Snow-Induced Building Failures

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Abstract: This study examines 1,029 snow-induced building failure incidents in the United States between 1989 and 2009 and 91 international incidents between 1979 and 2009. Incidents were identified through newspaper archives, including 1,345 articles from 883 unique sources. Most U.S. incidents occurred in New York, New Hampshire, and Massachusetts. Findings show that 37% of all buildings experiencing snow-induced failure incidents in the United States were of metal/steel construction and another 37% were of timber, while 53% of international incidents were metal/steel and 17% were concrete. Warehouses, factories, and commercial buildings were the most common buildings affected. Failures were attributed to the amount of snow, rain-on-snow mixes, and building problems. Monetary impacts included building damages ranging between $1,000 and $200 million and business interruption associated with an average building closure of four months. Nineteen fatalities and 146 injuries were reported for the United States, while 293 fatalities and 586 injuries were reported internationally. These findings describe building failure trends, which may be significant, considering potential impacts of accelerating global climate change on the patterns of snowfall frequency and density. **DOI:** 10.1061/(ASCE)CF.1943-5509.0000222.

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Introduction

Extreme snow loading can cause significant damage to buildings and lead to roof collapse, sometimes requiring costly repairs, interrupting business, damaging building contents, or endangering occupants. High-profile American building failures due to snow have included the Hartford Arena in Connecticut (1978) and the C.W. Post College Theater on Long Island (1978) (Levy and Salvadori 2002); recent international failures include the collapse of the Basmanny Marketplace in Russia and the Katowice Exhibition Hall in Poland, both of which occurred in the spring of 2006, killing a total of 131 people. Snow-induced building failures can also have significant economic and societal impacts on businesses and communities. In January 1996, a large winter storm damaged buildings from Kentucky to Maine, including shopping malls, manufacturing facilities, supermarkets, theater complexes, and sports facilities (DeGaetano et al. 1997). Similarly, a March 1993 snowstorm caused damages and business disruption exceeding $200 million (1993 dollars) in the southeastern United States (O'Rourke and Auren 1997). More recently, three blizzards in February 2010 damaged buildings in Mid-Atlantic and New England states, including an ice rink and corporate jet hangars at both Manassas Regional and Dulles International Airports in Virginia (Kiser 2010). Some states, including New York, require yearly inspections of school roofs to prevent failure, but oftentimes there is no obligation that building owners inspect or monitor roofs of other building types (Fish 1994). Although a number of studies have examined general trends in building failures, studies of snow-induced building failure incidents are limited.

This paper examines the risk of building failure and damage due to snow loading, characterizing the relative susceptibility of different types of structures and the human and economic impacts of these incidents. The research methodology examines snow-induced building failure incidents in the United States between 1989 and 2009 and worldwide between 1979 and 2009 using records of building damage and impacts gathered from databases of archived newspaper articles. These incidents include not only high-profile building failures, like the Hartford Civic Center Arena, which have been investigated through detailed forensic studies, but also warehouses, strip malls, and other structures whose failure generally garners little attention—but may have significant impact on business and communities. By collecting and analyzing data regarding snow-induced building failure incidents, this study uncovers patterns of failure, damage, and risk and considers the implication of these results for design and assessment of buildings subjected to extreme snow loads.

Past Research on Snow-Related Building Failures

A number of studies have investigated major trends in building failures, including Hadipriono (1985), Hadipriono and Diaz (1988), Eldukair and Ayyub (1991), Wardhana and Hadipriono (2003), and others. Eldukair and Ayyub (1991), for example, found that 41% of building failures in the United States between 1975 and 1986 were the result of severe weather. Wardhana and Hadipriono (2003) analyzed 225 U.S. buildings that failed due to weather, poor maintenance, or construction deficiencies from 1989 to 2000, concluding that low-rise buildings were the most likely to fail, constituting 63% of all cases, with multistory buildings the second most susceptible category. In addition to noting that the number of failures per year increased over the 11-year period, that study also confirmed Eldukair and Ayyub's (1991) observations of the significant

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role of weather in causing building failures. However, neither classified nor quantified the effects of these failures or distinguished snow from other weather events. O'Rourke et al. (1983) found that snow-related roof failures for industrial buildings exceeded those due to rain loads, structural deterioration, and other causes, contributing to 55% of all roof-related insurance claims from 1974 to 1978.

A few studies have looked specifically at the relationship between snow loading and building failures. O'Rourke et al. (1982) showed that the conversion factors to determine roof snow loads from ground snow loads in U.S. building codes lead to conservative estimates of design roof loads. Following two large January 1996 snowstorms in the Mid-Atlantic and New England states, DeGaetano et al. (1997) showed that snowfall exceeded the 50-year snow loads, which are the basis for snow loads in design standards, contributing to the building collapses during those storms. A follow-up study by DeGaetano and Wilks (1999) found that most of the buildings damaged during the 1996 storms were not engineered correctly or were built prior to the establishment of stringent building codes. Meløysund et al. (2006) examined existing buildings in Norway after an unusually large number of collapses took place during the winter of 1999–2000, concluding that older Norwegian buildings have reduced safety against snow-induced collapse in comparison to buildings meeting Norwegian modern code provisions. These findings were based on data from insurance companies and government agencies, calculations of design loads at the time of construction, and structural analyses, but due to differences in design codes, it is unclear whether the results are also applicable to older U.S. buildings.

Other studies have used numerical building simulation to evaluate the reliability of structures subjected to large snow loads. Takahashi and Ellingwood (2005) found that simply supported structures having high snow to dead load ratios in design had a higher risk of failure than heavier structures. Likewise, Holicky (2007) examined current European design procedures, again concluding that the reliability of structural members is highly variable, with lightweight (low dead load) roof systems failing to meet a specified target reliability level. A follow-up study by Holicky and Sykora (2009) found that insufficient code provisions for lightweight roofs and human and design errors were the most common causes of the large number of roof failures in Europe during the 2005–2006 winter.

With regard to specific snow-related building failures, major U.S. case studies include the Hartford Civic Center and the C. W. Post College Dome Auditorium collapses. The collapse of the steel space frame roof of the Hartford Civic Center has been attributed to overconfidence in computer analysis. Excessive deflections that occurred during construction were ignored by engineers, who claimed that discrepancies between actual and theoretical deflections were expected. In fact, these excessive deflections were found to be the result of design and construction errors, specifically inadequate lateral bracing and weak supports of the roof members (Martin and Delatte 2001). The C.W. Post Auditorium, a shallow, rectangular steel mesh dome, collapsed due to uneven loading associated with drifting snow and ice, resulting in the overstressing of structural members (Levy and Salvadori 2002). Significant studies into international snow-induced building failures in recent years investigated the Bad Reichenhall Ice-Arena (Germany) in 2004 and the Katowice Exhibition Hall (Poland) (Biegus and Rykaluk 2009). Mistakes in structural calculations, defective construction, and lack of maintenance contributed to the failure of the cross-girder timber roof system of the Bad Reichenhall Ice-Arena (Winter and Kreuzinger 2008). The Katowice Exhibition Hall's steel truss roof system was shown to have collapsed due to insufficient strength and stiffness of main structural elements and overloads from a thick layer of ice and snow (Biegus and Rykaluk 2009).

Although these studies have investigated general building failure trends, forensics of specific snow-related building failures, and code compliance, the authors are aware of no previous study attempting to create a database of snow-induced building incidents as a means of investigating the patterns and significance of these types of failures.

Study Design

Snow-related building incidents and failures were identified and classified using newspaper reporting on snowstorms and their effects. The database of U.S. incidents was developed by searching the 'U.S. Newspapers and Wires' references in LexisNexis Academic (2010). This source consists of major U.S. newspapers and wire services, from which more than 60% of the stories originate in the United States (including the well-known Associated Press). Snow-related building failure incidents were identified using "snow and roof and collapse" as the search criteria; articles containing these terms, but not relevant to snow-related building failure, were eliminated. A total of 1,221 articles from 131 newspapers in 37 states were identified to satisfy the search and relevance criteria in the study period between January 1, 1989 and December 31, 2009. Reporting in the selected articles covered descriptions of snow and weather events, effects on city systems and infrastructure and, most importantly for this study, impacts on buildings and other structures, including damage, economic impacts, and other factors. Before selecting LexisNexis Academic, a variety of sources known to publish information on snow-related building incidents were investigated. With a total of 687 unique U.S. sources and newspapers from all states and major cities, LexisNexis Academic is sufficiently comprehensive for this investigation and, in addition, included references to all critical incidents found in a review of other sources, including *Engineering News-Record*. Insurance data, while useful, is not publicly available and was therefore not used in this study.

LexisNexis Academic was also used to identify international incidents of snow-induced building failures, searching 'Major World Publications'. This database contains 752 full-text news sources, including newspapers, magazines, and trade publications (2010). Since LexisNexis Academic produced a limited number of hits for international incidents, the Factiva (2010) database was also used to search 'Major News and Business Publications', which includes key publications with large circulation. Major U.S. publications were excluded from the search, and only English-language articles were included. Together, LexisNexis Academic and Factiva produced 124 relevant articles from 39 different international newspaper sources published between January 1, 1979 and December 31, 2009. A longer study period was considered for international incidents to increase the number of relevant articles.

Articles were coded according to a set of instructions for identifying and classifying reported snow-related failure incidents. As shown in Table 1, each article meeting search and relevance criteria was assigned a unique source index and pertinent article information including date, newspaper, and byline was recorded. Each snow-related building failure, (which may have been reported in one or more articles) corresponds to a unique incident index, and the details about date and location of incident are recorded in Table 2. Tables 1–3 include examples of the information gathered, representing a subset of the database created in this research.

Basic terminology used in this study is defined as follows. Any building that was damaged, collapsed, closed, or required occupants

Table 1. Article Source Details (from U.S. Database)

Source index	Incident indices	Newspaper	State	Date	Byline	Title	Section	Page	Word count
1	1	Spokesman Review	Washington	8/14/09	Boggs	Old school…	A	1	729
2	1	Lewiston Morning	Idaho	7/25/09	—	Idaho offi…	—	—	127
3	1	The Associated Press	—	7/24/09	—	Displaced…	B	—	135
4	2	The Asociated Press	—	7/10/09	Robbins	Company…	C	—	676
…continued for source indices 5 to 1,221									

Table 2. Incident Identification (from U.S. Database)

Incident index	Source indices	Building name	City	State	Date
1	1, 2, 3	Lakeside elementary	Worley	Idaho	7/15/09
2	4, 5, 6	Philadelphia regional…	Philadelphia	Pennsylvania	1/31/09
3	5, 6	Warehouse building	Fort Plain	New York	1/31/07
…continued for incident indices 4 to 1,029					

Table 3. Incident Classification (from U.S. Database)

Incident index	Damage	Collapse	Closure	Evacuation
1	—	—	—	1
2	1	—	—	1
3	—	1	1	—
…continued for incident indices 4 to 1,029				

to be evacuated as a result of snow loading is referred to as an incident. Therefore, every incident represents a building whose structure, contents, or occupants have been impacted by snow loads. Collapse refers to any incident in which the roof's structural system fails and a portion of the roof falls in, while damage refers to the loss of integrity of any structural or nonstructural component not resulting in collapse (e.g., cracking, rotting, deflection of structural members, broken pipes, or water damage). Incidents could be classified as either damage or collapse, but not both. In other cases, warnings, such as cracking of structural members, deflections, or creaking noises, notified occupants of danger previous to damage or collapse. Building closure identifies those structures that were closed following an incident for repair or maintenance. Closure is distinguished from evacuation, which refers to the suspension of operation to ensure occupant safety. Evacuation can occur before any damage. Incidents classified as experiencing closure, evacuation, or warning may or may not have also been characterized as damaged or collapsed. In Table 3, a 1 is used to identify those classifications that are associated with a particular incident.

In total, 1,029 incidents and 840 (77% of the total) collapses were recorded in the U.S. database over the 1989–2009 study period. The international database consists of 91 incidents occurring between 1979 and 2009, of which 80 (88%) were collapses. In the United States, 182 (18%) incidents reported evacuation, 587 (57%) reported closure, and 32 (3.1%) reported both evacuation and closure; internationally, 25 (28%) incidents reported evacuation, 14 (15%) reported closure, and 4 (4.4%) reported both evacuation and closure. Only 6.7% (69) of U.S. incidents and 16% (12) of international incidents were associated with warnings reported in newspaper articles.

Additional details provided about each incident were classified according to major themes, including (1) building characteristics, (2) loading and damage, (3) attributed causes, and (4) disruption and impacts. Building characteristics recorded include the activity of the building (i.e., recreational facility, school, warehouse, church, etc.), the construction type (i.e., metal/steel, timber, masonry, fabric, etc.), and the age of the building at the time of incident. Loading and damage details recorded in the database include the amount of snow or severity of storm and the physical impact of the snow load on the building. In the attributed causes section (shown in Table 4), the database lists the causal factors identified by the article as contributing to each incident. As shown in Table 4, common incident causes include the amount of snow, rain-on-snow, drifting snow, melting snow, building problems, person on the roof, and drainage issues. Drainage issues include ponding and blocked or frozen drains. The disruption and impacts section records the consequences of the incident in terms of building downtime, monetary impacts, legal implications, disabled infrastructure systems, and other factors (Table 5). An entry of "1" signals that the cause (Table 4) or disruption (Table 5) shown was discussed in incident reports.

To verify consistency of the coding procedures, two individuals independently implemented the coding instructions for nine randomly selected articles, including 27 incidents. Although the

Table 4. Attributed Causes (from U.S. Database)

Incident index	Amount of snow	Rain-on-snow mixes	Drifting snow	Melting snow	Building problems	Person on roof	Drainage issues
1	—	1	—	—	1	1	—
2	1	—	1	—	1	—	—
3	—	—	—	1	—	—	1
…continued for incident indices 4 to 1,029							

Table 5. Disruption and Impact (from U.S. Database)

Incidentindex	Closure	Closure time	Evacuation	Evacuation time	Repair	Demolition	Rebuild	Economic impact	Legal implications
1	—	—	1	4 h	1	—	—	—	—
2	1	13 days	—	—	1	—	1	$20,000	Lawsuit
3	1	—	—	—	—	1	—	—	—
…continued for incident indices 4 to 1,029									

degree of agreement was good, the procedure was subsequently updated to eliminate discrepancies and ensure repeatability in coding the remaining articles.

To examine the relationship between storm severity and building failure, snowfall records were collected for three U.S. states: Massachusetts, Ohio, and Washington. These states were selected because they reported a relatively large number of snow-failure incidents and represent three distinct climatic and cultural regions of the country. Using the National Climatic Data Center's Storm Events Database, snowfall data was gathered from January 1, 1993 to September 31, 2009 (National Climatic Data Center 2009). No snowstorm data was available before 1993, so the period between 1989 and 1993 could not be examined. Snow data collected relevant to this study includes storm date, storm location by county and state, reported property damage, and smallest and largest reported snow accumulations per storm.

Results: U.S. Snow-Related Building Failure Incidents

Information about snow-related building failures collected from newspaper reports is used to identify and describe trends in the United States and abroad. This analysis of failures, closures, and warnings provides information to characterize when and where snow-related building failures may occur and the types of buildings that are most at risk, accounting for construction type, activity, and age. In addition, incident data provides insight into the most frequently cited causes of failure and impacts on buildings, property damage, business interruption, and life safety.

Regional and Seasonal Variation

Factors such as building location, time of year, and weather patterns affect a building's susceptibility to extreme snow loads. Incidents were reported in 42 states, as shown in Fig. 1, and clustered, as expected, in northern regions of the country. The majority of reported incidents (58%) occurred in the Mid-Atlantic and New England states, delineated in Fig. 1. The highest numbers of database incidents per state were from New York, New Hampshire, and Massachusetts with 149, 99, and 87, respectively, comprising in total just under one-third of all U.S. incidents. Eight states had no recorded snow-related building damage or failure incidents: Alabama, Arizona, Florida, Hawaii, Louisiana, Mississippi, South Carolina, and Tennessee.

Although reported incidents appear to be concentrated in more populous states, the data shows only a weak positive correlation between population and incident occurrence. New Hampshire, Maine, and North Dakota had the highest ratio of snow-related building failure incidents relative to population size (based on 2008 data from the U.S. Census Bureau). Maine and North Dakota only had 39 and 13 reported incidents, respectively, but the number of incidents relative to these states' small population and building stock indicates a higher susceptibility to snow-induced failure than other states. Similar patterns were observed comparing the number of incidents to building stock data on a state-by-state basis (U.S. Census Bureau 2009).

Not surprisingly, 94% of reported snow-induced failure incidents occurred in the winter months of December, January, February, and March, as shown in Fig. 2. Database incidents in June, July, August, and September were generated from newspaper reporting on building problems including design deficiencies, deterioration, and damage observed during building inspections. More incidents occurred in January and February (61% of total incidents) compared to December and March (34% of incidents), which is consistent with the Northeast States Emergency Consortium's observation that the most severe winter storms typically occur during January and February (NESEC 2008).

The number of incidents greatly depends on weather patterns for a given year. In years with the greatest number of incidents—1996, 2003, and 2008—major snowstorms occurred. One large storm may dominate the incident total for a particular year. The Blizzard of January 1996, for example, deposited as much as [illegible] of snow in some places, impacting a region from Kentucky to Maine. This storm alone contributed to 86 of the 136 (63%) incidents reported

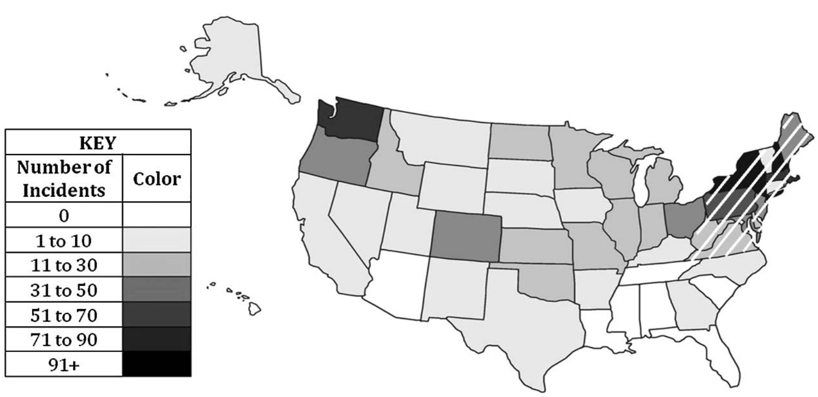

Fig. 1. Distribution of U.S. database incidents by state

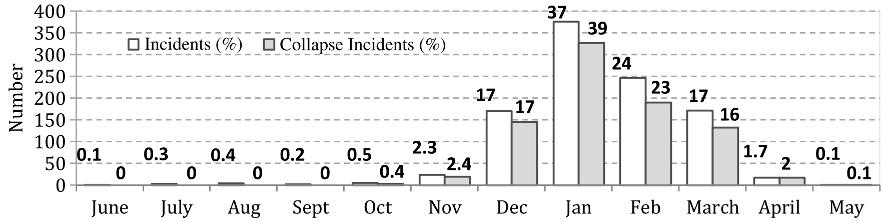

Fig. 2. Distribution of U.S. database incidents by month, with percentages of total incidents and collapse incidents

that year. To examine the effect of individual storms, major snowstorms were classified as those causing at least 10 database building failures. This analysis showed that 19 major snowstorms occurring between 1994 and 2009 contributed to 571 incidents, just over half of all reported incidents in this period. The majority of incidents can therefore be attributed to a small number of large storms.

The relationship between snowfall data and building incidents was further investigated using the storm and snowfall data collected for Massachusetts, Ohio, and Washington. To summarize this data, the depth of snow on the ground in each state was estimated from storm accumulations included in weather data and aggregated during the first half (days 1–15) or second half (days 16–end) of each month. Each state was taken as a uniform unit, neglecting geographic variation in snowfall. The semimonthly windows were chosen to approximately represent the amount of snow on the ground at any given time. As shown in Fig. 3 for Massachusetts, a positive relationship is observed between snowfall in a semimonthly period and the number of incidents in a semimonthly period, with increasing snowfall tending to be associated with a larger number of incidents. Data points along the *y*-axis showing incidents without any record of snowfall may reflect snow buildup on roofs over days or weeks before the incident, or the additional weight from rain and ice in addition to snow, which could not be determined from available weather data. Large snow depths causing no incidents (i.e., *x*-axis data points) may represent snow falling on unpopulated areas, or less-dense or quickly melting snow that imparts smaller loads to buildings. Using the available weather data, it was not possible to determine whether or not snow loads exceeded code design loads for any particular incident. The most impactful storm recorded in the Massachusetts data is the 1996 Blizzard, which deposited an average snow depth of [illegible]n. across the state from January 7–15, leading to 19 reported incidents statewide. The snow depth from this blizzard, combined with the snowfall from a January 2 storm, produced the largest semimonthly value plotted in Fig. 3 for Massachusetts ([illegible] of snow and 19 reported incidents). Similar trends were obs[illegible] for Ohio and Washington.

Characteristics of Impacted Buildings: Structure, Function, and Age

Of the 233 (23%) incidents with information about construction type, the majority of impacted buildings are identified as metal/steel (37%) and timber (37%) construction, as shown in Table 6. Metal/steel buildings appear frequently in the database because they are commonly used in industrial and retail applications. Their construction consists of various combinations of cold-formed and hot-rolled steel members for roof systems with different types of walls. Certain types of metal/steel construction with high snow

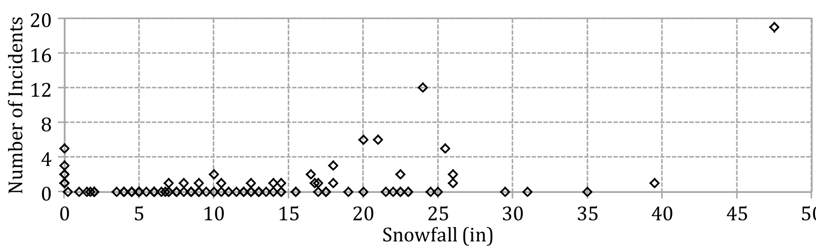

Fig. 3. Massachusetts database incidents versus snowfall for semimonthly periods between 1993 and 2009

Table 6. Classification of the Number of Database Incidents by Construction Type and Incident Type

Construction type	All incidents		Collapse incidents		Damage incidents		Closure incidents		Evacuation incidents	
	U.S.	International	U.S.	International	U.S.	International	U.S.	International	U.S.	International
Metal/steel	91	19	78	18	11	1	69	4	14	2
Concrete	6	6	4	6	1	0	4	1	2	1
Masonry	28	3	21	2	6	1	23	3	2	0
Timber	91	3	76	2	15	1	74	2	10	1
Fabric	5	2	4	1	1	1	3	1	0	1
Air-supported	23	3	21	3	1	0	19	3	2	0
Total[a]	244	36	204	32	35	4	192	14	30	5

[a]Eleven U.S. and two international incidents reported multiple construction types. The total double-counts these buildings (i.e., 244 total incidents includes 233 unique events; 11 are associated with more than one construction type).

to dead load ratios, such as those with lightweight roof and/or wall systems (open-web steel joists, metal roof decking, light-gauge steel walls, etc.) may be particularly at risk under snow loads. Other significant construction types identified in the incident database include masonry (11%) and air-supported structures (9.4%). The number of air-supported structures reported in the database is notable, given that these structures make up a relatively small percentage of the overall U.S. building stock. Air-supported structures and fabric structures seem to be especially susceptible to collapse (21 of 23 and 4 of 5 incidents reported involved collapse, respectively) due to their small dead load, vulnerability to uneven loading, and difficulty associated with clearing snow and ice when overloaded.

Table 7 categorizes incidents by building activity, which was reported for 95% of U.S. incidents. The four most commonly reported building activities were industrial (accounting for 20% of all incidents and 24% of collapses), retail and commercial (17% of incidents and 15% of collapses), government and public (16% of incidents and 8.0% of collapses), and minor structures and garages (11% of incidents and 13% of collapses). The government and public building category includes schools, colleges, and universities. In both the U.S. and international databases, educational buildings made up a large percentage of incidents within the government and public building category, accounting for 65 incidents in the U.S. database or 39% of all government and public building incidents. Emergency and medical facilities accounted for 22 U.S. incidents (2.1%), with 55% of these resulting in collapse. These findings illustrate the large number of commercial and institutional incidents as compared to residential incidents, which account for only 7.2% of database entries.

Fig. 4 illustrates the number of incidents recorded for each year of the study. On average, 44 incidents and 35 collapses (represented by the solid and dashed lines in Fig. 4, respectively) were reported for U.S. buildings each year (with an additional five incidents per year associated with minor structures such as garages). These data correspond to an average annual incident rate of at least 4.1×10^{-7} [incidents per building] and an average annual collapse rate of at least 3.3×10^{-7} [collapses per building]. In other words, one out of every 2.4 million buildings nationwide has a newspaper-reported 3
snow-related failure incident each year and one out of every 3.0 million buildings nationwide has a newspaper-reported snow-related collapse each year. If one assumes the average service life of a structure is 50 years, one out of every 48,000 buildings nationwide reports an incident over its lifetime. (These calculations use the 2007 building stock, which indicate that the United States has approximately 106 million buildings, excluding minor structures (U.S. Census Bureau 2009). Incident rates should be taken as lower bounds because there are failures that are unreported each year; the impact of reporting biases and trends are discussed in more detail below. The small number of incidents in the early years of the study

Table 7. Classification of the Number of Database Incidents by Building Activity and Incident Type

	All incidents		Collapse incidents		Damage incidents		Closure incidents		Evacuation incidents	
Building activity	U.S.	International	U.S.	International	U.S.	International	U.S.	International	U.S.	International
Agriculture	101	—	100	—	1	—	71	—	2	—
Churches	28	1	18	1	9	0	18	1	4	0
Emergency & medical facilities	22	—	12	—	4	—	5	—	8	—
Government & public buildings	165	21	82	17	41	2	70	10	70	4
Industrial	207	16	202	16	4	0	136	1	14	1
Minor structures & garages	110	3	110	2	0	1	63	0	5	0
Office buildings	6	18	1	16	4	2	1	6	4	2
Parking garages	1	1	1	1	0	0	1	0	0	1
Public attractions	19	5	17	5	0	0	18	0	1	0
Residential-single-family	37	—	36	—	1	—	19	—	1	—
Residential-multi-family	37	9	27	6	7	2	19	2	13	3
Restaurants	17	1	15	1	2	0	13	0	1	0
Retail & commercial	177	2	128	1	28	1	92	1	52	1
Recreational facilities	56	13	50	12	5	1	43	3	7	2
Stadiums	6	2	4	2	0	0	3	2	2	1
Vacant	46	—	44	—	1	—	29	—	0	—
Not enough information/other	48	1	41	1	4	0	17	0	3	0
Total[a]	1,083	93	888	81	111	9	618	26	187	15

[a]Total double-counts 53 U.S. and two international incidents that reported multiple building activities.

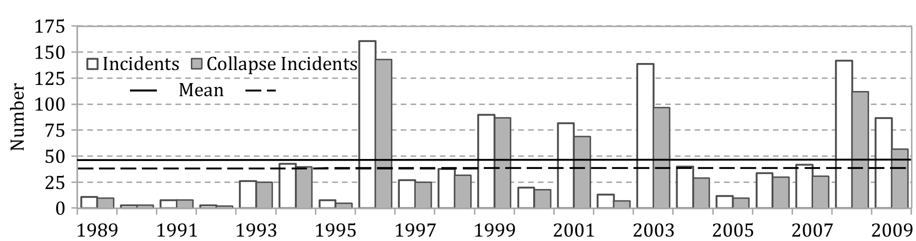

Fig. 4. Distribution of U.S. database incidents by year

most likely reflects news reporting trends and the growth in the building stock since 1980, rather than fewer actual incidents. If only the most recent decade is included (1999–2009), the average number of incidents per year is 57 (excluding minor structures). Census data from 1989 to 2008 show that the number of buildings in the United States has increased at an average rate of 1.5 million buildings (approximately 1.5%) per year (U.S. Census Bureau 2009). These rates are lower bounds since reporting biases will exclude some failures, leading to an underestimation of the number of incidents.

According to Census data, the U.S. has approximately 128 million total housing units and 4.6 million nonresidential buildings (U.S. Census Bureau 2009). The Census also provides 2007 data on the number of units (homes) per residential building, leading to an estimation of approximately 5.1 million multifamily residential buildings and 101 million residential buildings total (U.S. Census Bureau 2009). Of the 44 incidents reported on average annually, 32 collapses were reported for nonresidential buildings, corresponding to an average annual snow-induced nonresidential collapse rate of at least 6.9×10^{-6} collapses/total number of buildings. In other words, one out of every 145,000 nonresidential buildings reports a collapse each year. The residential failure rate is lower at 3.0×10^{-8} collapses/total number of residential buildings (one out of every 34 million residential buildings each year). Residential construction may have lower susceptibility to snow-related failure. However, residential building failures may also be less likely to be reported in newspaper articles than buildings with commercial activities. For comparison, seismic safety assessments find that older concrete buildings have a collapse rate of about 75×10^{-4} and modern buildings conforming to code requirements may have an annual collapse rate of 3.5×10^{-4} in high seismic regions (Liel et al. 2011). Earthquake loading is more uncertain and infrequent than snow loading, perhaps accounting for higher building collapse rates. Under gravity loading only, Ellingwood and Tekie (1999) estimate the annual probability of failure of normal buildings at 6 to 8×10^{-4}, though failure is defined as yielding, so the likelihood of structural collapse is probably much lower.

Certain types of incidents are more likely to be newsworthy because of their high occupancy, community, or economic significance. Newspapers tend to publish articles reporting on more noteworthy events, such as high-profile roof collapses or roof collapses involving casualties, with less emphasis on garage roof collapses or similar events. Consider the percentage of noncollapse incidents for each building activity category, inferred from Table 7. Incidents in high-visibility buildings, such as government and public buildings, retail or commercial buildings, or emergency and medical facilities, were far more likely to be reported when the incident did not constitute building failure. A large percentage of these noncollapse incidents were related to design deficiencies, deterioration, and damage reported by building inspections, and minor snow-related damage, evacuation, or closure. Low occupancy or importance buildings, such as agricultural structures and minor structures and garages, were only press-worthy if significant damage or collapse occurred. As shown in Table 7, 99–100% of all reported incidents for agricultural or minor structures were collapses. Other types of structures that were reported in the news only if collapsed include: parking garages, industrial buildings, single-family residential buildings, and vacant structures.

Newspaper articles reported building age for 188 incidents (18% of the total) and these structures ranged in age from newly constructed to 177 years old. As Fig. 5 illustrates, building age was classified into three rough categories: new (buildings 10 years or younger), midage (buildings between 10 and 50 years old), and historic (buildings older than 50 years). The average building age at time of incident was 50 years. Since a significant number of snow-related incidents were reported for structures built within the last 10 years, it can be observed that snow-related failures and incidents are not confined to old or deteriorating structures and that even new buildings, designed according to modern code provisions, may be susceptible to extreme snow loads. Four incidents were reported as failing during construction, with little detail as to the specific cause. The authors hypothesize that age was more likely to be reported for both new and historic building failures since details about building age is more noteworthy in these cases.

Principal Causes and Failure Modes

Each database incident was further characterized according to the cause(s) the newspaper article(s) attributed to the damage or failure. Table 8 shows the relationship between building age and attributed cause. For many incidents, news stories described more than one underlying cause. The most commonly reported causes of snow-related failures reported were excessive snow (89% of total incidents), rain-on-snow (13% of total incidents), and building problems (9.0% of incidents). As buildings age, structural members experience deterioration and may become damaged. A higher percentage of incidents in older buildings were attributed to building problems, including 28% of historic building incidents and 26% of midage building incidents, compared to 5.4% of new building incidents in the U.S. dataset. Other incidents were attributed to melting snow (6.8%), drifting snow (3.2%), drainage issues (1.0%), and people on the roof (1.0%). For 32 incidents (3.1%), articles described no specific cause.

More detail about building problems, such as design and construction flaws, is indicated by articles reporting legal action for 23 (2.2%) incidents; most common were lawsuits against the general contractor or building designer for improper design or construction procedures leading to the collapse (9 incidents). Information about construction type was available for 52 of the 93 incidents related to building problems; timber, masonry, and metal/steel contributed to 27%, 11%, and 8.6% of these incidents, respectively, while 44% of the buildings had unknown construction type. Interestingly, 36% of the U.S. incidents reported as associated with building problems were government and public buildings. Since it seems unlikely that these structures have higher prevalence of design and construction

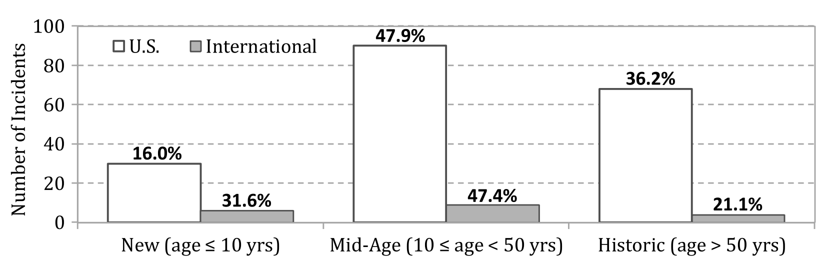

Fig. 5. Distribution of database incidents by building age

Table 8. Classification of Incidents by Attributed Cause and Age

Cause attributed	U.S.				International			
	Total reported	New	Midage	Historic	Total reported	New	Midage	Historic
Amount of snow	919	26	76	48	73	4	5	3
Building problems	93	5	24	26	13	2	4	2
Melting snow	70	2	7	9	10	0	2	1
Rain-on-snow mixes	136	3	15	11	7	1	0	0
Drifting snow	33	2	4	1	2	0	1	0
Person on roof	10	0	1	0	2	0	0	0
Blocked drains	10	0	1	1	0	0	0	0
Total[a]	1,261	38	128	96	107	7	12	6

[a]Total double-counts 249 U.S. and 15 international incidents with more than one failure cause.

flaws compared to other structures, the data appear to indicate a higher rate of reporting for these structures.

Other failures were attributed to specific snow and weather conditions. The high number of incidents attributed simply to a large amount of snow may represent, in part, the large number of incidents from northeastern states, which tend to see relatively heavy snowfall. Twenty-percent of incidents were reported to be caused by either melting snow or rain-on-snow, suggesting that the additional weight from high water content can be critical in causing snow loads to surpass building capacity. In many states, particularly those near the Great Lakes—Illinois, Missouri, Indiana, Ohio, and Pennsylvania—rain-on-snow may contribute significantly to building failures by increasing the weight on the roof. Of the 70 incidents of melting snow, 74% caused the building to collapse. The most commonly affected building types were retail and commercial (21%), followed by government and public buildings (16%). An additional 1% of incidents were attributed to blocked drains and were probably also associated with melting snow. The effects of ponding can be severe; 90% of incidents with drainage issues resulted in collapse. Of the 33 incidents (3.2%) reported due to drifting snow, 30 led to collapse, and 57% of these incidents were industrial, retail, or commercial buildings. Investigations of insurance data by O'Rourke et al. (1983) found that, of the 55% of all industrial roof failure insurance claims being attributed to snow, 75% of the failures were due to drifting on multilevel roofs, which is significantly larger than the 3.2% determined in this study. Differences in the importance of snowdrifts may be attributed to the generalizations made in reporting of failure causes.

In addition to information regarding the causes of collapse, the extent of building damage was also recorded in some cases. Reported details show that roof collapses ranged in severity from [illegible]0,000 ft^2, comprising anywhere from 1 to 100% of building area. Based on the 139 incidents reporting collapse area, the average collapse area was 1[illegible] ft^2 (e.g., 100 × 100 ft). Although details were not always provided, a few selected collapse modes are described to illustrate the relationship between snow loading, structural characteristics, and structural response. One example of progressive collapse is the March 7, 2001 failure of the [illegible] ft^2 Westford Bible Church (MA), built in 1973. Following the previous day's storm, the gable roof collapsed under approximately [illegible] of wet, drifted snow. One of the roof's timber scissor trusses, which supported the inclined cathedral ceiling over the main sanctuary, buckled due to a defect. The remaining trusses were unable to transfer the additional weight and failed, eliminating the lateral support to the concrete walls (Martinez 2001; Willhoit 2002; Burns 2002). In St. Paul, MN, the collapse of the steel roof of a distribution center warehouse in December 1991 illustrates a different failure mechanism. In this failur[illegible] 5 ft of compacted snow had drifted to one side of the flat roof against a taller adjacent structure. The steel beams were unable to hold the weight from this nonuniform load on the roof and a 5[illegible]0 ft section of the metal roof fell (deFiebre and Duchschere 1[illegible]). A third example is provided by a 40-year old structure housing Toys 'R' Us in Lanham, MD. On February 22, 2003, the lightweight metal joist roof structure of the 4[illegible] ft^2 building caved in without warning. That day, ove[illegible] of rain fell on the [illegible] snow that had already accumulate[illegible] week. A combination of rain, snow, and ice clogged drains on the flat roof. At the location of ponding, the lightweight metal roof girders suddenly deformed and pulled away from the reinforced-masonry walls, beginning a progressive failure that propagated from the back of the store to the front. In less than eight seconds, 60–70% of the roof area had failed (Manning 2003; Tucker and Wiggins 2003; Cella and Prince 2003). These examples illustrate the progression of structural failure during snow-induced collapse incidents and the role of load transfer, redundancy, and connection adequacy in resisting failure.

Human and Socioeconomic Impacts

Casualties were reported for 71 (6.9%) incidents, and included a total of 19 fatalities and 145 injured persons; 26 of the injuries (18%) were serious enough to require hospitalization. These 19 fatalities occurred in 18 separate incidents and only one incident (the failure of the Lusk's Disposal Recycling Center in Princeton, WV in 1998) caused more than one fatality. The most commonly reported injuries were cuts, bruises, broken bones, and head injuries. Somewhat surprisingly, minor structures and garages had the largest percentage of incidents involving casualties (including 25% of minor structure incidents), indicating that these nonengineered buildings may be susceptible to failure and damage without sufficient warning. In addition, incidents involving minor structures and garages may only be reported by newspapers if casualties occur. In many other cases, warning noises or structural distress alerted occupants, providing time for them to vacate the building. In four incidents, lawsuits were brought against the building owner by victims or their families. In other cases, newspaper stories reported Occupational Safety and Health Administration investigations of workplace safety violations.

Newspaper accounts reported a variety of economic impacts from damage or collapse, including costs to repair, rebuild, or demolish; damage to building contents, such as vehicles, manufacturing equipment and warehouse goods; and death and injury to livestock. In all, 37% of incidents reported economic impacts related to property and building damage, with estimates ranging from $1,000 (for the repair of a shed roof and walls) to $30 million (for the replacement of antique trains at the B&O Rail Museum in Baltimore); it is likely there were unreported economic impacts for many other incidents. Demolition may be expensive and several articles described legal action to determine who was financially responsible for this cost. Incomplete data exists about the fraction of overall costs covered by insurance and it likely differs according to the type of construction. Of the 82 buildings for which insurance status was reported, only 8.5% were not covered by insurance. Despite the apparent prevalence of insurance, coverage was reported to be inadequate in many cases, including the B&O Rail Museum and the Plymouth Sports Dome (MA).

Reported indirect economic impacts included permanent or temporary layoffs of employees and profit loss due to business interruption. Of all U.S. database incidents, 587 (57%) buildings were temporarily closed. Closure times reported for 115 incidents varied from one day to three years with an average closure time of 122 days or just over four months. Long closure times may significantly impact business profits or viability, especially for small companies. An additional 150 buildings were evacuated before the incident took place and stayed closed while repairs, rebuilding, and inspections took place; the average evacuation length was 31 days (obtained from data for 56 incidents). All told, the data implies that 737 buildings (72% of all incidents) were either evacuated or closed, while 11 buildings were closed permanently. Although insufficient data exist to directly quantify their impacts, indirect costs of these business interruptions likely contribute significantly to total economic impact (Comerio 2006). It is also worth noting that newspaper articles often publish the day after an incident occurs, when closure and evacuation information is limited, and rarely publish follow-up articles, so actual closure times may vary from original estimates.

Results: International Snow-Related Building Failure Incidents

Additional data on international snow-induced building incidents is included to examine differences between U.S. and international building failures and reporting trends.

Regional and Seasonal Variation

The compiled international database consists of 91 incidents in 16 countries spanning four continents, as detailed in Table 9. The majority of reported incidents occurred in North America with 51 incidents (56%) from Canada, mostly from the provinces of Ontario, Quebec, and British Columbia. Europe reported the second highest continent total with 29 incidents (32% of total international incidents), while Asia and Australia reported six incidents (7%) and five incidents (6%), respectively. The large number of Canadian incidents relative to other countries may reflect the focus of the English-language international press, rather than a particularly high risk of failure in Canada. Russia had the second highest country total with eight incidents. Certainly, there are a large number of incidents in other countries not reported. For example, one article from the South China Morning Post reported that 1,200 houses had collapsed and 1,900 more had suffered damage in China after unusually large snow storms occurred in late 2009 causing damages of more than $497 million (Clem 2009). Without specific information about each building, however, these incidents were not included in this study.

As with the U.S. database, most of the international incidents (86%) occurred in December, January, February, and March. On average, three incidents were reported each year over the 30-year database period, as shown by the solid line in Fig. 6. The increasing number of incidents over time likely represents a larger number of references in search databases for later years, leading to more reported incidents. The greatest number of incidents in a given year was 10 incidents in 2009.

Characteristics of Impacted Buildings: Structure, Function, and Age

As with the U.S. database, international incidents were classified by construction type and building activity (Tables 6 and 7). Of the 34 incidents (37%) whose construction type was reported, metal/steel (53%) and concrete (17%) construction made up the majority of building incidents. Masonry, timber, and air-supported structures each accounted for approximately 8% of the building incidents. Metal/steel buildings were much more prominent in the international database (53% of incidents) compared to U.S. incidents (37%). The easy availability of timber in the United States may account for its relatively greater contribution to American incidents (37% in U.S. database versus 8.3% in international database). A much larger percentage of incidents involved concrete buildings in the international database compared to the U.S. database (17% versus 2.5% of U.S. incidents). Articles reported construction errors (e.g., insufficient reinforcement), design flaws (e.g., failing to account for temperature loads), and inadequate maintenance (e.g., extensive rebar corrosion and concrete cracking) as the main causes of collapse in concrete buildings.

As shown in Table 7, the three most commonly reported building activities for international incidents were government and public buildings (23%), office buildings (20%), and industrial

Table 9. Distribution of International Database Incidents by Continent and Country

Europe		North America[a]		Asia	
Austria	3	Alberta, Canada	1	China	3
Belarus	1	British Columbia, Canada	8	Japan	2
Czech Republic	4	Manitoba, Canada	3	Lebanon	1
England	2	Newfoundland, Canada	1	Total	6
France	2	Nova Scotia, Canada	3		
Germany	1	Ontario, Canada	17		
Italy	1	Prince Edward Island, Canada	2		
Norway	3	Quebec, Canada	16	Australia	
Poland	2			New South Wales, Australia	3
Romania	2			South Australia, Australia	1
Russia	8			Victoria, Australia	1
Total	29	Total	51	Total	5

[a]Excluding United States of America.

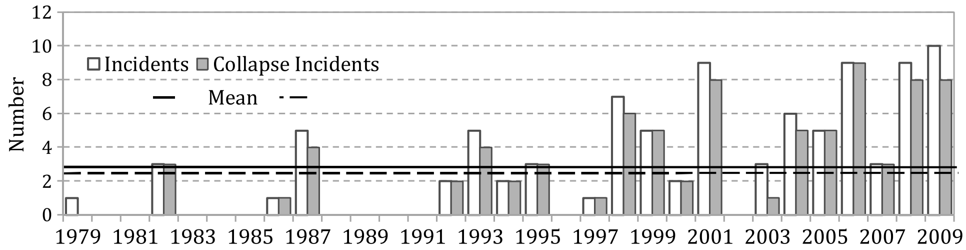

Fig. 6. Distribution of international database incidents by year

buildings (18%). No emergency or medical facility failure incidents were identified. While the U.S. incident database includes all types of building activities, the international database includes only large-scale buildings whose incidents were significant enough to be recorded in the international English-language press. Information on building age was available for 20 (22%) international incidents and ranged from new to 186 years old at the time of failure, as shown in Fig. 5. The average building age at the time of reported incident was 44 years. However, the percentage of new buildings is double that of the U.S. database. In addition to demonstrating that even new buildings may be susceptible to snow-induced building incidents, the greater contribution of new building failures in the international database may indicate differences in building code provisions and compliance in other countries.

Principal Causes

As shown in Table 8, international incidents were most commonly attributed to the large amount of snow (80%), building problems (14%), melting snow (11%), or rain-on-snow (7.7%). The most likely cause in both databases was the amount of snow, while a larger percentage of U.S. building incidents were attributed to rain-on-snow mixes and a larger percentage of international incidents were attributed to building problems. Six (46%) of the 13 international incidents reported as having building problems were recreational facilities. The design of recreational facilities appears to be particularly susceptible to design and construction flaws that may increase risk of failure under large snow loads.

Human and Socioeconomic Impacts

Eight hundred 79 casualties were reported in the international database, resulting from 27 incidents. These casualties included 293 fatalities and 586 injuries, a much larger number than in the U.S. database, demonstrating the severity of reported international incidents and the fact that major world publications tend to report international failures with human or economic significance. On average, 9.6 casualties occurred per incident internationally; no single U.S. incident was reported as causing more than nine casualties and the U.S. database failures led to a mean of 0.16 casualties per incident.

Approximately 35% of international incidents described the economic impact of building failure. The dollar value of these impacts was often significant, with total property and building damages ranging from a few thousand dollars (for repair of ceilings and structural members) to $200 million (for replacement of the BC Place Stadium retractable roof in Vancouver, British Columbia). Of all international database incidents, 35 buildings (38%) were unusable for some period of time, ranging from one day to two years. One building was closed permanently as a result of collapse. International and U.S. articles reported similar average closure lengths of 111 days (just over three and a half months) and 122 days, respectively.

Reporting of Snow-Related Building Failure Incidents

Article length and placement in the newspaper provides an indication of the prominence of snow-failure stories within a day's headlines. The first section in a newspaper generally includes major news stories, while the second section usually focuses on local and regional news. Generally, articles about U.S. roof collapses are in a position of regional prominence, with 14% of articles appearing on the front page, 60% reported in the first two sections, and 6.5% found in subsequent sections. (For 14% of articles, the position in the newspaper was unknown). In 68% of articles only one incident was reported, demonstrating their significance to the news story. Most (40%) of the U.S. articles were from midsize papers (with circulation between 100,000 and 750,000), while 33% were from small papers with circulation less than 100,000, 17% were from wire reports, 1.8% were from large papers with circulation over 750,000, and 8.2% were from unknown sources. According to the Annual Report on American Journalism (Project for Excellence 2004), small and midsize papers have an average article length of less than 600 words and 800 words, respectively. The average length of articles was 558 words in the U.S. database, approximately consistent with the average article length.

Worldwide, 4% of articles appeared on the front page, 51% were in the first two sections, 5.6% were included in later sections, and 40% of articles had unknown placement. Most of the articles (66%) were from midsize papers, 17% were from wire reports, 15% were from small papers, 2% were from other or unknown sources. The high number of midsize international papers reporting snow-related incidents may be attributed to the fact that this type of publication is more likely to cover (and translate) notable snow-induced building failures. International articles about building failure incidents had an average length of 341 words.

Study findings are inherently constrained by the type of information about building failures that tends to be included in newspaper and wire reports. Many articles did not include all desired information or omitted engineering details on construction type, building age, and cause of failure pertinent to this study. The emphasis on drama related to casualties and victims in newspaper reporting, at the expense of discussion of factors related to risk, has been observed in reporting on other types of events, including vehicular crashes (Rosales and Stallones 2008). In the articles examined as part of this study, personal recounts of the collapse or plans to rebuild were frequently reported. In addition, different size news outlets tend to emphasize and report on different characteristics and the impacts of these biases on the findings are difficult to quantify. Nevertheless, newspaper reports present the most comprehensive source of snow-related incidents presently available and significantly expand our knowledge about failures in common types of commercial, residential, and industrial facilities.

Conclusions

The findings of 1,029 U.S. and 91 international snow-related incidents reveal patterns of building failure, damage, and risk due to extreme snow loads. The comprehensive incident database, gathered from a study of newspaper reports, was coded to classify information about construction type, building activity, building age, type of incident (failure, evacuation, etc.), and physical and socioeconomic impacts. The U.S. data includes incidents from 1989–2009, while the international data spans the time frame 1979–2009.

On average, at least one out of 3.0 million buildings nationwide suffers a snow-failure collapse each year. The collapse rate of nonresidential buildings is much higher than that of residential buildings in the U.S., with at least one out of 145,000 nonresidential buildings suffering collapse each year. Although newspapers do not report all failures, especially for minor structures, the data indicates a number of snow-related building failures each year.

New York, New Hampshire, and Massachusetts have the highest number of U.S. snow-related building failure incidents; if the number of incidents in each state is normalized by population and building stock, New Hampshire, Maine, and North Dakota are identified as the most susceptible to building-related snow incidents. From both U.S. and international incidents, categories of industrial, government and public, retail and commercial, and minor structures such as garages, contribute most significantly toward incident classifications. In terms of construction type, metal/steel, timber, and masonry buildings are particularly susceptible in the United States, while metal/steel and concrete buildings show up most frequently in the international database. The impacts of these failures have included: casualties, especially in large structural failures occurring outside the United States; business interruptions due to closure and evacuation, lasting four months on average; and repair costs of up to $200 million. Approximately 72% of U.S. incidents and 38% of international incidents caused the disruption of building activities for some period of time due to evacuation or closure. The high number of incidents reported for new buildings (i.e., those constructed in the last 10 years) in both the U.S. and international data sets indicates that a risk of snow-related failure can occur even in modern buildings designed according to current codes. The data also shows that snow-related building incidents increase with increased snowfall. Beside the amount of snow being reported as the main cause of incidents, rain-on-snow mixes and building problems were commonly attributed as causes in the U.S. and building problems and melting snow were commonly reported as causes internationally.

This study attempts to enhance our understanding of snow-related failure and damage trends, particularly structural design issues that may contribute to snow-induced building failures. The data gathered here indicates that buildings may be at risk of failure due to large or uneven snow loads, and that his susceptibility is particularly apparent in certain types of building construction, as well as those structures that are poorly maintained or designed. The susceptibility associated with different building systems disproportionately impacts economic and social activities that tend to concentrate in these buildings, for example retail and industrial activities in metal/steel buildings. These observations lead to a variety of possible risk mitigation strategies. Building owners, especially those with high-value structures, contents, or those sensitive to business closure, may be able to use data on the impacts of failures to value preventative maintenance. Quantitative differences in risk associated with different types of building construction motivates further examination of the consistency of reliability provided by current building code snow load provisions. In addition, the large number of failures attributed to rain-on-snow may also indicate the need for more carefully considering this phenomenon in design procedures.

The observed relationship between snow failures and snowfall is of particular interest given changes in global climate occurring worldwide, leading to increases in average temperature. Although the overall frequency of snowstorms is expected to decrease on a global scale, snowstorms have become increasingly more severe since the 1950s (U.S. Climate Change Science Program 2008). As a result, the occurrence of large, dense snowfalls is expected to increase in certain regions of the world. Ongoing work investigates the application of performance-based design and assessment methods to quantify risk of snow-related failures in buildings using nonlinear simulation and improved weather data.

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Queries

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31. Please provide the page number for Willhoit (2002).

32. Is Winter and Kreuzinger (2008) a journal article? A newspaper article? Please provide appropriate additional information, such as volume, issue, and page numbers.