Final Draft

Snow Study Summary Report

Observations of Snow Load Effects on Four School Buildings in New England

October 2016

FEMA

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ASCE	American Society of Civil Engineers
CRREL	Cold Regions Research and Engineering Lab
FEMA	Federal Emergency Management Agency
HVAC	heating, ventilation, and air conditioning
LCD	Local Climatological Data
NOAA	National Oceanic and Atmospheric Administration
psf	pounds per square foot

During February 2015, reports of snow load-induced roof failures at essential facilities in the Greater-Boston and Southern New Hampshire area triggered deployment of a FEMA Building Science Branch assessment team. The assessment team observed snow loading conditions and building/site characteristics at four affected schools and developed conclusions and recommendations about the effects of this snow event based on their observations.

The assessment team's conclusions on snow load determinations and resulting design implications are described below.

- At all four schools, the structural performance problems were caused by localized snow drift loading. Based on observations, available design information, and the age of damaged roof areas, it is reasonable to assume that the roof systems did not meet current snow load requirements, which include snow drift loads.

The assessment team's recommendations are:

- Update FEMA P-957, *Snow Load Safety Guide*: Incorporate findings from this report into FEMA P-957. Recommended topics to be included or updated in the next edition of FEMA P-957 are described in the conclusion section of this report.
- Prepare a fact sheet or research report: Develop guidance in the form of a fact sheet or research report to address the following drift loading conditions, which are not adequately addressed in American Society of Civil Engineers (ASCE) 7-10, *Minimum Design Loads for Buildings and Other Structures*: (1) combination of over-the-ridge drift loads with roof step drift, (2) distribution of drift loads when the space available for drift formation varies in the direction perpendicular to the upwind fetch, and (3) slope of the top surface of a gable roof drift as a function of roof slope.
- Work with ASCE to encourage use of the developed drift load guidance (described in previous bullet) to serve as the basis for a future update of ASCE 7.

SECTION ONE EVENT DESCRIPTION AND PURPOSE OF STUDY

1.1 EVENT DESCRIPTION

The 2014–2015 winter was one of the snowiest seasons on record for New England. Accumulated snow loads caused widespread damage in the region. The Boston area was hit especially hard, with a total of 110.6 inches of snowfall that winter, breaking the previous record for the snowiest season, which was 107.6 inches of snowfall in the winter of 1995–1996. In January 2015, 34.3 inches of snow was recorded. February was the snowiest month on record, with 64.8 inches of snow. February was also one of the coldest months on record, so the accumulated snow did not melt. These two circumstances made for unusually high accumulations.

1.2 PURPOSE OF STUDY

On February 25, 2015, the Federal Emergency Management Agency (FEMA) deployed a Building Science assessment team to assess the performance of a few selected school buildings in response to a succession of snow events in the Northeastern United States. The assessment team consisted of nationally recognized subject matter experts in structural engineering and snow loads.

The assessment team visited two schools in Massachusetts and two schools in New Hampshire whose roofs experienced structural failure due to the weight of snow. Buildings observed in Massachusetts were on the campuses of Mitchell Elementary School in the Town of Bridgewater and Plymouth River Elementary School in the Town of Hingham. Buildings observed in New Hampshire were on the campuses of the Milford High School in the Town of Milford and Sanborn Regional Middle School in the Town of Newton.

This report discusses snow loading, damage observations, and when available, snow removal procedures used and operational impacts of snow-related damage for each site. The design considerations and mitigation measures discussed in the conclusions and recommendations of this report are based on the assessment team’s observations. The recommendations and conclusions are intended to provide decision-makers and design professionals with information and technical guidance for improving building performance and consequently reducing future damage from snow loads.

SECTION TWO FINDINGS

The 2014–2015 winter in the Greater Boston and Southern New Hampshire area, where the subject facilities are all located, featured four significant snow storms. The first began on January 26 and extended through January 31. More than 26 inches of snow fell,[1] with a corresponding ground snow load of over 6 pounds per square foot (psf).[2] During this first storm, there were over 90 hours when the wind speed was above the 10 mph snow drifting threshold as defined in “Analytical Simulation of Snow Drift Loading” (O’Rourke et al., 2005). The winds blew out of the northwest, north, and northeast during this first significant storm.

The other three significant storms (February 2–5, 7–12, and 14–17) resulted in 17, 25.3, and 16.8 inches of snow,[1] respectively, with corresponding ground snow loads of 4.6 , 7.33, and 3.33 psf,[2] respectively. As with the first storm, strong wind nominally out of the north accompanied the storms.

The assessment team’s observations of snow loading and its effects at each of the four sites are discussed in more detail below.

2.1 MITCHELL ELEMENTARY: 500 SOUTH STREET, BRIDGEWATER, MA

Figure 1 shows an aerial view of Mitchell Elementary School. The area where the roof collapsed is on the south side of the central wing gable roof (the ridge line is nominally east-west). In addition, there is an upper-level roof to the right (nominally east) of the damaged area. Since the wind directions were from the north and west, the roof was subject to over-the-ridge gable roof drifts due to the north wind, and windward roof step drifts due to the west wind (see Figures 2 and 3). Unfortunately, there is no current guidance on how to combine the over-the-ridge drifts with windward or leeward roof step drifts when both types of drifts occupy the same roof area.

[1] Based on National Oceanic and Atmospheric Administration (NOAA)-recorded snowfall depths at Logan Airport.
[2] Based on NOAA-recorded water equivalence of precipitation at Logan Airport.

Figure 1: Aerial photograph of Mitchell Elementary School (red outline shows damage location) (Source: Google Earth)

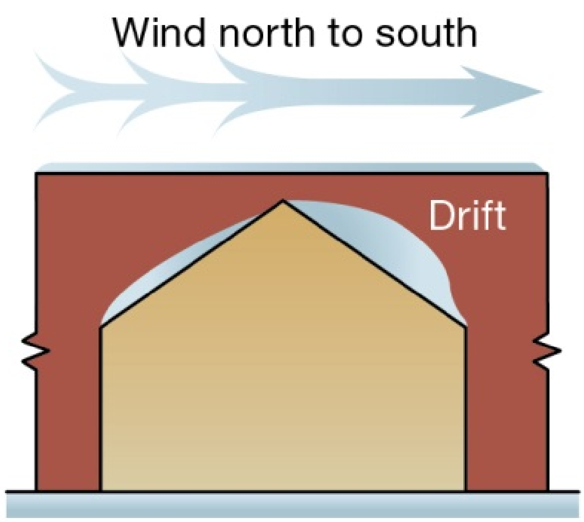

Figure 2: Cross section looking east through the drift area (not to scale)

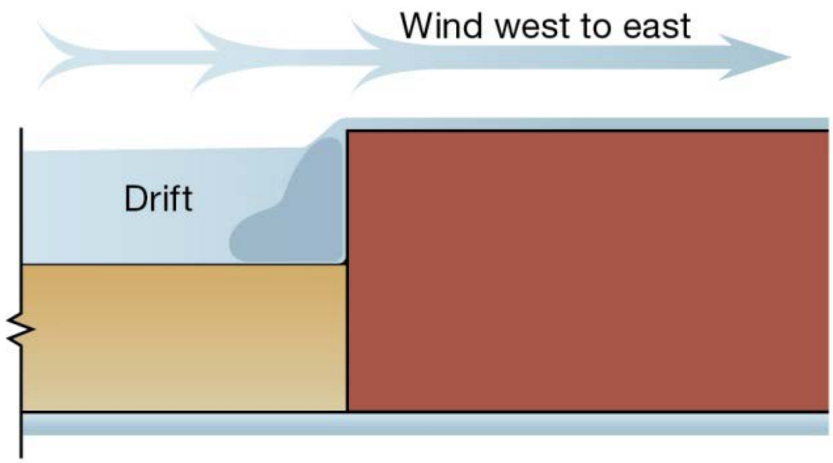

Figure 3: Cross section looking north toward the drift area (not to scale)

Table 1 presents estimated actual roof snow loads at Mitchell Elementary and corresponding design loads per the American Society of Civil Engineers (ASCE) 7-10, *Minimum Design Loads for Buildings and Other Structures* load standard. The estimated loads are based on snow loads on the ground measured during the local site visit, and NOAA wind speed, wind direction, and daily precipitation as measured at Logan Airport. More local wind speed, wind direction, and daily precipitation values would have yielded more accurate estimates but were not readily available. Based on the described approach and results of the analytical procedures described in O'Rourke et al. (2005), the estimated roof snow drift loads were substantial, exceeding the corresponding design drift loads in the ASCE 7-10 by 14 percent and 13 percent for leeward over-the-ridge drift and windward step drift, respectively.

Table 1: Summary of Mitchell Elementary School Snow Loads

Snow Loads	Estimated Actual Loads[i] (psf) and Limits (ft)	ASCE 7-10 Design Loads[ii] (psf) and Limits (ft)
Ground Snow Load	43.9 psf	35 psf
Uniform Roof Snow Load: Leeward Slope	30.7 psf	24.5 psf
Leeward Over-the-Ridge Drift Load (without steps)	28.5 psf	25 psf
Horizontal Limit of Leeward Over-the-Ridge Drift (without steps)	11.6 ft	10.8 ft
Windward Step Drift Load (without gable)	71.9 psf	63.6 psf
Horizontal Limit of Windward Step Drift (without gable)	14.6 ft	13.7 ft

[i] Estimate based on NOAA wind speed, wind direction, and daily precipitation as measured at Logan Airport, as well as ground snow loads measured during the local site visit
[ii] Design loads based on the following ASCE design parameters: $I_s=C_e=C_t=1.0$
psf = pounds per square foot; ft = feet

According to the construction drawings, the school (including the damaged building area) was built between 1995 and 1996, and had a specified uniform design snow load of 30 psf. Design live loads are listed under the plans' General Notes, but the notes do not address loading due to drifting snow.

Building Damage Observations

On Thursday, February 19, 2015, the roof above Classroom 218 collapsed due to snow loading. Fortunately, Massachusetts schools were on winter vacation that week, so the area was unoccupied. Classroom 218 is located on the southeastern end of the central wing indicated by the outline in Figure 1. As noted above, the roof failure appeared to have been triggered by loading from snow drifts that formed in a roof valley on the leeward side of the building's medium-sloped gable roof. The roof was demolished shortly after failure, but the collapsed roof prior to demolition is shown in Figures 4 and 5.

Figure 4: Collapsed roof prior to demolition/removal, looking east (Photo courtesy of RebuildEx)

Figure 5: Collapsed roof prior to demolition/removal, looking north (Photo courtesy of RebuildEx)

By the time the assessment team arrived, the collapsed roof and ceiling above Classroom 218 had been removed and temporarily replaced with shored wood I-joist rafters, as shown in Figure 6. The steel valley beam (specified in the construction plans as W21x50) and valley supports remained in place. Based on discussions with local officials, a cursory plan review, and observations of surrounding areas, the assessment team learned that the removed roof structure consisted of wood truss members that spanned 28 feet from a steel support beam extending east-west (specified in the construction plans as W18x40) to the exterior classroom wall. A combination of dimensional lumber rafters (which remained in place) and wood trusses (which were removed) spanned the steel support beam and valley. According to the roof framing plan above Classroom 218, shown in Figure 7, all roof members in the area were specified at 24 inches on center spacing.

Figure 6: Classroom space beneath collapsed roof area, looking south. Note temporary I-joist rafters installed with shoring.

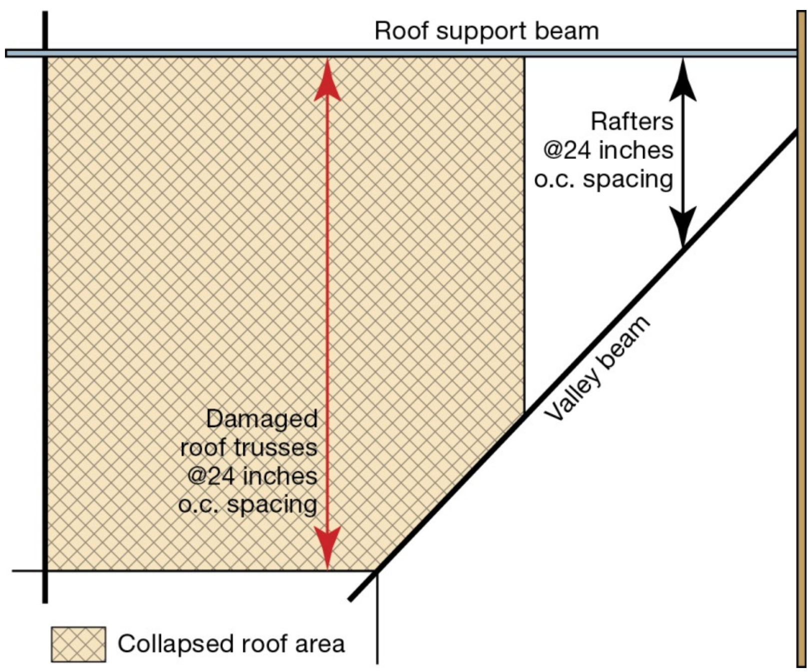

Figure 7: Roof framing above Classroom 218

The type of valley attachment of rafters and roof trusses that remained intact varied. While all trusses on the opposing side of the valley were supported vertically by approximately 12-inch-long 2x12 blocks nailed into the valley beam's 2x12 web nail plate, some attachments were enhanced by skewable metal connectors (see Figure 8) that were nailed into the valley's double top flange nail plate. The damaged (removed) trusses appeared to have been toe-nailed into, and supported atop, similar 2x12 blocks that remained in place, but it is unknown whether the removed trusses were attached to the valley web nail plate with metal connectors. Likewise, skewed rafter hangers were present for some 2x12 rafters on the opposing side of the valley, but not found on the rafter-to-valley connection above Classroom 218, as shown in Figures 9 and 10.

Figure 8: Roof truss supported by 2x12 bearing block and attached to valley beam nail plates with skewable metal connector

Figure 9: Undamaged 2x12 rafter attached to opposing side of valley beam with skewed metal hanger

Figure 10: Undamaged 2x12 rafters (yellow arrows) above Classroom 218 toe-nailed to valley beam nail plates (green arrow is web nail plate and red arrow is flange nail plate)

Roof trusses adjacent to the collapsed area with the same truss types and spans were observed to have two rows of web bracing, as shown in Figures 11 and 12. In some cases the braces were installed closer to the truss chords, as opposed to closer to the center of the web as shown in Figure 11. Intermittent cross bracing or X bracing of truss web braces, which provides lateral restraint, was not observed near Classroom 218, as shown in Figure 12.

Figure 11: Roof truss web bracing installed close to the truss chords

Figure 12: Roof truss web bracing installed closer to the center of the web

Snow removal operations were in progress during the assessment team's site visit, as shown in Figure 13. According to school officials, snow removal was performed by a roofing contractor and commenced across the school district shortly before the roof collapsed. Snow was to be removed from all roof areas.

Figure 13: Snow removal commenced on this section of roof after the roof collapsed (red arrows indicate safety harnesses)

As a result of significant water damage (see Figure 14) due to frozen and ruptured water pipes—direct and indirect consequences of the actual roof collapse—the school was closed indefinitely. Students and teachers were reassigned to neighboring schools until repairs could be completed at Mitchell Elementary.

Figure 14: Water-damaged computers and drying equipment

2.2 PLYMOUTH RIVER ELEMENTARY: 200 HIGH STREET, HINGHAM, MA

An aerial view of Plymouth River Elementary School is shown in Figure 15. The area of observed damage was on a flat roof adjacent to higher roofs to the north and east. As such, the area was subject to both a leeward roof step drift due to longer duration winds out of the north and a windward roof step drift due to shorter duration winds out of the west. In addition, the upwind fetch distances for wind out of the north were longer than those for wind out of the west. These conditions caused leeward drift loads to be larger than windward drift loads at the time of damage (as estimated by the assessment team[3]). ASCE 7-10 design loads reflect similar disparity for the same damaged area (see Table 2). These values are consistent with the observed drift (left side of Figure 16), which shows the largest drift at the north end of the damaged area.

[3] Based on the described approach and results of the analytical procedures described in O'Rourke et al. (2005)

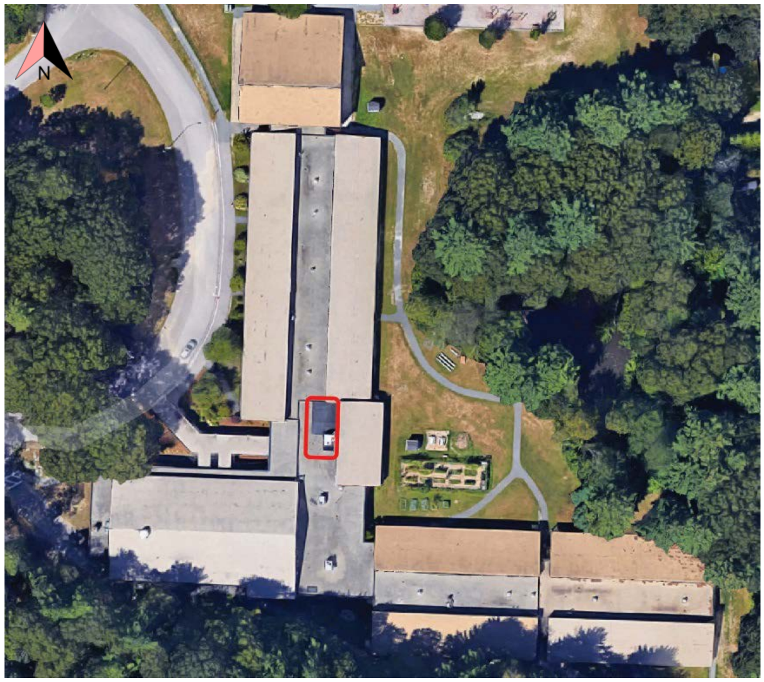

Figure 15: Aerial photograph of Plymouth River Elementary School (red outline shows damage location) (Source: Google Earth)

Figure 16: View (looking northeast) of the damaged roof area (yellow circle) before snow removal (left image) and after (right image) (photos courtesy of school official)

Table 2 presents estimated actual roof snow loads at Plymouth River Elementary and corresponding design loads per the ASCE 7-10 load standard. The estimated loads are based on snow load on the ground measured during the local site visit and NOAA wind speed, wind direction, and daily precipitation as measured at Logan Airport. More local wind speed, wind direction, and daily precipitation values would have yielded more accurate estimates but were not readily available. Based on the described approach and results of the analytical procedures described in O’Rourke et al. (2005), the estimated leeward step drift load was substantial, roughly equal to but marginally exceeding the corresponding design drift load in the ASCE 7-10 by 5 percent.

Table 2: Summary of Plymouth River Elementary School Snow Loads

Snow Loads	Estimated Actual Loads[i] (psf) and Limits (ft)	ASCE 7-10 Design Loads[ii] (psf) and Limits (ft)
Ground Snow Load	38.8 psf	35 psf
Uniform Flat Roof Snow Load	27.2 psf	24.5 psf
Leeward Step Drift Load	100.0 psf	95 psf
Horizontal Limit of Leeward Step Drift	21.0 ft	20.5 ft
Windward Step Drift Loads[iii]	38.1 psf	36 psf
Flat Roof Maximum Combined Snow Load	127.2 psf	119.5 psf

[i] Estimate based on NOAA wind speed, wind direction, and daily precipitation as measured at Logan Airport, as well as ground snow load measured during the local site visit
[ii] Design loads based on the following ASCE design parameters: $I_s=C_e=C_t=1.0$
[iii] Since Maximum Combined Snow Load does not include Windward Step Drift Load, Horizontal Limit of Windward Step Drift is omitted
psf = pounds per square foot; ft = feet

According to school officials, the portion of the building with the damaged roof area was constructed circa 1970. Construction drawings (dated 1968) made available to the assessment team indicate the school was constructed to conform with the intent of “The Structural Regulations for School Houses” of the Commonwealth of Massachusetts Department of Public Safety. The school was constructed before the provisions on snow drift in ASCE 7 and its predecessor ANSI A58 (1972) were published.

Building Damage Observations

On Thursday, February 19, 2015, a section of roof above the school library failed under snow loads. Fortunately, Massachusetts schools were on vacation that week, so the area was unoccupied. The school library is near the convergence of the three wings, as indicated by the red outline in Figure 15. As noted above, the damage appeared to have been triggered by loading from drifts that formed on a section of flat roof that abutted a clerestory roof. Figure 16 shows the damaged area before and after snow removal.

By the time the assessment team arrived, the suspended ceiling above the library had been removed below the snow-damaged area, allowing them to observe damaged open web steel joists that support the roof deck. The 14-inch-deep joists (which the construction plans specified as “H5 series”) were spaced at 6 feet on center and simply spanned at 19 feet 8 inches in the nominal east-west direction. As illustrated in Figure 17, joist failure from overloading occurred over the eastern portion of the span nearest the clerestory support, where drifting was deepest due to windward (from the west wind) roof step. Likewise, deformed joists were all located at the northern end of the flat roof adjacent to the clerestory, where drifting was deepest due to leeward (from the north wind) roof step.

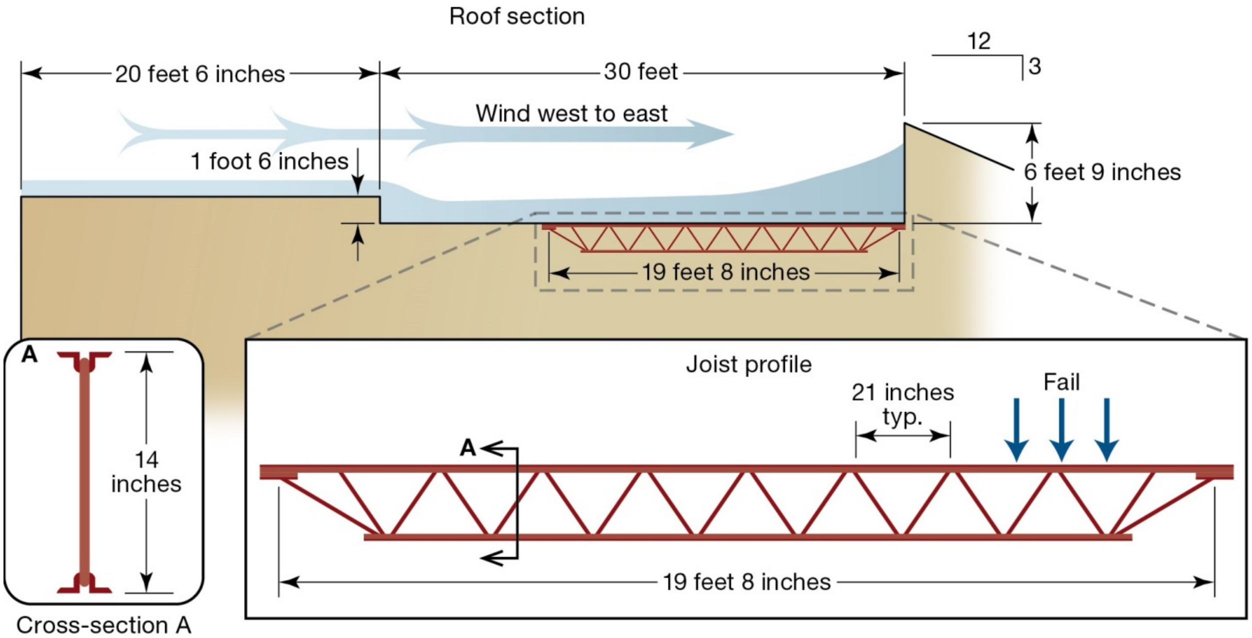

Figure 17: Damaged steel joists shown in roof cross section, joist profile, and joist cross section (looking north)

The damaged joists had been temporarily shored along the bottom flanges with a series of 4x4 blocks supported by adjustable steel pipe columns, as shown in Figure 18. As shown in Figure 19, both the joist flanges (top and bottom) and web chords were badly deformed at the end of the span, where snow drift loading is greatest. One joist web had completely separated from the end of the bottom flange at the same clerestory end support (see Figure 20).

Figure 18: Damaged steel joists with temporary shoring

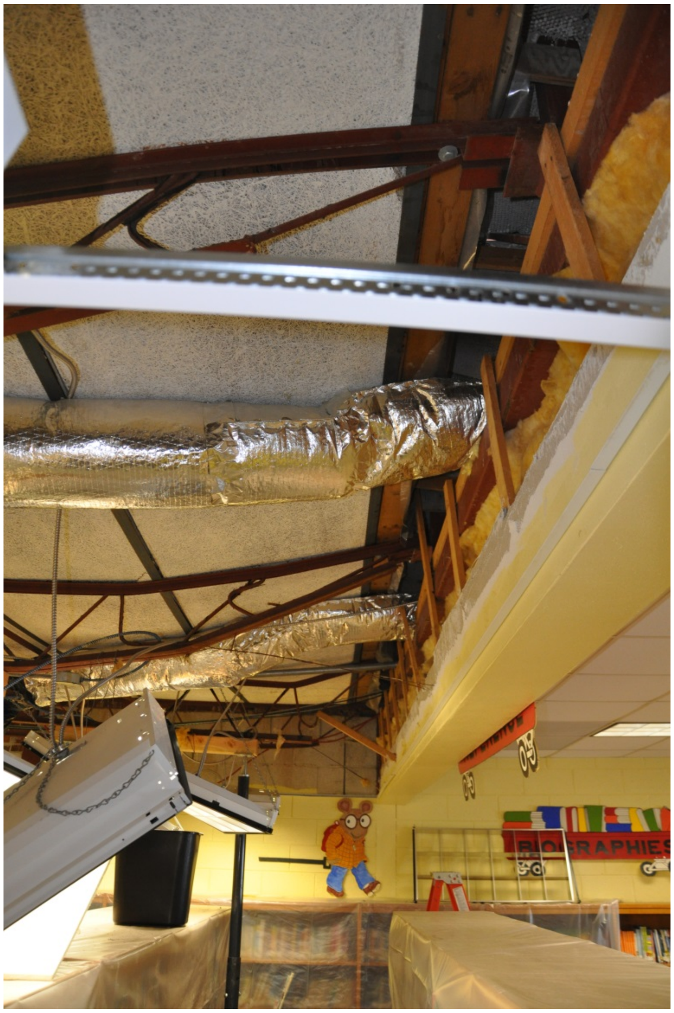

Figure 19: Damaged steel joists with deflected flanges and webs at clerestory beam (looking north)

Figure 20: Damaged steel joist with joist web separated from bottom flange (looking south)

The assessment team observed that snow had been removed from all areas of the school building's roof. While the school library was closed until repairs were completed, the remainder of the school was open to staff and students.

2.3 MILFORD HIGH SCHOOL: 100 WEST STREET, MILFORD, NH

Figure 21 shows an aerial view of Milford High School. The damaged roof area is indicated by the red oval. It is a flat roof area with skylights. There are two higher roofs to the west of the damaged area; hence, the adjacent lower roof area is subject to leeward snow drifts due to wind from the west, as shown in Figure 22.

Figure 21: Aerial photograph of Milford High School (red oval shows damage location on lower flat roof, yellow double arrow indicates stepped higher flat roof)

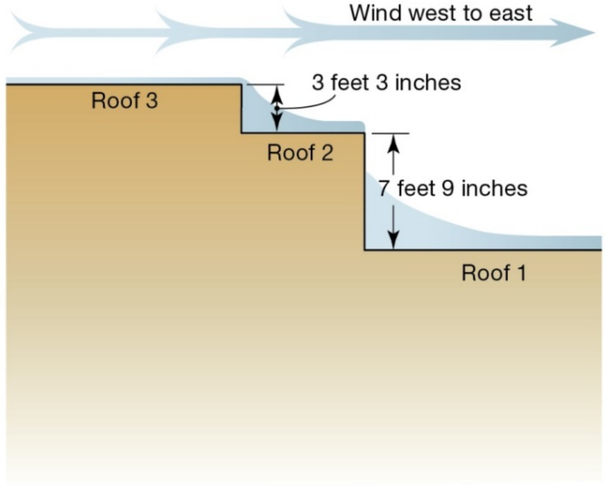

Figure 22: Cross section of the damaged (Roof 1) drift area (looking north; not to scale)

Table 3 presents estimated actual roof snow loads at Milford High School and corresponding design loads per the ASCE 7-10 load standard. Because of the location, the analysis used a design ground snow load of 70 psf as specified by the 2002 Cold Regions Research and Engineering Lab (CRREL) report TR-02 (USACE, 2002).[4] The estimated loads are based on ground snow load measured during the local site visit and NOAA wind speed, wind direction, and daily precipitation as measured at Logan Airport. Local wind speed, wind direction, and daily precipitation values would have yielded more accurate estimates but were not readily available. Based on the described approach and results of the analytical procedures described in O'Rourke et al. (2005), the ASCE 7-10 design roof snow load was larger than the estimated actual roof load.

Table 3: Summary of Milford High School Snow Loads

Snow Loads	Estimated Actual Loads[i] (psf) and Limits (ft)	ASCE 7-10 Design Loads[ii] (psf) and Limits (ft)
Ground Snow Load	26.5 psf	70 psf
Uniform Flat Roof Snow Load	18.6 psf	49 psf
Leeward Step Drift Load	62.5 psf	108 psf
Horizontal Limit of Leeward Step Drift	14.3 ft	18.7 ft
Flat Roof Combined Snow Load	81.1 psf	157 psf

[i] Estimate based on NOAA wind speed, wind direction, and daily precipitation as measured at Logan Airport, as well as ground snow load measured during the local site visit
[ii] Design loads based on the following ASCE design parameters: I_s=C_e=C_t=1.0
psf = pounds per square foot; ft = feet

[4] Much of New Hampshire is shown in a Case Study Region on the ASCE 7 ground snow load map. In such locations, local building officials frequently require ground snow loads to be determined as provided by the CRREL Report, which is referenced in ASCE 7.

According to school officials, the original school building was constructed circa 1962, with additions in the mid-1970s that included the damaged classroom area. The skylights in the damaged roof area were installed during renovations in 1997. Construction drawings for the damaged area were unavailable, so design load information is unknown.

Building Damage Observations

On Friday morning, February 20, 2015, school staff noticed ceiling deflection around the skylights above Classrooms 204 and 205. After consulting with the Director of Facilities and Grounds, the decision was made to close school for the day because of safety concerns related to the damaged roof area near the skylights. The following week was scheduled as winter vacation for New Hampshire schools, which gave staff enough time to complete structural repairs before classes resumed. As noted above, the roof damage appeared to have been triggered by loading from snow drifts that formed above the lower flat roof section adjacent to the higher stepped roofs (see Figure 23).

Figure 23: Lower roof area (looking west) with snow removed in foreground (blue arrows indicate skylights above Classroom 204, green arrow identifies adjacent skylight above Classroom 205)

By the time assessment team arrived, the suspended ceiling had been removed in the area of the skylight above Classrooms 204 and 205, revealing damaged framing members temporarily shored with 4x4 blocks or shims. In some areas, the blocks were supported at each end by adjustable steel pipe columns (see Figure 24), and in others by 4x4 wood posts.

Figure 24: Shoring around Classroom 205 skylight

The assessment team observed that the flat roof and suspended ceiling above Classrooms 204 and 205 were supported by 2x14 wood joists spaced 16 inches on center. The members spanned approximately 25 feet from the corridor wall to the opposite (rear) classroom wall, which extended upward to support the higher flat roof. Several 2x14 joists had split horizontally, most notably on either side of the skylight nearest the Classroom 204 egress door. The largest splits started where notches, approximately 3 inches deep, had been cut into the base of the joists to facilitate bearing at the rear classroom wall (see Figure 25). In addition to the joist sections being weakened by notch cuts, snow drift depths increased toward the rear classroom wall, generating greater support reactions (and shear stresses) from framing members than at the corridor wall support. Other joists in Classroom 205 had smaller horizontal splits that originated at nails used to attach cross bracing (see Figure 26).

Figure 25: Split joists at rear wall support around Classroom 204 skylight (arrows indicate horizontal splits and circles show notches at end bearing)

Figure 26: Split joists at nailed cross bracing around Classroom 205 skylight (arrows indicate splits)

Single 1.75x14 laminated veneer lumber (LVL) members that were installed to frame the skylight openings also showed signs of distress and were temporarily shored, as shown in Figure 27. Unlike the large horizontal splits at notched joists, the LVL member splits occurred away from the end supports and originated at the bottom surface, indicating strain in flexure.

Figure 27: Split LVL member at Classroom 204 skylight (circle indicates split)

After school staff noted the deflected skylights, a roofing contractor was retained to remove snow drifts from the roofs (see Figures 28 and 29), and from around rooftop heating, ventilation, and air conditioning (HVAC) units (Figure 30) and fans. This work was also undertaken at all of the other schools in the district.

Figure 28: View of the upper roof adjacent to the skylights after removal of the drift. The red arrow indicates the lower roof in the area of the deflected skylights.

Figure 29: View of another area where drifts were removed. Note the shovel marks on the snow, indicating that some snow was deliberately left over the roof membrane to avoid damage

Figure 30: Snow was removed around HVAC units so that they would remain operational

2.4 SANBORN MIDDLE SCHOOL: 31A WEST MAIN STREET, NEWTON, NH

Figure 31 shows an aerial view of the Sanborn Middle School. The roof damage occurred on the southeast side of the gable roof (see yellow outline). The ridgeline runs nominally northeast-southwest; hence, the damaged area is subject to over-the-ridge drift loads (unbalanced loads) due to wind out of the northwest.

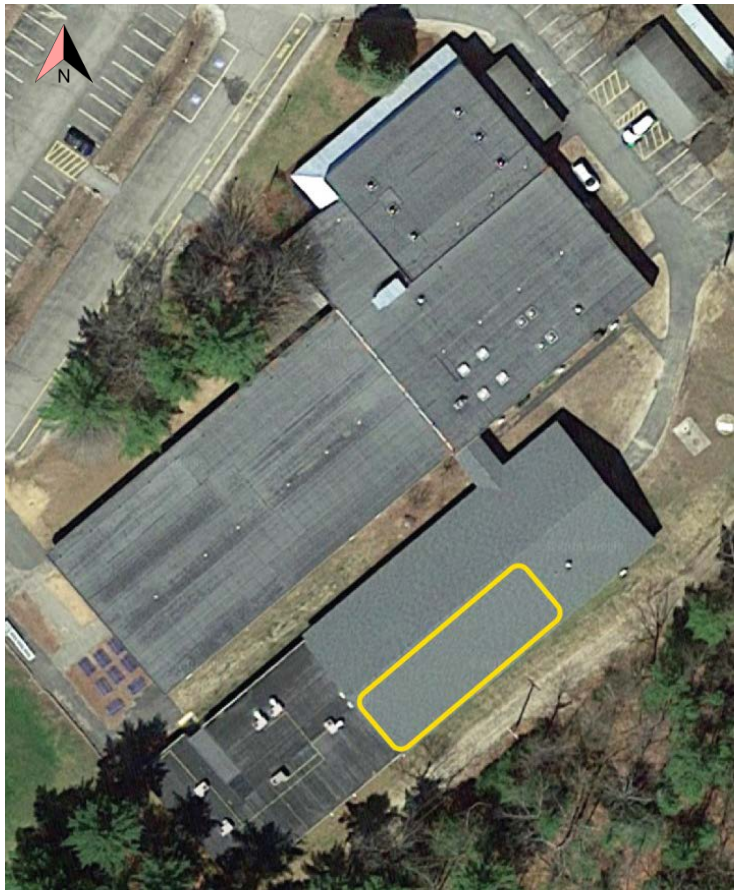

Figure 31: Aerial photograph of Sanborn Middle School (yellow outline shows damage location) (Source: Google Earth)

Table 4 presents estimated actual roof snow loads at Sanborn Middle School and corresponding design loads per the ASCE 7-10 load standard. Because of the location, the analysis used a design ground snow load of 50 psf as specified by the 2002 CRREL report TR-02 (USACE, 2002)[5] for the town of Newton. The estimated loads are based on ground snow load measured during the local site visit and NOAA wind speed, wind direction, and daily precipitation as measured at Logan Airport. Local wind speed, wind direction, and daily precipitation values would have yielded more accurate estimates but were not readily available. Based on the described approach and results of the analytical procedures described in O'Rourke et al. (2005), the ASCE 7-10 design roof snow load was larger than the estimated actual roof load.

[5] Much of New Hampshire is shown in a Case Study Region on the ASCE 7 ground snow load map. In such locations, local building officials frequently require ground snow loads to be determined as provided by the CRREL Report, which is referenced in ASCE 7.

Table 4: Summary of Sanborn Middle School Snow Loads

Snow Loads	Estimated Actual Loads[i] (psf) and Limits (ft)	ASCE 7-10 Design Loads[ii] (psf) and Limits (ft)
Ground Snow Load	35.2 psf	50 psf
Uniform Roof Snow Load: Leeward Slope	24.6 psf	35 psf
Leeward Over-the-Ridge Drift Load	25.6 psf	31.7 psf
Horizontal Limit of Leeward Over-the-Ridge Drift	8.8 ft	9.9 ft
Combined Roof Snow Load: Leeward Slope	50.2 psf	66.7 psf

[i] Estimate based on NOAA wind speed, wind direction, and daily precipitation as measured at Logan Airport, as well as ground snow load measured during the local site visit
[ii] Design loads based on the following ASCE design parameters: $I_s=C_e=C_t=1.0$
psf = pounds per square foot; ft = feet

According to school officials, the affected school building was constructed in 1995. Although architectural drawings were made available to the assessment team, no design load information was included.

Building Damage Observations

On Friday morning, February 20, 2015, school staff noticed deflection in the ceiling of Classrooms 18, 20, and 22. After consulting with the Director of Facilities, the decision was made to close school for the day because of safety concerns related to probable roof damage. Classrooms 18, 20, and 22 are located under the eastern (leeward) facing slope of the gable roof (pitch approximately 5:12) in the Eighth Grade Wing building (see Figures 32 and 33). Snow from the gym roof and other flat roofs to the west of the gable roof may have contributed to the drift over the damaged roof areas. The roof damage appeared to have been triggered by loading from snow drifts that formed on the leeward slope of the Eighth Grade Wing building.

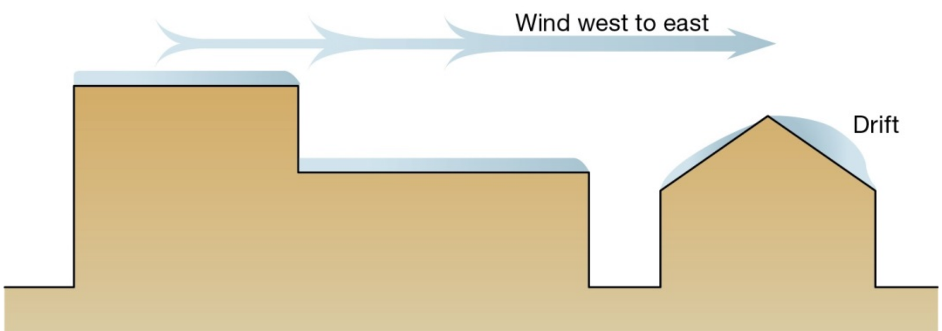

Figure 32: Cross section of the drift area (looking northeast, not to scale)

Figure 33: Sanborn Middle School Eighth Grade Wing (red lines show damage location)

The assessment team observed deflected suspended acoustical ceilings above Classrooms 18, 20, and 22 and cracked gypsum board attached to the bottom chords of roof trusses (see Figure 34). The deflected ceilings and cracked gypsum board appeared to result from excessive roof truss deflection. Upon request, the assessment team was allowed to access the attic to observe truss conditions above the damaged ceiling.

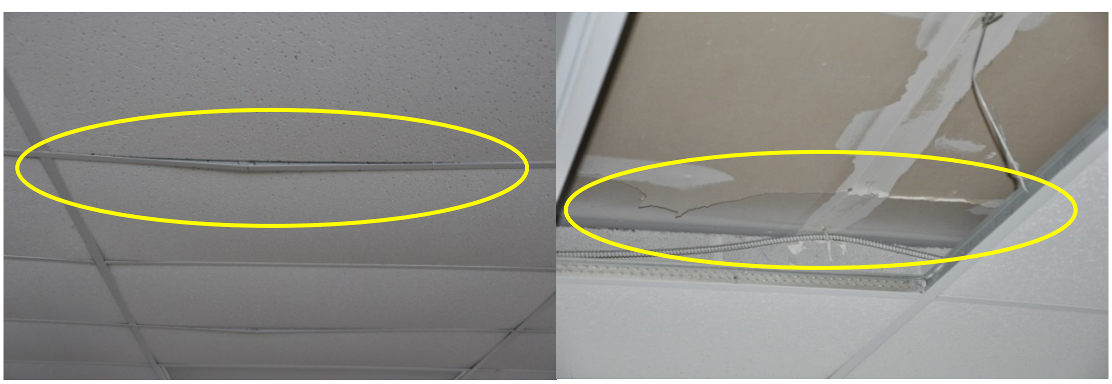

Figure 34: Deflected suspended ceiling T-bar and cracked gypsum board roof truss sheathing above affected Eighth Grade Wing classroom areas (shown in yellow circles)

Mono-slope wood roof trusses span from the exterior walls of Classrooms 18, 20, and 22 (southeast of the ridge line) to the classroom/corridor wall, with the top chord extending up to meet the top chord of the truss on the opposite side of the corridor to form the ridge over the center of the corridor. Approximately 18 consecutive roof trusses (24-inch spacing) above Classrooms 18 and 20 had separated at the same web-to-top-chord location, as shown in Figure 35 (looking southwest from attic access opening; additional damaged trusses observed toward the northeast not shown) and Figure 36 (close-up of typical gap between chords). Each connection had been made with 3-inch by 4-inch truss connector plates. The attic space above Classroom 22 could not be viewed, but damage to the ceiling followed the same pattern as the other classrooms, although it appeared to be less severe.

Figure 35: Separation of the web-to-top-chord connection in mono-slope trusses southeast of ridge line (shown in yellow circles)

Figure 36: Close-up of separated web to top chord connection

After school staff noted the deflected ceilings, snow removal commenced on all schools in the district. Snow was removed on all roof areas (both drifted and non-drifted). Some of this work was performed by school district employees, and some was performed by contractors. The school district hired several different contractors, including a roofing contractor and an asbestos abatement contractor, to obtain the number of workers desired.

The Eighth Grade Wing building was closed indefinitely, and eighth graders completed the school year at the regional high school.

SECTION THREE CONCLUSIONS

The following conclusions related to snow load determinations and resulting design implications are based on the assessment team's field observations.

At all four schools, the structural performance problems were caused by localized snow drift roof loading. As shown in Table 5, estimated actual drift loads were substantial at all sites. At Mitchell Elementary, the one school where the original design loads were available, the snow drift loads were not addressed in the construction drawings notes. The construction drawings listed only the uniform design snow load (under roof live loads) as 30 psf (uniform), which is significantly less than estimated loads for the localized area that collapsed due to drift loads. Since the other facilities visited were about the same age or older, it is reasonable to assume that the observed roof systems were not designed to current snow load requirements, which include snow drift loads.

Table 5: Site Snow Loads Summary

Site	Snow Load	Estimated actual snow load for damaged roof area[i]	ASCE 7-10 design snow load for damaged roof areas[ii]
Mitchell Elementary	Uniform Roof	30.7 psf	24.5 psf
	Leeward Over-the-Ridge Drift (without step)	28.5 psf	25 psf
	Windward Step Drift (without gable)	71.9 psf	63.6 psf
Plymouth River Elementary	Uniform Roof	27.2 psf	24.5 psf
	Leeward Step Drift	100.0 psf	95 psf
	Flat Roof Maximum Combined	127.2 psf	119.5 psf
Milford High School	Uniform Roof	18.6 psf	49.0 psf
	Leeward Step Drift	62.5 psf	108.0 psf
	Flat Roof Combined	81.1 psf	157.0 psf
Sanborn Middle School	Uniform Roof	24.6 psf	35.0 psf
	Leeward Over-the-Ridge Drift	25.6 psf	31.7 psf
	Leeward Slope Combined	50.2 psf	66.7 psf

[i] Estimate based on NOAA wind speed, wind direction, and daily precipitation as measured at Logan Airport, as well as ground snow load measured during the local site visit
[ii] Design loads based on the following ASCE design parameters: $I_s=C_e=C_t=1.0$
psf = pounds per square foot

SECTION FOUR RECOMMENDATIONS

Based on their field observations and conclusions, the assessment team has the following recommendations:

Recommendation #1: Incorporate findings from this report into the next edition of FEMA P-957, *Snow Load Safety Guide*. Recommended topics to be included or updated in the next edition of FEMA P-957 are described in Table 6.

Table 6: Recommendations for Update to FEMA P-957

General Topic	Specific Recommendation
Annual summer inventory	Include advice for building owners to inventory all of their buildings during the summer so they can decide whether to retain a structural engineer to determine if a building's roof structure is adequate. This guidance should be targeted for laypersons.
High-level guidance for structural engineers	Include: • Procedures for determining whether a building's roof structure is adequate • Guidelines for specifying when and where to remove snow (including consideration for unbalanced snow loads) • List of potential mitigation measures (e.g., retrofitting the roof and installing roof support that will withstand drift loads so that snow removal will not be necessary in the future).
Guidance for measuring ground snow loads	Ground snow load information can be used as part of the assessment for whether roof snow removal is prudent. NOAA publishes free monthly Local Climatological Data (LCD) sheets (http://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/quality-controlled-local-climatological-data-qclcd), which are very useful for forensic investigations. However, the LCD sheets are typically not published until a month or so later, so they would not be available for operational decision-making.
Update Section 5.3, "Removal of Snow from Roof"	Include 1) avoiding unbalanced snow loads, 2) removing snow around rooftop HVAC units, fans, relief air hoods, and wall louvers so they remain operational, and 3) inspecting the roof for roof covering damage after warm weather melts the snow, and repairing it if damage is found.
Add figures	Consider adding some of the figures from this study and other photographs to illustrate various issues.

Recommendation #2: Develop guidance in the form of a fact sheet or research report to address the following drift loading conditions, which are not adequately addressed in ASCE 7:

(1) Combination of over-the-ridge drift loads with roof step drift.

(2) Distribution of drift loads when the space available for drift formation varies in the direction perpendicular to the upwind fetch.

(3) Slope of the top surface of snow drift on a gable roof as a function of roof slope.

Recommendation #3: Use this new drift load guidance as the basis for a future update of ASCE 7.

SECTION FIVE REFERENCES

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