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Foreseeable Failure: Roof Collapses and Roof Drainage Deficiencies

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ABSTRACT

Roof collapses are often catastrophic events, with the potential to devastate property and to endanger the life and safety of building occupants. A common cause of catastrophic roof collapses is inadequate roof drainage and a resulting accumulation of rainwater that exceeds the capacity of the underlying framing. While numerous factors can contribute to inadequate roof drainage, the authors have observed that roof collapses can frequently be traced back to deficient drainage design or the lack of secondary drainage. Secondary drainage considerations are of particular interest because building codes have regressed and no longer directly require that secondary drainage be added to existing structures upon the replacement of the roof system. This paper discusses the authors' experiences regarding roof collapses caused by inadequate roof drainage. Case studies are utilized to illustrate the implications of inadequate roof drainage and the shortcomings of current building code requirements. Case studies are also presented that indicate the chilling potential for future roof collapses.

INTRODUCTION

Roof collapses are often significant, catastrophic failure events that result in major property damage and, in some cases, significant damage to costly building contents. Roof collapses are also dangerous events, with the potential for severe injury and loss of life to building occupants.

Topics related to roof drainage and roof safety are relatively well documented. In particular, Dr. Stephen Patterson and Dr. Madan Mehta have written numerous publications regarding roof drainage issues and overall roof safety, including co-authoring the in-depth *Roof Drainage* monograph (Patterson, Mehta, and Wagner 2003), which has a new edition published in 2021. While some brief discussion of roof drainage and the codes is necessary to orient the reader, the intent of this paper is to further document the causes of roof collapses related to drainage deficiencies and the devastating effects of collapse through case studies.

Proper roof drainage is an important part of building performance, and the importance of roof drainage appears under-appreciated, based on the conditions observed throughout the built environment. Inadequate roof drainage that leads to the accumulation of rainwater can cause premature deterioration of some roofing materials and can create conditions conducive to water intrusion into the building, resulting in interior damage. Inadequate roof drains, in combination with poor roof surface drainage and/or a lack of maintenance, can contribute to excess accumulation of water.

The weight of this accumulated water will cause deflection of the roof framing and, if a sufficient amount of water accumulates on the roof surface, can overload the framing and result in collapse. Roof collapses can be localized or widespread, and the nature and severity of the collapse will vary based on the characteristics of the framing and the extent of the water accumulation. Regardless, roof drainage design and construction are life safety issues, and the prevention and mitigation of collapses related to roof drainage is important to the health, safety, and welfare of the public.

BUILDING CODES AND STANDARDS

New Construction. For new buildings with low-slope roofs, the 2018 International Building Code (IBC) requires a minimum roof slope of 1/4"-per-foot (the 2018 IBC was the most recent edition at the time of the initial preparation of this paper). For roofs that are enclosed by walls extending above the roof perimeter (such as parapet walls or walls for adjacent construction), the IBC also requires a secondary drainage system (also commonly referred to as "overflow" drainage) that is separate from the primary drainage and is designed for the same rainfall rate as the primary system (ICC 2017).

Determination of the proper design load for the roof structure involves knowledge related to the overall roof design and layout by the architect, and the drainage system design by the engineer for the plumbing systems. Per the IBC and ASCE 7, the structural engineer is to design the roof framing using the calculated depth of water based on the total head of water on the roof in a condition where the primary drainage system is blocked. This calculation requires knowledge of the static head of water at the secondary drain inlet plus the hydraulic head of water for the secondary drain system at design flow (ICC 2017, ASCE 2017). Therefore, the determination of design rainwater weight requires careful coordination between the members of the design team to communicate the relevant information between design disciplines.

The lack of proper consideration of rainwater loading in the structural design of roof systems has been well documented and discussed (Lawson 2012 and O'Rourke and Longabard 2019). As noted by O'Rouke and Longabard, "Unlike snow and wind losses, rain losses occurred with more frequency and consistency in portions of the country where the hazard is not necessarily the highest." This suggests that the loads imposed on structures by rainwater are not calculated or considered with the same diligence as are other load types, such as wind and snow, and this is further substantiated by the authors' experience that rainwater loads are not commonly communicated on design documents, although multiple other load types are often listed.

Additionally, the importance of the as-built drainage meeting or exceeding the requirements of the design becomes apparent when the effect on water accumulation on the roof, and the resulting loading imposed on the structure, is considered. If the secondary drainage is placed with an inlet that is higher than anticipated, this can have a profound effect on the accumulated weight of water (water weighs approximately 5.2 lbs. per square foot per inch of depth). Also, if the as-built flow rate of a drain is lower that the flow rate used in the design calculations, the hydraulic head (and the associated weight of the accumulated water) will increase.

Because the as-built drainage conditions have such a significant effect on the actual loading on the structural system of a building, there should be robust oversight to ensure that the drainage conforms to the design. Based on the authors' experience, such oversight is often lacking in the built environment.

Reroofing. As detailed by Patterson and Mehta, building code provisions related to drainage requirements for reroofing have weakened over time (Patterson and Mehta 2018). For existing structures where the roof is recovered or replaced, the 2018 IBC does not require the roof to meet the slope requirements or the secondary drainage requirements for a new roof provided that the roof provides for "positive roof drainage", i.e., drainage of the roof within 48 hours of a precipitation event (ICC 2017). Therefore, an existing roof that lacks a secondary drainage system but meets the code requirements for "positive roof drainage" can currently be recovered or replaced without the addition of secondary drainage.

The addition of a secondary drainage system to an existing structure can be inconvenient and costly. However, building codes require many inconvenient or costly items to enhance building performance or building safety. It appears that the life safety issues related to deficient roof drainage are underappreciated.

CASE STUDIES OF ROOF COLLAPSE AND DRAINAGE DEFICIENCIES

Case Study 1: Roof drainage modifications. A roof collapse occurred at a large warehouse-type building for a manufacturing facility in Texas. The roof covering of the subject building was a gravel-surfaced built-up roof (BUR) membrane on a steel deck, supported on steel joist roof framing. The structure was more than 30 years old at the time of the collapse and the roof was sloped to drain freely over the low side (Figure 1).

Figure 1. A view of the facility before the construction of the new building addition. The direction of the roof slope is indicated on the subject building.

In the year prior to the collapse, a new building was added to the facility. This new building was to abut the existing facility along the drainage edge of the subject building. Because this would block the free drainage condition of the existing building, a "cricket" was designed and constructed to re-direct the roof drainage (Figure 2). The collapse occurred within approximately eight months of the erection of the walls for the new building addition (Figure 3).

Figure 2. A view of the facility during the construction of the new building addition. Note the drainage "cricket" installed along the drainage edge.

Figure 3. View of the facility with the new building addition and the collapse area.

It was determined that the addition of the new building and the associated drainage modifications resulted in a more than 50% reduction of the free drainage of the existing building. The original roof slope was 1/8" per foot. However, with the drainage modifications, the overall slope along the valley of the cricket was approximately 1/32" per foot. To make matters worse, the cricket valley was interrupted by an expansion joint, which was higher than the adjacent roof surface and impeded the drainage at the valley.

As seen in Figure 4, the collapse area generally aligned with the center portion of the cricket. Evaluation of the roof framing indicated that the pattern of the collapse was consistent with excessive gravity loads on the framing. Analysis determined that the joist framing was sufficient for the original design loading and that the roof framing was not susceptible to ponding instability when the roof was allowed to drain freely. With further analysis and consideration of the potential causes of collapse, it was determined that the roof collapse was the result of water accumulation on the roof in the area of the drainage modifications installed concurrent with the construction of the abutting new building addition.

Figure 4. A view of the roof collapse. The new building addition is on the right.

A review of the available information, including documents produced for the design of the new building addition, indicated no evidence of a detailed analysis of the drainage modifications on the existing structure. Additionally, no structural analysis of the existing roof framing was performed considering any anticipated increase in loads on the structure associated with the drainage modifications.

This case study illustrates the potentially devastating consequences of modifying the roof drainage of an existing building without analyzing the effects this will have on the roof drainage and the roof structure. The collapse area was significant and occurred in a busy part of the facility. The dangers of such a collapse are obvious, as is the potential for disruption of business operations.

The building was repaired, and the new roof design did not repeat the cricket detail, but rather included a series of roof drains along the area where the roof terminates into the wall of the new building addition. These new drains consisted of primary and secondary drains and are indicative of the result of a proper drainage analysis.

Case Study 2: Inadequate roof drainage. A roof collapse occurred at a stand-alone restaurant, with the collapse occurring at a corner of the building over the kitchen (Figure 5). The roof covering was modified bitumen membrane roofing over a wood deck, supported on metal plate connected wood truss roof framing. There was a rain event at the time of the collapse; however, the rainfall was far less than the code-prescribed design rainfall.

Figure 5. Collapsed roof framing at the building corner above the kitchen.

The building was approximately 10 years old at the time of the collapse, but had changed ownership less than 2 months prior to the collapse. An inspection report generated during the sales process indicated that 3" to 4" of water had accumulated on the roof in the area where the collapse later occurred. While some minor roof repairs were performed, no significant drainage modifications were made to the roof.

Upon investigation of the collapse, defects were discovered in the truss framing, including loose and missing connection plates and poor quality wood truss members. Some truss defects had been previously repaired while others had not. These defects caused excessive truss deflection and contributed to the framing collapse.

The roof drainage consisted of three scupper drains through the parapet at the low side of the roof. Localized areas of reverse slope at the roof in the vicinity of the scupper drains and a slight elevation of the scupper inlets above the adjacent roof surface led to water accumulation near the low side of the roof (Figure 6). There was no secondary drainage system installed. In combination with the defects at the roof framing, the poor roof drainage contributed to the roof collapse. The inadequate drainage, the pre-existing roof profile, and the subsequent framing deflections resulted in water ponding and, ultimately, the collapse.

This case study illustrates that multiple causes may contribute to a roof collapse and again illustrates the lack of consideration that is given to roof drainage. The collapse occurred not very long after evidence of poor roof drainage and water accumulation were identified in an inspection report. However, the conditions at the roof prior to the collapse were not identified as a safety concern and no actions were taken to significantly enhance the roof drainage or to provide secondary drainage. This is further indicative of the lack of consideration given to roof drainage and the potentially catastrophic consequences.

Figure 6. Standing water near the low side of the roof. Note the primary scupper drains and the lack of secondary drains.

Case Study 3: Drain obstruction and lack of secondary drainage. This roof collapse occurred on a one-story commercial office building (Figure 7). The building was approximately 40 years old and the roof framing consisted of long-span metal plate connected wood trusses. The roof covering was modified bitumen membrane roofing, and the roof drains consisted of 4" diameter internal drains. This roof also included a perimeter parapet (Figure 8) and lacked a secondary drainage system.

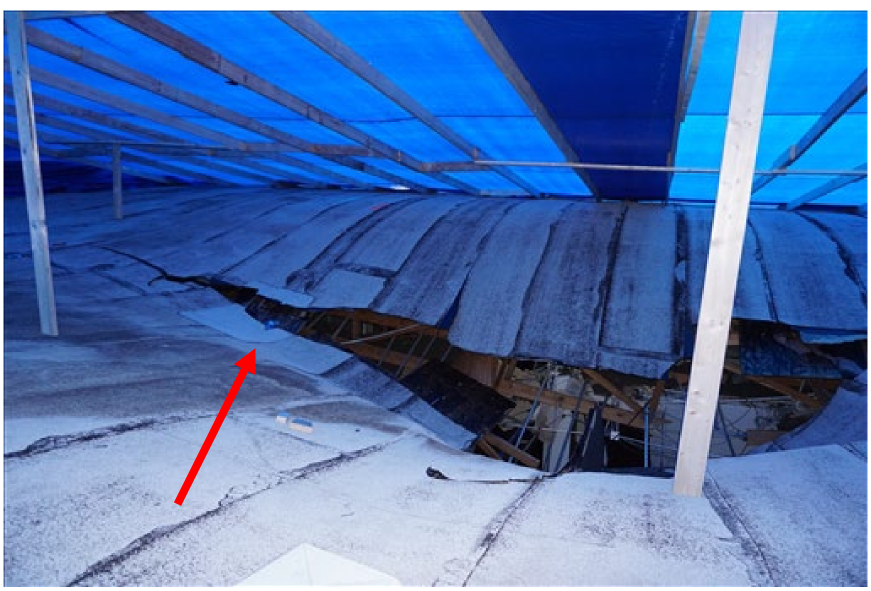

Figure 7. Collapse area at the roof. The blue tarp installed over this area is a temporary roof cover. The arrow indicates the approximate location of a previously abandoned drain.

Figure 8. Perimeter roof drains. Note the lack of a secondary drainage system.

The roof was reported as having been replaced approximately 15 years prior to the collapse, and no roof drainage changes had taken place since this roof replacement. Therefore, the collapse was not the result of a recent alteration of the roof drainage.

While the drains for the roof section where the collapse occurred were generally located along the roof perimeter, there was one isolated drain located at the interior portion of the roof, adjacent to the collapse area. When the strainer for this interior drain was removed, debris was observed within the drain opening, and water could be seen standing in the drain pipe (Figure 9). Therefore, this drain was obstructed (blocked), and was not functioning.

Figure 9. Debris and standing water at the drain pipe of the interior roof drain adjacent to the collapse area.

Also observed near the collapse area was an abandoned roof drain (refer to Figure 7). The drain piping was visible beneath, but the previous drain opening had been covered by the modified bitumen roof membrane. The presence of the interior drain and the abandoned interior drain are indicative of previous issues with water accumulation and post-construction drainage modifications at the interior portion of the roof in the collapse area.

The obstruction of the interior drain resulted in the accumulation of rain water on the roof. Due to the lack of secondary drainage, the roof did not have the ability to drain the accumulated water, and the water weight ultimately overloaded the roof framing, resulting in the roof collapse. As noted herein, and in the relevant building codes and standards, the purpose of secondary drainage systems is to allow water to drain from the roof in the event that primary drainage is obstructed and to avoid a collapse.

This case study illustrates in a very direct way the critical importance of secondary roof drainage. The building existed for 40 years, including 15 years since the most recent roof re-covering, before the obstruction of a roof drain resulted in collapse. This case study is a representative indication that just because a building has existed for a significant period of time without a roof collapse, roof drainage deficiencies cannot be overlooked, and the future performance is not guaranteed.

CONCLUSIONS

The authors have worked on numerous other collapses caused or contributed to by inadequate roof drainage. Based on these experiences and on conditions that we have observed throughout the built environment, it is clear that roof drainage and the water loads on roof framing resulting from deficient drainage are not properly considered in the design, construction, maintenance, and repair of buildings.

The case studies presented herein illustrate the potentially catastrophic consequences of inadequate roof drainage and the associated life safety issues. More attention should be given to roof drainage. A good start would be for the building codes to provide clearer guidance for drainage design, to require the addition of secondary drainage systems (if they do not already exist) upon reroofing, and include more robust requirements for roof drainage evaluations on existing buildings.

Based on the prevalence of dangerous drainage deficiencies and the repeated occurrences of resultant roof collapses, it is the authors' opinion that roof drainage should be treated as a critical life safety issue. Many collapses could be prevented, and the roof drainage improvement cost for a given building would be far less than the cost of repairs and the other monetary damages that typically result from a collapse.

REFERNCES

American Society of Civil Engineers (ASCE). (2017). *ASCE Standard 7-16: Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. Reston, VA: American Society of Civil Engineers.

International Code Council, Inc. (ICC). (2017). *2018 International Building Code (IBC)*. ICC: Country Club Hills, IL.

International Code Council, Inc. (ICC). (2017). *2018 International Plumbing Code (IPC)*. ICC: Country Club Hills, IL.

Lawson, John. (2012). "Roof Drainage – Not my Problem…Maybe'" *Structural Engineers of California 2012 Convention Proceedings*, p.136-151.

O'Rourke, M. and Longabard, A. (2019). "Do Structural Engineers Design for Rain Loads?" *Structure Magazine*, April 2019, p. 28-30.

Patterson, S., Mehta, M., and Wagner, J. (2003). *Roof Drainage.* Roof Consultants Institute Foundation (RCIF) Publication No. 02.03, Raleigh, NC. [note: 2nd edition published in 2021].

Patterson, Stephen L. and Mehta, Madan. (2018). "Roof Drainage Design, Roof Collapses, and the Codes", *Proceedings of the RCI 33rd International Convention*, p. 121-131.