Raising the Bar in Standards:

The ASCE 7 Standard and Low-Slope Roof Drainage

By Stephen Patterson, RRC, PE; and Madan Mehta, PE, PhD

Three important safety issues related to low-slope roofing are: 1) fires on roofs from internal or external sources, 2) roof collapses resulting from the ponding of water (and snow, where present) from extreme storms, and 3) roof blow-offs from extreme windstorms.

Fire safety falls within the realm of fire engineering, and the two important U.S. organizations focusing on its study are the Society of Fire Protection Engineers (SFPE) and the National Fire Protection Association (NFPA). Roof collapses from water ponding and blow-offs are related to the roof's structural design. The organizations focused on structural safety in buildings are the American Society of Civil Engineers (ASCE) and the Structural Engineering Institute (SEI).

An important document dealing with structural safety in buildings, published jointly by ASCE and SEI, is the ASCE/SEI standard, titled *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, commonly known as the ASCE 7 Standard. This standard deals comprehensively with all types of loads on buildings and non-building structures, such as rooftop equipment, decks, billboards, signages, etc. It specifies minimum loads for which buildings and other structures must be designed, such as dead loads, live loads, snow loads, rain loads, earthquake loads, wind loads, and so on.

Although the standard by itself is not legally enforceable, most of its provisions are adopted by building codes of various U.S. jurisdictions, indirectly bestowing legal authority upon it. For example, Chapter 16 of the *International Building Code* (IBC), titled "Structural Design," which covers "minimum design requirements so that the structural components of buildings are proportioned to resist the loads that are likely to be encountered," is based almost entirely on the ASCE 7 standard.

The standard is updated periodically to keep abreast of the developments in this complex but important field because an accurate determination of loads on a building is fundamental to its structural safety. Various editions of the standard are distinguished from each other by a two-digit number at the end of their designation, which refers to the year of publication (or the target year of publication). For example, the ASCE 7-02 standard was published in 2002. On the other hand, its current edition, ASCE 7-16, was planned for 2016 publication, but was released in 2017. Its next edition is planned for release in 2022.

The changes made in ASCE 7 affect almost all aspects of a building's structural safety. However, the discussion presented here deals with the effect on a building's structural safety related to the design of its roofing system. More specifically, this paper covers the contribution of the current ASCE 7 standard (ASCE 7-16) to the design of low-slope roof systems to prevent roof collapses from rainwater ponding from extreme rainstorms.

ROOF PONDING FUNDAMENTALS

Water accumulates on parapeted (raised-edge) roofs, which are typically low-slope roofs. As explained later in this section, water accumulation (commonly referred to as ponding) on a parapeted, low-slope roof is an inescapable design issue. It can be mitigated through good design but cannot be eliminated entirely and must be accounted for in the design of the roof system. Three factors affect ponding on such roofs: 1) roof slope, 2) the roof deck's structural stiffness, and 3) the roof's drainage design.

A fundamental strategy to reduce roof ponding is to provide an adequately sloped roof. Increasing the slope helps in several ways. First, it ensures that water will reach the drainage elements (roof drains or scuppers) more rapidly. Theoretically, if the roof is perfectly flat (an ideal dead-level roof), it will drain water toward the drainage elements, but do so slowly.

Additionally, construction tolerances and workmanship lapses can be such that high and low spots are always present on a roof deck. These surface irregularities on an otherwise dead-level roof will produce some pools of ponded water. Therefore, the second advantage of increasing roof slope is that it overcomes the obstructions caused by incidental surface irregularities and reduces the adverse effect of shallow ponds on drainage and a roof membrane's durability.

Apart from surface irregularities, an additional contributor to ponding is the deflection of roof decks due to the weight of the roof structure and rooftop equipment. The most significant cause of ponding, however, is the deflection of the deck from the buildup of water during rainfall. Stiffness of the deck plays an important role in reducing such ponding. In fact, the provisions of the ASCE 7 standard, as will be described further, clearly highlight the role of roof deck stiffness and roof slope on roof ponding loads.

Hydraulic Head and Static Head

Because the discharge rate through drainage elements (drains or scuppers) is a function of the head of water over them (referred to as the hydraulic head), they discharge rainwater slowly in the beginning. Hydraulic head is the height of water above the inlet level of a drainage element. *Figure 1* explains what hydraulic head is with respect to a primary roof drain.

As the hydraulic head increases, the discharge rate through the drainage element increases. So, at the beginning of a rainfall, a thin layer of water travels to the drainage elements. The layer of water must become thicker for a drainage element to increase its discharge rate. This implies that, under a design rainfall rate, water must build up sufficiently on the roof for a drainage element to function up to its full (design) discharge capacity. Stated differently, a low-slope, parapeted roof will always be subjected to ponding loads and must, therefore, be designed for the maximum estimated ponding loads.

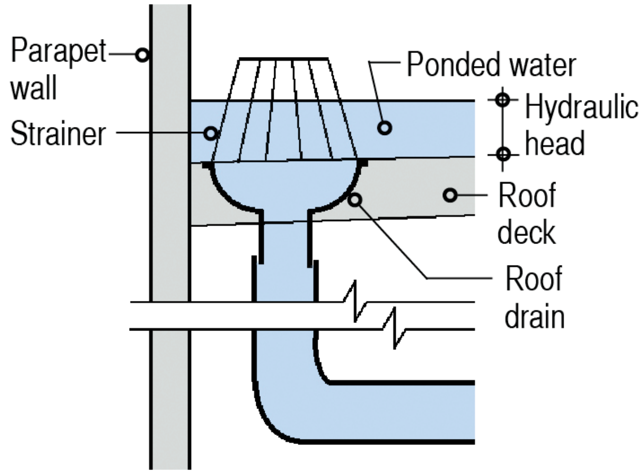

Figure 1 – Hydraulic head explained with respect to a primary roof drain.

The weight of ponded water causes the roof deck to deflect. As the deck deflects, it is able to hold more water, causing additional deflection, which increases the depth of standing water further, which in turn causes additional deflection, and so on. If the deck (and its supporting frame) have not been designed with sufficient stiffness, the increase in ponding due to progressive deflection may exceed the structural strength of the deck, leading to its collapse.

A term closely related to hydraulic head is static head. Static head refers to the elevation of the inlet level of the drainage element above the roof surface. Static head exists only with secondary (overflow) drainage elements, together with hydraulic head (*Figure 2*). Static head is constant and is not influenced by the depth of ponded water. With primary drainage elements, only the hydraulic head exists (i.e., the static head is absent), as shown in *Figure 1*.

Like the U.S. plumbing codes, the ASCE 7 standard[1] requires that a roof be designed "to sustain the load of all rainwater that will accumulate on it if the primary drainage system is blocked plus the uniform load caused by water that rises above the inlet of the secondary drainage system at its design flow." The standard provides the following equation for estimating the load of rainwater (rain load):

$$R = 5.2(d_s + d_h)$$

where
R = rain load in pounds per square foot (psf)
d_s = static head of water in inches
d_h = hydraulic head of water in inches

The constant "5.2" represents the weight of a 1-in.-thick layer of water in psf, obtained from the density of water being 62.4 pounds per cubic foot (pcf).

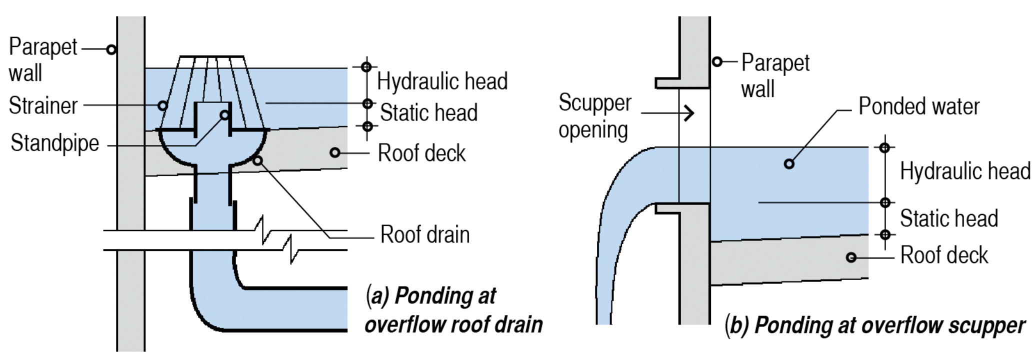

Figure 2 – Hydraulic head and static head explained with respect to secondary (overflow) roof drain and overflow scupper.

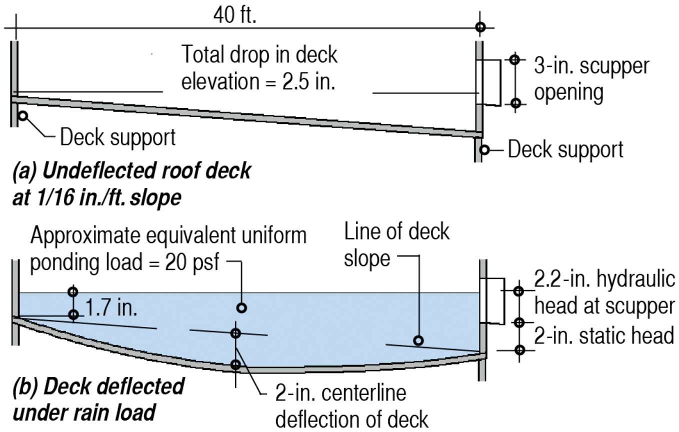

Figure 3 – Ponding on the hypothetical roof at 1/16 in.-per-ft. slope. The first sketch represents the original, unponded roof, and the second sketch illustrates the extent of ponding and the resultant deflection of the same roof.

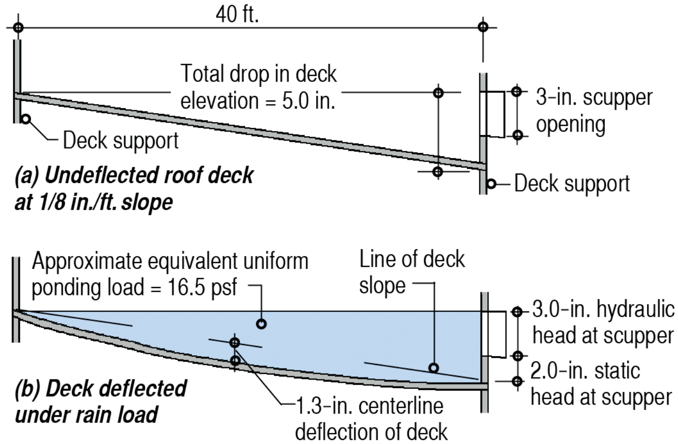

Figure 4 – Ponding on the hypothetical roof at 1/8-in.-per-ft. slope. The first sketch represents the original, unponded roof, and the second sketch illustrates the extent of ponding and the resultant deflection of the same roof.

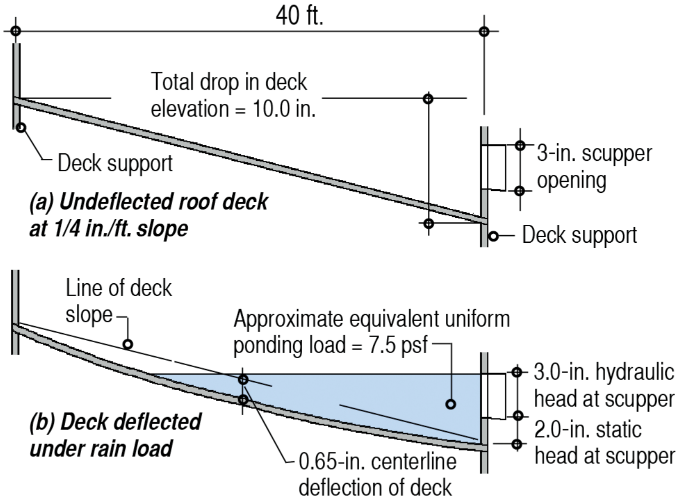

Figure 5 – Ponding on the hypothetical roof at 1/4-in.-per-ft. slope. The first sketch represents the original, unponded roof, and the second sketch illustrates the extent of ponding and the resultant deflection of the same roof.

ROOF SLOPE AND PONDING INSTABILITY

The phenomenon of progressive deflection is referred to as ponding instability. Ponding instability is caused by ponding load that is greater than that for which the roof structure has been designed based on the roof's strength and stiffness. Because ponding instability can lead to a roof's collapse, the first line of action (not the only one) for its prevention is to provide adequate slope in the roof that renders adequate hydraulic head at drainage elements—to increase their drainage rate—and hence, preclude ponding overload on the roof.

The IBC requires that the minimum roof slope be 1/4 in. per ft. for membrane roofs (built-up roofs, modified-bitumen roofs, and single-ply roofs), except coal tar built-up roofs, for which the minimum required slope is 1/8 in. per ft.[2] Although the code specification of minimum roof slope is not based on ponding overload alone, it is important to understand that roof slope plays an important role in reducing ponding overload. To fully appreciate this fact, we will examine the extent of ponding and the corresponding ponding load on a roof for the following three values of roof slope:

1. 1/16-in.-per-ft. slope
2. 1/8-in.-per-ft. slope
3. 1/4-in.-per-ft. slope

We will assume a parapeted roof whose deck slopes in one direction (supported on two opposite ends) and has a span of 40 ft. in the direction of the slope. We will further assume that: 1) the secondary drainage system consists of scuppers provided at the low end of the roof with their inlet levels raised by 2 in. above the roof and 2) the minimum required hydraulic head at the scuppers is 3 in. in order for them to discharge rainwater equal to the maximum rainfall rate on the roof. In other words, the minimum hydraulic head at the scupper must be 3 in. for its drainage rate to match the design (maximum) rainfall rate on the roof.

We will also assume that the roof has been designed for a live load of 20 psf with maximum permissible deflection of span/240—a typical specification for the stiffness of roof decks. Thus, for a 40-ft. span, the maximum permissible deflection under the design rain load is (40×12)/240 = 2.0 in. In other words, the roof deck will deflect 2 in. at its center when the equivalent uniform rain load on it reaches 20 psf.

We will first consider the drainage of this hypothetical roof with 1/16-in.-per-ft. slope. On determining the amount of ponding on it, we see that the equivalent uniform ponding load on the roof reaches the maximum allowed rain load of 20 psf (with centerline deck deflection of 2 in.) when the hydraulic head at the scupper is approximately 2.2 in. (*Figure 3*). As this is below the minimum hydraulic head of 3.0 in. required for the drainage rate through the scuppers to be in equilibrium with the rainfall rate, the ponding on the roof will increase progressively until the hydraulic head at the scupper equals 3.0 in. In that situation, the ponding load on the roof would be greater than its designed capacity of 20 psf, which could cause the roof's collapse.

For the roof with 1/8-in.-per-ft. slope, the hydraulic head at the scupper reaches the minimum required value of 3.0 in. when the equivalent uniform load on the roof becomes approximately 16.5 psf with a centerline deflection of 1.3 in. (*Figure 4*). Because this is less than the maximum allowed live load of 20 psf, ponding overload will not occur at the design rainfall rate. However, as 16.5 psf is fairly close to 20 psf, ponding overload may occur during a short burst of rainfall that exceeds the design rainfall rate, causing ponding instability in that situation. (Short bursts of rainfall with rainfall rate substantially greater than the code-recommended design rainfall rate are common. As discussed in Section 5, ASCE 7 recommends taking this into account for the design of the overflow system.)

Note that although the *IBC's* requirement of minimum ⅛-in.-per-ft. slope for a coal tar built-up roof is primarily based on its propensity for slippage at higher slopes, coal tar pitch is more resistant to ponding water than asphalt.

The amount of ponding on the roof with ¼-in.-per-ft. slope is approximately 7.5 psf when the hydraulic head at the scupper reaches 3.0 in., explaining its relatively high degree of safety against ponding overload (*Figure 5*).

Note that for the sake of clarity, the vertical scales in *Figures 3* through *5* have been exaggerated with respect to the horizontal scale. However, because the deck deflection and the slope of the deck are on the same scale, the portrayal of water ponding is correct.

Roof Slope Greater Than ¼ In. Per Ft.

As the illustrations of *Figures 3* through *5* demonstrate, increasing roof slope decreases the ponding load on the roof, which may lead to ponding instability, and a ¼-in.-per-ft. (¼:12) slope is the minimum required. However, a steeper slope is not always better. A steeper slope no doubt improves roof drainage, reduces ponding load, and also increases the roof membrane's durability. However, it creates some problems. For instance, the fire resistance of a roof decreases with increasing slope. More importantly, increasing the slope increases the depth of plenum space (between the roof and ceiling), thus increasing the building volume and façade area; hence, increasing the building's cost. Therefore, most low-slope, membrane roofs are built with the minimum ¼:12 slope.

STRUCTURAL FRAMING OF ROOF DECK AND PONDING INSTABILITY

The calculation of ponding loads on roofs of different slopes, shown in *Figures 3* through *5*, concluded that for roof slope equal to (or greater than) ¼ in. per ft., the ponding overload (and hence, ponding instability) does not occur. This, however, is true only for a certain configuration of a roof's structural framing. In other words, ponding instability is not simply related to roof slope but also to the relationship of roof slope with a roof's structural framing configuration.

An additional factor that affects ponding instability is the stiffness of a roof's structural framing members—primary framing members, secondary framing members, and the deck. The stiffer the members, the less likely the ponding instability. The current (2018) IBC states that ponding instability of roofs from rainwater (and snow, where present) should be evaluated according to the provisions given in the ASCE 7 standard.[3] The current version, ASCE 7-16, requires that the roof's structural framing be analyzed to ensure that the structure has adequate stiffness and strength to "preclude progressive deflection (i.e., instability)." (The American Institute of Steel Construction, (AISC), and the Steel Joist Institute (SJI) provide resources for the investigation of ponding instability on roofs.[4,5]

Susceptible Bays

ASCE 7-16 identifies the following bays of a roof's structural framing that may be subjected to instability, referred to as susceptible bays. The standard requires particular attention to the following situations.

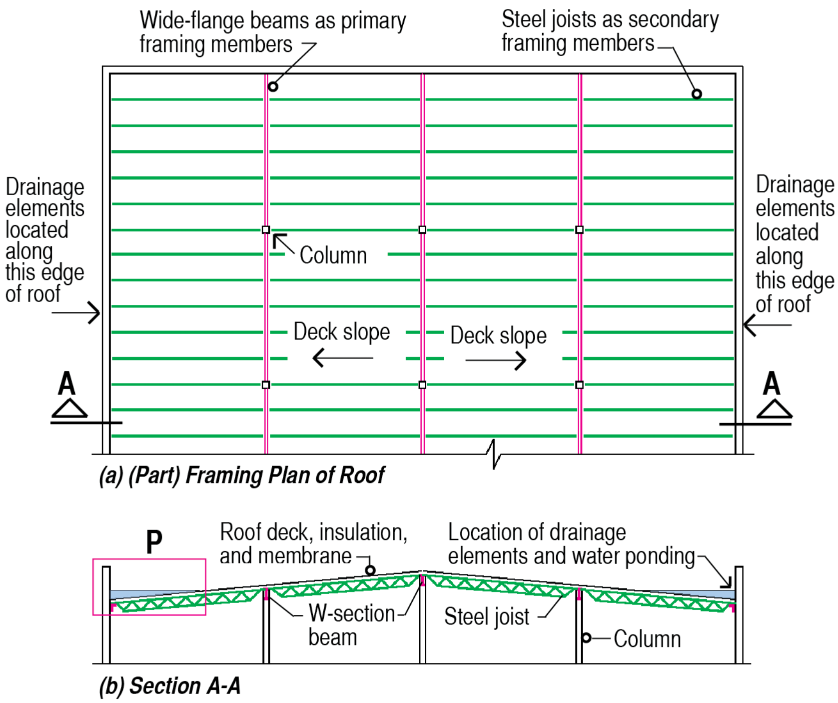

Figure 6 – Framing plan and section of a roof where the secondary framing members are perpendicular to the roof's edge that houses the drainage elements.

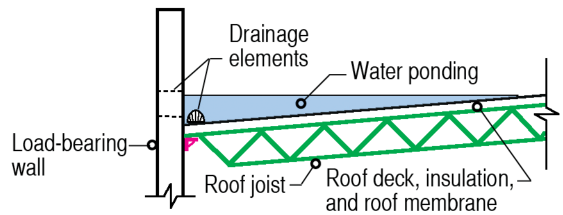

Figure 7 – Detail section P refers to Figure 6. *The joists near the roof's drainage edge are subjected to gradually decreasing ponding loads, limited to a small part of their spans.*

Situation 1 — "Bays with a roof slope less than ¼ in. per ft. (1.19°) when the secondary members are perpendicular to the free-draining edge"

It is the authors' interpretation that the "free-draining edge" in this provision refers to the edge of the roof where drainage elements (scuppers or roof drains) are located and requires that their discharge rate be equal to or greater than the rainfall rate so that they provide "obstruction-free" drainage.

Figure 6 and *Figure 7* illustrate the roof framing plan and section of a roof referred to in this provision—where the secondary framing members (roof joists, shown in green color) are perpendicular to the roof's edge, which houses the drainage elements. Note that in this situation, the joists are subjected to gradually decreasing ponding loads, which are limited to a small part of their spans. Note also that the lesser the slope, the greater the spread of ponding. This provision, therefore, requires that a roof whose framing plan is as shown in *Figure 6*, and which has a slope less than ¼ in. per ft., be investigated for ponding instability.

Note that the discussion of roof slope, illustrated in *Figures 3* through *5*, tacitly assumed the roof configuration mentioned in this provision. The discussion concluded that if the roof slope is equal to (or greater than) ¼ in. per ft., the ponding load on the roof will be too small to cause ponding overload (hence, ponding instability).

Situation 2 – "Bays with a roof slope less than 1 in. per ft. (4.76°) when the secondary members are parallel to the free-draining edge."

Figure 8 and *Figure 9* illustrate the roof framing configuration of this provision, which shows that the ponding on secondary framing members (steel joists, shown in green color) that are in the vicinity of the roof's edge (housing the drainage elements) are subjected to (relatively large) ponding loads over their entire spans, requiring investigation of ponding instability in them if the roof slope is less than 1 in. per ft.

Situation 3 – "Bays with a roof slope of 1 in. per ft. (4.76°) and a span-to-spacing ratio for the secondary members greater than 16 when the secondary members are parallel to the free-draining edge."

This provision is related to Provision 2 and refers to long-span secondary members. Because of their long span, the secondary members are subjected to large deflection. For example, if secondary members are spaced 6 ft. on center (typical spacing for steel roof joists), and if their span is greater than 6 × 16 ft. or 96 ft.—a fairly long span—this provision requires attention to this situation to ensure that the secondary members (joists) have sufficient stiffness to preclude progressive deflection under ponding load.

Note that ASCE 7 provisions (Situations 1 to 3) for minimum slope of ¼ in. per ft. and 1 in. per ft. are based on maximum deflection-to-span ratios of $1/240$[6]—the same as that assumed in the ponding illustrations of *Figures 3* through *5*.

Situation 4 – "Bays on which water accumulates (in whole or part) when the primary drain system is blocked but the secondary system is functional. The larger of the snow load or the rain load equal to the design condition for a blocked primary drain system shall be used in this analysis."

The first part of this provision reiterates the commonly understood drainage design principle for low-slope roofs in that the roof ponding load is to be determined assuming that the primary drainage system is fully blocked and the secondary system is functioning. Note that the illustrations of ponding in *Figures 3* through *5* are based on this requirement.

The provision also implies that ponding instability be investigated where water ponding exists on a part of the roof or over the entire roof. As some water ponding will always exist on a low-slope roof under design rainfall rate, this provision is an across-the-board requirement; i.e., ponding instability is to be investigated over the "entire part" of all low-slope roofs. A typical example of this reminder is a roof with a small projected area, which can be more severely ponded as compared with its adjacent area(s). Additionally, this may also result in the overflow drainage system in the adjacent area(s) being deprived of attaining the design hydraulic head to provide the

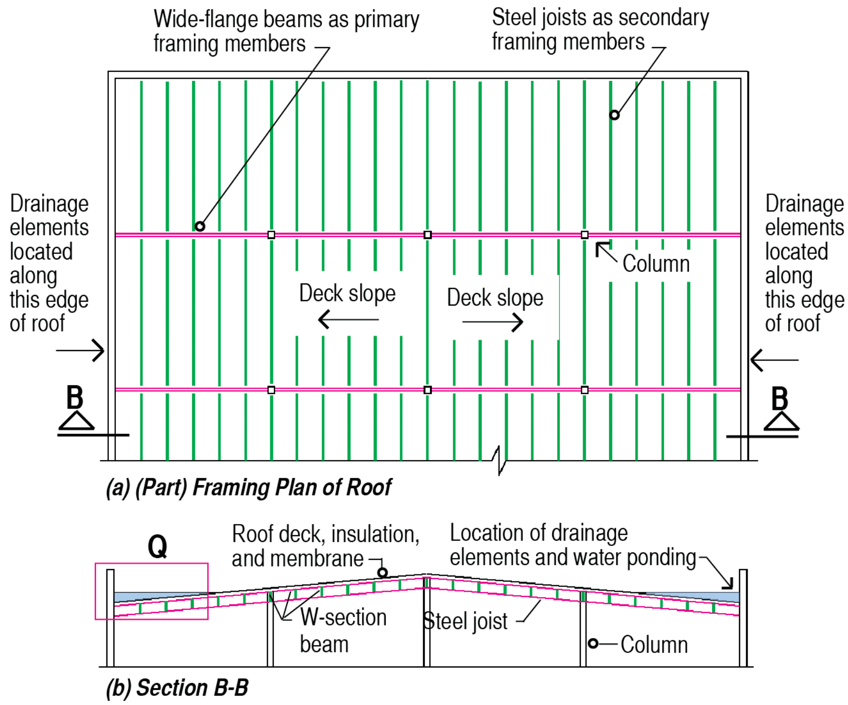

Figure 8 – Framing plan and section of a roof where the secondary framing members are parallel to a roof's edge that houses the drainage elements.

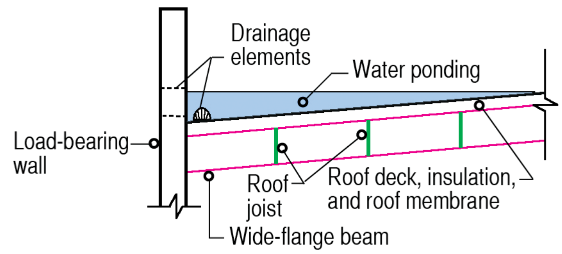

Figure 9 – Detail section Q (refers to Figure 8*). Note that the secondary members (joists) near the roof's drainage edge are subjected to relatively large ponding loads over their entire spans.*

required drainage because most of the water will flow to the projected area, requiring ponding instability investigation (*Figure 10*).

The second part of this provision states that ponding instability can also occur from excessive snow load in addition to that from the rain load.

REROOFING, PONDING INSTABILITY, AND ROOF DESIGNERS' DILEMMA

As one of the most authoritative documents on structural safety in buildings, the ASCE 7 standard has led the way in the consideration of ponding instability on roofs, and the building codes have either adopted the standard's provisions by reference or through their verbatim inclusion. The first mention of ponding instability in ASCE 7 appeared in its 1993 edition (ASCE 7-93), described in just ten words: "Roofs shall be designed to preclude instability from ponding loads." This narrative simply cautioned the design professionals on ponding instability without providing any design guidance.

The narrative was refined in the standard's next edition (ASCE 7-95) as: "Roofs with a slope of less than ¼ in. per ft. shall be investigated by structural analysis to assure that they possess adequate stiffness to preclude progressive deflection (i.e., instability) as rainfall on them or meltwater is created from snow on them." There was neither any change in the above narrative, nor any additional provision introduced for several editions of the standard until its most recent edition—ASCE 7-16. As described in Section 4 (under title: "Susceptible Bays") of this paper, ASCE 7-16 has identified four situations for which ponding instability of roofs must be investigated.

The narrative of ASCE 7-95 has been identified as Situation 1 in ASCE 7-16. Expanding the need for ponding instability investigation from one to four situations, which have obviously been overlooked for too long, ASCE 7-16 standard has made a significant contribution to life safety in roof design. Stated differently, according to previous editions of ASCE 7, investigation of ponding instability of low-slope roofs was required only for roofs with a slope of less than ¼ in. per ft. The current edition requires this investigation for roofs with a slope of less than 1 in. per ft. where the roof deck's structural framing demands it. This demand is articulated under Situation 2 (where secondary framing members are parallel to the roof's free-draining edge) and, more pointedly, in Situation 3 (where the span-to-spacing ratio of secondary framing members exceeds 16 and they are parallel to the roof's free-draining edge).

Historically, virtually all low-slope roofs have been built to less than 1 in. per ft. The authors' presumption is that the roofs for which the secondary framing members are parallel to the roof's free-draining edge have also been built with a slope of less than 1 in. per ft., and no investigation of their ponding instability was undertaken because the codes did not require it.

ASCE 7-16's expanded definition of framing bays, susceptible to ponding instability, presents a serious dilemma for the contemporary roof designer for reroofing. Does the roof designer need to examine the structural framing configuration of the existing roof to ensure that it conforms with the current ASCE 7 standard? This question is particularly important where the existing roof framing requires a minimum 1-in.-per-ft. slope to meet with the current ASCE 7 standard but has been provided with a lower slope.

Presumably, the building to be reroofed was built in accordance with the applicable building code at the time; so, roofs with slope less than ¼ in. per ft. were analyzed

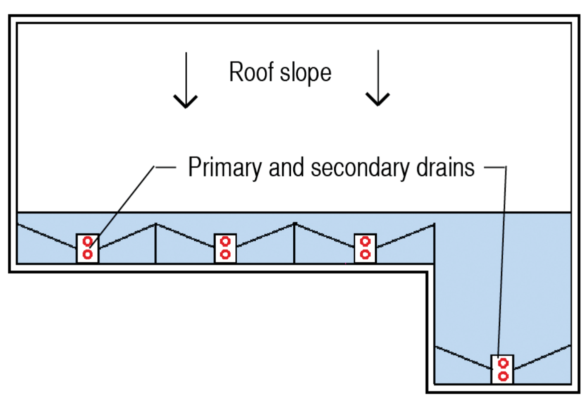

Figure 10 – A roof with a small projected area that can be more severely ponded than the adjacent roof.

for ponding instability. However, it is most likely that the roofs with secondary framing members parallel to the free-drainage edge and slope less than 1 in. per ft. were not analyzed for ponding instability because the applicable codes did not require it. In that scenario, what should the roof designer do?

It has been our experience that buildings with secondary framing members parallel to the free-drainage edge are far more likely to collapse than structures with secondary members perpendicular to the free-drainage edge. The failure to analyze such roofs for ponding instability at reroofing could result in a serious life-safety issue.

DESIGN RAINFALL RATE FOR OVERFLOW DRAINAGE AND PONDING INSTABILITY

U.S. plumbing codes require that both primary and secondary (overflow) drainage for low-slope roofs be designed for 100-year, 60-minute-duration rainfall rate. ASCE 7 agrees with U.S. plumbing codes for this rainfall rate for the design of primary drainage but not for the overflow drainage. For overflow drainage, it recommends a 100-year, 15-minute rainfall rate.[7] The National Oceanic and Atmospheric Administration (NOAA) National Weather Service Precipitation Frequency Data Server gives rainfall rates for various rainfall return periods (in years) and rainfall duration (in minutes).

Generally, a 100-year, 15-minute rainfall rate is approximately double the 100-year, 60-minute rainfall rate for most U.S. locations. In other words, determining ponding instability on low-slope roofs using 100-year, 60-minute rainfall rates grossly underestimates the real ponding instability that exists on roofs. The disagreement between the plumbing codes and the ASCE 7 standard for design rainfall rates for secondary drainage design is again a dilemma for the roof designer.

In an earlier paper, the authors endorsed the ASCE 7 standard recommendation, giving the rationale for the endorsement.[8]

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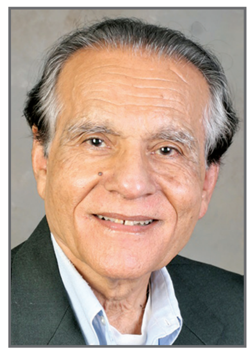

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ENR Releases TOP FIRMS Lists

Engineering News-Record released lists of top firms in various arenas. Following are the top ten design firms, and the top ten environmental firms based on reported income.

	Top 10 Design Firms	Top 10 Environmental Firms
1	Jacobs (Dallas, TX)	AECOM (Los Angeles, CA)
2	AECOM (Los Angeles, CA)	Jacobs (Dallas, TX)
3	KBR, Inc. (Houston, TX)	Tetra Tech, Inc. (Pasadena, CA)
4	Tetra Tech, Inc. (Pasadena, CA)	Bechtel (Reston, VA)
5	Wood (Houston, TX)	Mortenson (Minneapolis, MN)
6	HDR (Omaha, NE)	WSP (Montreal, QC, Canada)
7	WSP USA (New York, NY)	Webuild S.p.A (Milan, Italy)
8	Stantec, Inc. (Irvine, CA)	Stantec (Edmonton, AB, Canada)
9	Burns & McDonnell (Kansas City, MO)	HDR (Omaha, NE)
10	Gensler (Los Angeles, CA)	Garney Holding Co. (Kansas City, MO)

