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# The Rain Must Drain:
# An Engineering Perspective on a Common Pitfall of Overlay Reroofing

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## ABSTRACT

Rehabilitation of commercial roofs is often accomplished by overlaying existing roof coverings with new single-ply membranes. In preparation for this type of recovering, evaluation of the subject building's existing structural system, and analysis of the new roof system's drainage characteristics by properly licensed design professionals, are usually necessary. Often, such evaluation and analysis are also required by municipal authorities having jurisdiction over construction activities to ensure the adequacy of the new systems, their compatibility with the existing structure, and their conformance to applicable building codes. In recent years, and in separate occurrences, operators of a galleria in Oklahoma and a joint retail and service facility in North Texas retained contractors to overlay the existing roofs at the respective buildings with single-ply roof membrane systems. In the months following each reroofing, a portion of each building's roof collapsed during rainfall events. The objective of this paper is to explain the authors' investigation of the causes of these two collapses, with the ultimate goal of providing a memorable reminder to those involved in future recovering projects. The entire investigative process is discussed, from initial site evaluation to determination of causation, including structural analysis and the associated calculation of estimated rainwater loading through iterative flow modeling. The two investigations revealed remarkably similar failures, each characterized by accumulated rainwater on the roofs that overloaded the structural framing; both accumulations having occurred due to inadequacy of the roof drainage systems.

## INTRODUCTION

Covering an existing roof system with an overlay is a common and often cost-effective method of recovering an existing building, most often utilized for low-slope reroofing. Overlaying of existing roof systems which do not freely drain over their edge(s), due to a parapet or other obstruction, require special attention by the remediation designer to ensure the adequacy of the primary and secondary roof drainage systems. If the interdependence of the roof's structural adequacy and the characteristics of the roof drainage system are ignored, a catastrophic structural failure can occur.

This paper emphasizes the importance of proper evaluation of both structural *and* roof drainage systems during the overlay reroofing process by discussing two roof collapses investigated by the authors at separate buildings, each of which featured a low-slope roof with parapets. The subject buildings consisted of a galleria in Oklahoma and a joint retail and service facility in North Texas, the latter of which will be referred to hereinafter as the "service facility." The pre-existing roofing, roof drainage, and structural systems were dissimilar between locations; however, both buildings had existed prior to the respective collapses for decades, without incident.

At the galleria, two gravel-ballasted built-up roof (BUR) systems were installed one over the other, the bottom-most of which was fastened to a metal deck. The steel superstructure supporting the roof consisted of open-web bar joists and joist girders on wide-flange columns. This building's roof also included primary and secondary interior roof drainage systems. These drains were located throughout the field of the roof, which also included parapet wall located around its entire perimeter. The only significant difference between the two drainage systems at this building were the elevations of the secondary drain inlets above the roof surface, which were slightly higher than those of the adjacent primary system's drains.

At the service facility, a standing-seam metal panel roof sloped toward the parapets. The steel superstructure supporting the roof primarily consisted of steel C- and Z-purlins with concrete tilt-up panel exterior walls. At the convergence of the roof slopes with the parapet walls was a gutter and downspout system, with integral scuppers.

During the reroofing process at both buildings, the aforementioned roofing systems were overlain with single-ply membranes atop substrate boards; the existing roofs were not removed. Unfortunately, during the reroofing process, the existing roof drainage systems were modified in blatant disregard for the repercussions which those modifications engendered. It was only *after* these overlay reroofing activities, and associated roof drainage modifications, that portions of each roof collapsed during rain events which occurred a short time after each reroofing operation.

The methodology applied by the authors for the forensic evaluation of both collapses closely followed the process of the Scientific Method; including field investigation and data collection, consideration of causal hypotheses, exploration and engineering analysis of hypothetical alternatives, and the formation of conclusions based upon the analytical findings.

## INVESTIGATIONS

The collapses at both buildings were remarkable and easily identifiable, as shown in Figure 1 and Figure 2.

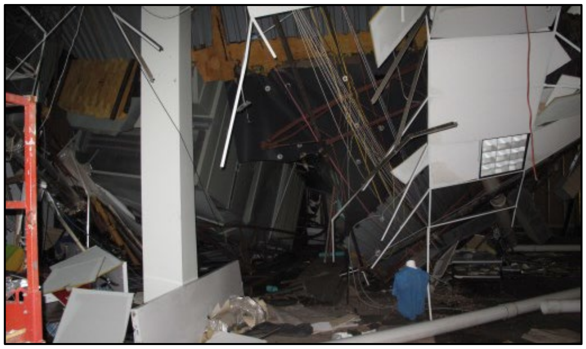

Figure 1. Collapsed portion of galleria roof from the interior of the building

Figure 2. Collapsed portion of service facility roof

The field investigations began shortly after each collapse occurred, and continued throughout periods of incremental, piecewise demolition of the collapsed portion of each building. During the investigations, measurements of the roofing, roof drainage system, and structural system components were obtained. These measurements included the general configuration and geometry of each roof in plan and section, the size and location of the roof drainage systems, and the sizes and configuration of the underlying structural framing systems. Additionally, portions of each building's roof and drainage systems were extracted and stored at an off-site location for further evaluation. Of particular interest at each location were the easily identifiable retrofit modifications to each building's roof drainage systems. The modified drains were configured integrally with the single-ply roof overlay at both buildings, indicating that the modifications were installed synchronously with the respective roofing overlays.

As previously mentioned, the galleria's primary and raised secondary drainage systems *prior to the reroofing* consisted of multiple 11" diameter drain bowls with <u>6" diameter drain outlets</u>. The authors observed that each of these drains had been modified with a retrofit insert intended for installation into an existing drain bowl with a drastically smaller, <u>3" diameter outlet</u>. The resulting effective drain inlet opening for each of these inserts measured 2 1/4" in diameter, and even that inlet was obstructed by mounting hardware, as shown in Figure 3. <u>The inlet area of the retrofit drains was thus reduced by over 75% when compared with the pre-existing roof drains.</u>

Figure 3. Modified drain inlet opening at the galleria

The galleria's roof overlay system was installed over two pre-existing roof systems, which is not only in conflict with the provisions of contemporary building codes (2018 IBC), but is also suggestive of an added dead load which was not likely contemplated in the building's structural design. A conceptual illustration of the modified roof drain configuration at the galleria is presented in Figure 4.

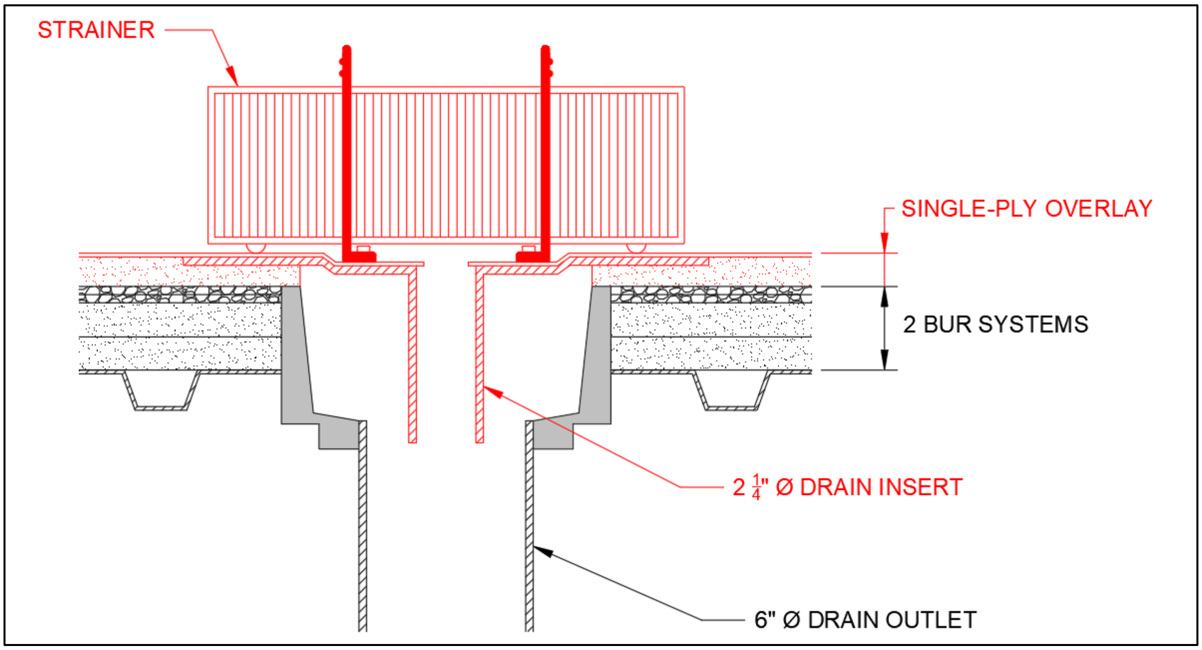

Figure 4. Modified galleria roof drain configuration (roof overlay components in red)

At the service facility, it was similarly evident that the drainage systems had been modified as part of recent reroofing activity. This building's roof *prior to the reroofing* was sloped to drain toward the perimeter parapets, and included 9 x 11" rectangular gutters along the entire length of each of the long sides of the building, just inside of the parapet footprint. The gutters further included multiple 3 1/2" diameter square vertical conductors extending downward from each gutter, each of which discharged at grade. This building also contained a secondary roof drainage system comprised of multiple through-parapet scuppers located at a slightly higher elevation than each downspout conductor. These scuppers would allow drainage from the roof in the event that the primary gutter and downspout system was compromised.

The authors observed that the gutter was bypassed entirely by the installation of square drain inlets at the new roof surface matching the location of each conductor downspout, and that the roof membrane was extended over the gutter itself and up the parapet. To accomplish this, conductor inserts constructed of light-gauge 3 1/4" square metal tubing were in inserted into the existing downspout openings, thereby extending each conductor downspout up to the elevation of the new roof overlay.

Additionally, the single-ply membrane overlay was flashed into and down the conductor insert, reducing the effective opening size to 3" on each side. A wire mesh strainer was fashioned to press-fit within each opening, further reducing the effective size of the openings. Significant organic growth and debris was observed to be caught on the mesh strainers, further obstructing each of the drains. Figure 5 illustrates the typical condition of the obstructed drains.

As configured prior to the reroofing, the building's secondary drainage system would have provided for drainage of rainwater if the primary roof drains became obstructed. However, the scuppers comprising the original roof's secondary drainage system were located within the abandoned gutters, below the elevation of the roof overlay surface. The secondary drainage system was abandoned by the obvious installation of metal plates over the inside faces of the scuppers (Figure 6), which was concealed by the roof overlay. No secondary drainage system was installed in place of the abandoned scuppers. Conceptual illustrations of the configuration of the service facility roof drainage systems before and after modification are presented in Figure 7 and Figure 8.

Figure 5. Organic growth and debris at a service facility roof drain

Figure 6. Metal plate over inside face of scupper opening

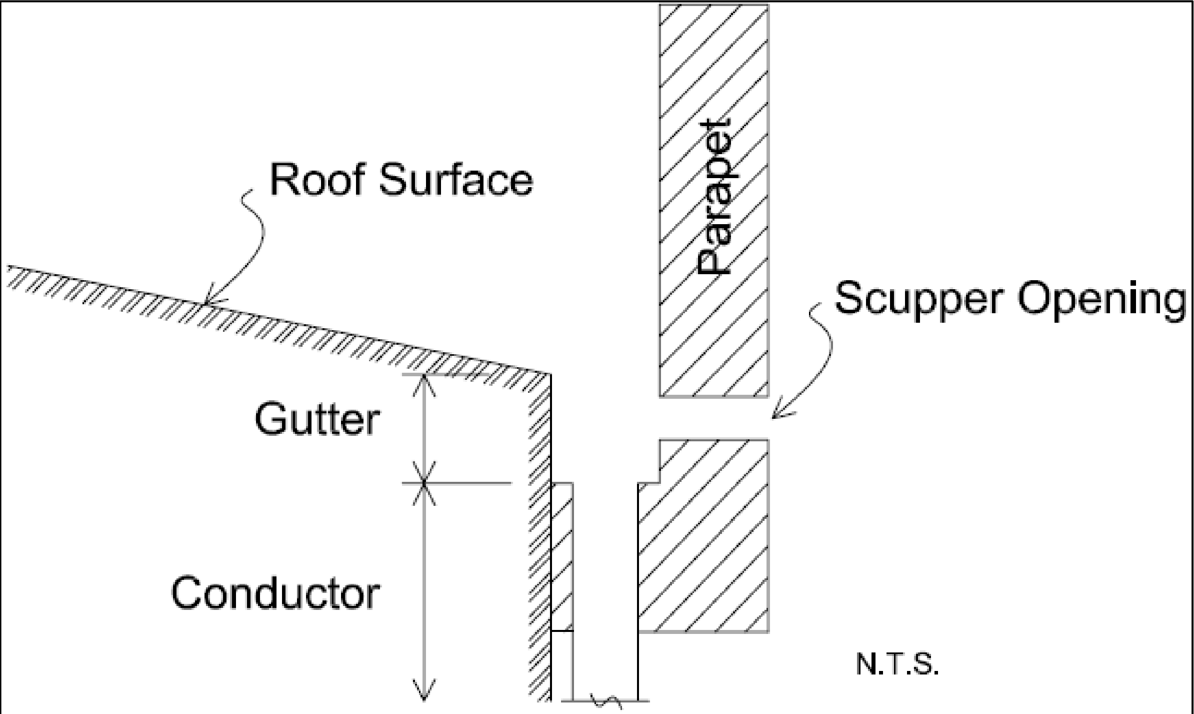

Figure 7. Roof drain configuration at the service facility before overlay installation

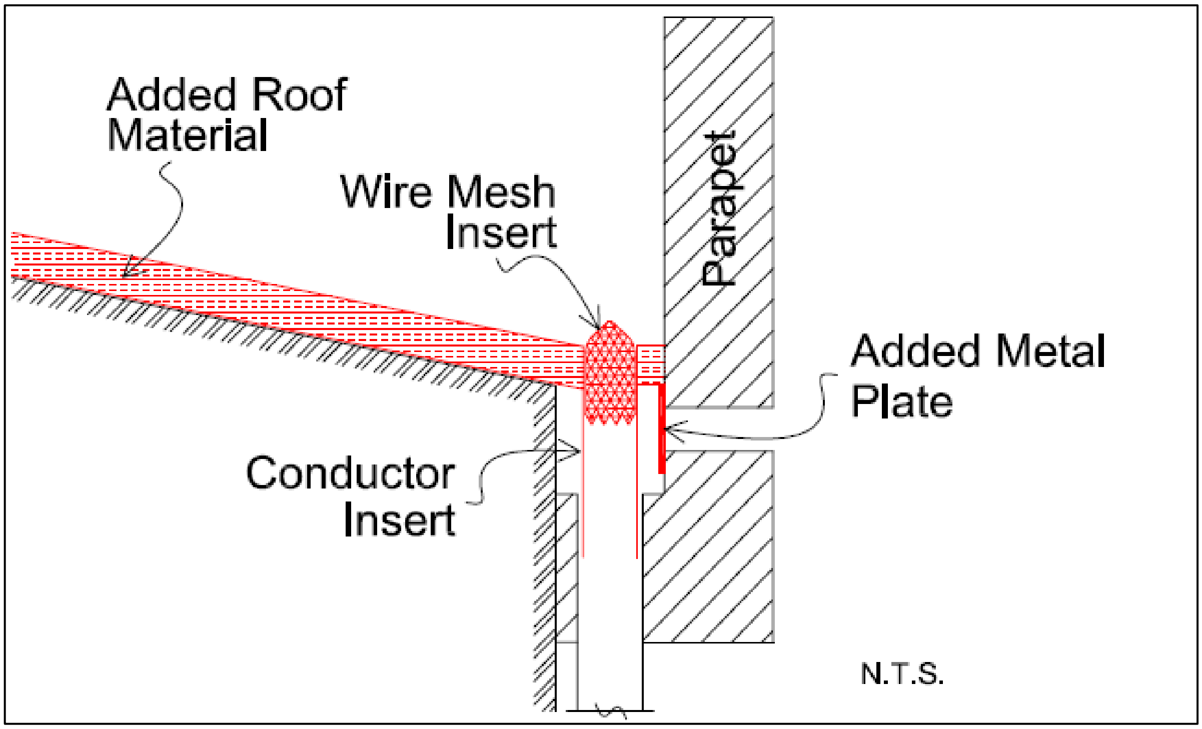

Figure 8. Modified roof drain configuration at the service facility

Following initial site familiarization, observations, and data collection; the authors considered multiple potential causal hypotheses for each collapse. These included, but were not necessarily limited to, overload of the structural framing supporting the roof due to transient non-environmental (live) loads, deterioration of structural components, vehicular impact or previous damage to vertical framing elements, recent modifications to the buildings and/or their structural systems, and deferred maintenance. These hypotheses were diligently investigated both in the field and through discussions with involved parties, and were systematically excluded from further consideration, as no prerequisite evidence supporting these hypotheses was discovered. Based upon the authors' observations and data collected during the respective investigations, in concert with the fact that both roofs collapsed during rain events, the authors converged on a leading hypothesis that modifications of the roof drainage systems during recent reroofing operations were primary contributors to both collapses. To further explore this leading hypothesis, it was necessary to perform a structural analysis of the collapsed portions of each building.

## ANALYSIS

Two primary factors are considered when analyzing structures: the load which is applied to the structure, and the structure's resistance, or load-carrying capacity. In order for a structure to safely perform, the resistance provided by the structure must be greater than the forces which develop in the structure due to the applied loads.

If the actual forces developed in a structure due to applied loads exceed the structural resistance provided, the structure, or a portion thereof, will fail. Therefore, the required relationship of load versus resistance can be described as follows:

Structure load-carrying capacity (resistance) > Applied force (load)

For the subject analyses, the loads to which each building were subjected were first determined, and then the capacities of the structures were calculated for comparison, as described below in further detail.

The load development phase for each of the evaluated structures included determination and superposition of the:

1. Self-weight of the structural members determined from published values and/or field measurement and subsequent calculation;
2. Dead (non-moving) load from fixtures, finishes, and roofing materials; in addition to mechanical and electrical equipment. These were determined by comparison of in-situ materials to published values and by collection and weighing of evidence samples.
3. Environmental load from rainwater accumulation; iteratively calculated as a function of roof geometry, incremental rainfall rate, and incremental drainage capacity.

Superimposed live (transient) loads were not included in the analysis for either of the subject locations; as none were reported to have been present at the time of, or just prior to, each collapse. Further, no evidence of the presence of transient roof loads was observed during authors' field investigations. Also, *design* load amplification factors and material strength reduction factors were not considered in the analysis, as the *in-service* behavior of each structure was of primary interest.

The third component of the load development, that which involved determination of the rainwater load, was not necessarily intuitive. The drainage models necessary to determine the roof rainwater load are iterative and largely reliant on the granularity and accuracy of meteorological data in the timeframe leading to each collapse, specifically with respect to the amount of rainfall per unit time. Potential sources of this rainfall rate information included publicly available historical weather data from the National Oceanic and Atmospheric Administration (NOAA) and information from local weather monitoring stations. However, as in most cases, this available information was recorded by monitoring stations at some distance from the subject sites, and the available information was reported in sizeable time steps (15 minutes to 1 hour is typical). Therefore, to obtain rainfall data useful for analysis, it was necessary to retain a forensic meteorologist to provide site-specific rainfall analyses with reporting periods in smaller time increments.

With sufficiently granular precipitation data in hand, drainage models were developed using the measured three-dimensional geometry and configuration of each building's roof. This required detailed measurements of not only the roof surfaces, but also the primary and secondary roof drains: their sizes, quantities, and locations on each roof surface. The accuracy of these measurements was critical, as the distribution of water about each roof's surface is a function of the roof's geometry, and each drain's geometric characteristics determined the applicable fluid mechanics equations to model the flow through the drains.

Each drainage model involved calculation of the amount of water which had fallen onto each roof (flow into the system) and calculation of the amount of water which could be accommodated by each roof's drainage system (flow out of the system) for each time interval. For example, the rainfall data provided by the forensic meteorologist for the service facility was reported in 5 minute intervals throughout the duration of the storm. Thus, the respective drainage model calculated the flow characteristics of that roof for every five minute time interval. The calculations performed for each time interval can be generally described in order as follows:

1. Determine the volume of water introduced into the system during the time interval by multiplying the incremental rainfall rate by both the time period of the interval and the horizontal projection of the roof's area.
2. Calculate the total volume of water on the roof surface at the end of the time interval. This includes the volume of new water introduction calculated in step 1, as well as any remnant water on the roof from the prior time interval, if any.
3. Considering the roof's three-dimensional geometry, calculate the height of the water above each of the roof drains (hydraulic head) using the volume of water calculated in step 2.
4. Calculate the flow into each roof drain using principles of fluid dynamics, as a function of the hydraulic head determined during the previous step and the geometry of each roof drain.
5. Compare the flow into the drain from step 4 against the calculated maximum flow capacity of the drain and conductor assembly (the pipes transporting water away from the drain), which may be determined from published values or by calculation using principles of fluid dynamics. Take the sum of the smaller of these values for each drain as the total flow out of the system.
6. Calculate the sum of the volume of water introduced into the system by rainfall (a positive number) and the volume of water allowed to flow out of the system (a negative number). If a positive result, this is the volume of water retained on the roof per time step. If a negative result or zero, the roof drains were able to accommodate the rainfall, and water was not accumulated on the roof surface. In the latter case, use zero for reiteration in step 2.
7. Iterate step 1 through step 6 to model the volume of water retained on the roof surface throughout the storm event.

Given the calculated volume of water retained on the roof surfaces at each time interval, the weight of the water and its distribution about the roof surfaces was calculated. This process ultimately yielded the rainwater component of the total gravity load to which each roof structure was subjected.

Next, the capacity of each structure in the area of the respective collapses was determined through fundamental principles of structural analysis, and load-deflection interactions were analyzed. The structural analysis for the service facility was conducted through use of first-order principles. The analysis for the galleria required consideration of second order (P-Δ) effects arising from significant elastic deflection of the roof framing elements under the applied loads.

## CONCLUSIONS

### Galleria

The authors' analysis revealed that the roof drainage system (including both primary and secondary drains) at the galleria was incapable of draining the rainfall which occurred just prior to the time of the collapse. The drainage system was rendered ineffective by the installation of undersized retrofit inserts into the existing roof drains as part of the recent overlay reroofing activities. The retrofit roof drains at the galleria did not comply with the provisions of the applicable building codes (2009 IBC, 2009 IPC). Based on further analysis, the roof drains present prior to the roof overlay would have been capable of adequately draining the rainfall that occurred just prior to the collapse.

The deficient roof drainage system resulted in a weight of accumulated water that exceeded the capacity of the roof framing, which analysis showed to have failed due to localized buckling of components of the open-web bar joist system. Such structural deformation was indeed observed during the field investigation, and again the model indicated that the failure would have occurred within minutes of the reported time of the collapse.

Service Facility

The authors' analysis at the service facility revealed that the primary drainage system in place at the time of the collapse was barely capable of draining the reported rainfall without overwhelming the structural capacity of the roof, provided that the drain openings were unobstructed. However, the authors observed pervasive and near-complete blockage of the drains due to debris at the wire mesh inserted into the retrofit drains (refer to Figure 5). This blockage severely restricted the capacity of the already non code-compliant retrofit primary roof drainage system (2015 IBC, 2015 IPC). Recall that the secondary drainage system in this case had been completely abandoned and could not contribute to any drainage from the roof.

When the partial drain blockage in the field was considered, the analysis revealed that the roof drains were incapable of draining the water from the roof before the weight of the accumulated water exceeded the calculated capacity of the roof framing, resulting in structural failure and collapse. The analysis further revealed that the failure initiated as elastic buckling at a critical roof framing member followed by tear-out of the member's bolted connections. Both of these conditions were visible at the time of the site investigation, corroborating the model's validity. Further, the model indicated that the failure would have occurred within minutes of the reported time of the collapse. The foregoing parallels provide evidentiary validation for the analytical methodologies utilized and the results thereof.

## CLOSING

While installing an overlay is a common and often cost-effective alternative to the complete removal and replacement of an existing roof system, the importance of concurrent evaluation of the roof drainage system to ensure occupant safety subsequent to roof recovering is paramount. Notwithstanding, it is the authors' experience that existing, properly-functional drainage systems are often retrofitted as part of the roof overlay process, with little or no consideration of the adverse effects of same on the flow characteristics of the system.

While post-failure analysis of roof drainage during a storm event is computationally complex and rather time intensive; pre-construction considerations by a qualified design professional are considerably less cumbersome. Simply put, the rain must drain. Required drainage rates can be determined from the rainfall intensity, duration, and frequency of a code-specified design storm event, and drainage capacity can be determined through review of product data provided by the manufacturers of code-compliant roof drain assemblies (2018 IBC, 2018 IPC). Had this relatively simple approach been applied at either of the subject buildings, the collapses, danger to building occupants, resulting damage to property, and associated interruption of business operations, would not have occurred.

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