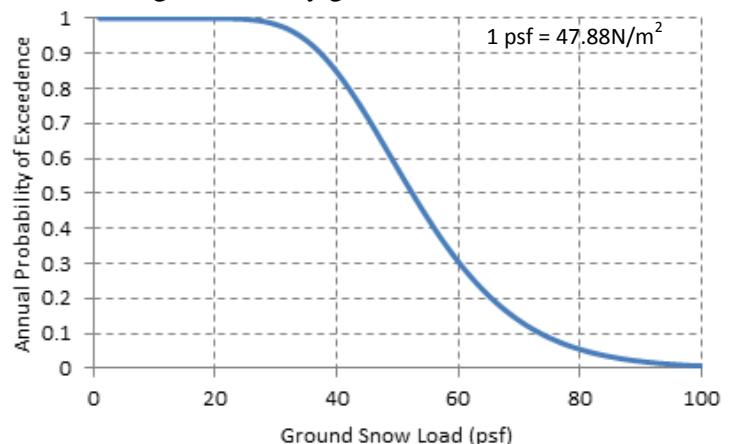


Figure 3. Ground snow hazard curve for Copper Mountain, Colorado.

Roof snow loads depend on the snow load on the ground, as well as the exposure (accounting for terrain and wind conditions), building thermal properties (specifically the amount of insulation, measured by the roof's thermal resistance), and roof material (*e.g.*, shingled roofs vs. metal roofs) and geometry (slope). Of these, the building exposure has the largest effect and the thermal factor is the second most significant, according to a dataset gathered by O'Rourke *et al.* (1983) and described in more detail below. The impact of roof steepness varies, with roof slopes larger than about 30° generally having less snow than flatter roofs, due to snow sliding or falling off. In addition, the conversion factor seems to decrease as ground snow load increases, such that the ground and roof snow load will be closer in value when the ground snow load is smaller; larger ground snow loads tend to have roof loads that are relatively lower. Drift loads will depend on wind speed and direction, snow density, obstructions (*e.g.*, gables, parapets, mechanical equipment), and roof configuration (slope, multi-levels *etc.*).

We have developed a probabilistic model to predict the distribution of roof snow loads as a function of ground snow load. This model acknowledges the many sources of uncertainty related to snow transport, drift distribution and formation, weather conditions, and

correlations between these factors. The model takes on the functional form:

$$RSL = K_e * K_t * K_s * K_m * K_{gs} * GSL \quad (3),$$

where  $RSL$  is the predicted value of roof snow load,  $GSL$  is the ground snow load,  $K_e$  is the factor relating to exposure,  $K_t$  is the factor relating to building thermal properties and insulation,  $K_s$  relates to the roof slope,  $K_m$  relates to the roofing material and  $K_{gs}$  relates to the amplitude of the ground snow load. The mean and standard deviation of the key parameters have been calibrated to data gathered by O'Rourke *et al.* (1983) on ground and roof snow loads for 199 structures throughout the northern regions of the U.S. (Jackson 2010). The database also includes information about building thermal and roof characteristics.

Roof snow loads can then be determined through Monte Carlo simulations which generate realizations of the roof snow load, depending on the ground snow load and the functional model in Equation (3) relating ground and roof loads. An example for uniform roof snow loads on a 3/12 (14°) sloped roof is shown in Figure 4, for two ground snow load cases: 10 psf (478.9 N/m<sup>2</sup>) and 25 psf (1197 N/m<sup>2</sup>). Data in Figure 4 corresponds to a metal roof that is semi-sheltered from the wind and unheated.

At this stage, the probabilistic models are preliminary and will be validated against more data. In addition, these roof snow load distributions will be modified to distinguish between buildings for which site-specific information is available, including detailed snow and wind data, and those for which only general information is available. The former is useful for site-specific assessment of particular structures. Work is also ongoing to extend the probabilistic models to account for the likelihood of snow drifting, which creates nonuniform loads and significantly increases the snow load on some parts of the roof.

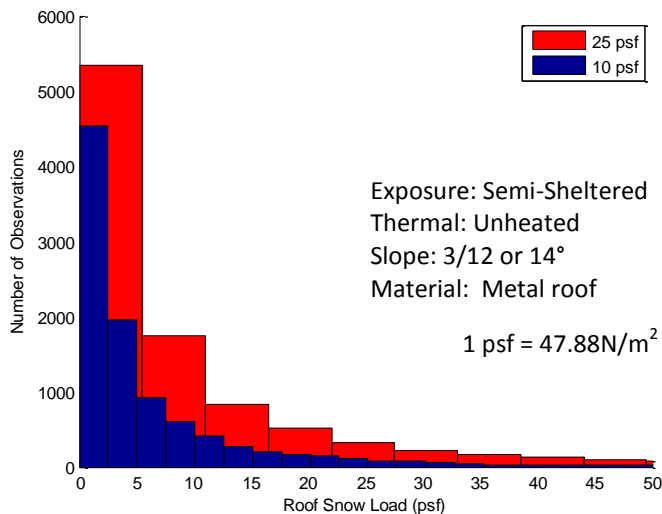


Figure 4. Monte Carlo simulations for 10,000 realizations of roof snow load, based on ground snow loads of 10 psf and 25 psf. These simulations assume uniform load, *i.e.* no drifting.

### 4.3 Evaluation of Structural Response

The outcome of the roof load probability models is a set of possible realizations of roof snow load for each value of ground snow load. Approximately 1,000 to 10,000 realizations of roof snow load are required, depending on the magnitude of the ground snow load, inherent model variability and uncertainties in structural response. Each realization produces a different magnitude and distribution of roof load to which the structure will be subjected. Accordingly, each of these different loading scenarios leads to a different prediction of structural response, as illustrated in Figure 5.

The assessment methodology is illustrated here with analysis of a real structure that failed under large snow loads in Copper Mountain, Colorado. This case study of an existing building is used as a preliminary demonstration and validation of the performance-based snow engineering methodology. The structure consists of a six-story condominium structure 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 pre-failure garden-roof structure is modeled using MIDAS Gen structural software. The simulation model consists of the 75 ft. (22.9 m) section of the 122 ft. (37.2m) walkway roof structure that failed. Member sizes were obtained from a framing plan provided by Knott Laboratory (2008). The existing roof system was supported by a 16 in. (40.6 cm) deep rod truss system, running at 44 in. (101.6 cm) on center, and connecting to a wide-flange W16x26 beam. 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 HSS post supports are pinned at the base, allowing for rotation between the posts and the base plate/concrete foundation connection.

In the preliminary models, all materials are modeled as linear-elastic. 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.

Structural response can then be evaluated at a variety of different levels of ground snow loads, as shown in Figure 5, to obtain predictions ranging from very low to high snow loads for a particular structure. The variability in roof deflection associated with each level of ground snow load is associated with uncertainties in the prediction of roof snow load and, potentially, structural modeling. Besides roof deflection, other structural response parameters of interest may include the ratio



of stress in critical member to yield stress and prediction of collapse (indicated by very large deflections).

Analyses need to be conducted with models that can account for large deformations and material nonlinearities to predict collapse. Effects of snow loads can typically be analyzed statically, unless dynamic effects or impact loads could be important; time-varying loads can be incorporated easily into the procedure, but computational time increases.

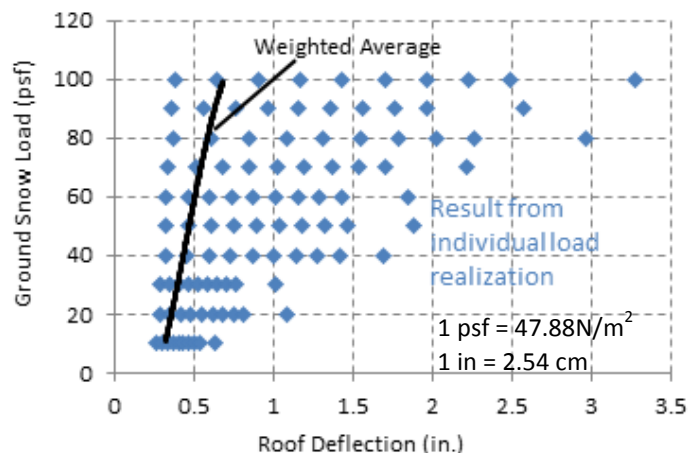


Figure 5. Illustration of the prediction of maximum roof deflection as a function of ground snow load for the linear model of the case study garden walkway structure.

The statistical analyses and structural simulations to predict the effects of snow loads on structural response are applicable to a wide variety of structures. These estimations of structural response are needed for probabilistic assessment of building performance limit states, which are of importance to building owners and other stakeholders. The statistical robustness of the approach also quantifies the effects of different sources of uncertainty on structural response.

#### 4.4 Assessment of Limit State Probabilities of Exceedance

Building performance limit states of interest are related to the potential consequences building owners or society wish to avoid. Extreme snow loads can cause structural and nonstructural damage, economic losses due to costs associated with repairing snow-related damage, downtime and business interruption, or collapse. Broadly speaking, building owners and occupants are interested in assessments of safety (*i.e.*, collapse risks) and downtime and economic losses, which facilitate life-cycle assessment of design decisions. Therefore, metrics for performance-based snow engineering may include the probability of (i) repair costs exceeding  $X\%$  of building replacement cost, (ii) building closure or downtime exceeding  $Y$  days, or (iii) structural collapse within a certain time frame, or given a particular ground snow load.

Figure 6 illustrates the type of results that may be obtained from a performance-based assessment of an in-

dividual building subjected to snow loading. Although not shown here, with advanced nonlinear capabilities, collapse can be predicted directly from simulation models. Limit state probability distributions, for any limit state of interest, may be integrated with ground snow hazard curves to compute the mean annual probability of exceedance associated with each limit state, as shown in Figure 6.

#### 4.5 Models for Building Closure and Downtime

While the risks of snow-induced collapse can be directly evaluated from nonlinear simulation models, limit states related to building closure and downtime cannot be predicted from structural response alone. Nevertheless, these limit states are of significant interest to building owners and society. The building closure limit state relates to voluntary evacuation that may occur due to concern about large snow loads on the structure's roof. Even if the structure is not damaged, closure may be costly if the building is not operational during the evacuation period. Decisions about building evacuation are particularly interesting because the relatively slow build-up of snow loads during the storm provides an opportunity for mitigating actions to protect safety. However, there is little information available to help building owners or city building officials make these decisions.

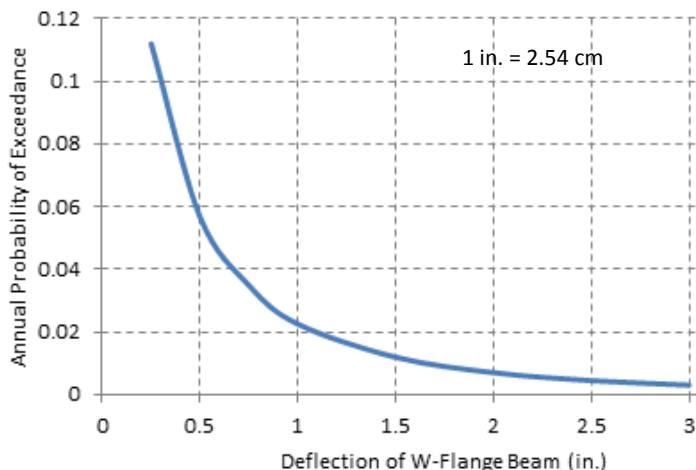


Figure 6. Example performance assessment, showing probability of exceeding different deflection levels in the wide-flange beam of the case study walkway structure.

The downtime limit state relates to the time needed to repair a damaged structure, including time for planning, financing and construction. Downtime and business interruption may be a large contributor to total economic losses in snowstorms.

A recent study of U.S. snow-related building failures found that, on average, damaged buildings are closed for four months. In addition, building evacuation may lead to building closure for up to one month, even if no damage occurred (Geis et al. 2011). Research is ongoing to determine the costs of building closure and downtime and to relate these costs to structural response such that risks of building closure and

downtime can then be predicted from structural analysis and factored into predictions of life-cycle costs associated with snow design decisions.

## 5 CONCLUSIONS

This framework for performance-based snow engineering can be used to quantify the behavior and reliability of structures subjected to extreme snow loading, advancing risk-informed decisions about snow design. It is applicable to a wide variety of structures and, by extension, vulnerable lifeline systems. Assessments of building performance under snow loads, such as collapse and building closure, improves understanding of the key sources of uncertainty governing snow design and the impacts of snow design decisions and code provisions on structural response and other limit states of interest to building owners.

Snowstorms contribute significantly to the number of structural failures and the value of economic losses and business disruption associated with natural hazards in the U.S. Performance-based snow engineering is an important step toward a safer and more resilient built environment, especially in the face of increasingly uncertain weather due to global climate change. For the design of special buildings, performance-based approaches can facilitate design by making the safety implications and life-cycle costs of design decisions transparent. For regular buildings, it provides a mechanism to improve the consistency and efficiency of building codes through explicit evaluation of design provisions.

Future research will explore the application of this methodology to complex real structures, focusing on long-span light-frame metal structures that have been shown to be particularly susceptible to snow-related building damage and collapse (Geis et al. 2011).

## 6 ACKNOWLEDGMENTS

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