LOW-SLOPE ROOFS

DESIGN SOLUTIONS FOR BUILDING CODE-PERMITTED LOW-SLOPE APPLICATIONS THAT CAUSE PONDING WATER.

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CHAPTER 15 IN THE 2015/2018 INTERNATIONAL BUILDING CODE (IBC) contains installation guidelines that permit a design slope of 1/4 in 12 for certain types of roof covers. Specifically, the code text typically reads, "…roofs shall have a design slope of not less than one-fourth unit vertical in 12 units horizontal (2 percent slope) for drainage." The stated and intended purpose of the code-specified 1/4 in 12 slope is to provide drainage; however, ponding water is often observed in these low-slope roofs. The standing water is a primary source of roof cover discoloration and deterioration that may result in framing member damage and contribute to premature failure of the structural system.

Additionally, building code deflection ratios fail to consider the short-term deflection that exacerbates the potential for ponding water. Therefore, the 1/4 in 12 code-permitted slope requires further investigation by the building design professional. The focus of this article is wood framing members; however, the principles presented are applicable to framing members of any material.

IBC and ASCE

The reason water ponds on a low-slope roof is a possible misinterpretation of the 1/4 in 12 minimum slope by the building code. Significant insight may be found in ASCE 7 Section 8.4 as referenced in IBC Section 1611.2. ASCE 7-10 (2015 IBC) attributes ponding water to the deflection of relative flat roofs and identifies a susceptible bay for ponding as a "roof slope" less than 1/4 in 12. ASCE 7-10 further clarifies, "Roof surfaces with a slope of at least 1/4 inch per foot (1.19º) towards points of free drainage need not be considered a susceptible bay."

ASCE 7-10 recognizes that relative flat roofs deflect when subjected to load. A structural member designed and installed to a 1/4 in 12 "design slope" deflects under the initial short-term dead load to create a roof surface (slope) less than 1/4 in 12. The 1/4 in 12 design slope is reduced more from live load and long-term dead load (creep) to exacerbate water retention. Therefore, a roof designed and installed to a 1/4 in 12 slope deflects downward and needs to be analyzed as a susceptible bay, according to ASCE 7-10.

ASCE 7-16 (2018 IBC) omits the ASCE 7-10 sentence that attributes ponding water to the deflection of flat roofs. However, ASCE 7-16 continues to identify a susceptible bay to include:

- "bays with a roof slope less than 1/4 inch per foot (1.19º) when the secondary members are perpendicular to the free drainage edge;" and
- "bays with a roof slope less than 1 inch per foot (4.76º) when the secondary members are parallel to the free drainage edge."

Secondary members are defined as structural members not having direct connection to the columns (e.g., joists, purlins, or rafters). Commentary for ASCE 7-16 Section 8.4 alludes to ponding from secondary member deflection and states the 1/4 in 12 limit is based on a maximum deflection-to-span ratio of L/240. The authors interpret the words "maximum deflection" to be total load that includes short-term and long-term deflection from dead load in addition to live-load deflection.

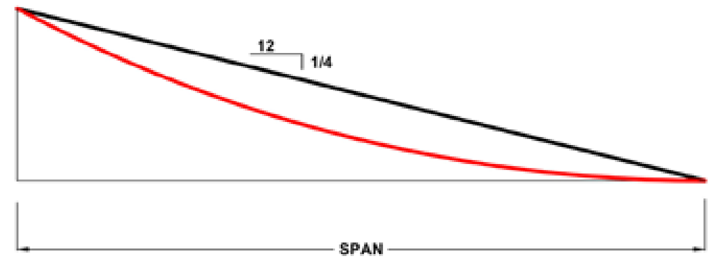

Figure 1: Wood members installed to a design slope of 1/4 in 12 often deflect from the initial dead load to create a "flat" area toward the low end.

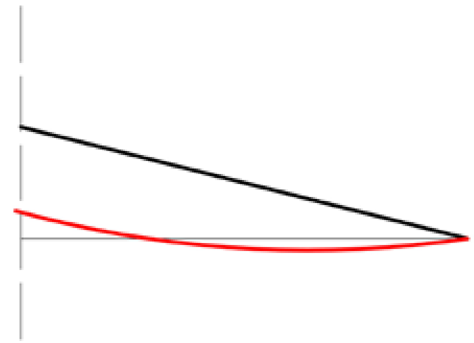

Figure 2: As the code-permitted L/120 or L/180 ratios are approached, the deflection curve extends below a horizontal datum to create a "bowl."

Therefore, framing members designed to a 1/4 in 12 slope should be analyzed for the total load at a minimum deflection ratio of L/240. This deflection criterion is more stringent than required by the IBC deflection table. However, footnotes to the IBC deflection table caution that the published deflections do not ensure against ponding. ASCE 7-10 and ASCE 7-16 recognize that structural members deflect and sufficient member stiffness is necessary to promote free drainage of a 1/4 in 12 design slope. Additionally, ASCE 7-16 requires a minimum 1 in 12 roof slope to promote free drainage for secondary members parallel to a free drainage edge. The 1 in 12 is significantly more than the commonly specified 1/4 in 12 and reflects the need of an increased slope to promote free drainage.

Analysis

There is a significant difference between "design slope" found in IBC Chapter 15 and "roof slope" used in ASCE 7. A specified design slope is absent of member deflection whereas the roof slope reflects the actual in-service deflection. The authors investigated the deflected shape of a member using the properties of a circle. The maximum midspan deflection was set to published code deflection ratios. This method is reasonable for wood since member design approaches published deflection ratios for economy.

Field observations and investigations by the authors have found wood

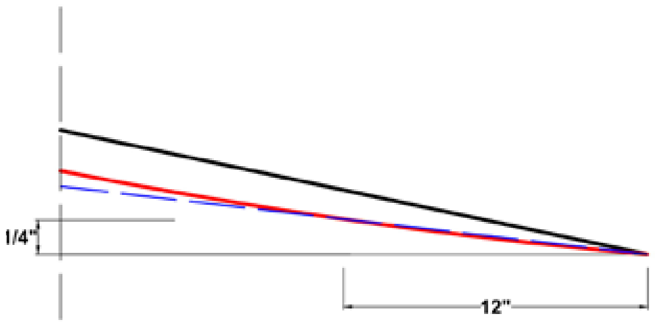

Figure 3: Increasing the code minimum 1/4 in 12 design slope to compensate for member total load deflection promotes free drainage and helps mitigate the potential for ponding by deflecting below a 1/4 in 12 surface.

members installed to a design slope of 1/4 in 12 often deflect from the initial dead load to create a "flat" area toward the low end (Figure 1). The relative "flat" region retards and/or prevents free drainage. As the code-permitted L/120 or L/180 ratios are approached, the deflection curve extends below a horizontal datum to create a "bowl" (Figure 2). (The same deflection principles apply to any material.) The bowl becomes more prominent for structural members that support roof-top units and/or for long-term deflection (creep). The authors found the bowl is eliminated for members designed to the ASCE 7-16 maximum deflection-to-span ratio of L/240. However, the deflection curve remains relatively flat (less than 1/4 in 12) for a distance of approximately L/6 to inhibit free drainage.

Additionally, deflection tables published by the IBC are limited to live load and a long-term deflection (creep) component. The omission of a short-term dead load deflection component combined with IBC published L/180 or L/120 ratios permit calculated deflection numbers to exceed the L/240 maximum found in the ASCE 7 commentary.

According to the AITC Timber Construction Manual (TCM), actual measurements of ponded water found the deflection curve to be more parabolic. The deflection at any point may be found from the equation:

$$\Delta_x = \Delta_{max} \sin \frac{\pi x}{L}$$

From this equation, the deflection curve does not extend below a level datum to create a bowl for the L/180 and stiffer ratio. However, the deflection curve remains relatively flat (less than 1/4 in 12) for a distance of approximately L/4, and this can inhibit free drainage. Therefore, water-retention/ponding can be expected for the commonly specified 1/4 in 12 design slope.

Solution 1: Increase design slope

Increasing the code minimum 1/4 in 12 design slope to compensate for member total load deflection will promote free drainage and help mitigate the potential for ponding by deflecting below a 1/4 in 12 surface (Figure 3). This approach is consistent with the 1 in 12 roof slope requirement found in ASCE 7-16. Table 1 summarizes the minimum design slope necessary to achieve a minimum 1/4 in 12 residual surface for common deflection ratios. The deflection ratios are for Total Load, which include short-term and long-term dead load in addition to the live load.

A precedence exists to increasing the minimum design slope to a value greater than 1/4 in 12 for drainage. The U.S. Department of Defense (DOD) published the Unified Facilities Criteria (UFC) for planning, design, and construction criteria for all DOD projects. The 2017 UFC Roofing section was updated to coordinate with the latest editions of the National Roofing Contractor's Association Roofing Manual and Metal Building Manufacturers Association Roofing manual to meet the latest DOD requirements.

UFC Section 2-3 pertains to low-slope roofing requirements and addresses minimum slope for positive drainage. Specifically, "The minimum slope for construction of new buildings is 1/2:12 to achieve positive drainage." The UFC requirement is consistent with the authors' belief that the 1/4 in 12 design slope found in the building code should be increased to provide free drainage of a roof surface. The 1/2 in 12 design slope is also consistent with the authors' findings for L/180 and stiffer deflection ratios.

Solution 2: Camber

The AITC TCM and National Design Standard for Metal Plate Connected Wood Truss Construction (TPI) recognize camber as a means to ensure adequate drainage. The building designer specifies the amount of camber to be fabricated into a structural component (e.g., glued laminated timber members and wood trusses) by introducing curvature, circular or parabolic, opposite to the anticipated deflection. For low-slope applications, the camber must be sufficient to mitigate the likelihood of a structural framing component to deflect below the 1/4 in 12 plane. Additionally, the camber is to promote free drainage. Minimum camber recommendations found in the AITC TCM for glued laminated timber beams in roof applications is 1.5 times the dead load deflection. The TPI commentary for Section 7.6.2 also recognizes a camber amount equal to 1.5 times the dead load due to deflection. Other proprietary wood truss products publish camber criteria as a function of dead load and live load. Extreme care is necessary when camber is specified, and an experienced wood design professional and/or fabricator should be consulted. In the absence of specific camber criteria, a minimum amount equal to 1.5 times the dead load deflection is recommended for roofs when a camber solution is desired.

T.L. Ratio	Slope in 12
L/120	0.75
L/180	0.625
L/240	0.5
L/360	0.5
L/480	0.375

Table 1: Design slope for residual 1/4 in 12 surface

Standing water is a primary source of roof cover discoloration and deterioration that may result in framing member damage and contribute to premature failure of the structural system on low-slope roofs.

Solution 3: Ponding design for a 1/4 in 12 design slope

The most effective method to prevent ponding is to provide adequate slope to achieve positive drainage. However, design constraints may exist that limit the design slope to 1/4 in 12 as permitted by the building code. When the 1/4 in 12 design slope is specified, a building designer should use an acceptable design method to ensure wood framing members have adequate strength and stiffness to mitigate potential ponding. For members without camber, an acceptable method is to increase calculated deflections and design stresses by a magnification factor for the wood member. The magnification factor, C_p, is:

$$C_p = \frac{1}{1 - W'L^3/\pi^4 EI}$$

Where:

W' = total load of 1 inch of water on the roof area supported by the member (pounds). One inch of water weighs approximately 5.2 pounds per square foot.

L = member span (inches)

E = modular of elasticity of the member (pounds per square inch)

I = moment of inertia of member (in^4)

The calculated design stresses are increased by C_p and compared to the published allowable stresses. Likewise, the calculated deflection is increased by C_p and compared to the total load deflection ratio. The wood component is acceptable for anticipated ponding loads if the design stresses and deflection values increased by C_p are less than allowable values. An abbreviated example for bending moment and deflection is shown for a sawn lumber member:

C_p =1.082
F_b = 750 psi
L/240 = 0.83

f_b = 659 psi x 1.082
= 713 psi < 750 psi (OK)

$\triangle_{TL}$ = 0.58 inches x 1.082
= 0.63 < 0.83 inches (OK)

The total load deflection ratio is limited to L/240 to be consistent with ASCE 7.

The magnification factor may also be applied to a wide range of proprietary engineered wood products such as structural composite lumber

(SCL) and prefabricated wood I-joists. The design shear and moment values are increased by the magnification factor and compared to the manufacturer's published allowable values. The calculated total load deflection is also increased by the magnification factor and compared to a total load deflection ratio of L/240 or stiffer.

Modulus of elasticity (E) adjustment

The values of "E" published in the National Design Specification for Wood Construction (NDS) are average values. All wood strength properties, including the modulus of elasticity, are variable expressed by the coefficient of variation, COV_E. The variations of the modulus of elasticity (E) for wood approaches a statistical normal distribution. Therefore, when a designer desires to estimate a lower value for "E" at some percentile of the total population, such as the fifth percentile, it may be calculated by the following equation:

$$E_{0.05} = E - 1.645\ E\ COV_E$$

Where:
$E_{0.05}$ = estimated "E" at lower fifth percentile (psi)
E = published modular of elasticity of the member (psi)
1.646 = statistical constant to determine values at the fifth percentile
COV_E = 0.25 for visual grade lumber; 0.15 for machine evaluated lumber (MEL); 0.11 for machine stress-rated (MSR), and 0.10 for glued laminated timber (NDS Appendix F)

For example, the NDS published "E" value for No. 2 Grade southern yellow pine lumber is 1,400,000 psi. Therefore, the $E_{0.05}$ is:

$$E_{0.05} = 1{,}400{,}000 - (1.645 \times 1{,}400{,}000 \times 0.25)$$
$$= 824{,}250 \text{ psi}$$

This variation of "E" should be considered by a building designer when specifying a design slope of 1/4 in 12 because members with a lower "E" will deflect more. The $E_{0.05}$ is appropriate to calculate the magnification factor, C_p, and deflection of wood truss members with a 1/4 in 12 design slope. The $E_{0.05}$ is the average of the top chord and bottom chord lumber in wood truss design.

Recommendations

The intent of the IBC and ASCE 7 is to provide adequate slope for drainage and to mitigate ponding. The authors recommend that design professionals consider the following design slopes to be specified for nearly flat, low-slope applications:

- Roofs — 1/2 in 12 and a total load deflection of L/180 and stiffer.
- Exterior balcony — 3/8 in 12 and a total load deflection of L/480 and stiffer.

When design constraints necessitate a 1/4 in 12 design slope be used, the framing members should be cambered or investigated for ponding. A building designer should reference wood industry standards or contact the product fabricator when specifying camber to prevent ponding. As previously noted, only products such as glued laminated timber and metal plate connected wood trusses can be cambered. The minimum recommended camber for roofs is an amount equal to 1.5 times the dead load deflection.

Design stresses and deflection should be increased by a magnification factor for wood members that are not cambered, such as sawn lumber and timbers. The increased design stresses are to be less than the published values and the increased deflection value is compared to the L/240 ratio consistent with ASCE 7. A similar approach may be used for proprietary products such as SCL and prefabricated wood I-joists by increasing the design moments and shears by the magnification factor and comparing them to allowable values published by the manufacturer.

The designer should increase the stiffness of wood trusses designed without camber for a 1/4 in 12 slope. The $E_{0.05}$ is determined for the truss chord material and used in the deflection analysis. The calculated deflection is compared to L/240 or stiffer ratio.

Conclusion

Building designers routinely stipulate a 1/4 in 12 design slope for roofs and exterior balconies. This practice, on the surface, appears to satisfy the IBC requirement for drainage and eliminate special analysis for ponding. However, ASCE 7 indicates a 1/4 in 12 roof surface is necessary for free drainage and to mitigate ponding. The need to consider member deflection is the subtle difference between "design slope" and "roof slope." A member designed to a 1/4 in 12 design slope deflects when subjected to load that creates a surface less than 1/4 in 12. This is considered to be a primary reason roof and balcony surfaces fail to drain and ponding is often observed.

The most effective method to minimize the effects of ponding is to increase the recommended minimum design slope to 1/2 in 12 for roof applications and 3/8 in 12 slope for floor applications. The total load deflection limit is L/180 and L/480 for the roof and floor, respectively. The increased slope for drainage mitigates ponding and helps prolong the lifespan of the roof cover. When a 1/4 in 12 design slope is a design constraint, using camber or increased member stiffness and stresses should be considered using acceptable wood industry methods. Additionally, the total load deflection ratio of L/240 or stiffer should be used for secondary wood members installed to a 1/4 in 12 design slope to meet ASCE 7 criteria.

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