STRUCTURAL FORENSICS

investigating structures and their components

Snow Related Roof Collapse and Implications for Building Codes

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The winter of 2010-2011 was particularly snowy in the Northeast. Heavy snows resulted in nearly 500 problem roofs in the states of Connecticut, Massachusetts, New York and Rhode Island, of which 382 were full or partial collapses. This large number of roof problems led to questions raised by engineers and state building officials as to the adequacy of current building codes in relation to roof snow loads. Specifically, were the 2010-2011 winter roof problems due mainly to roof components not as strong as envisioned by current codes, or were the 2010-2011 roof snow loads larger than those envisioned by building codes?

Weather data from multiple sources was used to estimate the 2010-11 ground snow loads. Similarly, weather information – specifically snowfall, wind speed, wind direction and duration of wind storms – was used to simulate 2010-11 drift snow loads for various roof geometries at selected locations in southern New England. Building performance databases from state officials in Connecticut and Massachusetts were gathered as well as case histories from structural engineering practitioners. These case histories contained roof snow load measurements as well as descriptions of typical problem roofs. In turn, the measured roof loads were compared to requirements in the current American Society of Civil Engineers' ASCE 7 load standard.

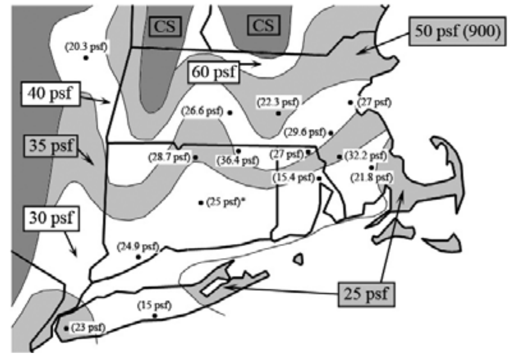

Figure 1: Estimated 2010-2011 peak ground snow load in parentheses overlaid on ASCE 7-10 map.

Ground Snow Loads

Following Canadian practice, roof snow loading for structural design purposes in the U.S. is based upon the ground snow load. This approach is sensible given that historically there are many more available measurements of the ground snow loads than available measurements of roof snow loads. The ASCE 7-10 load standard has a map showing regions with what is intended to be the 50 year Mean Recurrence Interval (MRI) ground snow load $(P_g)_{50}$.

Actual ground snow loads for the 2010-2011 winter were simulated using weather data for the region. Specifically, a combination of data from COOPerative (COOP) stations and Local Climatological Data (LCD) stations was used to estimate ground snow loads at 15 locations across the region. The 2010-11 ground snow loads were compared with the ASCE 7-10 map values in *Figure 1*. *Table 1* shows that the ratio of 2010-11 winter loads to ASCE 7 mapped load ranged

Table 1: Comparison of COOP, LCD, and practitioner ground snow loads with corresponding values from ASCE 7-10.

#	Station	Elevation [ft]	2010-2011 Pg [psf]	ASCE 7-10 Pg [psf]	2010 – 2011 / ASCE 7-10
1	Albany, NY	280	20.3	40	51%
2	Ware, MA	475	26.6	35	76%
3	Worcester, MA	1003	22.3	50	45%
4	Boston, MA	19	27.0	40	68%
5	Walpole, MA	150	29.6	40	74%
6	Norton, MA	105	32.2	35	92%
7	Middleboro, MA	141	21.8	30	73%
8	Providence, RI	52	15.4	30	51%
9	Woonsocket, RI	184	27.0	40	68%
10	Staffordville, CT	627	36.4	40	91%
11	Windsor Locks, CT	170	28.7	35	82%
12	Bridgeport, CT	8	24.9	30	83%
13	Islip, NY	82	15.0	30	50%
14	New York, NY	156	23.0	25	92%
CS	Portland, CT	180	25.0	30	83%

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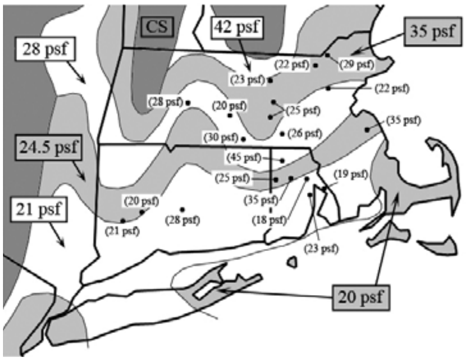

Figure 2: Measured roof snow load for heated and presumably heated structures overlaid on ASCE 7-10 design load map (Design load equal to the larger of P_f and minimum roof load).

from 45% to 92%, with an average of 71%. The ground loads were closest to the ASCE 7 values in Connecticut, where the average ratio was 85%. The ground snow loads were less severe in MA, NY and RI where the average ratios were 71%, 64% and 59% respectively. In no instance was the estimated simulated 2010-11 ground snow load larger than that prescribed by ASCE 7.

Return Period for 2010-2011 Winter

The question of the exact return period for the 2010-11 winter ground snow load is more difficult to answer. This is due in part to the fact that the ASCE 7 mapped values are different, and typically larger, than the corresponding site specific 50 year MRI ground load values within the particular map region. In addition, different sources list different values for the 50 year MRI ground snow load at various available sites.

Never-the-less, in terms of the maximum annual ground snow loads, the 2010-2011 winter was roughly a 25 year MRI event in Albany, NY, Boston, MA, and Providence, RI; a roughly 50 year MRI event in Bridgeport, CT, and a roughly 100 year MRI event in New York City. That is, as noted above, the 2010-2011 winter in the Northeast was indeed snowy with ground snow loads at a few locations larger than the site specific 50 year MRI value. However, again due to differences between the mapped design values in ASCE 7 and individual site specific 50 year values, the 2010-2011 winter ground snow loads approached the mapped 50 year design values but did not exceed them.

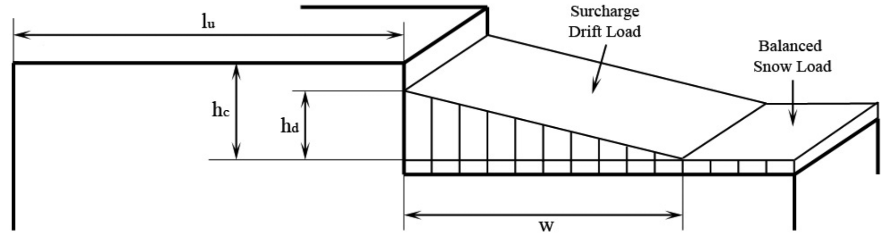

Figure 3: Schematic of leeward roof step snow drift.

Nominally Uniform Roof Snow Loads

Roof collapses, due to nominally uniform snow loading, were an observed "apparent failure mechanism" during the 2010-11 winter in Southern New England. The flat roof snow load in ASCE 7-10, P_f, is a function of the ground snow load and three factors related to the building and its surroundings:

$$P_f = 0.7 C_e C_t I_s P_g$$

Where: C_e is the exposure factor, C_t is the thermal factor, and I_s is the importance factor. Herein the exposure and importance factors are taken to be 1.0. Furthermore, since someone was on the roof taking snow measurements, it is assumed that the roof slope is small and the flat roof design load is appropriate for comparison with measured roof loads.

A total of 33 case studies were available which provided roof snow load measurements. Twenty of the structures were heated (C_t = 1.0) and four were unheated (C_t = 1.2). For the remaining nine, the thermal condition was unknown.

A comparison was made between measured roof loads, primarily from practitioner case histories and the flat roof design load prescribed in ASCE 7-10. The comparison was made for three classes of structures: heated and presumably heated structures, unheated and presumably unheated structures, and structures with an unknown thermal condition. For 16 of the 20 heated structures (80%) as shown in *Figure 2*, the ASCE 7-10 design load was larger than or only slightly below the measured roof load. For the remaining four heated case histories, the measured roof load was significantly larger (33% to 61% larger) than the ASCE 7 flat roof snow load. These "outliers" were then compared to the estimated 2010-11 ground snow load. As shown in *Table 2*, the outlier roof load measurements were also significantly larger than the ground snow load. Note that for a heated building, absent drifting loads, sliding loads, and impounded water due to blocked drains, one does not expect the roof snow loads to be larger than the ground snow. Hence, assuming the measurements were made properly, the four roof snow measurements in *Table 2* do not appear to represent nominally uniform roof snow loads. It is conceivable that they were taken near a parapet wall and include some drift loading. It is also conceivable that they were taken near a blocked roof drain.

The comparison for unheated and unknown thermal condition structures was similar. Hence, if one discounts the roof load measurements which are inconsistent with flat roof snow loading (i.e. load measurements apparently include drifted snow load and/or impounded water), the ASCE 7-10 procedures provide reasonable balanced roof snow loads in comparison to the 2010-2011 measurement.

Snow Drift Loads

Roof profiles with irregular geometries create areas of aerodynamic shade. These areas often trap windblown snow, forming drifts. Snow drift loads have been a common root cause of roof structural performance problems in the past. Insurance records suggest that about 75% of past U.S. snow related roof failures were due to drifted snow. Roof snow drifts were also reported to be an apparent failure mechanism for a number of buildings during the 2010-2011 winter.

Table 2: Measured roof load and estimated ground load for outlier heated structures.

#	Municipality	Measured Roof Load (psf)	Estimated Ground Snow Load (psf)	Roof Load / Ground Load
16	Abington MA	35	24.85	141%
22	N. Scituate RI	35	20.65	169%
25	Chepachet RI	45	23.60	191%
27	Middletown CT	28	25.50	110%

continued on next page

*Table 3: Weather data for drift surcharge simulation at LCD stations. *Average for times with wind speed ≥ 10 mph.*

#	Station	Simulated P_g (psf)	Wind duration t_i (hrs)	Wind speed* V_i (mph)	Wind Direction	Available "Driftable" Snow		Dates where drifting occurred
						Inches H_2O	Load (psf)	
1	Albany, NY	20.3	111	15.2	W	1.47	7.6	1/9-1/15 1/19-1/23
3	Worcester, MA	22.3	189	16.4	NW	2.22	11.5	1/9-1/14 1/21-1/27
4	Boston, MA	27	66	16.6	NW	0.73	3.8	1/21-1/24
8	Providence, RI	15.4	33	14.5	NW	0.36	1.9	1/21-1/24
11	Windsor Locks, CT	28.7	117	15.4	NW	2.97	15.4	1/9-1/13 1/21-1/27
12	Bridgeport, CT	24.9	72	14.7	NW	1.7	8.8	1/11-1/13 1/21-1/23
13	Islip, NY	15	30	16.2	NW	0.38	2	1/21-1/24
14	New York, NY	23	63	12	W	1.27	6.6	1/12-1/13 1/21-1/24

Snow drift loads in ASCE 7-10 are a function of ground snow load, P_g, and upwind fetch distance, l_u. As sketched in *Figure 3 (page 19)* for the leeward roof step geometry, a triangular drift surcharge, placed atop the balanced or flat roof snow load, is prescribed. The peak drift height, h_d, in feet is given by:

$$h_d = 0.42\sqrt[3]{l_u}\sqrt[4]{P_g + 10} - 1.5$$

Where: l_u is the upwind fetch distance in feet and P_g is the design ground snow load in pounds per square foot (psf). Again, for the roof step geometry the horizontal extent of the triangular surcharge, w, is taken as

$$w = 4h_d$$

The peak drift surcharge load, at the roof step, P_d in psf is

$$P_d + h_d\gamma_g$$

Where: γ_g is the snow density in ASCE 7 equation 7.7-1. Finally the total drift surcharge load, TS, in pounds per linear foot parallel to the roof step is

$$TS = ½P_d w$$

Simulated Drift Loads

There are three elements needed for roof snow drift formation; an area of aerodynamic shade (geometric irregularity) on the roof where the drift can form and grow, a source of "driftable" snow upwind of the geometric irregularity, and wind speed sufficient to cause transport of "driftable" snow across the aerodynamic shade region. In relation to driftable snow, a proposed set of weather conditions which preclude snow transport was used. Specifically, snow is considered driftable as long as none of the following apply:

1) Snowfall followed by rain, sleet, or freezing rain.
2) Snowfall followed by temperatures above 32° F.
3) More than 3 days since the last snowfall.

The size of a roof drift is related to the amount of snow (snow flux) flowing past the aerodynamic shade region and the percentage of the snow flux which remains at the drift accumulation (aerodynamic shade) region. The snow flux, Q, having units of pounds of snow per hour per foot width perpendicular to the wind direction is a function of wind speed above a threshold, V, (in mph):

$$Q = 0.00048V^{3.8}\left(\frac{l_u}{750}\right)^{1/2}$$

Herein, the threshold is taken to be 10 miles per hour (mph). If the wind speed varies over time, the total transport, Q_t in pounds per foot width (lbs/ft) is:

$$Q_t = \Sigma Q_i t_i$$

Where: Q_i is the hourly transport for wind velocity, V_i, and t_i is the duration in hours of wind velocity V_i.

Based upon water flume studies and comparison with full scale case histories, the trapping efficiency (percentage of transported snow which remains at the aerodynamic shade region) is taken to be 50% for the step roof geometry. Hence, the simulated drift surcharge is

$$TS = ½Q_t$$

Data needed to calculate roof snow drifts at each LCD station are shown in *Table 3*. This includes the duration of wind with speed above the 10 mph threshold, t_i, the average wind speed during t_i, and the driftable snow available during t_i. Also listed are the days when drifting occurred (driftable snow available and wind speed greater than 10 mph), as well as the 2010-2011 peak ground snow load. In calculating the simulated snow drifts, eight compass directions (N, NE, E, etc.) were considered. Wind characteristics for the compass direction with the largest snow flux, and hence largest simulated drift, are shown in *Table 3*. Note for the 2010-2011 winter, the peak ground snow load at the site typically occurred well after episodes of drifting. That is, drifting at the LCD sites in question occurred in January 2011, while the peak ground snow load as well as the onset of reported roof problems typically occurred in early to mid-February 2011.

As noted above, snow drift size is a function of the amount of available driftable snow and the ability of wind (speed and duration) to transport the driftable snow. As shown in *Table 3*, during the 2010-2011 winter, some sites, such as Worcester, MA and Windsor Locks, CT, had comparatively large amounts of both. Other sites, such as Islip, NY and Providence, RI, had comparatively small amounts of both.

Table 4 presents a comparison of the Leeward roof step drifts. Specifically, the ratio of the total surcharge for the 2010-2011 winter simulation to the corresponding ASCE 7 value is presented for each of the eight LCD stations with upwind fetch distances ranging from 50 to 500 feet. Again, the simulated value is for the worst wind direction, the one with the largest resulting drift. Note that the simulated drift loads were significant at Worcester, MA and the two Connecticut stations. Simulated drift loads were generally smaller in comparison to the ASCE 7 design values in New York, Rhode Island and Boston, MA. Also, the ratios generally decreased with increasing upwind fetch. There is only one instance, Windsor Locks, CT with l_u = 50 ft, where

Table 4: Ratio of simulated total surcharge to ASCE 7-10 drift surcharge for leeward roof step geometries.

	Leeward Roof Step Drift Loads	$\frac{TS_{simulation}}{TS_{ASCE}} \times 100\%$			
Station	l_u (ft)	50	100	250	500
	Albany, NY	67.1%	66.8%	47.0%	37.8%
	Worcester, MA	83.0%	85.3%	96.2%	86.8%
	Boston, MA	33.6%	34.1%	38.0%	40.0%
	Providence, RI	21.7%	21.4%	15.0%	11.9%
	Windsor Locks, CT	117.5%	83.6%	58.5%	46.7%
	Bridgeport, CT	79.2%	56.0%	38.8%	30.8%
	Islip, NY	22.6%	22.6%	23.1%	18.3%
	New York, NY	30.4%	21.1%	14.6%	11.4%

the simulated drift load exceeded the ASCE value. Given the influences of the balanced snow load and dead load, as well as safety factors in structural design, it seems unlikely that a 18% overload for the drift surcharge would, of and by itself, result in roof performance problems.

What Went Wrong?

As shown above, the ground snow loads in 2010-11 were significant, but did not exceed those prescribed in ASCE 7. The same holds for roof snow loads including drift. So, why all the roof problems?

There are two general reasons for this "unexpected" poor roof performance. The first has to do with when modern building codes were adopted and which structures are designed per code. For example, Connecticut adopted its first state-wide building code in 1971. Of the problem roofs in the Connecticut database for which the construction date is known, 61% (107 of 175) were built prior to the 1970s. Similarly, snow drift provisions in some older codes were arguably inadequate or non-existent. For example, modern drift provisions in which the load is related to the upwind fetch distance were first introduced into ASCE 7 in 1988. Finally, there are structures that are exempt from code provisions. For example, barns in New York State are exempt.

The second general reason for the "unexpected" poor roof performance is that significant loading reveals "hidden" structural defects. There is a long laundry list of such hidden defects. They include: a) initial design defects such as the absence of web stiffener plates at continuous girder-over-column connections, b) initial design/construction defects such as inadequate slope to drainage and resulting ponding loads, c) improper maintenance resulting in blocked roof drains, d) additional "unanticipated" dead loads due to post construction installation of solar panels, e) improper post construction structural modifications such as removal of inconveniently located column braces in metal buildings, f) improper building additions resulting in a "new" unreinforced lower level roof, and g) material deterioration over time such as that resulting from wooden structural components exposed to water.▪

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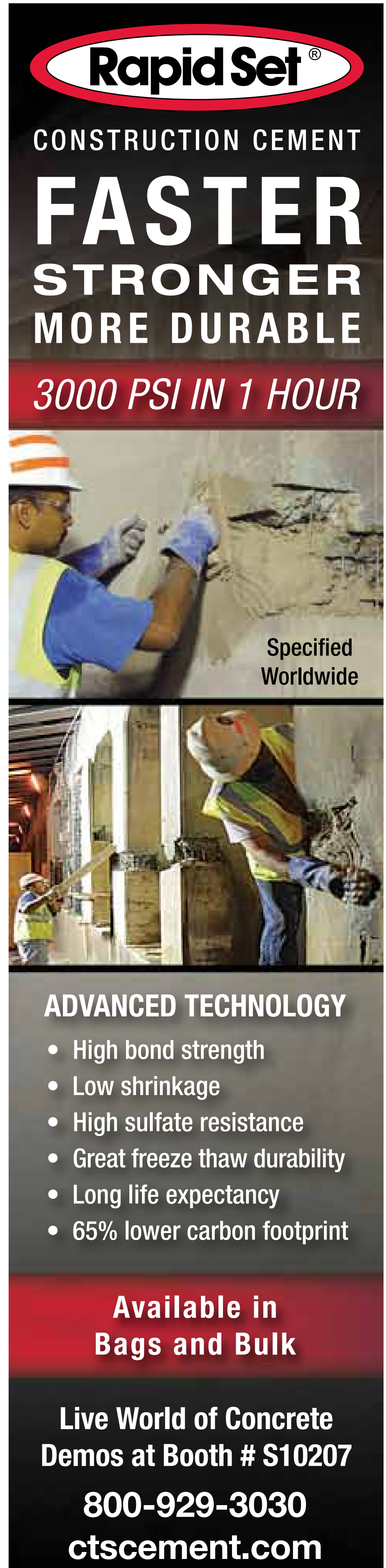

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