

BUILDING ENVELOPE TECHNOLOGY SYMPOSIUM

COMBINATION OF WIND LOAD AND RAIN LOAD ON FLAT (LOW-SLOPE) ROOFS

STEPHEN PATTERSON, RRC, PE

ROOF TECHNICAL SERVICES, INC.

1944 Handley Road, Ft. Worth, TX, 76112

Phone: 817-233-9450 • Fax: 817-496-0892 • E-mail: spatterson@rooftechusa.com

AND

MADAN MEHTA, PE, PhD

UNIVERSITY OF TEXAS AT ARLINGTON

609 West Nedderman Dr., Arlington, TX 76019

Phone: 713-842-0393 • E-mail: mmehta@uta.edu



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ABSTRACT

It is generally assumed that wind causes only uplift pressures on a low-slope roof—an assumption widely reflected in various publications of the roofing industry. This assumption is not entirely correct because wind can also cause downward pressures on a low-slope roof.

In most situations, the downward wind pressure on low-slope roofs is so small that it can be ignored, but in some situations the downward wind pressure can be substantial. This paper highlights situations where downward wind pressures, in combination with rain load, must be examined by designers and forensic experts for reasons of life safety and the prevention/reduction of property loss on buildings with low-slope roofs.

SPEAKER

STEPHEN PATTERSON, RRC, PE — ROOF TECHNICAL SERVICES, INC.

STEPHEN L. PATTERSON is a licensed engineer and registered roof consultant who specializes in roofing and waterproofing. He has more than 40 years of experience in all phases of the roofing industry. Patterson founded ROOFTECH in 1983 and has consulted on more than 30 roof collapses in his career. He coauthored *Roof Design and Practice* (Prentice Hall, 2001), *Roof Drainage* (RCI Foundation, 2003), and *Wind Pressures on Low-Sloped Roofs* (RCI Foundation, 2005).

MADAN MEHTA, PE, PHD — UNIVERSITY OF TEXAS AT ARLINGTON

DR. MADAN MEHTA is a professor in the School of Architecture at the University of Texas at Arlington and teaches courses in building structures and building construction. He is a licensed professional engineer and author of several full-length books on architectural engineering, published by Pearson Inc. He is also a coauthor (along with Stephen Patterson) of the book entitled *Roofing Design and Practice*, published by Prentice Hall (2001), and two monographs, titled 1) *Wind Loads on Low-Slope Roofs* and 2) *Roof Drainage*, published by the Roof Consultants Institute Foundation Inc.

COMBINATION OF WIND LOAD AND RAIN LOAD ON FLAT (LOW-SLOPE) ROOFS

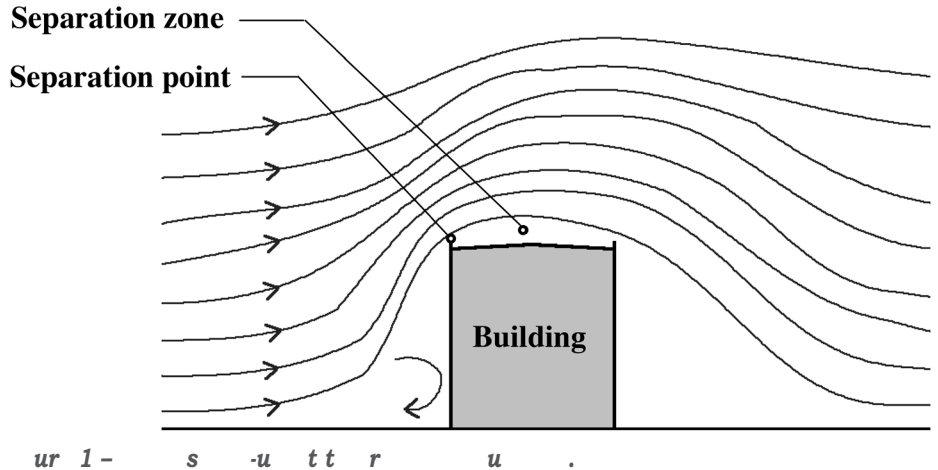
Almost all publications on wind-resistant design of low-slope commercial (flat) roofs deal with wind uplift pressures. This is reflected in roofing industry literature that focuses on either the anchorage of roof assembly (insulation, cover board, and the waterproofing membrane) to the roof deck, or on the weight of ballast or pavers over loose-laid membranes to counter the wind uplift.

Consequently, for the design of the structural components of a low-slope roof assembly (roof deck and its supporting elements), it is generally assumed that wind causes only uplift pressures on a low-slope roof. In other words, in determining the downward design loads on the structural components of a low-slope roof assembly, we ignore the wind loads and consider only the gravity loads obtained from the most unfavorable of the three combinations: (1) dead load plus roof live load, (2) dead load plus rain load, and (3) dead load plus snow load.

This approach is incorrect because wind can also cause downward pressures on a low-slope roof. In most situations, the downward wind pressure is small (well below the roof live load) so that it can be safely ignored; but in some situations, the downward wind pressure can be substantial. Because strong winds are often accompanied by high rainfall intensities, large downward wind pressures and large accumulation of rainwater can occur simultaneously on a low-slope roof. The sum of downward wind pressures and the rain load may govern the design of roof components in some situations that, if ignored, could lead to an unsafe design.

This load combination is particularly important for buildings that are designed to the minimum requirements of the building code for reasons of economy (e.g., storage facilities and distribution centers^o). For example, most designers take advantage of live-load reduction for such buildings to the maximum extent permitted by the building code.

This paper highlights situations where the combination of downward wind pressures and rain load must be examined by designers and forensic experts for reasons of life safety and the prevention/reduction of



property loss. It is based on the provisions of *Minimum Design Loads for Buildings and Other Structures*, published by the Structural Engineering Institute of the American Society of Civil Engineers in 2010, generally referred to as ASCE 7-10 Standard.

Although the provisions referred to in this paper relating to wind pressure are from ASCE 7-10 Standard, it should be noted that these provisions (the values of external pressure coefficient $[GC_p]$ and internal pressure coefficient, $[GC_{pi}]$) have not changed from the previous editions of this standard (e.g., ASCE 7-05, ASCE 7-02, and ASCE 7-98).

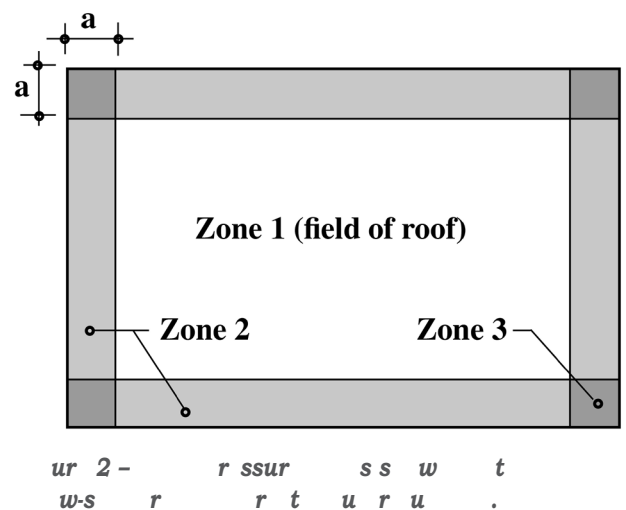
It follows from this paper that in regions where snow load exceeds the rain load, the combination of snow load and downward wind pressures should be examined. However, as previously stated, this paper focuses only on the combination of rain load and downward wind pressure.

1. Wind Uplift Pressures on Low-Slope Roofs

Wind uplift is indeed critical for low-slope roofs, which are subjected to high uplift due to wind speedup that occurs in the separation zone—the zone produced on the roof when a strong wind approaching

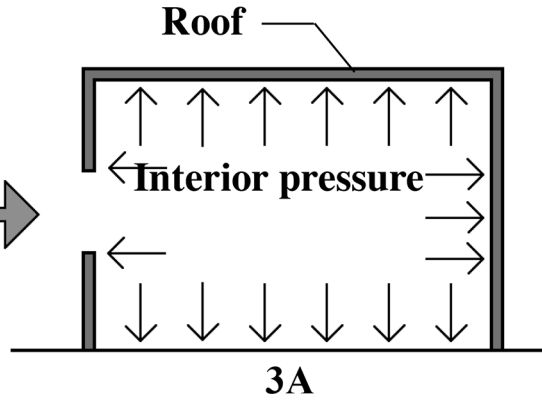
the building is pushed over the roof edge so that the airflow separates from the roof, as in *Figure 1*.

The speedup effect maximizes at the separation point and decreases as the wind travels over the roof away from the separation point. Therefore, the wind uplift is higher at the roof's leading edge (where the separation occurs) than in the central region of the roof. ASCE 7-10 Standard divides a rectangular low-slope roof in three wind pressure zones: (1) corners, referred to as zone 3, (2) perimeter, referred to as zone 2, and (3) the central region of the roof, referred to as the field of roof or zone 1 (see *Figure 2*). Zone 1 is subjected to the least uplift pressure, followed by the uplift pressure in Zones 2.



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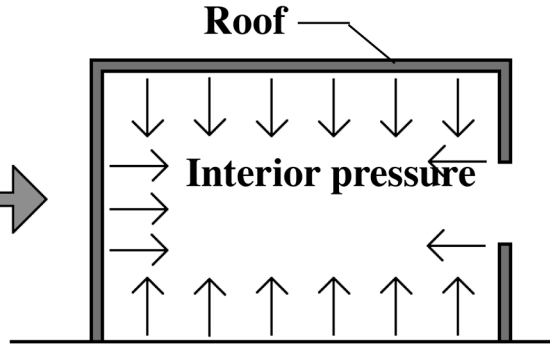
Wind direction →



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Wind direction →



3B

The speedup effect is also a function of the direction of wind relative to the building. It is most pronounced when wind approaches a rectangular building in between its two major axes. Therefore, the roof corners experience the highest wind uplift. Because wind can come from any direction, all four corners (zone 3) of a rectangular building are assumed to experience the same (highest) uplift. Similarly, all four perimeter areas (zone 2) are assumed to have equal uplift, and the rest of the roof—the field of roof (zone 1)—is assumed subjected to a uniform uplift throughout.

In addition to the uplift on the exterior surface of the roof, the roof also experiences wind uplift pressure from within as the strong wind leaks into the envelope and pressurizes the building from the inside.

Thus, the exterior and interior uplift pressures add to give the resultant uplift pressure on a roof.

The leakage effect is large where a building has dominant opening(s) on its windward wall to produce a ballooning effect from within (Figure 3A). In such buildings, referred to as partially enclosed buildings, the interior pressure is high. Most buildings do not belong to the partially enclosed classification but to the enclosure classification, referred to as an enclosed building. In such buildings, the interior pressure is much smaller than in a partially enclosed building.

Note that the interior pressures within a building can cause either uplift pressure or downward pressure on the roof (Figure 3B). Both uplift and downward pressures must be considered.

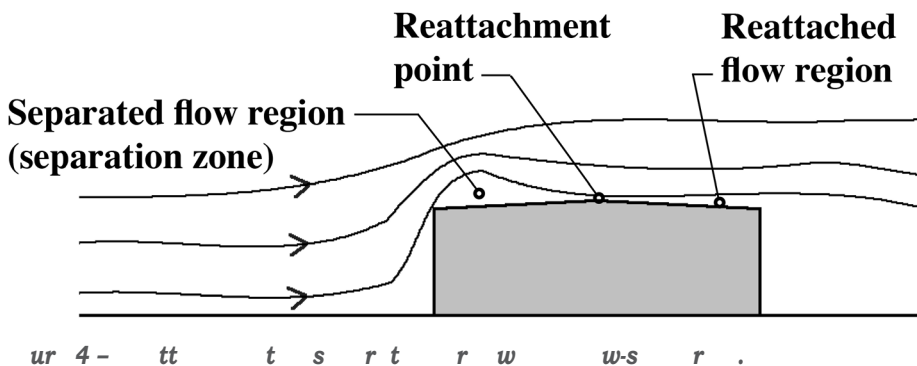
2. Downward Wind Pressures on Low-Slope Roofs

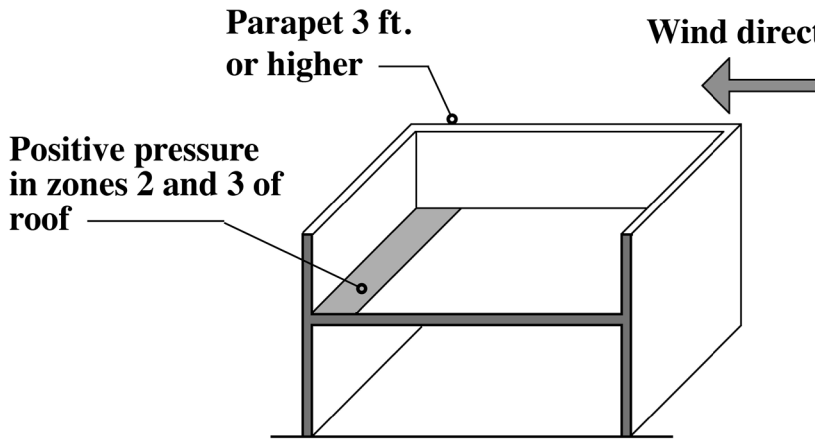
If the downwind dimension of the building is relatively large compared to its height, the separated airflow descends and reattaches to the roof and continues forward parallel to the roof (Figure 4). Apart from roof height, the length of the separated flow region is also a function of the roughness of the upwind terrain. A rougher upwind terrain yields a shorter length of the separated flow region, increasing the length of the reattached flow region because it creates a more turbulent flow on the roof.¹

Within the reattached flow region, wind uplift pressures are much smaller than those in the separated flow region, and this region also experiences downward pressures. ASCE 7-10 Standard gives downward wind pressure values on low-slope roofs (slope $\leq 7^\circ$) for buildings with roof height ≤ 60 ft. (Note that the downward pressures can also be present in the separated-flow region, but their magnitude and occurrence frequency are relatively small.)^{2,3}

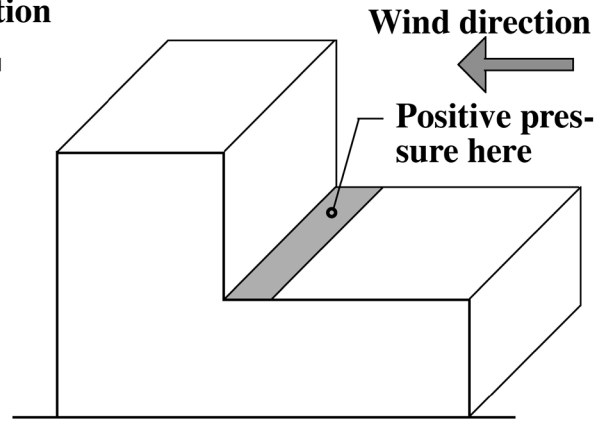
While the downward wind pressures in zone 1 of a low-slope roof are quite small, they can be high in the vicinity of a parapet (Figure 5A) or in the vicinity of an obstruction that creates a stepped roof, such as where a tall block meets a flat-roof podium (Figure 5B)⁴ or in multilevel flat roofs.⁵ ASCE 7-10 Standard requires that downward pressures be considered in zones 2 and 3 of a low-slope roof if (1) roof height ≤ 60 ft. and (2) it is provided with a 3-ft.-high or higher parapet.

Another factor contributing to the downward pressure on a low-slope roof is the depressurization of the building's interior as shown in Figure 3B. Both enclosed and partially enclosed buildings are subjected to this phenomenon; the latter category experiences a much higher downward wind pressure.





5A: Roof with a parapet



5B: Stepped roof

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3. Rain Load

The rain load on a low-slope roof depends on the depth of the accumulated rainwater and must be determined for each individual roof, based on roof geometry, drainage design, and the design rainfall intensity for the location.

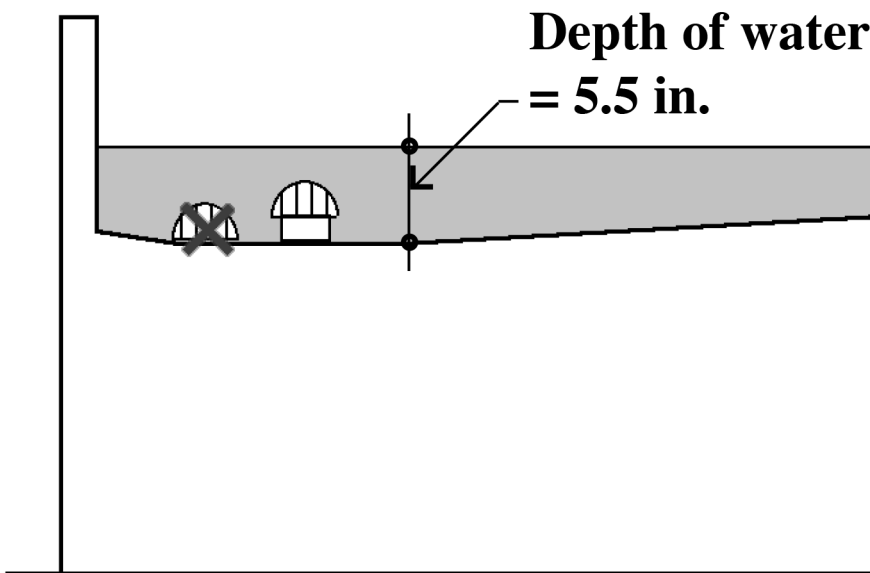
As per ASCE 7-10 Standard,⁶ an (interior) roof drain or an (exterior) scupper must

have a certain minimum hydraulic head to achieve its full (design) drainage capacity. For instance, a 4-in.-diameter roof drain requires a hydraulic head of at least 2.5 in., and a 6-in.-diameter drain requires a head of at least 3.5 in. to be fully effective. The hydraulic head required for scuppers is generally larger.

In order to obtain a rough estimate of

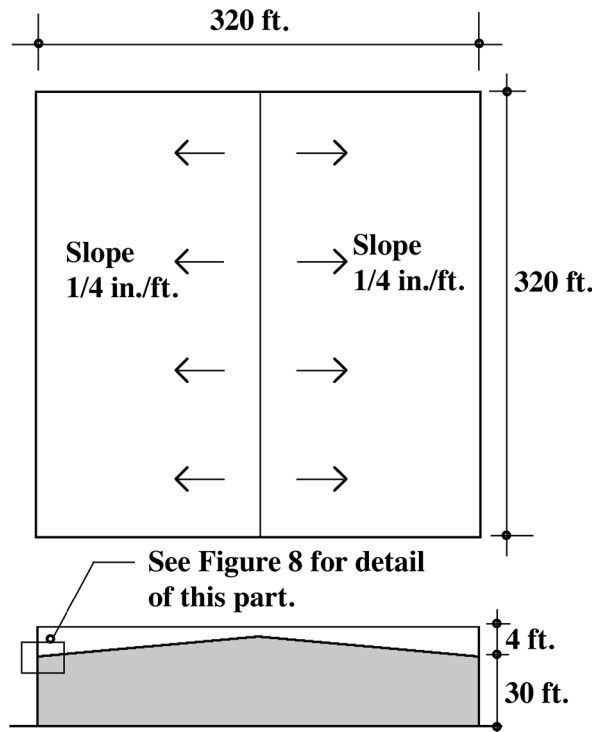
the maximum rain load on a typical low-slope roof, we will assume a hydraulic head of 3.5 in. over the drainage elements. We will further assume that the primary drainage system is nonfunctional (blocked), and the overflow drainage is raised 2 in. above the primary drains so that the total depth of accumulated water over a drain is at least 5.5 in. (Figure 6). Because the roof is sloped and the drains are generally located at the lowest point on the roof, the actual rain load on the roof varies and is generally concentrated over the drains.

In Figure 6, the maximum rain load occurs immediately over the drains and equals $(5.5 \times 5.2) = 28.6$ psf, where 5.2 implies that 1-in. depth of water over a 1-sq.-ft. area weighs 5.2 lb. (density of water = 62.5 pcf). Note, however, that the rain load of 28.6 psf may be exceeded for short time intervals because the roof drainage system is typically designed for a 100-year, 1-hour rainfall intensity. The rainfall intensity during a shorter period can exceed the 1-hour design rainfall intensity. For instance, the rainfall intensity for the 100-year, 15-minute rainfall is generally two times the 100-year, 1-hour rainfall intensity.⁷ During these short periods, the roof is subjected to a higher load.



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4. Examples of Load Calculations on a Building

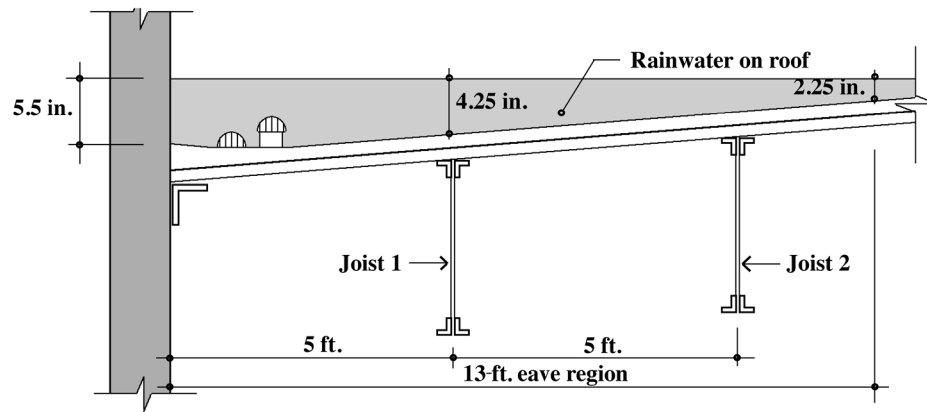
In the examples that follow, we calculate the design loads under different conditions (considering simultaneous presence of wind and rain loads) on the roof deck and a joist of the building of Figure 7. We use the allowable stress design (ASD) load combinations of Chapter 2 in ASCE 7-10.

We assume that the building is a single-story structure with a low-slope roof measuring 320 x 320 ft. (eight 40-ft. bays in both directions), and the roof deck is supported by open-web steel joists 5 ft. o.c., and a 4-ft.-high parapet is provided at the eaves. Additional details of the building are

shown in Figures 7 and 8.

In Example 1, we calculate the downward design loads for the roof structure, considering that the roof is subjected to rain load and uplift wind pressures. Although the focus of this paper is on downward design loads, we first consider uplift wind pressures on the roof because this represents what a low-slope roof structure is typically designed for (i.e., we ignore downward wind pressures on the roof in Example 1).

In Examples 2 and 3, we consider downward wind pressures along with the rain load on the roof. The loads so obtained are compared with those obtained from Example 1.



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s ≈ 20 s. st 1 4.25(5.2) 5 110.5 #/t.

The difference between Example 2 and Example 3 is that in Example 2, the building is assumed as an enclosed building, while in Example 3, the building is assumed as partially enclosed. In Example 1, we assume that the building is an enclosed building.

All three examples (Examples 1 to 3) have two parts: part A and part B. Part A deals with loads on roof deck and part B deals with loads on joist 1 of Figure 8. To improve the readability of this paper, all three examples have been placed in the appendix at the end of this paper. Table 1 summarizes and compares the downward loads obtained from these examples.

The calculations show that under the conditions assumed, the downward design load on the roof deck (or the joist) of this building is not controlled by the dead load + roof live load (or rain load) combination as is generally assumed (represented by Example 1). Instead, as shown in Examples 2 and 3, the downward design load is controlled by a combination of dead load + rain load + downward wind pressure.

5. A Recent Roof Collapse Due to Combination of Wind and Rain Loads—A Case Study

The importance of designing buildings for the appropriate loads is never more obvious than after a roof collapse. The failure to consider the combination of wind and rain loads can, in some situations, lead to catastrophic results. One example was a roof collapse of a very large distribution center in Fort Worth, TX. Like most collapses, there were a number of complex factors, but the only complete explanation of the issues related to the collapse was the combination of wind and rain loads.

The building is more than a million square feet and well over a quarter-mile long with a thermoplastic single-ply roof. The building was oriented east and west and drained from a ridge at the center to drains and scuppers located along all four walls. A section of the roof collapsed in the southeast corner during an intense thunderstorm that included high winds blowing from west to east accompanied by a brief but intense downpour and small hail. The

	Example 1 (Enclosed building) <i>Uplift wind pressures considered</i> A typical design consideration	Example 2 (Enclosed building) <i>Downward wind pressures considered</i>	Example 3 (Partially enclosed building) <i>Downward wind pressures considered</i>
Downward design load on deck	30 psf (field of roof) 30 psf (eave region)	30 psf (field of roof) 57 psf (eave region)— an increase of 90% over Example 1	41 psf (field of roof) 67 psf (eave region)— an increase of 120% over Example 1
Downward design load on joist 1	170 #/ft.	265 #/ft.— an increase of 56% over Example 1	316 #/ft.— an increase of 86% over Example 1

Figure 9—Structural analysis of a building under construction during a storm.

two photographs in Figure 9 show the area of the building that collapsed.

There were several issues involved in this collapse, including a complicated drainage system and unusual geometry of the roof structure in the area of collapse—both of which made the evaluation of the collapse difficult. Determining the amount of water accumulation in the corner was difficult, and several models were used to estimate the rain load in the area of collapse. The rain load occurring as a result of the water accumulation from these models was significant but not quite enough to collapse the structure—until the additional positive downward pressure from the wind load was taken into consideration.

Without question, this was an intense storm, but this is the type of storm that commonly occurs in North Texas and in many other locations around the country. While this was an intense thunderstorm, the wind speeds and rainfall rates were

below the minimum code standards. There were 86-mph winds reported at a weather station very near the site, and the consensus was that this was the likely wind speed at the site. The estimated total rainfall was 2 in., which fell in less than an hour, so the 1-hour rainfall rate was 2 in. per hour. However, it was estimated that 0.5 in. of rain fell in 5 minutes, so there was a peak 5-minute rainfall rate of 6 in. per hour.

It is helpful to imagine the interaction of the wind, rain, and hail on this roof. There were 80- to 90-mph winds blowing across a quarter mile of a flat, slick roof surface more than 30 ft. off the ground and a parapet wall at the east end of the roof. There was a brief but intense downburst, and the slope of the roof and direction of the wind drove

the water into the southeast corner. There was small hail, which has a tendency to restrict the flow of water into the drains. The skylight near the area of collapse blew out, perhaps increasing the downward pressure on the roof.

The result was a roof collapse that caused over \$30 million in damages (building and contents). This was a case where neither the rain nor wind alone was enough to collapse the structure; but taken together, the rain and wind loads exceeded the structural capacity of the building.




Figure 9—Structural analysis of a building under construction during a storm.

6. Conclusions

This paper has highlighted the situations where downward wind pressures must be considered along with the rain load for the design of a low-slope roof or in forensic investigation of a roof collapse. As discussed, these situations can occur in parapeted roofs, stepped (multilevel) low-slope roofs, in high-wind locations, and in enclosed or partially enclosed buildings.

In such situations, the downward wind pressure on the roof is also accompanied by the wind forcing the accumulated water toward the parapet (or the wall adjoining the roof), which justifies the simple addition of the two fluid pressures (air and water) on the roof.

While this paper has focused on rain-load and wind-load combinations, similar considerations should apply to snow-load and wind-load combinations.

Finally, it should be stated that this paper has only focused on the downward wind pressures on roofs. Wind uplift pressures are important; and, as stated in the introduction, they are often more critical than downward wind pressures on low-slope roofs. The ASCE 7 Standard, publications by the Roof Consultant Institute Foundation,⁹ and other literature¹⁰ provide guidance to the designers in this respect. 

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