Structural Design

design issues for structural engineers

¼ in 12 Design Slope and Water Drainage

Part 1

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Construction Science and Engineering, Inc., an architectural and engineering firm, has investigated several low slope roof applications with water stains, ponding, framing damage on the lower side of the roof span, and structural collapse. Further examination typically reveals a relatively level surface when compared to other roof locations (*Figure 1*). A similar occurrence is often found in exterior deck applications. (*Figure 2*). In studying this potentially problematic issue, two building code parameters were identified that contribute to low slope roof and deck serviceability issues. This article examines susceptible bays with respect to the ¼ in 12 design slope and code permitted deflection ratios. Part 2 will identify design and construction practices that contribute to serviceability issues.

Background

The 2015 *International Building Code* (IBC) identifies ponding instability as a design consideration for snow and rain loads. The 2010 edition of the *Minimum Design Loads for Buildings and Other Structures* (ASCE 7-10), referenced by the IBC, defines "ponding" as the "retention of water due solely to the deflection of relative flat roofs." The standard requires "susceptible bays" be investigated to ensure adequate member stiffness is present to prevent progressive deflection. Specifically, "Bays with a roof slope less than ¼ in./ft. …shall be designated as susceptible bays. Roof surfaces with a slope of at least ¼ inch per foot (1.19°) toward points of free drainage need not be considered a susceptible bay." The phrase "toward points of free drainage" is critical because it gives meaning to what is meant by a slope of ¼ inch per foot. The same principle may be applied to exterior decks, although decks are not specifically identified within ASCE 7-10.

Building designers routinely stipulate within construction documents the well-known code minimum ¼ in 12 design slope for low slope roofs and exterior deck applications. This practice, on the surface, appears to eliminate the code requirement to investigate a susceptible bay. Additionally, common practice is to specify or accept minimum building code deflection ratios for low slope applications. However, many building designers apparently fail to give due consideration to footnote "e" in IBC Table 1604.3 which states in part; "The above deflections do not ensure against ponding…"

A code defined deflection ratio is a function of the span and is therefore not influenced by material characteristics and design load variables. Each deflection ratio defines the deflection limits that are commonly approached as structural members are optimized for cost. Bender and Woeste recognized this relationship and showed a beam member installed to a ¼ in 12 slope that deflects to a code permitted deflection ratio results in an average slope less than ¼ in 12. They also noted the average slope is further reduced when a long-term creep deflection component is introduced.

The Bender and Woeste (2011) study validates the author's field observations for serviceability complaints and water retention associated with low slope roof and deck applications. The deflection curve was approximated using the properties of a circle to verify the average slope was independent of the span and remained unchanged for a specified deflection ratio. Additionally, the lower end of the deflection curve was noted to be relatively flat, which explained potential causes of observed ponding. In the author's company's study, surfaces with a design slope of ¼ inch per foot <u>or less</u> should be considered as a susceptible bay. Specifically:

1) The average slope of the deflected member is less than ¼ inch per foot; and,
2) At and near the lower reaction, the deflected member is relatively horizontal or flat.

Figure 1. Evidence of ponding on the roof.

Figure 2. Ponding water on deck.

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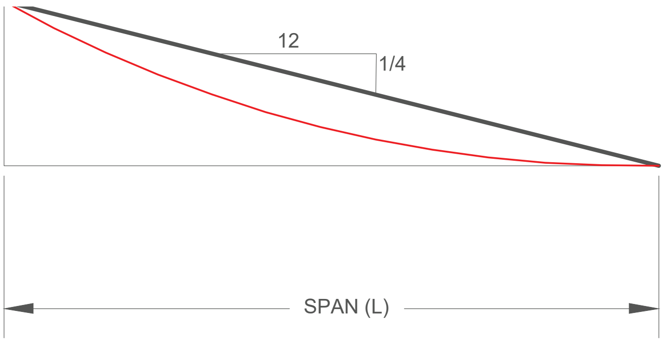

Figure 3. Deflected shape of beam with uniform load.

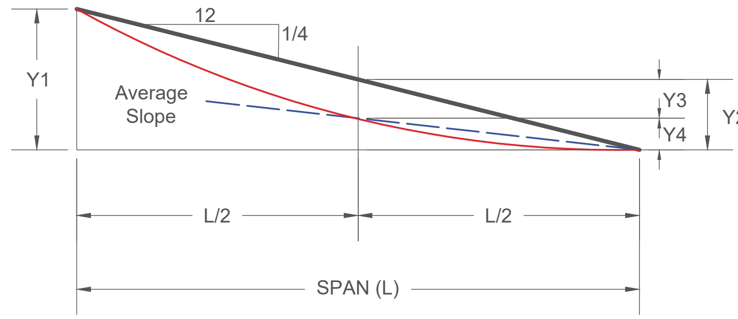

Figure 4. Average slope of deflected member

Figure 3 visually depicts the downward movement of a beam member subject to load and vulnerability to ponding at the low end.

Average Slope Example

The average slope for the performance of a member installed to a ¼ in 12 design slope and permitted to deflect to a code permitted L/180 ratio is illustrated by the following example:

- Member Span: 25 feet
- Roof Total Load Deflection Limit: L/180
- Right Support Datum Elevation: 0.00 inches
- Left Support Elevation: 6.25 inches (Y1)
- Midpoint Elevation: 3.13 inches (Y2)
- Member Total Load Deflection (L/180): 1.67 inches (Y3)
- Distance from datum to deflected member: 1.43 inches (Y4)

The "average slope" is the slope of a line from the low-end support to the point of maximum deflection for a member. For a simply supported beam member subjected to a uniform load, the average slope is from the center of the span to the low-end support. In this example, the right support is the low end and point of free drainage.

Figure 4 shows the original member slope and deflected shape. The distance from a level datum to the deflected member is $1\frac{7}{16}$ inches (Y4); the difference between the member's original position and code permitted deflection ratio at the mid-span. The average slope from the center of the member's deflected shape to the low-end support is 0.117 inches per foot, a slope less than ⅛ in 12 or nearly flat. When a member initially installed to a ¼ in 12 design slope deflects and approaches the total load L/180 code permitted deflection ratio, the average slope becomes less than ⅛ in 12. The calculated 0.117 in 12 average slope is constant for any span designed to the L/180 deflection ratio.

ASCE 7-10 explicitly identifies member stiffness as a means to control progressive deflection of a susceptible bay. Design professionals typically specify a more limiting deflection ratio than required by the building code for the application to achieve a stiffer member. As expected, the average slope approaches the ¼ in 12 design slope for a stiffer member or a higher deflection design ratio. However, a beam element subject to gravity load deflects, and the average slope remains less than the designed ¼ in 12 design slope. Therefore, a beam element installed with ¼ in 12 slope requires a "susceptible bay" analysis based on ASCE 7-10, since all members deflect under load.

Deflection Curve at the Lower End

The lower end of the deflection curve is also a typical location for ponding, water stains, and damaged framing members (*Figure 5*). This opinion is based on observations made during forensic investigations. The vertical difference between a ¼ in 12 plane and the L/180 deflection curve was calculated for spans of ten feet to forty feet in 2-foot increments. The deflected shape crosses the horizontal datum in the region of L/16, creating negative slope and a "bowl" at the low end. A "bowl" naturally retains water and restricts free drainage or water discharge. Ponding or water retention should be expected toward the low end of a plane designed to a ¼ in 12 slope.

Long-Term Creep Effects and Example

Structural materials susceptible to long-term creep intensify the deflection curve. The IBC estimates the creep component of long-term deflection to be half the immediate dead load deflection or a 1.5 factor. The creep deflection component may approach the initial dead load deflection, a 2.0 factor for wood products. The 2014 *Truss Plate Institute Standard* (TPI) recommends the 2.0 factor where the building designer does not specify adjustment factors for serviceability. The 1.5 building code factor was applied by the author for a "best case" scenario to study the effects of creep deflection.

Continuing the previous example, the initial dead load deflection is taken as the difference between the roof's total load (L/180) and roof's live load (L/240) deflection ratios. This calculates to 0.42 inches (1.67 – 1.25) for a 25-foot span. The long-term creep

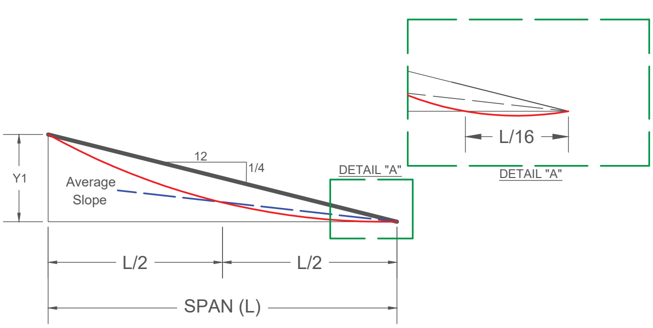

Figure 5. A typical location for ponding.

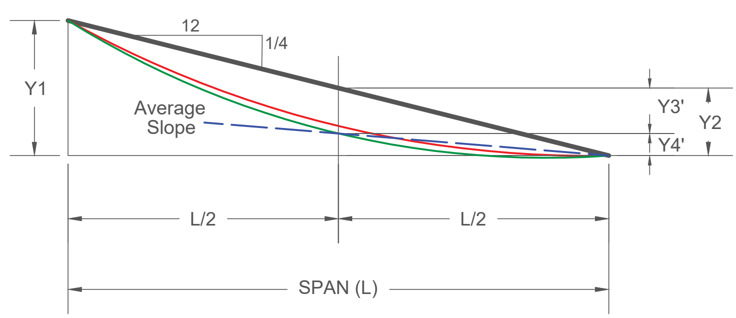

Figure 6. The average slope of the member with creep.

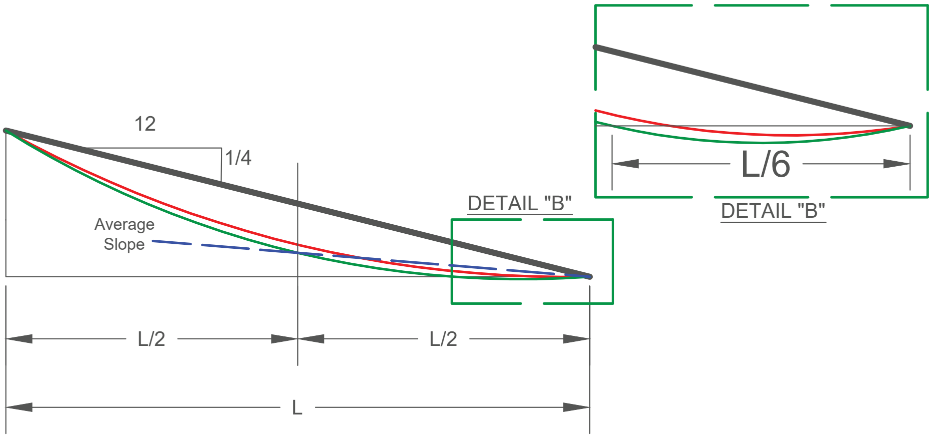

Figure 7. Increased "bowl" is caused by member creep.

component is 0.21 inches (½ * 0.42). The center of the deflected member is 1.25 inches (Y4′) above the right end support (3.13 – 1.67 – 0.21). The average slope from the center of the member deflection curve to the support is 0.10 inches, or essentially no slope, and remains constant for any span (*Figure 6, page 25*).

Although the average slope with a creep deflection component remains positive, albeit small, the low end of the member deflection curve remains of particular interest. The deflected shape crosses the horizontal datum in the region of L/6, creating a larger "bowl" area for ponding (*Figure 7*). As the dead load becomes a greater percentage of the total load, creep deflection increases and the "bowl" effect becomes more pronounced at the low end. It is imperative that deflection calculations include material long-term creep effects when compared to the ordinary live and total load code permitted deflection ratios.

Potential Design Solutions

Potential solutions to mitigate low slope serviceability issues are limited. ASCE 7-10 indirectly promotes a more stringent deflection ratio to prevent progressive deflection. The ASCE solution is imperfect because stiffer members increase the cost and the average slope remains less than ¼ in 12. A member or plane designed to an "average slope" of ¼ inch per foot is one method to mitigate ponding and resultant material damage. For a simply supported beam member subjected to a uniform load, the average slope line is from the point of maximum deflection at the center of the span to the low-end support.

A more practical solution is a combination of increased slope and member stiffness. Design tools currently available afford a quick and efficient means for a designer to calculate the average slope of a member; the "average slope" being the slope of a line from the low-end support to the point of maximum member deflection. A combination of increased member stiffness and design slope that results in a surface with an average slope of at least ¼ inch per foot towards points of free drainage should eliminate susceptible bays.

Summary and Conclusions

The building code establishes the minimum parameters for building design. A member or system that satisfies each code parameter may create a less than ideal condition when multiple minimum code parameters are combined. The combination of the ¼ inch per foot design slope and a maximum permitted deflection ratio creates such a condition for free drainage. The code, however, does recognize this potential condition in IBC Table 1604.3 footnote "e" and instructs a building designer to investigate applications with insufficient slope or camber for ponding.

Building designers, contractors, and perhaps code officials have come to believe a roof or exterior deck surface designed to the ¼ inch per foot slope is satisfactory because it meets building code intent. However, member deflection creates an average slope that limits free drainage and contributes to ponding toward the low end.

Members optimized to a code permitted deflection ratio further reduce the average slope and may create a negative slope or a "bowl" at the low end that limits or prevents free drainage. The condition is exacerbated for materials susceptible to creep deflection. Beam elements designed or installed to the ¼ inch per foot slope should be considered a susceptible bay.

In the absence of code performance limits for low slope roofs, a building designer should consider implementing a more stringent total load deflection ratio, increase the minimum slope for positive drainage, design to an "average slope" of ¼ in 12, or a combination of each. The practice should also be extended to decks.▪