Structural Technical Appendix for Residential Rooftop Solar Installations

(Appendix to California's Solar Permitting Guidebook's Toolkit Structural Document, based on the 2013 California Residential Code and 2013 California Building Code)

GOVERNOR'S OFFICE OF PLANNING AND RESEARCH
STATE OF CALIFORNIA

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Table of Contents

Introduction **4**
Overall Intent 4
Criteria for Expedited Permitting are not Limits for other Systems 4
Background/History 4
Purpose of the Structural Technical Appendix 5
Code Basis 5
California Residential Code (CRC) versus California Building Code (CBC) *5*
Design Wind Speeds in CRC versus CBC *5*
Organization of the Remainder of this Technical Appendix 6
Part 0. Region and Site Checks **8**
Assumptions Regarding Snow and Wind Loads 8
Optional Additional Site Checks in Atypical Regions 9
Part 1. Roof Checks **15**
Code Compliant Wood-framed Roof 15
1.A. Visual Review 15
Site Auditor Qualifications *15*
Digital Photo Documentation *16*
1.A.(1). No Reroof Overlays *16*
1.A.(2). No Significant Structural Deterioration or Sagging *17*
1.B. Roof Structure Data: 18
1.B.+ Optional Additional Rafter Span Check Criteria 18
Choose By Advantage *19*
Horizontal Rafter Span Check *20*
Prescriptive Rafter Strengthening Strategies *21*
Roof Mean Height 22
Part 2. Solar Array Checks **24**
2.A. "Flush-Mounted" Rooftop Solar Arrays 24
2.B. Solar Array Self-Weight 24
2.C. Solar Array Covers No More than Half the Total Roof Area 27
2.D. Solar Support Component Manufacturer's Guidelines 27
2.E. Roof Plan of Module and Anchor Layout 27
2.F. Accounting for Concentrated Loads Acting Downward 27
2.F.1. Roof Live Load *28*
2.F.2. Concentrated Load Sharing (Load Redistribution) Between Rafters: *28*
2.F.2.1. Further Refinements to the Model *38*
2.F.3. Distinction Between Concentrated Load Sharing Factor and Repetitive Member Factor *38*

2.F.4. Calculating Demand/Capacity Ratios (DCRs) *40*
2.F.4.1. Additional Reserve Strength *43*
2.F.4.2 Summary Tables *44*
2.F.4.3 Summary Graphs *60*
2.F.5. Statistical Analysis of the Conservatism of EBGC and State Assumptions *69*
2.G. Wind Uplift Checks 75
2.G.1. Alternative Tables in Lieu of Manufacturer's Guidelines *75*
2.G.2. Distance to Edge of Roof Requirements *79*
Part 3. Unusual Wind Conditions **81**
3.1 Typical "Exposure B" Conditions 81
3.2 Nearshore "Exposure D" Conditions 81
3.3 Topographic Effects Equivalent to Exposures C and D 81
Part 4. Frequently Asked Questions **84**
4.1 Wood Allowable Stress Code Changes 84
4.2 Seismic Roof Mass 84
4.3 Asymmetric Loading 85
Part 5. Applicability to Other Regions of California and United States **86**
5.1 High Snow and Wind Load Regions 86
5.2 Comparison with the Solar ABCs 86
5.3 City of Los Angeles Expedited Solar Permitting and Similar Ordinances 87
Part 6. Research Topics **88**
6.1 Wind Uplift 88
6.2 Dynamic Resonance 89
6.3 Wood-Framed Residential Roof Downward Load Capacity 89
6.4 Manufactured Plated Wood Trusses 89
6.5 Lag Screw Edge Distance Under Seismic Loads 89
Part 7. References **91**
Part 8. Contacts and Acknowledgements **93**
8.1 Contacts 93
8.2 Acknowledgements 94
Original East Bay Green Corridor Document *94*
2013 CBC Update *95*
2014 California Solar Permitting Guidebook's Toolkit Structural Document *95*

Introduction

Overall Intent

The impetus to clarify and simplify residential solar structural permitting is threefold:

- Code officials aren't sure if the proposed solar installation will be structurally sound,
- Contractors and home owners don't want the added cost of unneeded structural engineering,
- Solar support components manufacturers provide design assurance for the array above the roof, but usually leave it to others to determine if the roof framing can support the array.

The Toolkit's Structural Criteria are valuable to the public, to the solar industry and to code officials for several reasons:

- It increases code officials' confidence that structural safety issues have been appropriately addressed,
- It decreases the percentage of projects where costly custom structural engineering is required,
- It reduces the uncertainty about permitting/engineering costs for solar installers, and
- It enables a rapid permit approval process, either over-the-counter or over-the-web, for many solar installations.

Criteria for Expedited Permitting are not Limits for other Systems

The purpose of the State Solar Permitting Guidebook's Toolkit Structural Document is to provide a process for expedited structural permitting, where appropriate, based on existing structural codes. The Toolkit document should never be misconstrued as setting "code limits" on residential rooftop solar installations. The Toolkit Structural Document is based on a series of conservative assumptions to apply over a wide range of conditions. Where structural analysis by a California-licensed Civil or Structural Engineer indicates that criteria limits can be exceeded and still meet code, such systems should be allowed and permitted. Examples of Toolkit Structural criteria that should not be considered absolute limits include, but are not limited to, panel weight, anchor spacing, tilted arrays, and arrays in high snow or wind load regions.

Background/History

California's Solar Permitting Guidebook Toolkit Structural Document is based on an earlier expedited permitting initiative by the East Bay Green Corridor. The East Bay Green Corridor's

Rapid PV Permitting Guidelines were adopted in 2013 by nine contiguous cities along the east side of San Francisco Bay, extending from Hayward in the south to Richmond in the north. Those guidelines included explicit guidance about how to reasonably interpret and apply the structural requirements the California Residential and Building Codes. The first edition (2012) of the California Solar Permitting Guidebook did not include such detailed structural guidance, and so under the leadership of the Governor's Office of Planning and Research, the advice of its task force on solar permitting, and the assistance of the Center for Sustainable Energy, the planners of the second edition decided to incorporate more structural information, based on the East Bay Green Corridor's model. The effort was funded through the US Department of Energy's Sunshot Initiative, with significant volunteer contributions from task force members and stakeholders. In evolving from the East Bay Green Corridor to a statewide initiative, the structural guidelines have been expanded to apply to most areas of California, and to apply to solar thermal systems as well as photovoltaic systems. Originally based on the 2010 California Residential and Building Codes, the structural guidelines have also been updated to conform to the 2013 California Residential and Building Codes.

Purpose of the Structural Technical Appendix

The Structural Technical Appendix provides the technical analysis and commentary that supports the California Solar Permitting Guidebook's Toolkit Document, *Structural Criteria for Residential Rooftop Solar Energy Installations*. This Technical Appendix describes the structural engineering principles and assumptions behind the Toolkit Document, and delineates how the document conforms to the California Residential Code and California Building Code. This Technical Appendix also discusses options that jurisdictions and Chief Building Officials may want to consider in implementing Toolkit Document. Finally, this Technical Appendix offers additional guidance to address some non-conforming items, such as when an anchor layout is not based on a solar support component manufacturer's guidelines, or when a dwelling is located within 200 yards of the ocean (Wind Exposure D).

Code Basis

California Residential Code (CRC) versus California Building Code (CBC): One- and two-family dwellings fall under the jurisdiction of the 2013 California Residential Code (2013 CRC), instead of the California Building Code (2013 CBC). Regarding structural requirements for wood-framed roofs, the requirements of the two codes are virtually identical. For instance, the roof rafter span tables governing conventional wood-framed construction in the two codes are identical.

Design Wind Speeds in CRC versus CBC: One area of potential confusion between the two codes is design wind speed. Both the CRC and the CBC reference ASCE 7-10, Minimum Design Loads for Buildings and Other Structures. ASCE 7-10 introduced changes to the way design wind speeds are defined and associated wind pressures are calculated. For California under the old ASCE 7-05 / CBC 2010, the basic design wind speed in most regions of the state (and all of the East Bay Green Corridor) was 85 mph, representing the highest expected 3-second gust in a 50

year period. Under ASCE 7-10 / CBC 2013, the design wind speed has increased to 110 mph, representing the highest expected 3-second gust in a 700 year period.

Despite these very different design wind speeds, the actual design wind pressure (i.e., the predicted maximum load applied to the structure) remains unchanged in California. Hurricane-prone regions of the gulf coast and east coast of the United States have more significant changes in this latest code cycle, but even there the changes in wind pressure are on the order of 10 to 15%. The procedure for determining the wind pressures have changed, but the end result has not. ASCE 7-10 Table C26.5-6 shows that California's 85 mph design wind speed under ASCE 7-05 is equivalent to California's 110 mph design wind speed under ASCE 7-10.

While the wind speed maps and tables in the 2013 CBC were updated to show the 110 mph, the wind speed maps and tables in the 2013 CRC still show the outdated ASCE 7-05 values of 85 mph. We anticipate that the CRC will be corrected to show wind speeds consistent with ASCE 7-10. It is not clear whether this correction will occur as an amendment to the 2013 CRC, or will occur at the next code cycle, in the 2016 CRC.

Because the Toolkit's structural document is intended to be forward looking, all wind speeds in the Toolkit document are based on the ASCE 7-10. This is clearly stated in the caption to the state wind speed map, and in the Table 1 footnotes. This anticipates an obvious and expected code correction; otherwise the Toolkit would become immediately outdated when the CRC is amended to change 85 mph to 110 mph.

Organization of the Remainder of this Technical Appendix

The remainder of this Technical Appendix is organized into three major parts that follow the order of the Structural Criteria items. They are:

<u>0. Region and Site Checks</u> are listed as number zero because, in most instances, it is the jurisdiction (not the applicant) that makes the region and site checks, determines whether most of its housing stock is located within standard wind and snow load limitations, and decides to implement the standard structural criteria in its expedited solar permitting process. A few jurisdictions will have at least some areas that fall outside of the standard wind and snow load limits, but can still apply the structural criteria if it adds additional items for the applicant to check.

<u>1. Roof Checks</u> are made to verify that the roof structure generally meets structural code requirements at the time it was built, and remains in acceptable structural condition. This check is made because the solar array checks are based on the underlying assumption that the roof is code compliant.

<u>2. Solar Array Checks</u> are made to verify that specific aspects of the solar array meet criteria that ensures structural code compliance. These aspects include overall geometry, weight limits, anchor layout, and compliance with support component manufacturers' recommendations.

Various discussion and research topics, plus references and acknowledgements, are located at the end of this document. They include:

3. Unusual Wind Conditions
4. Frequently Asked Questions
5. Applicability to Other Regions of California and the United States
6. References
7. Contacts and Acknowledgements

Part 0. Region and Site Checks

The structural analysis behind the criteria checks, particularly Table 1's maximum horizontal/east-west spacing for anchors/feet/mounts/stand-offs/attachment points, are based on several key assumptions discussed below.

Assumptions Regarding Snow and Wind Loads

The Toolkit's structural document is based on several assumptions about wind and snow loads. While these assumptions are valid for the great majority of densely and moderately populated areas in California, each jurisdiction and Chief Building Official (CBO) will want to review them.

The majority of California has a design wind speed of 110 mph (3 second gust in 700 years per ASCE 7-10), which is the lowest design wind speed tier in the United States. There are special wind regions in California where higher design wind speeds are required, such as those subject to Santa Ana winds in the Inland Empire.

Likewise, most of California's residents live in zero snow load regions. High elevation areas such as Lake Tahoe are the exception, where high snow loads can occur.

The region and site environmental assumptions are:

- The dwelling is located in a ZERO snow load area (see Map 1).
- The dwelling is not in Wind Exposure D (within 200 yards of the ocean or a large coastal bay).
- If in Wind Exposure B (urban, suburban or wooded areas), the dwelling may be located:
  - in a Special Wind Region (see Maps 2, 3a and 3b) with design wind speeds over 110 mph and less than 135mph, or
  - on a tall hill, provided average slope is no steeper than 15%.
- If in Wind Exposure C (within 500 yards of large open fields or grasslands), the dwelling is:
  - in a standard 110 mph design wind speed region, and
  - not on a hill with a grade steeper than 5%.

The snow and wind load restrictions are needed to ensure that the Table 1 horizontal spacing limits can be applied to the anchors/feet/mounts/stand-offs/attachment points for flush-mounted solar arrays. The purpose of these horizontal spacing limits is to control the concentrated loads imposed on individual rafters, as discussed in greater detail in the "Roof Checks" section.

Most dwellings in many jurisdictions will be in the Wind Exposure B category, that is, dwellings within typical urban, suburban or wooded areas. If located in Wind Exposure B, then

allowances can be made to include (1) special wind regions with wind speeds up to and including 130 mph, or (2) to include dwellings within a 110 mph region that are located on the top half of tall hills where wind speed-up effects occur. Both of these allowances account for 40% greater wind forces than Exposure B, 110 mph. While a 40% increase covers many topographic (hill wind speed-up) effects, very steep hills with average grades steeper than 15% can have even greater effects, hence the limit on average grade.

Jurisdictions with large open fields or grasslands, or with coastal areas (with transition zones between Exposures B and D), may have a significant number of dwellings within Exposure C. Table 1 is still valid in Exposure C, provided (1) the region is in the standard 110 mph design wind speed area (i.e. not in a special wind region), and (2) the dwellings are not on hills with average grades steeper than 5% (i.e. no significant topographic wind speed-up effects).

Optional Additional Site Checks in Atypical Regions

In jurisdictions with non-zero snow loads at higher elevations, or with significant areas of Exposure C or Exposure D, or with significant hilly areas, the Chief Building Official may consider adding additional checks at the beginning of the document, with questions such as:

Optional Additional Site Checks in Atypical Regions

[At option of CBO, insert rows above the Roof Check section of the Structural Criteria]

0. Site Checks

A. Snow Loads:
[for jurisdictions with zero snow loads at low elevations, and nonzero loads at higher elevations]

(1) Is the dwelling located below elevation ____ feet (in zero snow load area)? ❑Y ❑N

B. Coastal Wind Exposure Check:
[for jurisdictions with significant numbers of dwellings fronting the ocean or large coastal bays]

(1) Is the dwelling farther than 200 yards from the ocean or a large bay? ❑Y ❑N

(2) If the dwelling is between 200 & 500 yards from the ocean or a large bay, is the grade between dwelling and shore relatively flat (less than 5% grade)? ❑Y ❑N

C. Wind Exposure Checks for Special Wind Regions (115 - 130mph):
[for jurisdictions within Special Wind Regions with design wind speeds between and including 115 to 130 mph, per ASCE 7-10]

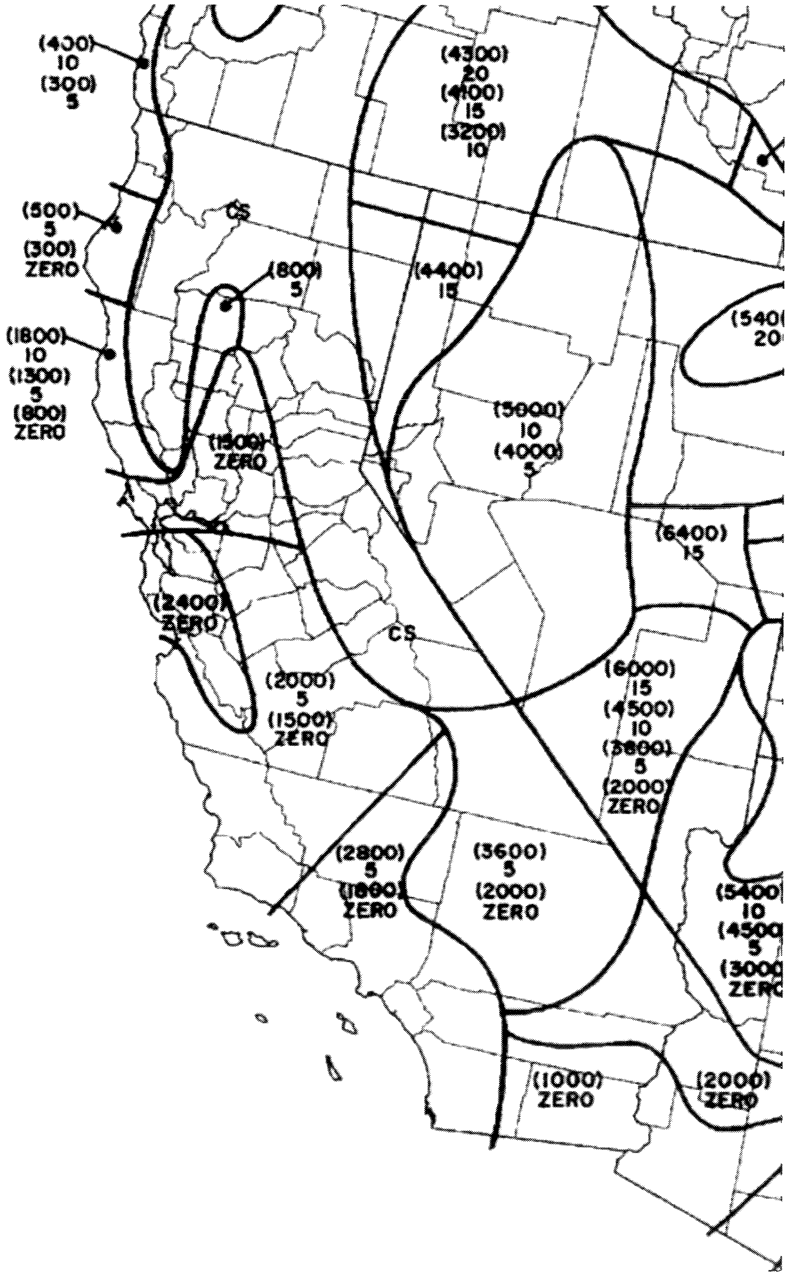
(1) Is the dwelling farther than 500 yards from large open fields or grasslands? ❑Y ❑N

(2) Is the dwelling in a relatively flat area (grade less than 5%) and not within 500 yards of the crest of a tall hill? ❑Y ❑N

D. Steep Hill Wind Exposure Check:
[for jurisdictions with significant numbers of dwellings on the top half of very steep hills with average grades greater than 15%]

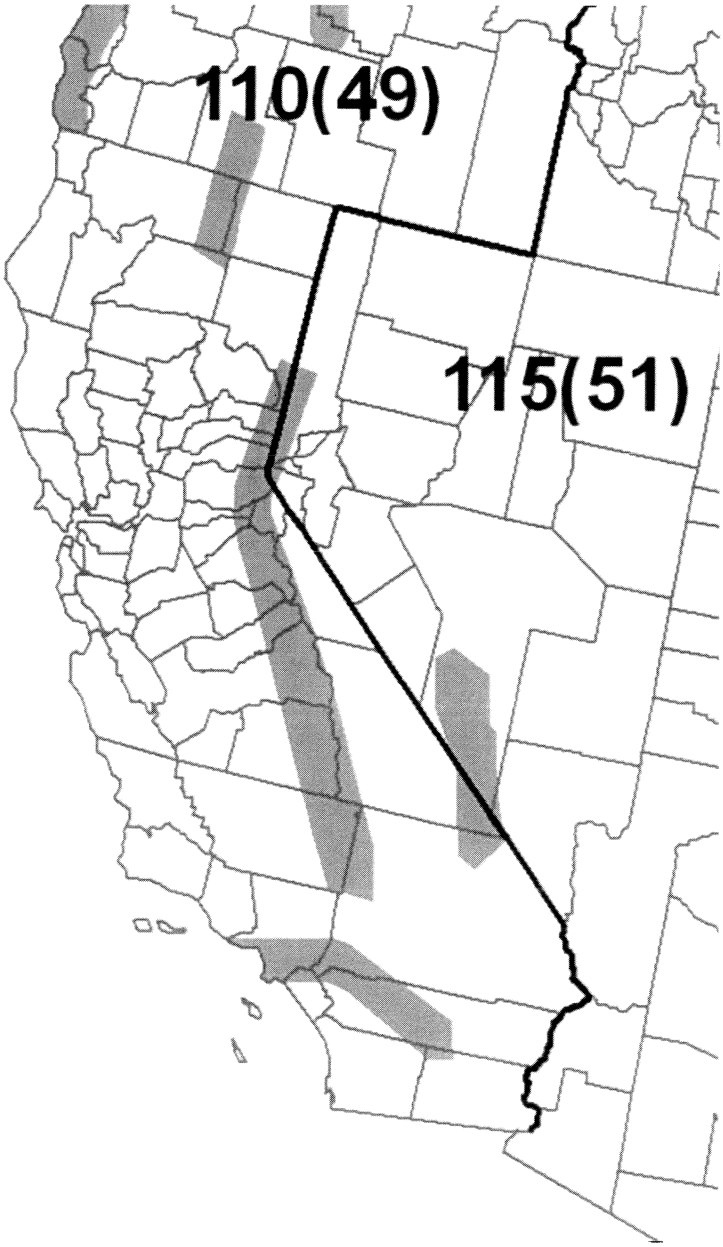
(1) Is the dwelling NOT on the top half of a very steep hill (average grade more than 15%), and NOT within 500 yards of the crest of such a hill? ❑Y ❑N

Later sections of this document provide guidance for some unusual cases, such as Wind Exposure D.



Map 1. California Ground Snow Load Map (Ref: ASCE 7-10).

The numbers in parentheses represent the upper elevation limits in feet for the ground snow load in psf listed below the elevation. Example: (2400) ZERO in the South San Francisco bay area indicates that zero ground snow loads occur from sea level up to an elevation of 2400 feet. CS indicates "Case Studies" where extreme local variations in ground snow loads occur. Non-zero snow load areas and Case Study (CS) areas are excluded from the use of this structural toolkit document.



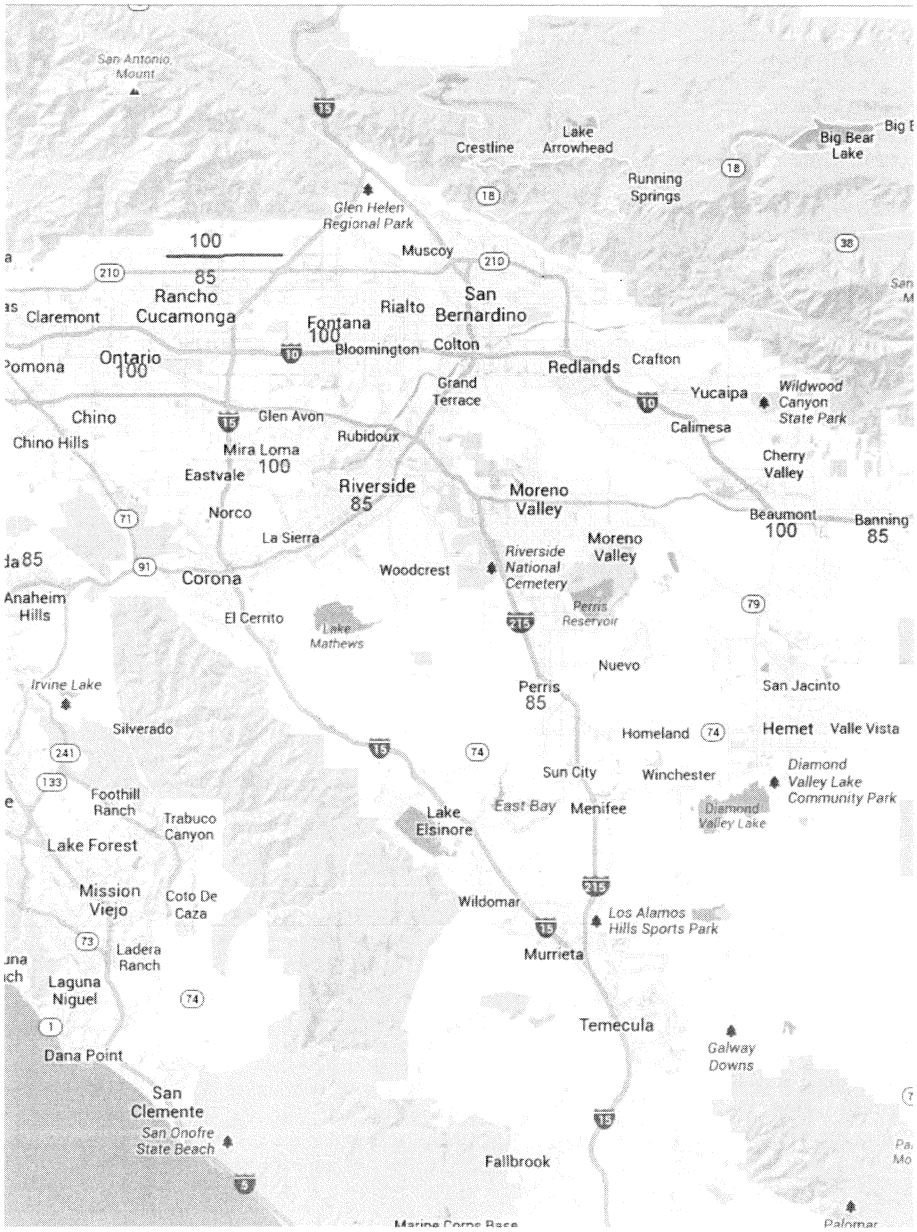
Map 2. Design Wind Speed Map (Ref: ASCE 7-10).

The number outside the parentheses represents the design wind speed in mph. Typical design wind speed is 110 mph per ASCE 7-10 and the 2013 California Building Code. See discussion under "Wind Speed in CRC versus CBC" for how the 85 mph under the CRC is equivalent to 110 mph under the CBC. The grey shaded areas on the map indicate "special wind regions" where higher wind speeds may apply. When the dwelling is in a grey shaded area, contact the local building department for the design wind speed.

Special Wind Regions

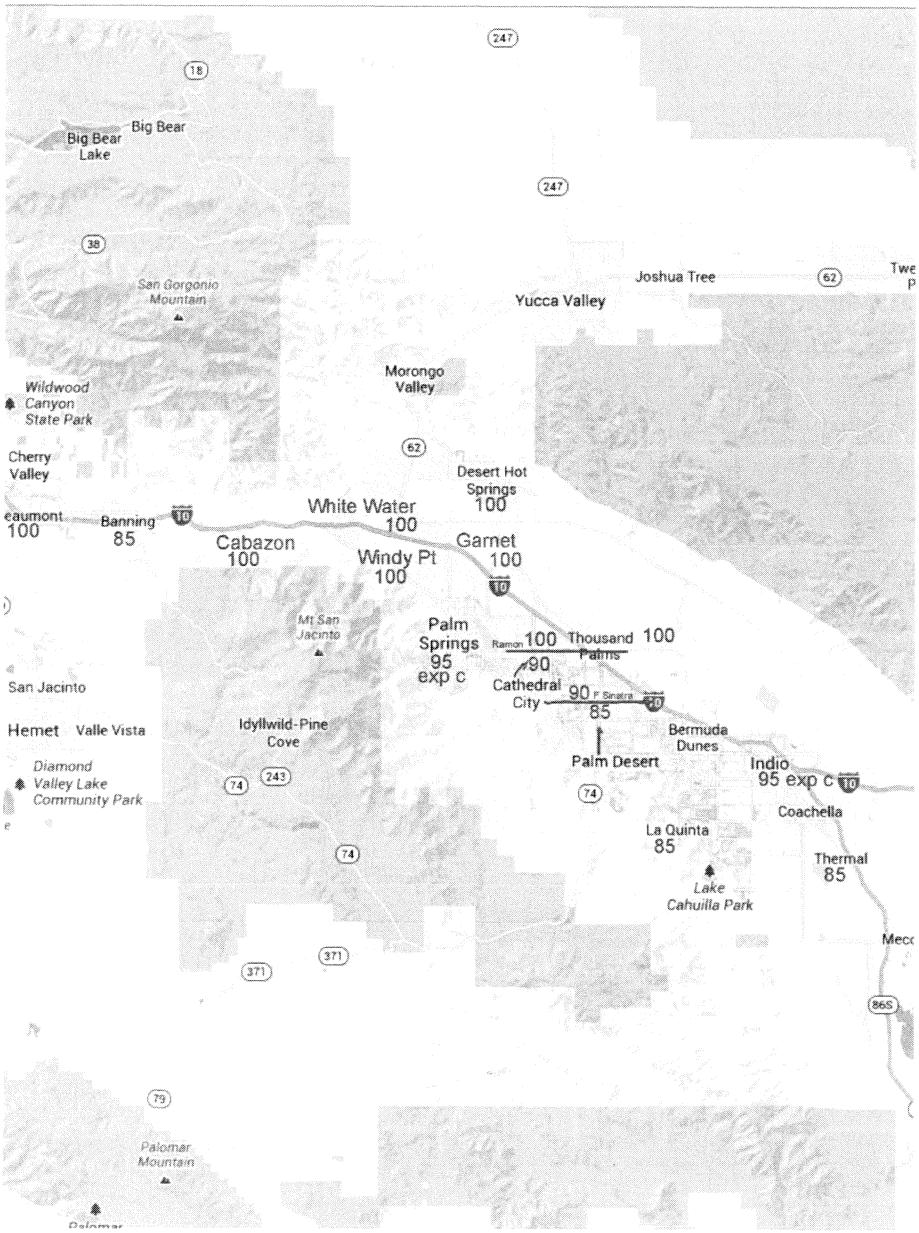
Map 2 only shows a general overview of where special wind regions may occur; local jurisdictions in these areas define the design wind speed for their jurisdiction. James Lai, Chair of the Structural Engineers Association of California (SEAOC) Wind Committee, is currently querying all jurisdictions in these areas to assemble a tabulated summary of locally required design wind speeds. Maps 3a and 3b show an earlier effort by the Division of the State Architect to show wind speeds for the Inland Empire special wind region of southern California. The design wind speeds on Maps 3a and 3b are based on the previous 2005 edition of ASCE 7, so the typical base wind speed is 85 mph instead of 110 mph. ASCE 7-05 equivalencies to ASCE 7-10 wind speeds are as follows. See ASCE 7-10 Table C26.5-6 for additional information.

ASCE 7-05	ASCE 7-10
85 mph	110 mph
90 mph	115 mph
95 mph	120 mph
100 mph	126 mph
105 mph	133 mph



Map 3. Design wind speeds for the west part of California's Inland Empire.

Wind speeds shown are based on the earlier ASCE 7-05. California's typical wind speed of 85 mph on this map equals 110 mph under ASCE 7-10. Other ASCE 7-05/ 7-10 equivalencies are 90 mph = 115 mph, 95 mph = 120 mph, and 100 mph = 126 mph.



Map 4. Design wind speeds for the east part of California's Inland Empire.

Wind speeds shown are based on the earlier ASCE 7-05. California's typical wind speed of 85 mph on this map equals 110 mph under ASCE 7-10. Other ASCE 7-05/ 7-10 equivalencies are 90 mph = 115 mph, 95 mph = 120 mph, and 100 mph = 126 mph.

Part 1. Roof Checks

Code Compliant Wood-framed Roof

The structural analysis behind the roof structural checks assumes that the residential buildings under consideration are wood-framed, with the resilience and robustness associated with wood-framing. In principle the analysis could be extended to metal-framed roofs, but key factors such as the concentrated load sharing factor (C_{LSF}) would need to be recalibrated and adjusted for metal framing.

The analysis also assumes that the wood-framed roof was designed to comply with the building code in effect at the time it was built. Building codes as far back as the early 1900s have required that roofs be designed to carry temporary construction loads termed "Roof Live Loads". Flush-mounted solar arrays are assumed to displace roof live loads, since piling bundles of shingles or other building materials on solar panels could scratch or damage the panels, and perhaps also slide off. Because the roof was designed for roof live load, where such loads cannot be placed, the roof has reserve load carrying capacity to support solar panels.

The major purpose of the Roof Check is to verify that it is reasonable to assume the existing roof is structurally code compliant.

1.A. Visual Review

A site audit by the Contractor is required to verify that the original structure is not carrying added loads (roof overlays), and has not been significantly weakened or compromised, with no significant decay, fire damage, or structural modifications (such as removal of web members from carpenter trusses). Figure 1 of the Structural Criteria (and Figure A1.1 of this document) illustrates the items to be visually reviewed.

Site Auditor Qualifications: The Permitting Subcommittee of the Structural Engineers Association of California (SEAOC) Solar PV Committee discussed whether site auditors should be required to have special training or certification. The group agreed that it was critical for site auditors to be properly trained, with sufficient understanding of roof framing to recognize unusual noncompliant conditions. The group disagreed about whether special licensing or certification other than a standard C46 Solar Specialty Contractor's license should be required for site auditors to ensure some knowledge of roof structural systems. Some members suggested that site auditors should hold a General Building Contractor's B license; others suggested North American Board of Certified Energy Practitioners (NABCEP) certification. The majority of the subcommittee believed that requiring site auditors to have special certification was onerous. While site auditors trained by, and working under, an installer with C46 licensure is implicitly considered sufficient in the Structural Criteria, most subcommittee members believed that proper training of site auditors is essential.

Digital Photo Documentation: There was consensus among the SEAOC Solar Permitting Subcommittee that digital photo documentation constituted best practice when conducting site audits. This allows more experienced staff to review field photos, and even experienced installers/auditors benefit from having photographs to refer to later. A cell phone or other small digital camera, used with a tape measure set alongside roof members, can readily document rafter depth, width, spacing, slope and span.

Some subcommittee members believed digital photographs were so important to ensuring quality site audits that such photos should be required as part of the Structural Criteria permit submittal package. Most of the subcommittee believed that requiring photographs would make the permitting process more onerous, and that imposing such quality control measures should be at the discretion of the local jurisdiction's Chief Building Official. Some jurisdictions, especially those that require horizontal span table checks (see next section), may want to consider adding a row in the Roof Checks section that asks:

Are at least 7 digital photos attached, showing overall roof from interior and exterior, as well as rafter depth, width, spacing, slope and span? (set tape measure alongside roof framing members) ❑Y ❑N

1.A.(1). No Reroof Overlays: The existing roof shall not have a reroof overlay, for the following reasons:

- To avoid "double-loading" the roof with both solar modules and a roof overlay.
- To avoid adding so much mass to the roof from both solar arrays and reroof overlays that top story seismic loads increase by more than 10%, triggering seismic evaluation and potentially seismic strengthening per 2013 CBC Chapter 34.
- To maintain the water tightness reliability of many types of anchors/stand-offs/feet/mounts/attachment points.
- To avoid costly reroofing during the service life of the solar array. Because roof overlays often have a remaining expected service life shorter than a new solar array, placing modules over a roof overlay may be unwise because of the likelihood that the roof will need to be replaced before the twenty-year or longer service life of the solar array. Replacing a roof during the service life of a solar array can be a costly unnecessary expense.
- To avoid reductions in lag screw capacity. A roof overlay creates a significantly thicker roofing assembly, forcing lag screw anchors to cantilever farther from the rafters. This can also reduce lag screw embedment. Both effects can reduce anchor shear and withdrawal capacities.

Recent and current building codes allow one asphalt composition reroof over an existing asphalt composition roof on a building of any vintage without requiring structural calculations. Previously, from 1979 through 1994, two reroofs over the original roof were explicitly allowed

(UBC 1979 Appendix Chapter 32 "Reroofing" through UBC 1994 Appendix Chapter 15 "Reroofing"). One reroof over the original roof has been explicitly allowed for all vintage buildings since 1997 (UBC 1997 Appendix Chapter 15 "Reroofing" through CBC 2013 Chapter 15, Article 1510 "Reroofing"). The last two editions of the code have added the proviso that reroofing is allowed provided that the roof structure is sufficient to carry the reroof overlay. Many code officials allow reroof overlays without requiring calculations showing sufficient lateral strength, since structural overload problems from reroof overlays are very rare.

According to a year 2000 technical brief by Tom Bollnow, Director of Technical Services for the National Roofing Contractors Association, typical 30-year asphalt roofs (or added reroofs) weigh up to 3.25 psf, 40-year asphalt roofs up to 3.85 psf, and lifetime roofs up to 4.25 psf (ref: http://www.professionalroofing. net/archives/past/july00/qa.asp). The historical experience that wood shingle and composition shingle reroof overlays seldom cause structural problems, along with the recent and current building codes' implicit allowance of the added dead load weight of a reroof, which can weigh up to 4 psf, can be used to justify the added weight of an equivalent solar array, so long as the solar array uniformly loads the roof by being anchored to *every* rafter (or anchored to every other rafter in a staggered row-to-row pattern). Note that unlike sloping wood shingle and composition shingle reroofs, excessive built-up reroofing overlays on flat roofs is a relatively common problem that sometimes results in problematic structural overloading.

Reroof overlays can increase seismic loads significantly. The increase in inertial mass (and subsequent shears at the top story) might be 3 psf / 25 psf = 12%, which exceeds the 2013 CBC Chapter 34 limit of no more than 10% increase in seismic loads before seismic re-valuation and potential seismic strengthening is required. Note that the denominator includes the weight of the roof, ceiling and top half of the walls of a one-story building. For multistory buildings, the code static-equivalent triangular lateral force distribution will further "dilute" (reduce) the shear increase percentage. Even if the 10% rule of Chapter 34 is slightly exceeded, wood-framed residences are typically very resistant to seismic collapse once obvious weak spots like unsheathed cripple walls are addressed. However, adding a solar array to the south half of the roof could add an additional 3.5 psf x 40% / 20 psf = 7 %, so a solar array plus reroof overlay could easily amount to 12% + 7% = 19%, well over the 10% limit. Hence, in seismically active regions of California (i.e. most of the state), for seismic load reasons alone, placing solar arrays over reroof overlays is not recommended and likely to be a code violation.

1.A.(2). No Significant Structural Deterioration or Sagging: Per the Toolkit Structural Document, the site auditor should verify the following:

1. No visually apparent disallowed rafter holes, notches and truss modifications as shown above.
2. No visually apparent structural decay or un-repaired fire damage.
3. Roof sag, measured in inches, is not more than the rafter or ridge beam length in feet divided by 20.

Roof rafters that fail the above criteria should not be used to support solar arrays unless they are first strengthened.

Excessive roof sag can indicate an originally under-designed roof, or subsequent deterioration of a correctly designed roof. Roof sag, measured in inches, is not to exceed span, measured in feet, divided by 20. This corresponds to a dead load deflection of span L/240. Per code, dead plus live load deflections are not to exceed L/180, and if dead load is 10 psf and live load is in the range of 12 to 20 psf, the expected original dead load design deflection is of the order of one third to one half of L/180, that is, L/360 to L/540. Hence a larger dead load deflection of L/240 could indicate problems, warranting further investigation.

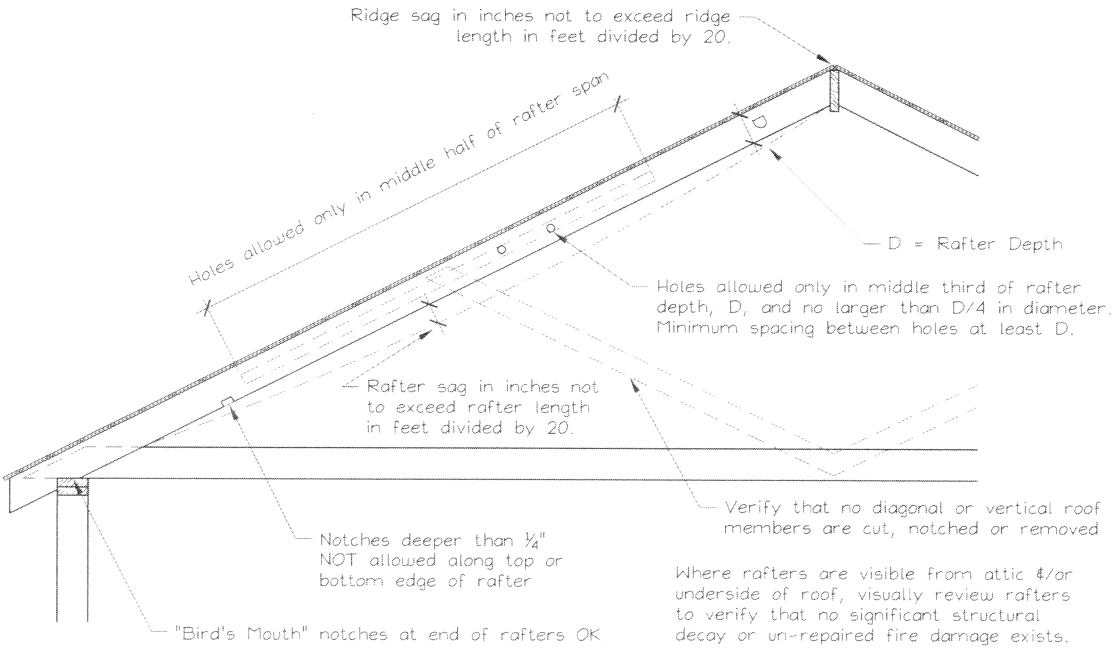


Figure A1.1. Roof Visual Structural Review (Contractor's Site Audit) of Existing Conditions.

1.B. Roof Structure Data:

Roof slope and rafter spacing is noted in this section of the Structural Criteria, for use in applying Table 1 (Horizontal Anchor Spacing) in the Solar Array checks.

1.B.+ Optional Additional Rafter Span Check Criteria

The Structural Criteria are based on an important underlying assumption that the existing roof was code-compliant at the time of construction, and has not deteriorated since then. One significant question for those designing criteria for expedited residential solar permitting is

whether rafter span checks should be made to verify that an existing roof is code compliant, or whether to instead assume the roof was originally designed to meet building code requirements at the time of construction. This decision requires considerable judgment, and reasonable engineers and code officials can and do have differing opinions on this question.

Choose By Advantage: One way of exploring the options for verifying that an existing roof is code compliant is through a "Choose By Advantage" (CBA) process, where key stakeholders such as code officials, structural engineers and solar industry representatives meet to list and quantify the advantages of various options. Figure A1.2 illustrates one possible outcome of such a process. In this example, the "Trust but Verify" option has the greatest advantages, but the "Accuracy Trumps Simplicity" option comes in a close second, where span tables for pre- and post-1960's vintage construction are used.

Solar Permitting Initiative Existing Roof Rafter Span Check Options

	Option	Condition Check	Span Check	**Span Table**					Nickname	Simplicity (10)	Rigor (8)	Least Cost (8)	Choose By Advantage Score
				Bldg Age	Pre-1960	Post-1960	Pre-1960	Post-1960					
1	No Span Check, No Condition Check								"Trust Everybody"	10	0	8	18
2	No Span Check, Do Condition Check	✓							"Trust but Verify"	9	3	7	19
3	Check Pre-1960 Only w/ Pre-1960 Table	✓	✓		✓				"Trust New Stuff"	5	5	6	16
4	Check All Bldgs w/ Pre-1960 Table (EBGC)	✓	✓		✓		✓		"Sorta Trust New Stuff"	6	5	6	17
5	Check All Bldgs w/ Applicable Tables	✓	✓		✓			✓	"Accuracy Trumps Simplicity"	4	8	6	18
6	Check All Bldgs w/ Modern Table	✓	✓			✓		✓	"Flunk Old Stuff"	6	7	2	15

Notes:
EBGC Solar Permitting Checklist currently based on Option 4 ("Sorta Trust New Stuff"), accepted by 8 of the 9 cities
City of Hayward has amended EBGC Solar Permitting Checklist to use Option 6 ("Flunk Old Stuff")
Per "Choose By Advantage" scoring shown here, Option 2 is recommended ("Trust but Verify")

Condition check = visual review of exposed elements:
- exterior roof, check for unusual sagging or deterioration, of exposed roof rafters in attics for cuts, notches, etc.
- exposed roof rafters in attics, check for cuts, notches, removed carpenter truss members, decay, fire damage, etc.

Post-1960 span tables:
- per current code Chapter 25 roof span tables
- modern lumber sizes (2x4 = 1.50"x3.50")
- Doug Fir No. 2 unless exposed lumber stamps indicate otherwise

Pre-1960 span tables:
- per custom span table provided with checklist
- mid-century (1920-1960) lumber sizes (2x4 = 1.75"x3.75")
- Doug Fir No. 1

Figure A1.2. Hypothetical results of a "Choose By Advantage" process where stakeholders meet to list and quantify the relative advantage of various options. In this example, the "Trust But Verify" option has the greatest advantages, but the "Trust Everybody" and "Accuracy Trumps Simplicity" options tie for second place.

The simplest version of the Structural Criteria uses the "Trust But Verify" approach. While checking for significant structural deterioration is always appropriate, omitting horizontal rafter span checks is considered appropriate, based on the following reasoning:

- Most roof structures are designed properly and are code compliant.
- Visual survey is done to check against weakening factors such as decay, fire damage or removal of truss web members.
- Roof overlays (reroofs) of similar weight to solar arrays have been allowed for many years, with no history of failures for sloping shingled roofs.
- The effect of placing an array on a non-compliant roof structure may, in a few cases, result in sagging and distress to finishes, alerting the owner to a problem and providing time to address. The chance of roof collapse is negligible due to roof sheathing's catenary and composite action. For instance, the Structural Engineers of Washington reports on the aftermath of a heavy snow load event where 57 roofs were damaged, but only two partial collapses occurred. Snow loads, with ongoing downward pressures that can drive a roof to collapse, are very different from the dominant wind load case in most of California, where downward wind loads are ephemeral and much less likely to drive a roof structure to collapse.
- Concentrated load effects from solar arrays are minimized if these guidelines are followed. Overloads from solar arrays on a non-compliant roof will result in Demand-Capacity Ratios (DCRs) of similar magnitude as the original DCR of the non-compliant roof for the dead load plus roof live load combination.
- The installation process of panels and workers on the roof is itself essentially a roof load test. If problems of over-deflection and rafter breakage do not occur during the solar array installation process, similar problems are unlikely to occur during service life, especially in regions of modest wind loads and zero snow loads typical of most of California.

Horizontal Rafter Span Check: In the Toolkit Structural Document, CBOs are also given the "Accuracy Trumps Simplicity" option of adding a roof rafter span check by adding four questions to the roof check, along with Table 1, which provides maximum rafter spans for both pre-1960 and post-1960 construction.

Looking at one region of the state as an example, the vintage of the housing stock of the cities of the East Bay Green Corridor ranges from the mid-1800s to the present, and therefore poses a special challenge because of the wide variation in roof framing approaches. Building department staff members from at least two east bay cities (Berkeley and Emeryville) believe

that rafter span checks are required, based on their experience that a significant percentage of their city's existing housing stock, especially pre-1960s, has roof framing with rafter spans that may exceed past and current code maximum span limits.

In the past, Berkeley has used span tables based on modern lumber dimensions and Douglas Fir No.2 to identify non-compliant construction in their over-the-counter solar permitting process. Applying Berkeley's table to pre-1960s construction can misidentify code-compliant roof framing as non-compliant. This is because pre-1960s construction has (a) larger actual member sizes (2x4s of typical dimensions of 1.75"x3.75" instead of modern 1.50"x3.50") and (b) typically better lumber grades (Doug Fir No. 1 rather than Doug Fir No. 2). Depending on specific rafter size and spacing, these two effects increase allowable spans for pre-1960s construction by 20% compared to modern span tables for DF No. 2, and even more for pre-1910 full dimension lumber.

Table 2 of the Structural Criteria is divided into two types of lumber and construction:

1. Modern post-1960 construction when current planed lumber sizes were established (e.g. a 2x4 is actually 1.5"x3.5"). Not only are modern lumber sizes smaller, but high quality virgin timber had been logged out so typical lumber species and grade is Douglas Fir #2 rather than #2.
2. Pre-1960 construction based on rough-sawn rafter sizes typical for years circa 1910 to 1960, a quarter inch larger than modern lumber sizes, and the assumption that the lumber species and grade is Douglas Fir No. 1 (note: the San Francisco Building Code specifically allows DF No. 1 to be assumed for existing wood construction).

In Table 2, spans are rounded to the nearest 3" increment.

For construction prior to circa 1910, lumber was usually full dimension (i.e. a 2x4 was actually 2.0"x4.0"). Spans for full dimension lumber may be increased by ten percent over that shown in Table 2 for pre-1960 lumber. The exact percentage of allowed span increase (square root of section moduli ratios) for pre-1910 full dimension lumber versus later rough sawn sizes, is 14% for 2x4s, 12% for 2x6s and 10% for 2x8s and 2x10s.

Prescriptive Rafter Strengthening Strategies: If a rafter span check indicates that the roof is not code-compliant, both Berkeley and Emeryville have prescriptive strengthening measures to allow installation of a solar array.

Berkeley provides a drawing showing a purlin of the same size as the roof rafters, set at midspan along the underside of all the rafters, with intermittent diagonal struts extending down to the top of walls below. The Berkeley prescriptive approach has the advantage that it is relatively easy and inexpensive to install. However, it has the drawback that diagonal struts can exert horizontal thrust at the top of walls, and impose vertical forces on walls that may not have been designed to carry such loads.

Emeryville allows a prescriptive strengthening approach that strengthens individual rafters that support solar panel anchors. The prescriptive roof rafter retrofit is:

- The maximum point load exerted on a roof rafter from the solar panels must not exceed 200 lbs.
- Solar panel supports are anchored to solid roof rafters or joists or to solid blocking.
- Reinforce existing roof rafter as follows:
  - Sister (reinforce) existing roof rafter with 2x6 member.
  - 2x6 members should be attached to existing roof rafter with 10d nails staggered at 6-inches on center.
  - 2x6 members should extend to within 12-inches of the support of existing roof rafter at each end.
  - Provide double sistering (sandwich) with 2x6's when the existing roof rafter span exceeds 12 feet.

The Emeryville prescriptive strengthening approach has the advantage that the roof structure's load path remains essentially unchanged.

Roof Mean Height

Wind loads on a roof-mounted solar array increase with mean roof height. Mean roof height is shown in the attached diagram. The wind checks in the Toolkit's structural criteria assume that the great majority of one- and two-family residences in a jurisdiction have a mean roof height

less than or equal to 40 feet. Some of the tables in this appendix distinguish between 30, 40 and 50 foot mean roof heights to allow fine-grained design option refinement.

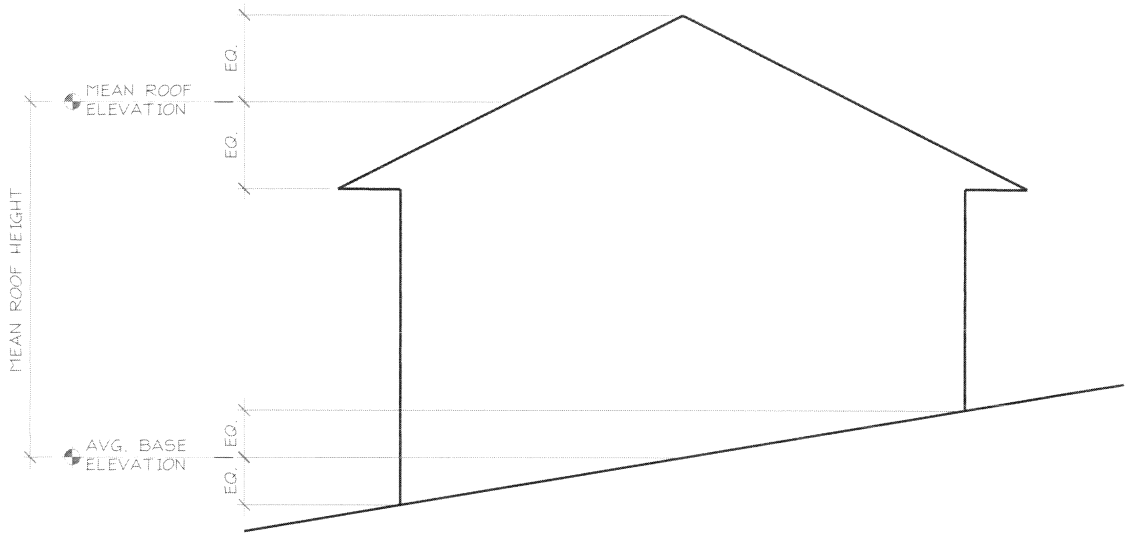


Figure A1.3. Definition of mean roof height. The Toolkit's structural criteria assumes a mean roof height of 40 feet or less.

Part 2. Solar Array Checks

2.A. "Flush-Mounted" Rooftop Solar Arrays

The Toolkit structural document is written to apply to "flush-mount" residential solar arrays, as defined by ICC AC 428: *Acceptance Criteria for Modular Framing Systems Used to Support Photovoltaic (PV) Panels*. These are solar arrays that are installed parallel to, and relatively close (2" to 10") to, the roof surface. Arrays that tilt away from the roof surface, or overhang edges of the roof, do not prequalify under the Toolkit structural criteria. ICC AC 428 has four geometric requirements, of which the first two are explicitly checked, and the third is partially checked:

- The plane of the modules (panels) is parallel to the plane of the roof.
- There is a 2" to 10" gap between the roof surface and underside of modules. This is explicitly checked.
- There is a 10" distance from edge of module to edge of roof (ridge, hip, gable ends or eaves). Earlier versions of the East Bay Green Corridor's Structural Check List included the 10" set back requirement or a similar check requiring the modules be set back by the "gap" distance from the roof edge. East Bay Green Corridor code officials reviewing the Structural Criteria thought that this added unnecessary complexity to the Check List and reduced available solar capture roof area. Per their input, the EBGC Structural Check List simply verified that the modules do not overhang roof edges. The State's Toolkit Structural Document follows the same reasoning, and has the same simplified requirement. Article 2.G.2. of this Technical Appendix discusses this issue in more detail.
- There is at least a 1/4" gap between rows of modules. This is assumed, since modules invariably require a space of at least a half inch between modules to accommodate the clips and clamps that fasten the modules to supporting rails or anchor assemblies below.

2.B. Solar Array Self-Weight

The weight of typical PV modules consistently average about 2.5 psf, with a standard deviation between brands and models of about 0.29 psf. Table A2.1.1 below lists the published self weight of PV modules from a sampling of various manufacturers. The self weight of the mounting hardware is assumed to be 1 psf or less, and is usually no more than 0.5 psf. The Structural Criteria states that the PV array and support components can weigh no more than 4 psf. In the calculations that follow, upon which the Structural Criteria's Table 1 is based, the combined weight of PV modules and support components is assumed to be 3.5 psf.

Typical solar thermal panels weigh a bit more than PV modules, ranging from 3.1 to 4.1 psf, with an average of 3.6 psf and a standard deviation between brands and models of about 0.32

psf. Table A2.1.2 below lists the self weight of solar thermal panels from various manufacturers. If the self weight of mounting hardware is assumed to weigh 1 psf or less, then an upper bound combined weight of 5psf appears reasonable, and is used in calculations to derive the Structural Criteria's Table 1 for solar thermal arrays.

Figure A2.1 shows histograms of the panel weight per area (psf) distribution comparing solar PV to solar thermal.

Table A2.1.1. Typical Photovoltaic Module Weights

Manufacturer	Model	Module Dimensions			Weight	
		Length (in.)	Width (in.)	Area (sq.ft.)	Per Mod. (lbs.)	Unit Wt. (psf)
CanadianSolar	CS5A	62.8	31.5	13.7	33.7	2.45
CanadianSolar	CS5P	63.1	41.8	18.3	44.8	2.45
CanadianSolar	CS6A	52.1	38.7	14.0	33.7	2.41
CanadianSolar	CS6P	64.5	38.7	17.3	41.9	2.42
CanadianSolar	CS6X	76.9	38.7	20.7	50.7	2.45
ET Solar	ET-P660250W	64.6	39.1	17.5	41.5	2.37
First Solar	Series 4	47.2	23.6	7.8	26.5	3.41
Grape Solar	390W	77.2	51.5	27.6	78.2	2.83
Grape Solar	250W	64.6	39.0	17.5	44.1	2.52
Kyocera	KD315GX-LPB	65.4	52.0	23.6	60.6	2.57
LG Solar	LG260S1C-B3	64.6	39.4	17.7	41.1	2.33
Lumos	LSX 250-60M	64.2	41.0	18.3	62.6	3.42
Panasonic Sanyo	HIT-N225A01	62.2	31.4	13.6	35.3	2.60
Panasonic Sanyo	HIT-195BA20	51.9	34.5	12.4	33.1	2.66
Panasonic Sanyo	HIT-200BA19	51.9	34.6	12.5	31.0	2.49
Panasonic	HIT Power 240S	62.2	31.4	13.6	33.1	2.44
Trinasolar	TSM-PA05	65.0	39.1	17.6	41.0	2.33
Trinasolar	TSM-PD05	65.0	39.1	17.6	41.0	2.32
Trinasolar	TSM_PDG5	66.3	39.3	18.1	52.9	2.93
Trinasolar	TSM-PD14	77.0	39.1	20.9	60.8	2.91
Samsung	LPC250SM	64.2	36.7	16.3	41.0	2.51
Sharp	ND-Q245F	64.6	39.1	17.5	41.9	2.39
Sharp	ND-F2Q235	64.6	39.1	17.5	46.7	2.66
Suniva	OPT 265-60	65.0	38.7	17.5	39.5	2.26
Suntech	STP255S-20	64.6	39.1	17.5	40.0	2.28
Upsolar	Z180-205M	62.2	31.8	13.7	34.0	2.47
Upsolar	Z222-245P	64.6	39.1	17.5	41.9	2.39
Yingli Solar	YGE 60	65.0	39.0	17.6	40.8	2.32
Yingli Solar	YGE-Z 60	65.0	39.0	17.6	43.4	2.47
Yingli Solar	YGE-U 72	77.6	39.0	21.0	56.2	2.67
Average						2.55
Std. Deviation						0.29

Table A2.1.2. Typical Solar Thermal Panel Weights

Manufacturer	Model	Module Dimensions			Wet Weight	
		Length (in.)	Width (in.)	Area (sq.ft.)	Per Mod. (lbs.)	Unit Wt. (psf)
AET Solar	AE-21	85.19	35.19	20.8	79.8	3.83
AET Solar	AE-24	97.19	35.19	23.8	90.3	3.80
AET Solar	AE-26	77.19	47.19	25.3	97.5	3.85
AET Solar	AE-28	85.19	47.19	27.9	107.0	3.83
AET Solar	AE-32	97.19	47.19	31.8	121.8	3.82
AET Solar	AE-40	121.19	47.19	39.7	88.4	3.40
Apricus	FPC			26.0	105.2	3.27
Apricus	FPC			32.2	34.0	2.5
NVI Solar	FP 1.20.0 HE			22.0	68.2	3.10
NVI Solar	SOL 27			27.3	91.5	3.35
NVI Solar	SOL 27 Premium W			27.3	93.3	3.41
Average						3.62
Std. Deviation						0.32

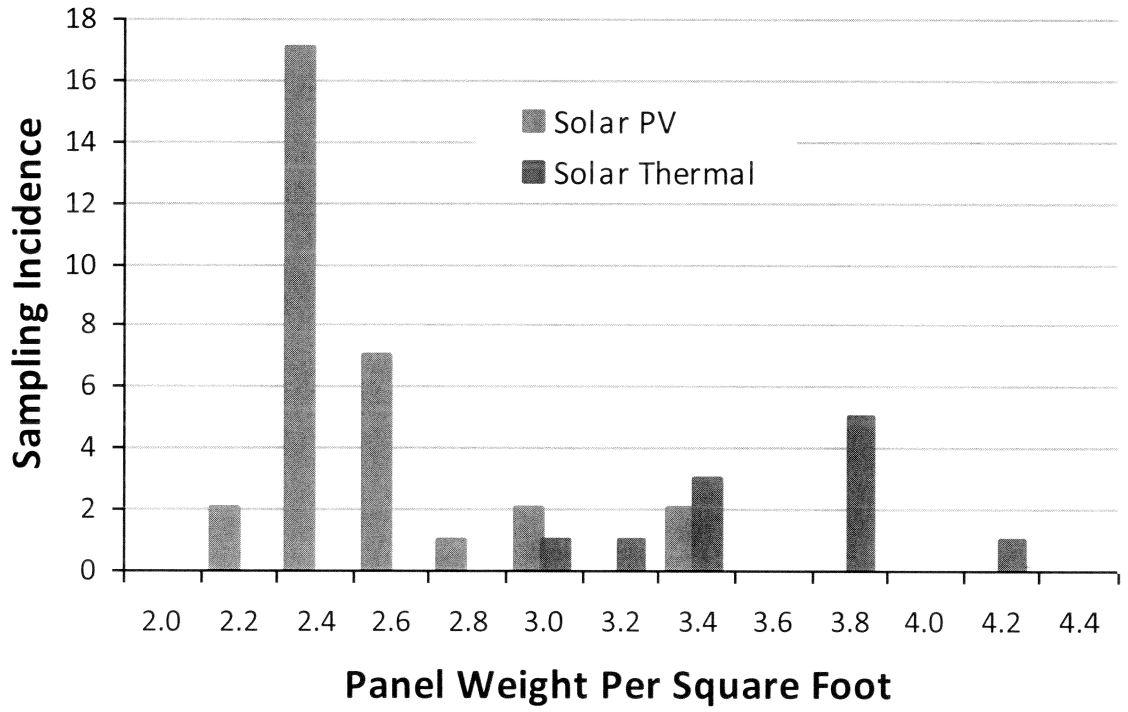


Figure A2.1 Distribution of panel weights per square foot, comparing Solar PV to Solar Thermal.

2.C. Solar Array Covers No More than Half the Total Roof Area

To avoid significantly adding to the inertial mass of the roof and seismic lateral loads, limits are set on the maximum roof area covered by solar arrays. To understand why the limit is set at half the total roof area, it's instructive to look at a typical case: solar array weighs 3.5 psf, and covers 80% of the south facing gable roof. In a single story building, the global increase in lateral loads to the building would be: 3.5 psf x 40% / 20 psf = 7 % (less than the 10% trigger in 2013 CBC Chapter 34, article 3404.4). Plan torsion effects may make loads to individual elements slightly greater than 7%, but still likely to be less than 10%. If the building was more than one story tall, multistory effects would further dilute (reduce) the percentage increase in loads. To keep solar arrays from adding more than 10% to the seismic loads of the building, limiting the array coverage to no more than half the total roof area appears to be appropriate for most cases. Note that the "total roof area" is the sum of all roof planes, not just the roof plane where the array is located.

2.D. Solar Support Component Manufacturer's Guidelines

Solar support component manufacturers typically provide guidelines, code compliance manuals and even web-based calculators to design the array above the roof, as well as the attachment to the roof. Good examples include code compliance materials found online for such manufacturers as Unirac, ZEP Solar, IronRidge and QuickMount. These guidelines typically provide guidance for the design and layout of the array above the roof, but do not check (and almost always include disclaimers regarding) the sufficiency of the supporting roof structure.

2.E. Roof Plan of Module and Anchor Layout

A roof plan showing the basic layout of modules and anchors, similar to Figure A2.13, is required to verify that the installer is properly planning the installation. Without such a plan, installation could be haphazard, and could easily violate the support component manufacturer's guidelines, or the Structural Criteria's Table 1, which sets anchor maximum horizontal spacing limits. This spacing limit is the cross-slope, "east/west," perpendicular-to-rafter distance between anchors. "Anchors" are also referred to in the industry as stand-offs, mounts, feet, attachment points or support points. The anchor spacing limits in Table 1 do <u>not</u> apply to anchor spacing in the upslope/downslope, "north/south," parallel-to-rafter direction.

2.F. Accounting for Concentrated Loads Acting Downward

Table 1 of the Structural Criteria determines the maximum spacing between photovoltaic (PV) array anchors, taking into consideration the concentration of dead loads and wind downward loads on individual rafters, ameliorated by (a) the displacement of roof live loads, and (b) rafter load sharing effects. Loads are modified appropriately by load duration factor. As discussed later in more detail, the concentrated load sharing (or redistribution) effect is separate from, and in addition to, the repetitive member factor.

2.F.1. Roof Live Load

Roof live loads are intended to represent temporary construction loads such as workers and their materials, such as bundles of shingles. The code has required that roofs be designed for roof live load in addition to dead load since the first edition of the UBC was published in 1927. In fact, the 1927 UBC required greater live loads than currently required. The 1927 UBC specified a vertical roof live load of 30 psf at low slopes up to 4:12, 25 psf between 5:12 and 12:12, and a 20 psf wind load normal to the roof for roofs steeper than 12:12. Going even further back, the 1911 Berkeley "Building Law" (Ordinance 129) required a similar roof live load of 30 psf at slopes less than twenty degrees, and a roof live load of 20 psf at steeper slopes. These early roof live load requirements are substantially greater than current code requirements of 20 psf for low slopes (up to 4:12) and 12 psf for steep slopes (above 12:12), especially since early vintages of the code did not recognize higher capacity factors under short duration roof live and wind loads. In this analysis, roof live loads as determined from the 1994 edition of the Uniform Building Code are assumed (i.e. a piece-wise linear relationship between roof slope and roof live load). Like other roof-mounted equipment, solar arrays are assumed to displace roof live loads. DSA IR 16-8 (rev. 10/16/2012), article 2.1.2, explicitly allows this assumption. It's reasonable to assume that building materials are never stacked on top of relatively fragile, scratch-prone and slippery solar arrays. This "live load reserve capacity" is an important consideration in structurally justifying the added loads from solar arrays, especially those anchored to every second, third or fourth rafter, instead of to every rafter.

2.F.2. Concentrated Load Sharing (Load Redistribution) Between Rafters:

Solar arrays anchored to every second, third or fourth rafter concentrate solar array dead loads and wind downward loads onto a single rafter. For solar array dead and wind loads, the effective tributary width for that rafter becomes the anchor spacing rather than the rafter spacing. This concentration of loads is ameliorated by the tendency of adjacent rafters to redistribute concentrated loads by the spreading effect of the roof sheathing (typically plywood, oriented strand board or 1x sheathing). RISA-3D models were made to compare the ratio of moments on a rafter with no load sharing to that on a rafter with sheathing that can spread loads to adjacent rafters. Uniform loads, and patterns of concentrated loads, were assessed. See Figures A2.2, A2.3 and A2.4.

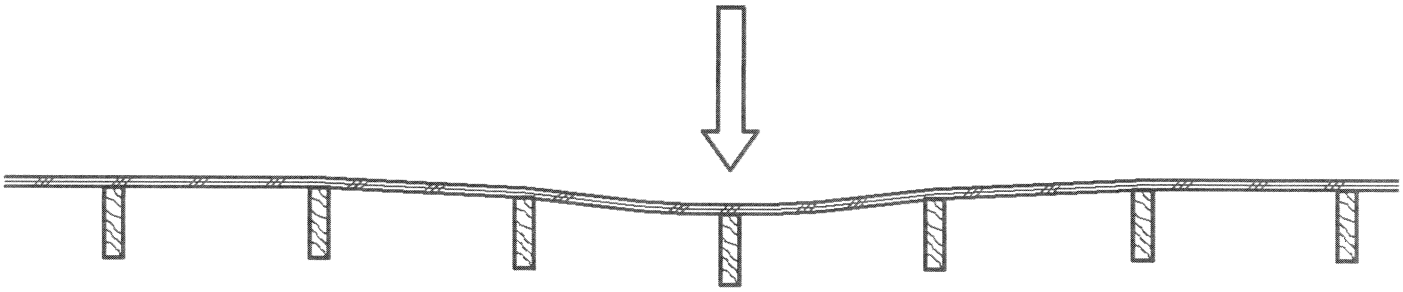


Figure A2.2. Illustration of the concentrated load redistribution effect, where sheathing interconnects rafters so that a load concentrated on one rafter is shared by adjacent rafters. The Concentrated Load

Sharing Factor, C_{LSF}, can be thought of as the effective number of rafters that resist a concentrated load imposed on a single rafter.

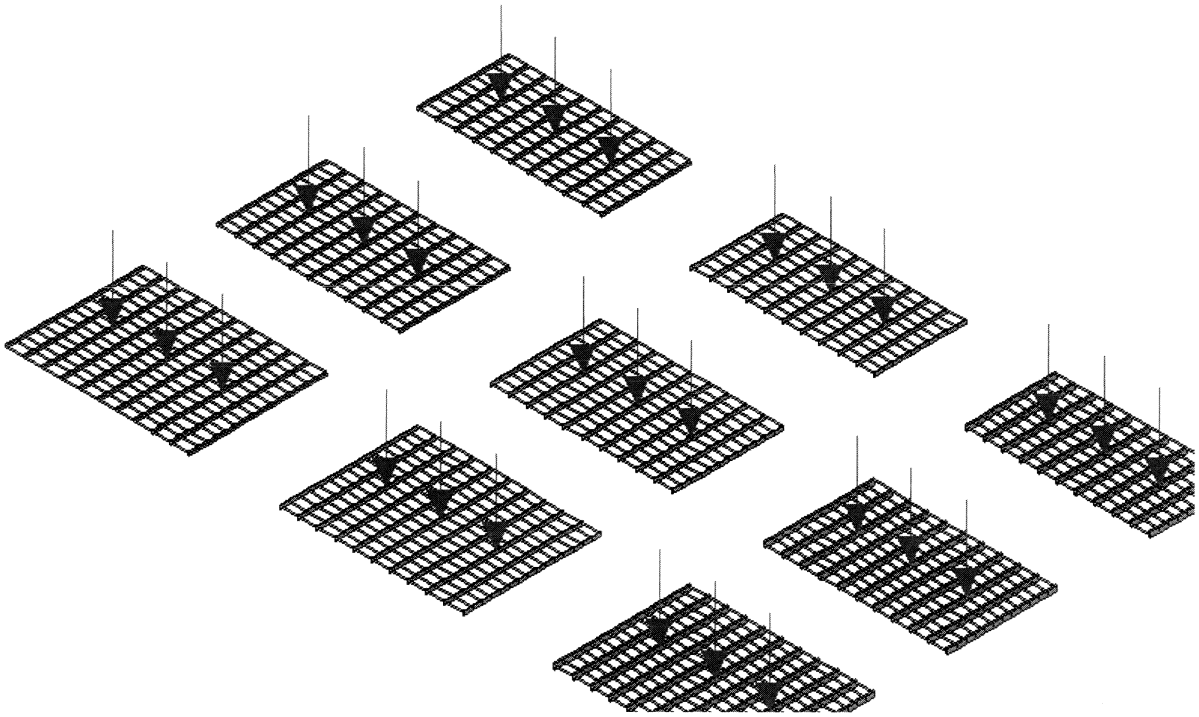


Figure A2.3. Subset of RISA-3D models to determine concentrated load sharing factors. Mid-span loads on every 3rd rafter are shown; continuous loads and loading to every 2nd rafter were also assessed.

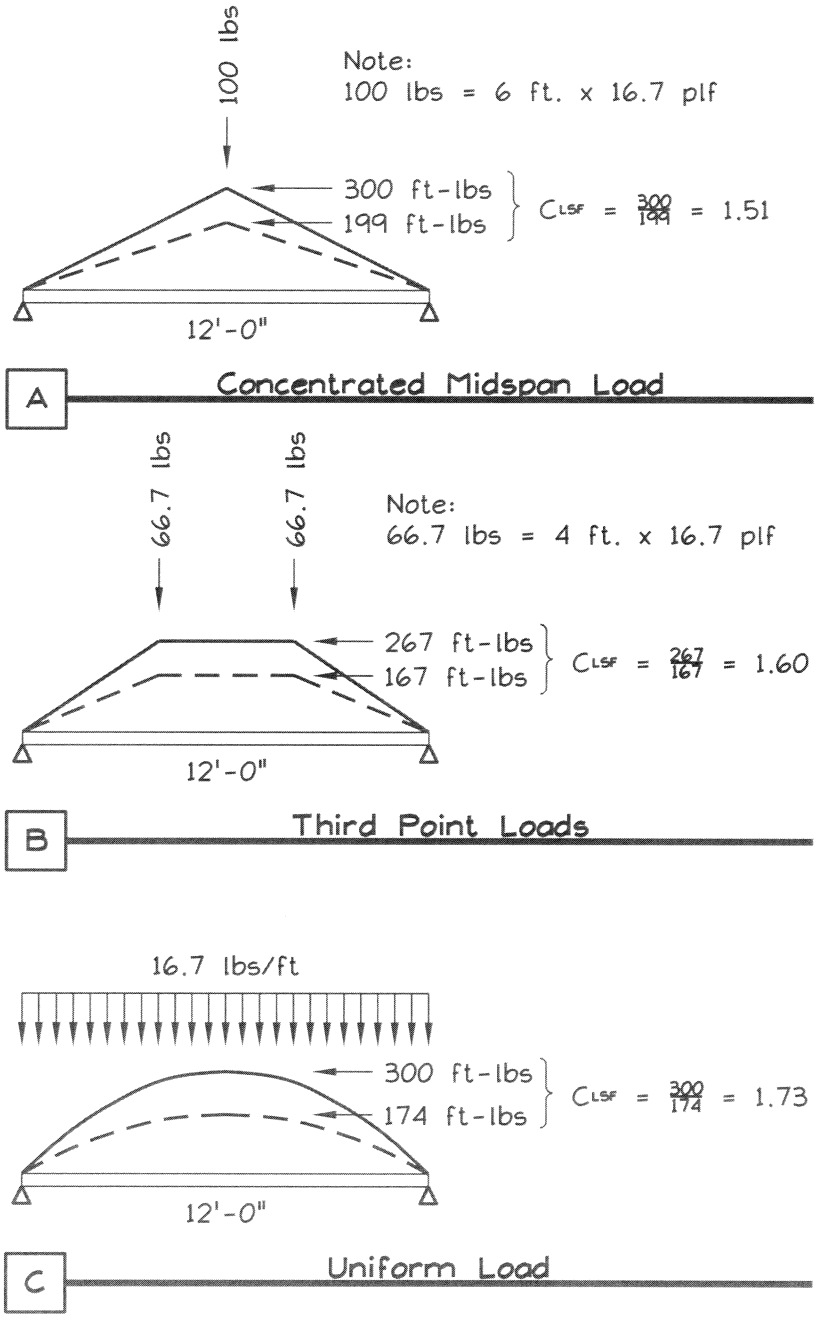


Figure A2.4. Comparison of maximum moments with and without load sharing effects from sheathing, for three loading patterns: midspan loading, third point loading, and uniform loading. The Concentrated Load Sharing Factor, C_{LSF}, is the ratio of the maximum moment without load sharing to the maximum moment with load sharing. As the figure shows, the midspan loading generates the lowest C_{LSF} (1.51 in this case). To be conservative, C_{LSF} based on the midspan loading case was used in the subsequent analysis. Note that uniform loading has a C_{LSF} that is 15% greater than midspan loading.

The concentrated load sharing factors determined from the RISA-3D analysis vary slightly according to modeling idealizations for how the sheathing connects to rafters at panel butt joints, and to rafters between butt joints. Figure A2.5 shows the idealized extreme assumptions at (1) panel butt joints (see subfigures 1A for the pinned idealization, and 1B for the fixed idealization), and at (2) plywood continuous over rafters (see subfigures 2A for pinned and 2B for fixed connection between sheathing and rafter). Panel butt joints are modeled in a staggered layout pattern ("case 1" illustrated in building code allowable diaphragm shear tables). Note that at both the butt joints and continuous sheathing over rafters, the question is whether the plywood can rotate independently of the rafter, forcing the nails to bend and withdraw to allow the sheathing to rotate free of the rafter, or whether the nails effectively clamp the sheathing to the rafter. A real roof structure probably falls somewhere between these idealizations of pinned versus fixed. This analysis calculates load sharing factors for the idealized cases, and takes the average.

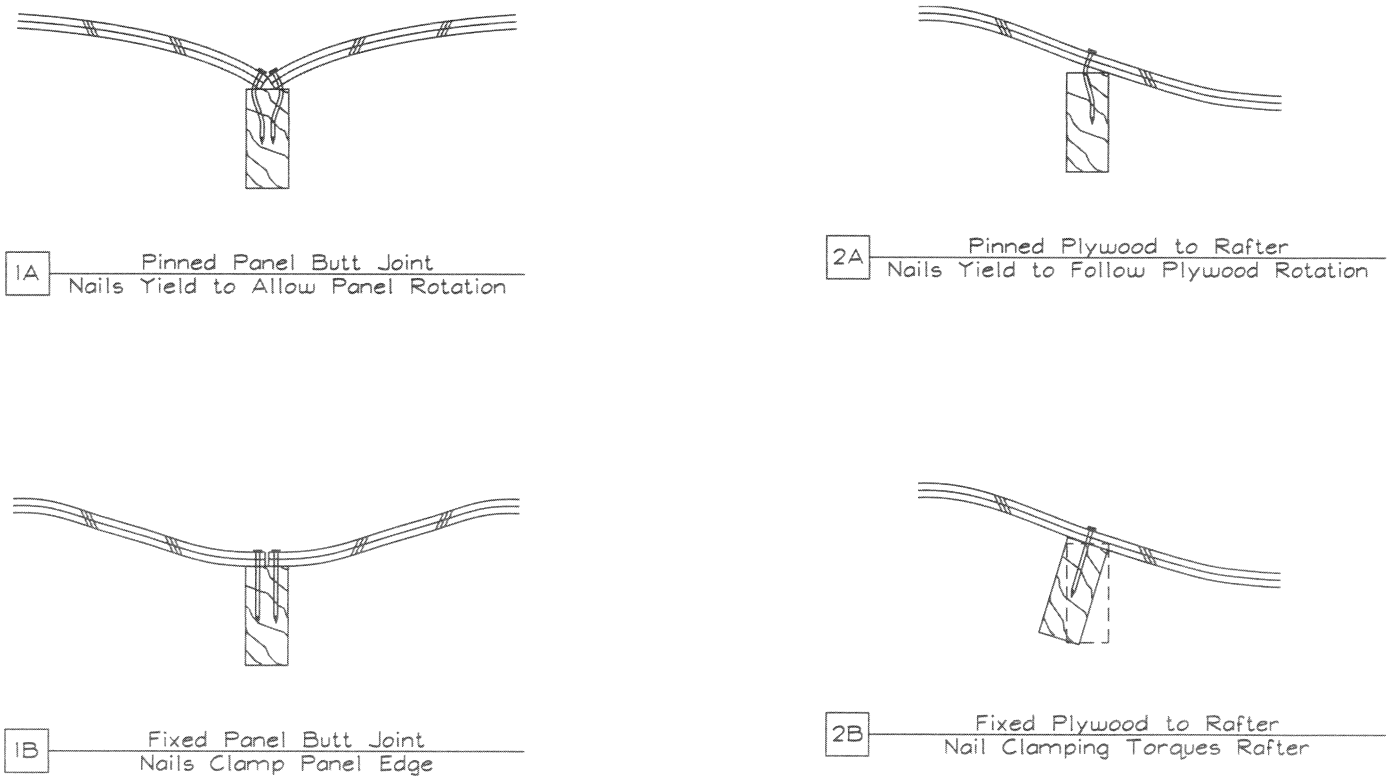


Figure A2.5. Sheathing connection to rafter idealized as pinned or fixed at panel butt joints (1A versus 1B) and where sheathing runs continuously over a rafter (2A versus 2B). Real roof structural behavior lies somewhere between these idealized extremes.

The results of the analysis, based on examining a wide range of sheathing thicknesses, rafter sizes and spans, and sheathing-to-rafter fixity, are summarized in Tables A2.2 and A2.3.

Table A2.2. Concentrated Load Redistribution Factor from Sheathing

Anchor/Rafter Spacing, n	Rafter Spacing (in.)	Rafter Span[5] (ft-in)	Concentrated Load Sharing Factor, C_{LSF}								
			7/16" OSB [1]			1/2" nominal plywood [2]			5/8" nominal plywood [3,4]		
			2x4	2x6	2x8	2x4	2x6	2x8	2x4	2x6	2x8
2	16"	9'-10"	1.61	1.46	1.38	1.66	1.51	1.42	1.76	1.58	1.49
		14'-4"	1.75	1.58	1.49	1.82	1.64	1.54	1.92	1.73	1.62
		18'-2"	1.85	1.67	1.57	1.93	1.73	1.62	1.94	1.83	1.71
	24"	8'-0"	1.41	1.29	1.23	1.46	1.33	1.26	1.53	1.39	1.32
		11'-9"	1.53	1.39	1.32	1.58	1.44	1.36	1.67	1.51	1.42
		14'-10"	1.61	1.46	1.38	1.67	1.51	1.42	1.76	1.59	1.49
3	16"	9'-10"	1.91	1.54	1.34	2.05	1.66	1.45	2.27	1.86	1.63
		14'-4"	2.26	1.85	1.62	2.41	1.99	1.75	2.63	2.20	1.95
		18'-2"	2.48	2.06	1.81	2.64	2.2	1.95	2.66	2.42	2.16
	24"	8'-0"	1.42	1.16	1.06	1.54	1.24	1.11	1.72	1.38	1.21
		11'-9"	1.72	1.37	1.21	1.85	1.47	1.3	2.06	1.67	1.45
		14'-10"	1.92	1.54	1.35	2.06	1.67	1.45	2.27	1.86	1.63
4	16"	9'-10"	1.99	1.53	1.31	2.18	1.68	1.43	2.48	1.92	1.63
		14'-4"	2.46	1.91	1.62	2.67	2.09	1.78	2.99	2.38	2.04
		18'-2"	2.78	2.19	1.87	3.00	2.39	2.05	3.04	2.69	2.33
	24"	8'-0"	1.39	1.14	1.06	1.52	1.21	1.09	1.75	1.35	1.18
		11'-9"	1.74	1.34	1.18	1.92	1.47	1.27	2.19	1.68	1.43
		14'-10"	2.00	1.53	1.31	2.19	1.68	1.43	2.48	1.93	1.64

Table Notes:

Green shaded values (7/16" OSB) are the basis of the State Permitting Guidebook's Structural Toolkit Document's Table 1 (Anchor Maximum Horizontal Spacing).

Blue shaded values (15/32" plywood = 1/2" nominal) are the basis of the East Bay Green Corridor's Structural Check List's Table 2 (Maximum Horizontal Anchor Spacing).

Yellow shaded values indicate the effect of 19/32" (5/8" nominal) plywood or1x skip sheathing, with twice the sheathing stiffness as 1/2" nominal plywood.

1. 7/16" thick OSB with 24/16 span rating and a minimum stiffness, EI = 78,000 lb-in^2/ft per 2012 AF&PA NDS Spec Table C9.2.3 and NDS Manual Table M9.2-1.
2. 15/32" and 1/2" thick plywood with 32/16 span rating and a minimum stiffness, EI = 125,000 lb-in^2/ft per 2012 AF&PA NDS Spec Table C9.2.3 and NDS Manual Table M9.2-1.
   Note : 15/32" OSB is slightly less stiff: EI = 115,000 lb-in^2/ft.
3. 19/32" and 5/8" thick plywood with 40/20 span rating and a minimum stiffness, EI = 250,000 lb-in^2/ft per 2012 AF&PA NDS Spec Table C9.2.3 and NDS Manual Table M9.2-1.
4. 1x sheathing typical stiffness, EI = (1,600,000)x(12x.75^3/12) = 675,000 lb-in^2/ft if solid sheathed, = approx 300,000 lb-in^2/ft if skip sheathed.
5. Rafter assumed to be Douglas Fir-Larch #2 with E = 1,600,000 psi per NDS Supplement Table 4A. Rafter span taken from 2013 CBC Table 1308.10.3(1) for Dead Load = 10 psf.

The concentrated load sharing factor (C_{LSF}) is a function of the relative stiffness of the sheathing and rafters, with thicker sheathing, tighter rafter spacing, shallower rafters and longer rafters exhibiting a greater load sharing effect. Deeper rafters have larger code-maximum spans, so relative stiffness and C_{LSF} values are quite similar for different size rafters at the same rafter spacing (16" or 24" o.c.). While C_{LSF} values for the DCR analysis are based on 2x6 rafters at their maximum code allowed span, Table A2.2 also shows that the analogous C_{LSF} values for 2x4 and 2x8 rafters are very similar. In Table A2.2, these are the lightly tinted values diagonally adjacent the darker tinted values. Along the tinted diagonals, the C_{LSF} values reflect rafter spans with DCRs in the appropriate range of 0.90 to 1.00.

The values of the concentrated load sharing factor highlighted in the darker tints in the Table A2.2 correspond to roof structures with 7/16" oriented strand board (OSB), 15/32" (1/2" nominal) plywood, or 19/32" (5/8" nominal) plywood with 2x6 DF #2 rafters at 16" on center spanning 14'-4" and rafters at 24" on center and spanning 11'-9".

Using the NDS Manual Table M9.2-1, the plywood sheathing stiffness for 15/32" thick panels was assumed to be 125,000 lb-in^2/ft. This corresponds to a span rating of 32/16, the "Predominant" span rating for 15/32" sheathing in NDS Table C9.2.3. The stiffness listed in the NDS Manual Table M9.2-1 is described as a "minimum" value, with average values being higher. The sheathing stiffness also disregards the added stiffness from roofing, blocking and underside gypsum board ceilings. For these reasons, a stiffness of 125,000 lb-in^2/ft for plywood is assumed to also apply to 15/32" Oriented Strand Board (OSB), with a minimum stiffness of 115,000 lb-in^2/ft.

Note that 1x sheathing is significantly stiffer than either 1/2" or 5/8" plywood (see Table A2.2 Note 4), even if skip sheathing is used with a 50% coverage (675,000 lb-in^2/ft/2 = 338,000 lb-in^2/ft). Therefore, 1x skip sheathing is expected to have greater concentrated load sharing effects than that assumed in the DCR analysis.

A poll of several lumber suppliers in central and northern California suggests that while 15/32" plywood or OSB has been, and remains, the predominant residential roof sheathing material, about 30% of tract home developments in the central valley may use 7/16" plywood or OSB. For this reason, the calculations underlying Table 1 conservatively assume 7/16" OSB and its associated lower stiffness. This results in slightly lower concentrated load sharing factors and slightly more conservative anchor span tables for the State's Toolkit compared to the East Bay Green Corridor's.

Table A2.3. Sheathing to Rafter Relative Stiffness for Typical Scenarios

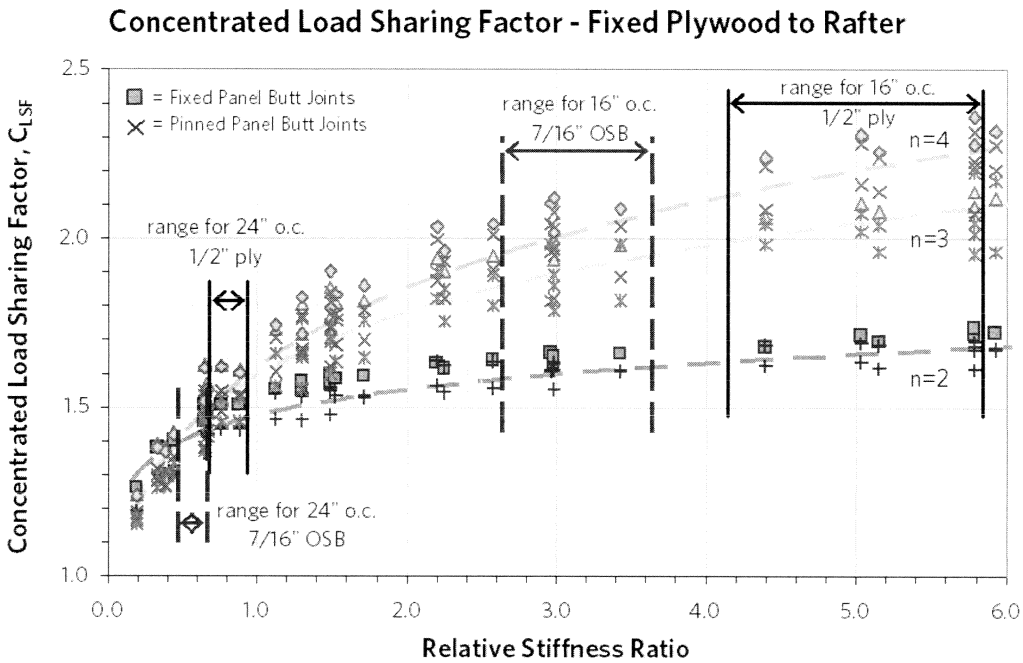
Rafter E (DF #2)(1) = 1,600,000 psi
Sheathing EI(2) = 15/32" = 125,000 lb-in²/ft Plywood (1/2" nominal)
7/16" = 78,000 lb-in²/ft OSB

Member	I (in^4)	Rafter Spacing (in.)	Max. Rafter Span(3) (ft-in)	Max. Rafter Span(3) (in.)	Rafter EI/L^3 (lb/in)	Sheathing EI/L^3 (lb/in)		Sheathing / Rafter Stiffness Ratio	
						15/32"	7/16"	15/32"	7/16"
2x4	5.36	16" o.c.	9'-10"	118	5.22	30.5	19.0	5.85	3.65
		24" o.c.	8'-0"	96	9.69	9.04	5.64	0.93	0.58
2x6	20.8	16" o.c.	14'-4"	172	6.54	30.5	19.0	4.67	2.91
		24" o.c.	11'-9"	141	11.9	9.04	5.64	0.76	0.47
2x8	47.63	16" o.c.	18'-2"	218	7.36	30.5	19.0	4.15	2.59
		24" o.c.	14'-10"	178	13.5	9.04	5.64	0.67	0.42

Table Notes:
1. Per NDS Supplement Table 4A.
2. Per NDS Manual Table M9-2.1.
3. Per 2013 CBC Table 1308.10.3(1) for Dead Load = 10 psf.

The Concentrated Load Sharing (Redistribution) Factor, C_{LSF}, is a function of the sheathing to rafter stiffness ratio. Table A2.3 shows the sheathing-to-rafter relative stiffness for typical scenarios. For 15/32" plywood, the nondimensional sheathing/rafter stiffness ratio ranges from 0.67 to 0.93 for rafters at 24" o.c., and from 4.15 to 5.85 for rafters at 16" o.c. For 7/16" OSB, the nondimensional sheathing/rafter stiffness ratio ranges from 0.42 to 0.58 for rafters at 24" o.c., and from 2.59 to 3.65 for rafters at 16" o.c.

Figures A2.5, A2.6 and A2.7 plot the concentrated load sharing (redistribution) factor across different ranges of sheathing-to-rafter stiffness ratios (relative stiffness) for anchor-to-rafter spacings n=2, 3 & 4. The sheathing and rafter stiffnesses are proportional to EI/L^3, where L = rafter spacing for calculating sheathing stiffness (sheathing EI/L^3), and L = rafter span for calculating rafter stiffness (rafter EI/L^3).



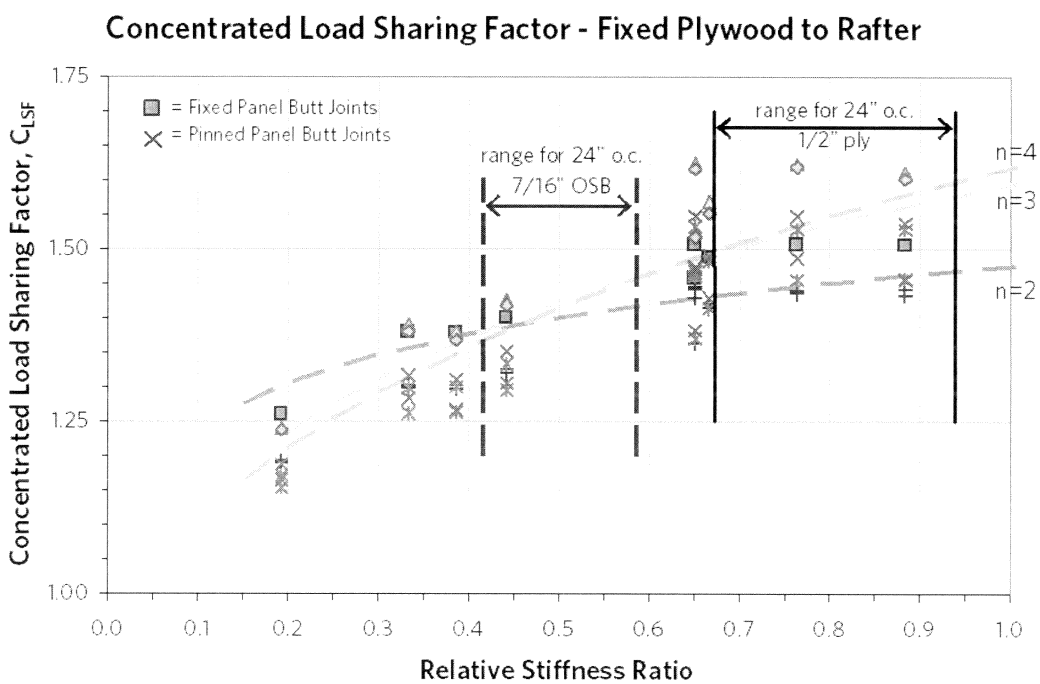
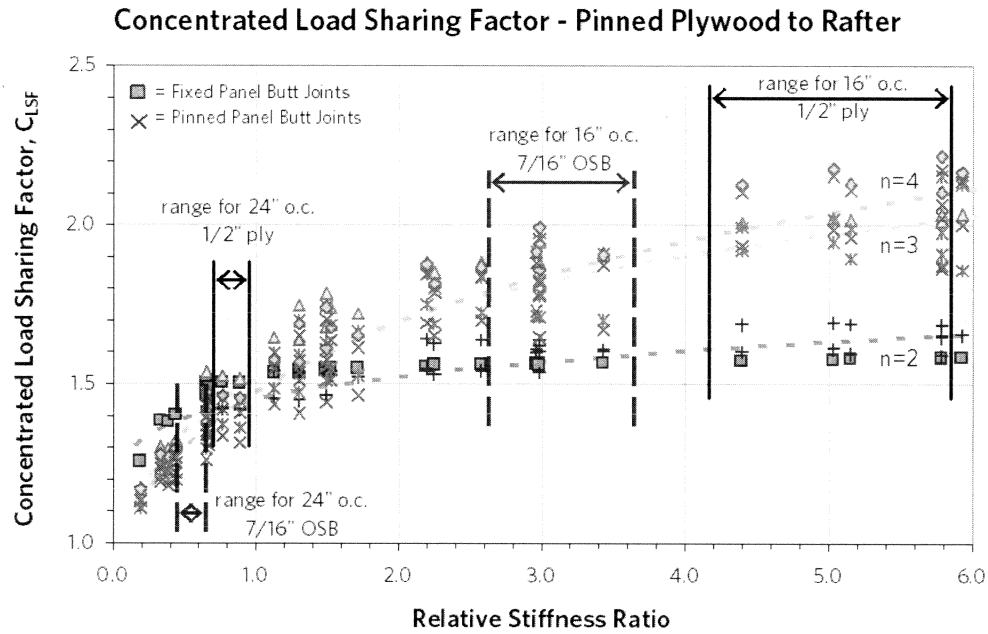


Figure A2.6. Concentrated Load Sharing Factor as a Function of Sheathing/Rafter Relative Stiffness, assuming sheathing-to-rafter field connections are fixed. The upper graph shows the stiffness range of interest for rafters at 16" on center, while the lower graph shows the range for rafters at 24" on center.



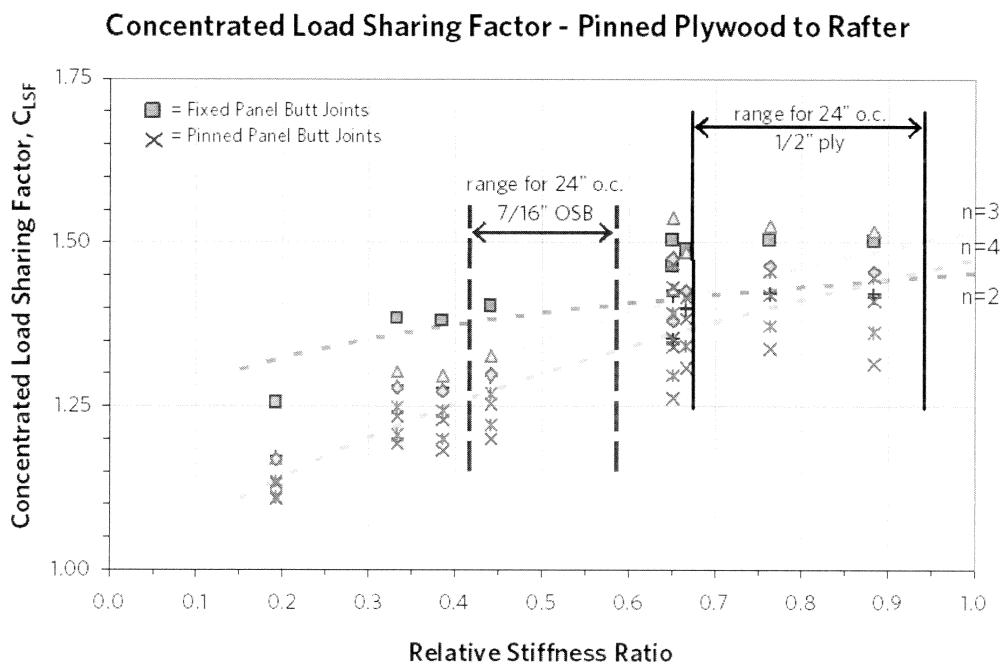
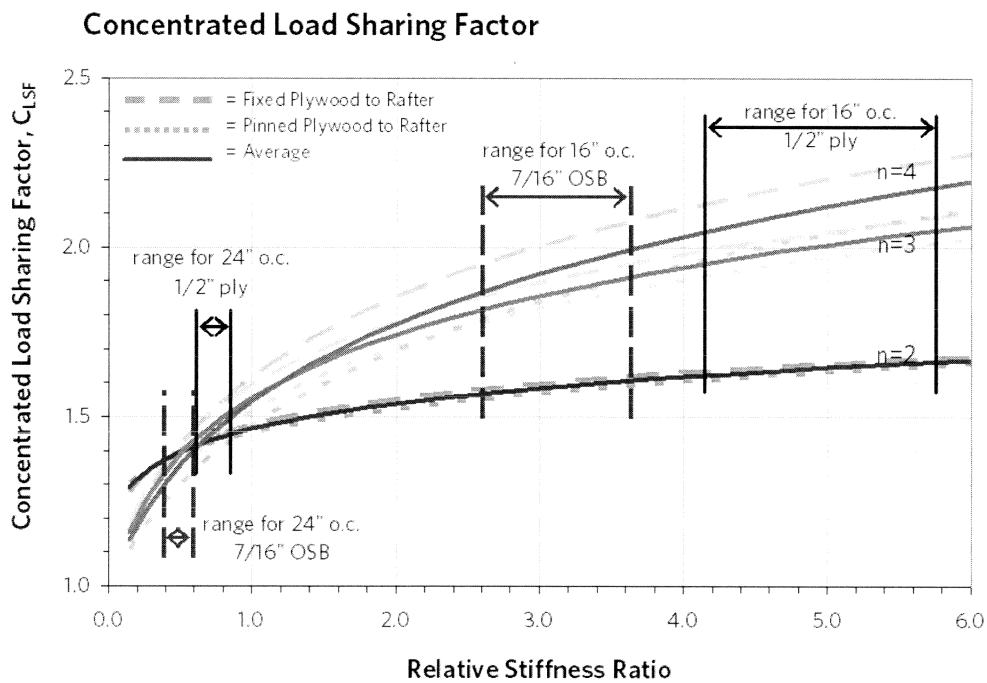


Figure A2.7. Concentrated Load Sharing Factor as a Function of Sheathing/Rafter Relative Stiffness, assuming sheathing-to-rafter field connections are pinned. The upper graph shows the stiffness range of interest for rafters at 16" on center, while the lower graph shows the range for rafters at 24" on center.



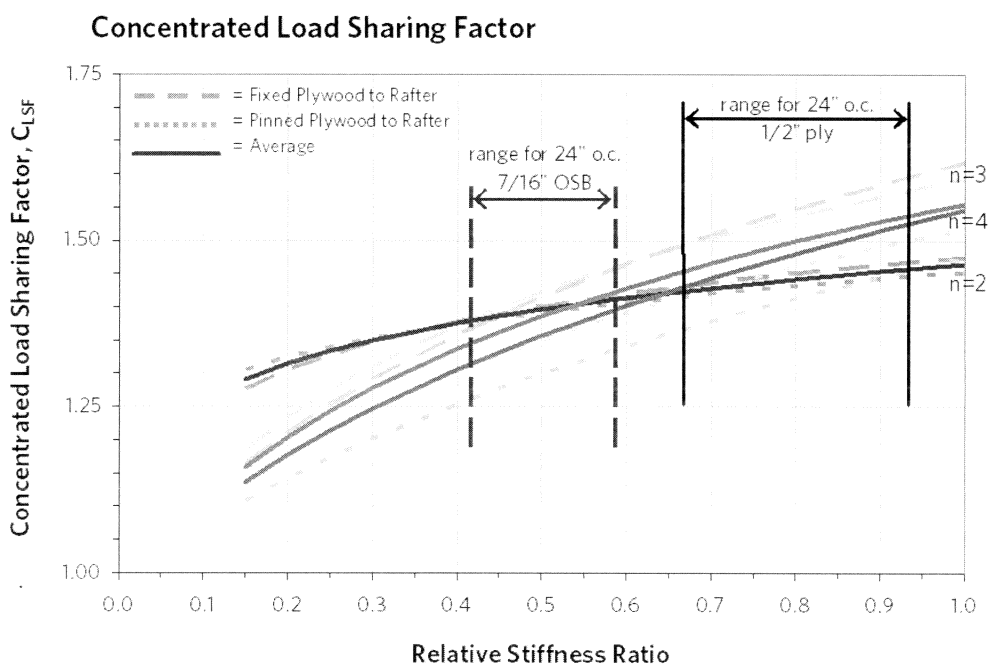


Figure A2.8. Concentrated Load Sharing Factors taken as the average of the plywood fixed-to-rafter and pinned-to-rafter idealized extremes. The upper graph shows the stiffness range of interest for rafters at 16" on center, while the lower graph shows the range for rafters at 24" on center.

2.F.2.1. Further Refinements to the Model: The following are potential future refinements to the Concentrated Load Sharing Factor (C_{LSF}) models. It is expected that such refinements would largely cancel each other out; the assumed load sharing factors might shift slightly, but the concluding tables (Table 1 of the Structural Criteria, maximum anchor spacing limits) would probably remain essentially unchanged. These refinements are:

- Model rafter stiffness as a T-section considering composite action with sheathing. Since this would increase the relative stiffness of the rafters, the current model is slightly unconservative in this regard.
- Increase sheathing stiffness from roofing. Roofing's contribution to sheathing stiffness has not been quantified. Rafter blocking and gypsum board applied to the underside rafters are assumed to be absent, so their potential stiffening effects are also ignored. Because consideration of roofing would increase the relative stiffness of the sheathing, the current model is slightly conservative in this regard.
- Assume that the solar arrays impose more distributed load patterns over the rafter (e.g. third point or quarter point loads) rather than midspan loading. As shown in Figure A2.4, the current model is conservative in this regard.
- Incorporate partial composite action. As discussed in the next section, composite action is ignored, even though its effect is potentially large, of the order of a 35% increase in capacity (Campos Varela, 2013).
- Incorporate statistical deviation from a constant stiffness/strength ratio. The model currently assumes stiffness (modulus of elasticity) and bending strength (modulus of rupture) have a linear proportional relationship (ref. Green and Kretschmann, 1991). In reality, stiffness and strength are not perfectly correlated (per comm. Brad Douglas, American Wood Council, 9/18/2014; ref. Kretschmann and Bendtsen, 1992). Concentrated loads on a stiff weak rafter will result in a lower effective C_{LSF}, while concentrated loads on a soft strong rafter will underestimate the actual C_{LSF}.

2.F.3. Distinction Between Concentrated Load Sharing Factor and Repetitive Member Factor:

The concentrated load sharing factor is different from the repetitive member factor, C_r. The 2012 NDS Commentary (C4.3.9) states: *[Cr] reflects two interactions: [1] [statistical] load-sharing or [statistical] redistribution of load among framing members and [2] partial composite action of the framing member and the covering material. Application of the Cr adjustment requires no assumption as to which of the two types of interaction is involved or predominates. A Cr value of 15 percent is generally considered to be conservative for sawn lumber assemblies.*

In other words, the repetitive member factor is based on two effects:

- Composite action between sheathing and rafters, creating a stronger effective T-section, and

- Averaging of strength variation between three rafters rather than a single rafter, resulting in a statistically predicted higher average strength.

Structural wood experts often use the term "load sharing" to describe the *statistical* load sharing (strength averaging) effect incorporated in Cr, while describing the Concentrated Load Sharing Factor (C_{LSF}) as "load *redistribution*". To these experts, the Concentrated Load Sharing Factor would be more accurately termed the Concentrated Load *Redistribution* Factor. Future editions of the Structural Technical Appendix may incorporate this nomenclature.

The statistical load sharing (strength averaging) effect deserves additional explanation. The breaking stress of a single rafter has a standard deviation σ around a mean μ, and an allowable stress at the 5% lower bound tail that is the mean minus 1.645 standard deviations, divided by the factor of safety. For the average of three members, the standard error around the mean is the standard deviation divided by the square root of three. Therefore, the statistically expected strength of three members, compared to one member, is:

$$\frac{\mu - 1.645\sigma/\sqrt{3}}{\mu - 1.645\sigma}$$

ASTM D245 indicates that F_b has a standard deviation of about 570 psi for Douglas Fir. Since for DF-L No. 2:

$$Fb = 900psi = [\mu - 1.645(570)]/2.16 \therefore \mu = 2{,}882psi$$

For the specific values for Douglas Fir-Larch No. 2, the calculated repetitive member factor based on statistical considerations alone is:

$$Cr = \frac{2{,}882 - 1.645(570)/\sqrt{3}}{2{,}882 - 1.645(570)} = 1.20$$

For Doug-Fir No. 2, the statistical C_r repetitive member factor of 1.15 is conservative without even taking into consideration *any* composite strength action. In general, the higher the design bending strength, the lower the statistical C_r. For instance, DF No 1 & Better, with F_b = 1200, yields C_r = 1.15, while DF No 3, with F_b = 525, yields C_r = 1.35. For non-composite floor assemblies, Rosowsky's Monte Carlo simulations suggest statistical C_r = 1.25 to 1.46.

The 2012 NDS commentary provides further clues about statistical C_r by pointing out that *the repetitive member increase also applies to an assembly of three or more essentially parallel members of equal size* [that*] are in direct contact with each other* [and fastened to each other]. Such an effect would be almost entirely statistical, that is, the standard deviation of three members is tighter (1/sqrt(3)) about the mean than one member, so the lower bound strength (5% tail) is higher.

Based on testing, partial composite action C_r is probably in the 1.25 to 1.40 range for lightly nailed roofs. Campos Varela's full scale tests suggest composite C_r = 1.35, and per comm. w/

Stephen Dwyer at Sandia Labs indicates that their much more extensive testing program is coming up with similar results (data not available until testing is complete in December 2014). Note that full composite action is in the range of 1.7 to 2.1, and is a function of sheathing thickness and rafter size and spacing; actual composite action is partial rather than full because of the limited capacity of typical sheathing field nailing.

The C_{LSF} is a concentrated load sharing effect that is distinctly different from either Cr statistical load sharing effects (more rafters sharing load increases expected lower bound strength) or Cr partial composite action effects. C_{LSF} is based solely on the fact that when you push down on one rafter on a sheathed roof, that rafter does not resist the full load because deformation compatibility causes adjacent rafters pick up part of the load. Fezio (p. 59 of text, p. 72 of pdf) reports that in their FEA analysis, a single rafter in a floor of ten unloaded rafters, under a single concentrated load, only resists 30% of the concentrated load applied directly to it, with adjacent rafters carrying 70%. This is a C_{LSF} of 1/0.30 = 3.33. Note that the technical appendix's C_{LSF} calculation is more conservative. Based on the relative stiffness (EI/L^3 ratio) of sheathing and joists used in Fezio's simulation, the technical appendix would have predicted C_{LSF} = 2.10, not 3.33.

The East Bay Green Corridor project assumed that Cr = 1.15, based on combined statistical averaging and composite action effects. For the statewide expedited permitting effort, a more conservative assumption is made, where Cr is based only on the statistical averaging of the number of effective members reflected by C_{LSF}. In other words, if C_{LSF} = 1.5, it reflects the effective number of rafters that resist the concentrated load, and the standard deviation about the mean is divided by sqrt(1.5) instead of by sqrt(3.0). This results in a Cr = 1.05 based entirely on the statistical averaging aspect of Cr, which is very conservative since it ignores any composite action.

2.F.4. Calculating Demand/Capacity Ratios (DCRs): Taking advantage of the displaced roof live load, Demand/Capacity Ratios can be calculated for roof rafters supporting solar arrays with different anchor spacings, considering a solar array's concentrated dead load and wind download effects.

Using Allowable Stress Design (ASD), the Demand/Capacity Ratio for roof rafters, if controlled by bending strength (the typical case), can be expressed as:

$$DCR = \frac{M_{demand}}{M_{capacity}} = \frac{wL^2/8}{C_D F_b S}$$

where:

$w =$ load per unit length (normal to rafter)= $p \cdot s$, where p = loading pressure and s = tributary width

$L =$ rafter span length (along slope)

C_D = load duration factor per NDS

F_b = rafter allowable bending stress, given its species, grade and size, including all relevant modification terms other than C_D

S = rafter section modulus, $bh^2/6$

Note that s, L, F_b and S are constant for a given roof geometry and rafter type. Thus, for a given structure and loading, the rafter DCR is proportional to the load demand modified for load duration:

$$DCR \propto \frac{w}{C_D} = D$$

If the original rafter was designed to a DCR = 1.0, then the DCR of the rafter supporting a solar array can be calculated as:

$$DCR = \frac{D_{withPV}}{D_{withoutPV}}$$

where:

$$D_{withPV} = \max\left(D_{PV+DL}, D_{PV+wind\_down+DL}, D_{wind\_up-PV-DL}\right)$$

is the maximum load demand from applicable load combinations on the roof rafter after installation of the solar array, and

$$D_{withoutPV} = \max\left(D_{DL+LLr}, D_{DL+wind\_down}, D_{DL+LLr+wind\_down}, D_{wind\_up-DL}\right)$$

is the maximum load demand from applicable load combinations on the roof rafter before installation of the solar array. The load demands on a roof rafter supporting a solar array are defined as:

$$D_{PV+DL} = \frac{(n/C_{LSF})\cdot\cos\theta\cdot DL_{PV} + \cos\theta\cdot DL_{roof}}{C_{D,DL}}$$

$$D_{PV+wind\_down+DL} = \frac{(n/C_{LSF})(\cos\theta\cdot DL_{PV} + 0.6p_{wind\_down}) + \cos\theta\cdot DL_{roof}}{C_{D,wind}}$$

$$D_{wind\_up-PV-DL} = \frac{0.6\cdot\left((n/C_{LSF})(p_{wind\_up} - \cos\theta\cdot DL_{PV}) - \cos\theta\cdot DL_{roof}\right)}{C_{D,wind}}$$

and the load demands on a roof rafter before installation of a solar array are defined as:

$$D_{DL+LLr} = \frac{\cos\theta\cdot DL_{roof} + \cos^2\theta\cdot LL_{roof}}{C_{D,LLr}}$$

$$D_{DL+wind\_down} = \frac{\cos\theta \cdot DL_{roof} + 0.6 p_{wind\_down}}{C_{D,wind}}$$

$$D_{DL+wind\_down+LL_r} = \frac{\cos\theta \cdot DL_{roof} + 0.75 \cdot 0.6 p_{wind\_down} + 0.75\cos^2\theta \cdot LL_{roof}}{C_{D,wind}}$$

$$D_{wind\_up-DL} = \frac{0.6 \cdot (p_{wind\_up} - \cos\theta \cdot DL_{roof})}{C_{D,wind}}$$

where:

$n =$ anchor spacing/rafter spacing

$C_{LSF} =$ concentrated load sharing factor

$\theta =$ roof slope where 0° = flat

$DL_{PV} =$ dead load of solar array (3.5 psf for photovoltaic arrays, 5 psf for solar-thermal arrays)

$DL_{roof} =$ dead load of roof (10 psf for typical wood-framed roof with composition shingles)

$LL_{roof} =$ roof live load (12 to 20 psf, depending on roof slope, per UBC 97 and CBC 2001 and earlier editions)

$p_{wind\_down} =$ wind downward pressure per ASCE 7-10 Chapter 30 Part 1, $c_{pi} = 0$ (without 16 psf minimum)

$p_{wind\_up} =$ wind upward pressure per ASCE 7-10 Chapter 30 Part 1, $c_{pi} = 0$ (without 16 psf minimum)

$C_L =$ beam stability factor (assumed to be 0.80)

$C_{D,DL} =$ load duration factor for dead load = 0.90

$C_{D,LL_r} =$ load duration factor for roof live load = 1.25

$C_{D,wind} =$ load duration factor for wind = 1.60

For wind upward load combinations, where the bottom of rafter is in compression, a beam stability factor of 0.80 is assumed. This takes into account modest torsional restraint and stiffness from three potential effects: roof sheathing is clamped by sheathing nailing to the top of the rafter, creating torsion stiffness; solar mounting components also brace the rafter against

torsional buckling through clamping action; and rafters are sometimes sheathed on the interior side, bracing the bottom of the rafter directly against torsional buckling.

2.F.4.1. Additional Reserve Strength: The DCRs calculated above are multiplied by 0.90 to account for the following effects:

- 2013 CBC Chapter 34 "Existing Structures" allows increases in design gravity loads of up to 5 percent (article 3403.3.) without recalculation or re-evaluation.
- Modules do not cover the entire slope from eave to ridge. The State Fire Marshall requirement of a three feet or greater set back from the ridge results in bending moments that are 88% for a 12 foot span, and 92% for a 15 feet span compared to a rafter fully and uniformly loaded from roof to ridge.
- Discrete incremental rafter sizes (2x4, 2x6 etc.) and spans (16" vs. 24") makes it unlikely that a roof framing design will precisely match the most efficient DCR of 1.00. In fact, as Table A2.4 shows, the average DCR increment between rafter nominal sizes with 16" o.c. and 24" o.c. rafter spacing options is 0.72. If we assume roof designs are equally distributed between DCR = 0.72 and 1.00, then 50% of the time the expected DCR will be 0.86 or less, and 90% of the time the expected DCR from this effect will be 0.97 or less.

Combining the last two effects suggests that the mean expected DCR is (.88)(.86) = 0.76 where 50% of DCRs are expected to be higher and 50% lower; and the 90% DCR is (.92)(.97) = 0.89 where 90% of DCRs are expected to be lower and 10% higher, showing that the 0.90 multiplier is a reasonable and conservative assumption, even without taking into consideration the existing building code's allowance that calculated DCR may be less than 1.05 instead of 1.00. This shifts the crossing point where DCR=1.00 to slightly steeper roof slopes. See the "Summary Graph" discussion.

Table A2.4 Rafter Design Strength Steps[1,2]

Rafter	Depth (in.)	Spacing (in.)	Strength Index	Incremental Relative Strength
2x4	3.5	24	0.51	0.67
		16	0.77	0.61
2x6	5.5	24	1.26	0.67
		16	1.89	0.86
2x8	7.25	24	2.19	0.67
		16	3.29	0.92
2x10	9.25	24	3.57	0.67
		16	5.35	-
			Avg:	0.72

Table Notes:
1. Strength Index = (d^2)/s where d = rafter depth and s = rafter spacing
2. Incremental Relative Strength = strength index at row i divided by strength index at row i+1

2.F.4.2 Summary Tables: Tables A2.5.1.1(a) through A2.5.2.2(f) list DCRs for a range of rafter spacings (16" and 24" o.c.), anchor-to-rafter spacings (n = 1 to 4 rafter spaces), slopes, mean roof heights (30, 40 and 50 feet) and wind exposures (B, C and D). DCRs of 1.00 or less are shaded green, while DCRs greater than 1.00 are shaded red.

The "SUMMARY" section at the bottom of each table lists allowable anchor rafter spacings as a function of roof slope and wind exposure. Anchor rafter spacings of three or four are shown in green, spacings of two are shown in orange, and spacings of one are shown in red.

The numbering hierarchy of the A2.5 tables are as follows:

Table A2.5

.1 = 3.5 psf (solar PV)

.2 = 5 psf (solar thermal)

.1 = 16" o.c. rafter spacing

.2 = 24" o.c. rafter spacing

(a) roof mean ht = 30 ft, sheathing = 1/2" plywood, Cr = 1.15

(b) roof mean ht = 40 ft, sheathing = 1/2" plywood, Cr = 1.15

(c) roof mean ht = 50 ft, sheathing = 1/2" plywood, Cr = 1.15

(d) roof mean ht = 30 ft, sheathing = 7/16" OSB, Cr = 1.05

(e) roof mean ht = 40 ft, sheathing = 7/16" OSB, Cr = 1.05

(f) roof mean ht = 50 ft, sheathing = 7/16" OSB, Cr = 1.05

The East Bay Green Corridor's Structural Check List Table 2 (Maximum Horizontal Anchor Spacing) is based on Tables A2.5.1.1(c) and A2.5.1.2(c). These tables cover Solar PV arrays on rafters at 16" and 24" on center, with the assumptions of roof mean height = 50 feet, sheathing = 1/2" nominal (15"/32" actual) plywood, Cr = 1.15 and Wind Exposure B.

The State Solar Permitting Guidebook's Toolkit Structural Criteria Table 1 (Anchor Maximum Horizontal Spacing) is based on Tables A2.5.1.1(e), A2.5.1.2(e), A2.5.2.1(e), and A2.5.2.2(e). These tables cover both Solar PV and Solar Thermal arrays on rafters at 16" and 24" on center, with the more conservative assumptions of roof mean height = 40 feet, sheathing = 7/16" OSB, Cr = 1.05 and Wind Exposure C.

Tables A2.6a and A2.7a (the "simple" tables) summarize the anchor maximum horizontal (cross-slope) spacing that is allowed in the EBGC Structural Check List Table 2, and the State Structural Criteria Table 1, respectively. The "simple" tables differ only in the 7:12 to 9:12 slope range. Tables A2.6b and A2.7b (the "comprehensive" tables) show allowed anchor spacing for wind exposures outside of the base assumption (i.e. Exposure B for EBGC, Exposure C for the State).

Table A2.5.1.1(a) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 30 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in²/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.73	0.79	0.86
7: to 9:12	(27° to 36°)	0.77	0.87	1.00	1.19
10: to 12:12	(37° to 45°)	0.91	1.04	1.20	1.43
13: to 17:12	(46° to 55°)	0.98	1.13	1.31	1.58
18: to 24:12	(56° to 63°)	1.00	1.16	1.36	1.65
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.73	0.79	0.86
7: to 9:12	(27° to 36°)	0.84	0.96	1.12	1.35
10: to 12:12	(37° to 45°)	0.95	1.09	1.28	1.54
13: to 17:12	(46° to 55°)	1.00	1.15	1.36	1.66
18: to 24:12	(56° to 63°)	0.99	1.15	1.36	1.67
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.73	0.79	0.89
7: to 9:12	(27° to 36°)	0.86	1.00	1.17	1.41
10: to 12:12	(37° to 45°)	0.97	1.12	1.32	1.60
13: to 17:12	(46° to 55°)	0.99	1.15	1.36	1.66
18: to 24:12	(56° to 63°)	0.98	1.14	1.36	1.67

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3*	3*
7: to 9:12	(27° to 36°)	3	2	2
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.2(a) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 30 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in²/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.76	0.88	1.00
7: to 9:12	(27° to 36°)	0.77	0.95	1.25	1.56
10: to 12:12	(37° to 45°)	0.91	1.13	1.50	1.89
13: to 17:12	(46° to 55°)	0.98	1.24	1.67	2.11
18: to 24:12	(56° to 63°)	1.00	1.28	1.74	2.23
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.76	0.88	1.06
7: to 9:12	(27° to 36°)	0.84	1.06	1.42	1.80
10: to 12:12	(37° to 45°)	0.95	1.20	1.63	2.07
13: to 17:12	(46° to 55°)	1.00	1.28	1.75	2.24
18: to 24:12	(56° to 63°)	0.99	1.27	1.76	2.28
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.76	0.93	1.23
7: to 9:12	(27° to 36°)	0.86	1.10	1.49	1.89
10: to 12:12	(37° to 45°)	0.97	1.24	1.69	2.16
13: to 17:12	(46° to 55°)	0.99	1.28	1.76	2.27
18: to 24:12	(56° to 63°)	0.98	1.27	1.77	2.35

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3	3
7: to 9:12	(27° to 36°)	2	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.1(b) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 40 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.73	0.79	0.86
7: to 9:12	(27° to 36°)	0.80	0.91	1.05	1.25
10: to 12:12	(37° to 45°)	0.92	1.05	1.22	1.46
13: to 17:12	(46° to 55°)	0.99	1.14	1.33	1.61
18: to 24:12	(56° to 63°)	1.00	1.16	1.36	1.66
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.73	0.79	0.86
7: to 9:12	(27° to 36°)	0.85	0.97	1.14	1.37
10: to 12:12	(37° to 45°)	0.96	1.10	1.29	1.57
13: to 17:12	(46° to 55°)	1.00	1.15	1.36	1.66
18: to 24:12	(56° to 63°)	0.98	1.15	1.36	1.67
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.73	0.79	0.91
7: to 9:12	(27° to 36°)	0.87	1.00	1.18	1.43
10: to 12:12	(37° to 45°)	0.98	1.13	1.33	1.62
13: to 17:12	(46° to 55°)	0.99	1.15	1.36	1.67
18: to 24:12	(56° to 63°)	0.97	1.14	1.36	1.68

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3*	3*
7: to 9:12	(27° to 36°)	2	2	2
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.2(b) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 40 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.76	0.88	1.00
7: to 9:12	(27° to 36°)	0.80	0.99	1.31	1.65
10: to 12:12	(37° to 45°)	0.92	1.15	1.53	1.93
13: to 17:12	(46° to 55°)	0.99	1.25	1.70	2.16
18: to 24:12	(56° to 63°)	1.00	1.28	1.75	2.24
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.76	0.89	1.09
7: to 9:12	(27° to 36°)	0.85	1.07	1.44	1.83
10: to 12:12	(37° to 45°)	0.96	1.22	1.65	2.10
13: to 17:12	(46° to 55°)	1.00	1.28	1.75	2.25
18: to 24:12	(56° to 63°)	0.98	1.27	1.77	2.29
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.76	0.95	1.32
7: to 9:12	(27° to 36°)	0.87	1.11	1.51	1.92
10: to 12:12	(37° to 45°)	0.98	1.25	1.71	2.19
13: to 17:12	(46° to 55°)	0.99	1.28	1.76	2.27
18: to 24:12	(56° to 63°)	0.97	1.27	1.78	2.39

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3	3
7: to 9:12	(27° to 36°)	2	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.1(c) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 50 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.73	0.79	0.86
7: to 9:12	(27° to 36°)	0.82	0.93	1.07	1.28
10: to 12:12	(37° to 45°)	0.93	1.06	1.24	1.48
13: to 17:12	(46° to 55°)	1.00	1.15	1.35	1.63
18: to 24:12	(56° to 63°)	1.00	1.16	1.36	1.66
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.73	0.79	0.87
7: to 9:12	(27° to 36°)	0.86	0.98	1.15	1.39
10: to 12:12	(37° to 45°)	0.96	1.11	1.31	1.58
13: to 17:12	(46° to 55°)	0.99	1.15	1.36	1.66
18: to 24:12	(56° to 63°)	0.98	1.14	1.36	1.67
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.73	0.79	0.93
7: to 9:12	(27° to 36°)	0.88	1.00	1.19	1.45
10: to 12:12	(37° to 45°)	0.98	1.14	1.34	1.63
13: to 17:12	(46° to 55°)	0.99	1.15	1.36	1.67
18: to 24:12	(56° to 63°)	0.97	1.14	1.36	1.68

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3*	3*
7: to 9:12	(27° to 36°)	2	2	2
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.1(c) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 50 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.76	0.88	1.00
7: to 9:12	(27° to 36°)	0.82	1.00	1.35	1.69
10: to 12:12	(37° to 45°)	0.93	1.16	1.56	1.97
13: to 17:12	(46° to 55°)	1.00	1.27	1.72	2.19
18: to 24:12	(56° to 63°)	1.00	1.28	1.75	2.25
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.76	0.91	1.13
7: to 9:12	(27° to 36°)	0.86	1.08	1.46	1.86
10: to 12:12	(37° to 45°)	0.96	1.23	1.67	2.13
13: to 17:12	(46° to 55°)	0.99	1.28	1.76	2.26
18: to 24:12	(56° to 63°)	0.98	1.27	1.77	2.30
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.76	0.99	1.39
7: to 9:12	(27° to 36°)	0.88	1.12	1.52	1.95
10: to 12:12	(37° to 45°)	0.98	1.26	1.72	2.21
13: to 17:12	(46° to 55°)	0.99	1.27	1.76	2.28
18: to 24:12	(56° to 63°)	0.97	1.27	1.78	2.42

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3	3
7: to 9:12	(27° to 36°)	2	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.1(d) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 30 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.77	0.84	0.93
7: to 9:12	(27° to 36°)	0.77	0.95	1.14	1.37
10: to 12:12	(37° to 45°)	0.91	1.14	1.37	1.66
13: to 17:12	(46° to 55°)	0.98	1.24	1.50	1.84
18: to 24:12	(56° to 63°)	1.00	1.28	1.57	1.93
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.77	0.84	0.94
7: to 9:12	(27° to 36°)	0.84	1.06	1.28	1.57
10: to 12:12	(37° to 45°)	0.95	1.21	1.47	1.80
13: to 17:12	(46° to 55°)	1.00	1.28	1.57	1.94
18: to 24:12	(56° to 63°)	0.99	1.28	1.58	1.96
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.77	0.85	1.01
7: to 9:12	(27° to 36°)	0.86	1.10	1.34	1.65
10: to 12:12	(37° to 45°)	0.97	1.24	1.52	1.87
13: to 17:12	(46° to 55°)	0.99	1.28	1.58	1.96
18: to 24:12	(56° to 63°)	0.98	1.28	1.58	1.98

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3*	3
7: to 9:12	(27° to 36°)	2	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.2(d) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 30 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.81	0.96	1.11
7: to 9:12	(27° to 36°)	0.77	1.07	1.45	1.83
10: to 12:12	(37° to 45°)	0.91	1.28	1.75	2.22
13: to 17:12	(46° to 55°)	0.98	1.41	1.95	2.49
18: to 24:12	(56° to 63°)	1.00	1.46	2.05	2.64
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.81	0.98	1.23
7: to 9:12	(27° to 36°)	0.84	1.20	1.66	2.12
10: to 12:12	(37° to 45°)	0.95	1.37	1.91	2.44
13: to 17:12	(46° to 55°)	1.00	1.46	2.06	2.66
18: to 24:12	(56° to 63°)	0.99	1.47	2.09	2.71
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.81	1.10	1.54
7: to 9:12	(27° to 36°)	0.86	1.25	1.74	2.24
10: to 12:12	(37° to 45°)	0.97	1.42	1.99	2.56
13: to 17:12	(46° to 55°)	0.99	1.47	2.08	2.69
18: to 24:12	(56° to 63°)	0.98	1.47	2.12	2.88

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3	3	2
7: to 9:12	(27° to 36°)	1	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.1(e) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 40 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.77	0.84	0.93
7: to 9:12	(27° to 36°)	0.80	1.00	1.19	1.44
10: to 12:12	(37° to 45°)	0.92	1.15	1.39	1.69
13: to 17:12	(46° to 55°)	0.99	1.26	1.53	1.87
18: to 24:12	(56° to 63°)	1.00	1.28	1.57	1.94
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.77	0.84	0.96
7: to 9:12	(27° to 36°)	0.85	1.07	1.30	1.59
10: to 12:12	(37° to 45°)	0.96	1.22	1.49	1.83
13: to 17:12	(46° to 55°)	1.00	1.28	1.57	1.95
18: to 24:12	(56° to 63°)	0.98	1.28	1.58	1.97
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.77	0.87	1.09
7: to 9:12	(27° to 36°)	0.87	1.11	1.36	1.67
10: to 12:12	(37° to 45°)	0.98	1.25	1.54	1.90
13: to 17:12	(46° to 55°)	0.99	1.28	1.58	1.96
18: to 24:12	(56° to 63°)	0.97	1.28	1.58	2.00

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3*	3
7: to 9:12	(27° to 36°)	2	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.2(e) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 40 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.81	0.96	1.11
7: to 9:12	(27° to 36°)	0.80	1.12	1.52	1.93
10: to 12:12	(37° to 45°)	0.92	1.30	1.79	2.27
13: to 17:12	(46° to 55°)	0.99	1.43	1.99	2.54
18: to 24:12	(56° to 63°)	1.00	1.46	2.06	2.66
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.81	1.00	1.33
7: to 9:12	(27° to 36°)	0.85	1.22	1.69	2.16
10: to 12:12	(37° to 45°)	0.96	1.39	1.94	2.48
13: to 17:12	(46° to 55°)	1.00	1.46	2.07	2.67
18: to 24:12	(56° to 63°)	0.98	1.47	2.09	2.77
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.83	1.18	1.64
7: to 9:12	(27° to 36°)	0.87	1.27	1.77	2.27
10: to 12:12	(37° to 45°)	0.98	1.43	2.01	2.59
13: to 17:12	(46° to 55°)	0.99	1.47	2.08	2.70
18: to 24:12	(56° to 63°)	0.97	1.47	2.16	2.92

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3	3	2
7: to 9:12	(27° to 36°)	1	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.1(f) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 50 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.77	0.84	0.93
7: to 9:12	(27° to 36°)	0.82	1.00	1.22	1.48
10: to 12:12	(37° to 45°)	0.93	1.17	1.41	1.72
13: to 17:12	(46° to 55°)	1.00	1.27	1.55	1.90
18: to 24:12	(56° to 63°)	1.00	1.28	1.57	1.95
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.77	0.84	0.99
7: to 9:12	(27° to 36°)	0.86	1.09	1.32	1.62
10: to 12:12	(37° to 45°)	0.96	1.23	1.50	1.85
13: to 17:12	(46° to 55°)	0.99	1.28	1.57	1.95
18: to 24:12	(56° to 63°)	0.98	1.28	1.58	1.97
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.77	0.89	1.15
7: to 9:12	(27° to 36°)	0.88	1.12	1.37	1.69
10: to 12:12	(37° to 45°)	0.98	1.26	1.55	1.91
13: to 17:12	(46° to 55°)	0.99	1.28	1.58	1.96
18: to 24:12	(56° to 63°)	0.97	1.27	1.59	2.03

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3*	3
7: to 9:12	(27° to 36°)	2	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.1.2(f) Rafter DCR's - PV Array (3.5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 50 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.69	0.81	0.96	1.11
7: to 9:12	(27° to 36°)	0.82	1.15	1.57	1.99
10: to 12:12	(37° to 45°)	0.93	1.32	1.82	2.31
13: to 17:12	(46° to 55°)	1.00	1.44	2.02	2.59
18: to 24:12	(56° to 63°)	1.00	1.46	2.07	2.67
		Exposure C			
0: to 6:12	(0° to 26°)	0.69	0.81	1.03	1.42
7: to 9:12	(27° to 36°)	0.86	1.23	1.71	2.19
10: to 12:12	(37° to 45°)	0.96	1.40	1.96	2.52
13: to 17:12	(46° to 55°)	0.99	1.46	2.07	2.68
18: to 24:12	(56° to 63°)	0.98	1.47	2.10	2.82
		Exposure D			
0: to 6:12	(0° to 26°)	0.69	0.84	1.24	1.73
7: to 9:12	(27° to 36°)	0.88	1.28	1.79	2.30
10: to 12:12	(37° to 45°)	0.98	1.44	2.03	2.62
13: to 17:12	(46° to 55°)	0.99	1.47	2.09	2.72
18: to 24:12	(56° to 63°)	0.97	1.47	2.19	2.96

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3	2	2
7: to 9:12	(27° to 36°)	1	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	1	1	1
18: to 24:12	(56° to 63°)	1	1	1

Table A2.5.2.1(a) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 30 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in²/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.83	0.90	1.00
7: to 9:12	(27° to 36°)	0.82	0.93	1.07	1.28
10: to 12:12	(37° to 45°)	0.96	1.10	1.28	1.53
13: to 17:12	(46° to 55°)	1.03	1.18	1.39	1.68
18: to 24:12	(56° to 63°)	1.06	1.22	1.43	1.74
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.83	0.90	1.00
7: to 9:12	(27° to 36°)	0.88	1.00	1.19	1.43
10: to 12:12	(37° to 45°)	1.00	1.15	1.35	1.63
13: to 17:12	(46° to 55°)	1.04	1.21	1.42	1.73
18: to 24:12	(56° to 63°)	1.02	1.19	1.42	1.73
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.83	0.90	1.00
7: to 9:12	(27° to 36°)	0.90	1.04	1.23	1.49
10: to 12:12	(37° to 45°)	1.00	1.17	1.38	1.68
13: to 17:12	(46° to 55°)	1.03	1.20	1.42	1.73
18: to 24:12	(56° to 63°)	1.01	1.18	1.41	1.73

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3*	3*
7: to 9:12	(27° to 36°)	2	2	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.2(a) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 30 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in²/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.87	1.04	1.21
7: to 9:12	(27° to 36°)	0.82	1.00	1.35	1.69
10: to 12:12	(37° to 45°)	0.96	1.21	1.61	2.03
13: to 17:12	(46° to 55°)	1.03	1.30	1.76	2.25
18: to 24:12	(56° to 63°)	1.06	1.35	1.83	2.35
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.87	1.04	1.21
7: to 9:12	(27° to 36°)	0.88	1.12	1.51	1.91
10: to 12:12	(37° to 45°)	1.00	1.27	1.72	2.19
13: to 17:12	(46° to 55°)	1.04	1.33	1.83	2.35
18: to 24:12	(56° to 63°)	1.02	1.33	1.83	2.37
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.87	1.04	1.26
7: to 9:12	(27° to 36°)	0.90	1.15	1.57	2.00
10: to 12:12	(37° to 45°)	1.00	1.30	1.78	2.27
13: to 17:12	(46° to 55°)	1.03	1.33	1.83	2.36
18: to 24:12	(56° to 63°)	1.01	1.32	1.83	2.38

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	2	2	2
7: to 9:12	(27° to 36°)	2	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.1(b) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 40 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.83	0.90	1.00
7: to 9:12	(27° to 36°)	0.85	0.96	1.12	1.34
10: to 12:12	(37° to 45°)	0.97	1.11	1.30	1.56
13: to 17:12	(46° to 55°)	1.04	1.20	1.40	1.70
18: to 24:12	(56° to 63°)	1.05	1.21	1.43	1.74
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.83	0.90	1.00
7: to 9:12	(27° to 36°)	0.89	1.03	1.20	1.45
10: to 12:12	(37° to 45°)	1.00	1.16	1.36	1.65
13: to 17:12	(46° to 55°)	1.04	1.20	1.42	1.73
18: to 24:12	(56° to 63°)	1.02	1.19	1.42	1.73
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.83	0.90	1.00
7: to 9:12	(27° to 36°)	0.91	1.05	1.24	1.50
10: to 12:12	(37° to 45°)	1.00	1.18	1.39	1.70
13: to 17:12	(46° to 55°)	1.03	1.20	1.42	1.73
18: to 24:12	(56° to 63°)	1.01	1.18	1.41	1.73

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3*	3*
7: to 9:12	(27° to 36°)	2	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.2(b) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 40 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.87	1.04	1.21
7: to 9:12	(27° to 36°)	0.85	1.06	1.41	1.77
10: to 12:12	(37° to 45°)	0.97	1.22	1.64	2.07
13: to 17:12	(46° to 55°)	1.04	1.32	1.79	2.28
18: to 24:12	(56° to 63°)	1.05	1.34	1.83	2.35
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.87	1.04	1.21
7: to 9:12	(27° to 36°)	0.89	1.13	1.53	1.95
10: to 12:12	(37° to 45°)	1.00	1.28	1.74	2.22
13: to 17:12	(46° to 55°)	1.04	1.33	1.83	2.36
18: to 24:12	(56° to 63°)	1.02	1.32	1.83	2.37
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.87	1.04	1.29
7: to 9:12	(27° to 36°)	0.91	1.16	1.59	2.03
10: to 12:12	(37° to 45°)	1.00	1.31	1.79	2.30
13: to 17:12	(46° to 55°)	1.03	1.33	1.83	2.37
18: to 24:12	(56° to 63°)	1.01	1.31	1.83	2.38

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	2	2	2
7: to 9:12	(27° to 36°)	1	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.1(c) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 50 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.83	0.90	1.00
7: to 9:12	(27° to 36°)	0.86	0.98	1.14	1.37
10: to 12:12	(37° to 45°)	0.98	1.12	1.31	1.57
13: to 17:12	(46° to 55°)	1.04	1.20	1.42	1.72
18: to 24:12	(56° to 63°)	1.04	1.21	1.43	1.73
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.83	0.90	1.00
7: to 9:12	(27° to 36°)	0.90	1.03	1.21	1.47
10: to 12:12	(37° to 45°)	1.00	1.16	1.37	1.66
13: to 17:12	(46° to 55°)	1.03	1.20	1.42	1.73
18: to 24:12	(56° to 63°)	1.01	1.19	1.41	1.73
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.83	0.90	1.00
7: to 9:12	(27° to 36°)	0.92	1.06	1.25	1.52
10: to 12:12	(37° to 45°)	1.00	1.19	1.40	1.71
13: to 17:12	(46° to 55°)	1.03	1.20	1.42	1.73
18: to 24:12	(56° to 63°)	1.00	1.18	1.41	1.73

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3*	3*	3*
7: to 9:12	(27° to 36°)	2	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.2(c) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 50 ft
Sheathing type = 1/2" nominal plywood (EI = 125,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.15

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.87	1.04	1.21
7: to 9:12	(27° to 36°)	0.86	1.08	1.44	1.82
10: to 12:12	(37° to 45°)	0.98	1.23	1.66	2.10
13: to 17:12	(46° to 55°)	1.04	1.33	1.81	2.31
18: to 24:12	(56° to 63°)	1.04	1.34	1.83	2.36
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.87	1.04	1.23
7: to 9:12	(27° to 36°)	0.90	1.14	1.55	1.97
10: to 12:12	(37° to 45°)	1.00	1.29	1.75	2.24
13: to 17:12	(46° to 55°)	1.03	1.33	1.83	2.36
18: to 24:12	(56° to 63°)	1.01	1.32	1.83	2.37
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.87	1.06	1.32
7: to 9:12	(27° to 36°)	0.92	1.17	1.60	2.05
10: to 12:12	(37° to 45°)	1.00	1.31	1.81	2.32
13: to 17:12	(46° to 55°)	1.03	1.33	1.83	2.37
18: to 24:12	(56° to 63°)	1.00	1.31	1.83	2.38

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	2	2	2
7: to 9:12	(27° to 36°)	1	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.1(d) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 30 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.87	0.98	1.11
7: to 9:12	(27° to 36°)	0.82	1.00	1.22	1.48
10: to 12:12	(37° to 45°)	0.96	1.21	1.46	1.77
13: to 17:12	(46° to 55°)	1.03	1.31	1.59	1.95
18: to 24:12	(56° to 63°)	1.06	1.35	1.65	2.03
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.87	0.98	1.11
7: to 9:12	(27° to 36°)	0.88	1.12	1.36	1.67
10: to 12:12	(37° to 45°)	1.00	1.27	1.55	1.90
13: to 17:12	(46° to 55°)	1.04	1.34	1.64	2.03
18: to 24:12	(56° to 63°)	1.02	1.33	1.64	2.04
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.87	0.98	1.11
7: to 9:12	(27° to 36°)	0.90	1.16	1.41	1.74
10: to 12:12	(37° to 45°)	1.00	1.30	1.60	1.97
13: to 17:12	(46° to 55°)	1.03	1.33	1.64	2.04
18: to 24:12	(56° to 63°)	1.01	1.32	1.64	2.05

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3	3	3
7: to 9:12	(27° to 36°)	2	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.2(d) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 30 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.94	1.15	1.36
7: to 9:12	(27° to 36°)	0.82	1.15	1.56	1.98
10: to 12:12	(37° to 45°)	0.96	1.37	1.88	2.39
13: to 17:12	(46° to 55°)	1.03	1.49	2.07	2.65
18: to 24:12	(56° to 63°)	1.06	1.54	2.16	2.78
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.94	1.15	1.36
7: to 9:12	(27° to 36°)	0.88	1.27	1.76	2.26
10: to 12:12	(37° to 45°)	1.00	1.45	2.02	2.59
13: to 17:12	(46° to 55°)	1.04	1.53	2.16	2.79
18: to 24:12	(56° to 63°)	1.02	1.53	2.17	2.82
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.94	1.17	1.47
7: to 9:12	(27° to 36°)	0.90	1.32	1.84	2.37
10: to 12:12	(37° to 45°)	1.00	1.49	2.09	2.70
13: to 17:12	(46° to 55°)	1.03	1.53	2.17	2.81
18: to 24:12	(56° to 63°)	1.01	1.52	2.18	2.84

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	2	2	2
7: to 9:12	(27° to 36°)	1	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.1(e) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 40 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.87	0.98	1.11
7: to 9:12	(27° to 36°)	0.85	1.06	1.28	1.55
10: to 12:12	(37° to 45°)	0.97	1.22	1.48	1.81
13: to 17:12	(46° to 55°)	1.04	1.32	1.61	1.98
18: to 24:12	(56° to 63°)	1.05	1.35	1.65	2.03
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.87	0.98	1.11
7: to 9:12	(27° to 36°)	0.89	1.13	1.38	1.69
10: to 12:12	(37° to 45°)	1.00	1.28	1.56	1.93
13: to 17:12	(46° to 55°)	1.04	1.34	1.64	2.04
18: to 24:12	(56° to 63°)	1.02	1.33	1.64	2.04
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.87	0.98	1.14
7: to 9:12	(27° to 36°)	0.91	1.17	1.43	1.76
10: to 12:12	(37° to 45°)	1.00	1.31	1.61	1.99
13: to 17:12	(46° to 55°)	1.03	1.33	1.64	2.04
18: to 24:12	(56° to 63°)	1.01	1.32	1.64	2.05

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3	3	3
7: to 9:12	(27° to 36°)	1	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.2(e) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 40 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.94	1.15	1.36
7: to 9:12	(27° to 36°)	0.85	1.20	1.64	2.08
10: to 12:12	(37° to 45°)	0.97	1.38	1.91	2.44
13: to 17:12	(46° to 55°)	1.04	1.51	2.10	2.70
18: to 24:12	(56° to 63°)	1.05	1.53	2.16	2.79
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.94	1.15	1.40
7: to 9:12	(27° to 36°)	0.89	1.29	1.79	2.30
10: to 12:12	(37° to 45°)	1.00	1.46	2.04	2.63
13: to 17:12	(46° to 55°)	1.04	1.53	2.16	2.80
18: to 24:12	(56° to 63°)	1.02	1.52	2.17	2.83
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.94	1.20	1.54
7: to 9:12	(27° to 36°)	0.91	1.33	1.87	2.40
10: to 12:12	(37° to 45°)	1.00	1.50	2.11	2.73
13: to 17:12	(46° to 55°)	1.03	1.53	2.17	2.82
18: to 24:12	(56° to 63°)	1.01	1.52	2.18	2.85

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	2	2	2
7: to 9:12	(27° to 36°)	1	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.1(f) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 16" o.c.
Mean roof height = 50 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.87	0.98	1.11
7: to 9:12	(27° to 36°)	0.86	1.08	1.30	1.59
10: to 12:12	(37° to 45°)	0.98	1.24	1.50	1.83
13: to 17:12	(46° to 55°)	1.04	1.33	1.63	2.01
18: to 24:12	(56° to 63°)	1.04	1.34	1.64	2.04
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.87	0.98	1.11
7: to 9:12	(27° to 36°)	0.90	1.14	1.39	1.71
10: to 12:12	(37° to 45°)	1.00	1.29	1.58	1.95
13: to 17:12	(46° to 55°)	1.03	1.34	1.64	2.04
18: to 24:12	(56° to 63°)	1.01	1.32	1.64	2.04
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.87	0.98	1.16
7: to 9:12	(27° to 36°)	0.92	1.18	1.44	1.78
10: to 12:12	(37° to 45°)	1.00	1.32	1.62	2.01
13: to 17:12	(46° to 55°)	1.03	1.33	1.64	2.04
18: to 24:12	(56° to 63°)	1.00	1.32	1.64	2.05

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	3	3	3
7: to 9:12	(27° to 36°)	1	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.5.2.2(f) DCR's - Solar Thermal Array (5 psf)

Rafter spacing = 24" o.c.
Mean roof height = 50 ft
Sheathing type = 7/16" nominal plywood (EI = 78,000 lb-in^2/ft)
Repetitive member factor, Cr = 1.05

Roof Slope		No. of Rafter Spaces			
X : 12	degrees	1	2	3	4
		Exposure B			
0: to 6:12	(0° to 26°)	0.77	0.94	1.15	1.36
7: to 9:12	(27° to 36°)	0.86	1.22	1.68	2.14
10: to 12:12	(37° to 45°)	0.98	1.40	1.94	2.47
13: to 17:12	(46° to 55°)	1.04	1.52	2.13	2.74
18: to 24:12	(56° to 63°)	1.04	1.53	2.16	2.80
		Exposure C			
0: to 6:12	(0° to 26°)	0.77	0.94	1.15	1.43
7: to 9:12	(27° to 36°)	0.90	1.30	1.81	2.33
10: to 12:12	(37° to 45°)	1.00	1.47	2.06	2.66
13: to 17:12	(46° to 55°)	1.03	1.53	2.16	2.80
18: to 24:12	(56° to 63°)	1.01	1.52	2.18	2.83
		Exposure D			
0: to 6:12	(0° to 26°)	0.77	0.94	1.22	1.62
7: to 9:12	(27° to 36°)	0.92	1.34	1.89	2.43
10: to 12:12	(37° to 45°)	1.00	1.51	2.13	2.75
13: to 17:12	(46° to 55°)	1.03	1.53	2.17	2.82
18: to 24:12	(56° to 63°)	1.00	1.52	2.18	2.89

SUMMARY

Roof Slope		Wind Exposure		
X : 12	degrees	B	C	D
0: to 6:12	(0° to 26°)	2	2	2
7: to 9:12	(27° to 36°)	1	1	1
10: to 12:12	(37° to 45°)	1	1	1
13: to 17:12	(46° to 55°)	N/A	N/A	N/A
18: to 24:12	(56° to 63°)	N/A	N/A	N/A

Table A2.6a EBGC Maximum Horizontal Anchor Spacing (Simple Table)[1,2,3]

Roof Slope		Rafter Spacing		
		16" o.c.	24" o.c.	32" o.c.
Flat to 6:12	0° to 26°	5'-4"	6'-0"	5'-4"
7:12 to 9:12	27° to 36°	2'-8"	4'-0"	5'-4"
10:12 to 24:12	37° to 63°	1'-4"	2'-0"	2'-8"

Notes:

1. Table applies to roofs with a mean height of 50 feet or less. Mean roof height is the distance from average grade to midway between roof eave and ridge (see Figure A1.1).
2. Table assumes Wind Exposure B and design wind speed of 110 mph (ASCE 7-10. See Table A2.6b for other wind exposures.
3. If anchors are staggered from row-to-row going up the roof, anchor spacing may twice that shown in the table, but no more than 6'-0".

Table A2.6b EBGC Maximum Horizontal Anchor Spacing (Comprehensive Table)[1]

Roof Slope		Wind Exposure (110 mph ASCE 7-10)		
		B	C	D
Rafter Spacing = 16" on center				
Flat to 6:12	0° to 26°	5'-4"	5'-4"	5'-4"
7:12 to 9:12	27° to 36°	2'-8" *	2'-8"	1'-4" *
10:12 to 24:12	37° to 63°	1'-4"	1'-4"	1'-4"
Rafter Spacing = 24" on center				
Flat to 6:12	0° to 26°	6'-0"	6'-0"	6'-0"
7:12 to 9:12	27° to 36°	4'-0"	2'-0"	2'-0"
10:12 to 24:12	37° to 63°	2'-0"	2'-0"	2'-0"
Rafter Spacing = 32" on center				
Flat to 6:12	0° to 26°	5'-4"	5'-4"	5'-4"
7:12 to 9:12	27° to 36°	5'-4"	2'-8"	2'-8"
10:12 to 24:12	37° to 63°	2'-8"	2'-8"	2'-8"

Notes:

* This entry applies to roof mean heights between 30 and 50 feet; at roof mean heights of 30 feet or less, anchors may be spaced at an additional rafter spacing (i.e. 1'-4" becomes 2'-8", and 2'-8" becomes 4'-0").
1. See Table A2.6a for other notes.

Color Coding of Cells:

Anchor at every 4th rafter
Anchor at every 3rd rafter
Anchor at every 2nd rafter
Anchor at every rafter

Table A2.7a California's Structural Toolkit's Anchor Maximum Horizontal Spacing (Simple Table)[1,2,3]

Roof Slope		Rafter Spacing		
		16" o.c.	24" o.c.	32" o.c.
Flat to 6:12	0° to 26°	5'-4"	6'-0"	5'-4"
7:12 to 9:12	27° to 36°	1'-4"	2'-0"	2'-8"
10:12 to 24:12	37° to 63°	1'-4"	2'-0"	2'-8"

Notes:

1. Table applies to roofs with a mean height of 40 feet or less. Mean roof height is the distance from average grade to midway between roof eave and ridge (see Figure A1.1).
2. Table assumes Wind Exposure C and design wind speed of 110 mph (ASCE 7-10. See Table A2.11b for other wind exposures.
3. If anchors are staggered from row-to-row going up the roof, anchor spacing may twice that shown in the table, but no more than 6'-0".

Table A2.7b California's Structural Toolkit's Anchor Max. Horiz. Spacing (Comprehensive Table)[1]

Roof Slope		Wind Exposure (110 mph ASCE 7-10)		
		B	C	D
Rafter Spacing = 16" on center				
Flat to 6:12	0° to 26°	5'-4"	5'-4"	4'-0"
7:12 to 9:12	27° to 36°	2'-8"	1'-4"	1'-4"
10:12 to 24:12	37° to 63°	1'-4"	1'-4"	1'-4"
Rafter Spacing = 24" on center				
Flat to 6:12	0° to 26°	6'-0"	6'-0"	4'-0"
7:12 to 9:12	27° to 36°	2'-0"	2'-0"	2'-0"
10:12 to 24:12	37° to 63°	2'-0"	2'-0"	2'-0"

1. See Table A2.7a for notes.

Color Coding of Cells:

Anchor at every 4th rafter
Anchor at every 3rd rafter
Anchor at every 2nd rafter
Anchor at every rafter

2.F.4.3 Summary Graphs: The DCR analysis can also be plotted as load-duration normalized demands and capacities, plotted as a function of roof slope, as shown in Figures A2.9.1.1(a) through A2.9.2.2(b). The duration-normalized loads are disaggregated into three rafter demand load combinations that occur with the new solar array: (1) dead loads of original roof and new solar modules, (2) dead loads of original roof and new solar modules plus wind down on the modules, and (3) wind up minus dead loads of the original roof and new solar modules. The four capacity load combinations for the originally designed roof rafter are also plotted: (1) dead plus roof live load, (2) dead plus wind down, and (3) dead plus 75% of roof live load and 75% of wind down, and (4) wind up minus dead load. Curves are traced between maximum loads for both demand and capacity. This provides insight into which load combinations control and define the DCRs at a given roof slope. The A2.9 figures are based on Wind Exposure B and a roof mean height of 30 feet. Graphs are provided for both 16" and 24" rafter spacing for n = 2 and 3 (i.e., anchoring to every other rafter, and every third rafter, respectively).

The demands and capacities shown the A2.9 have not been adjusted for reduced demand from the three feet set back from the ridge, or for the increased capacity considering the inability of designers to precisely design to DCR=1.00 because of the large incremental steps in bending strength given available rafter sizes and rafter spacing. A more accurate approach would be to both decrease the demand curves (set back from ridge effect) and increase the capacity curves (incremental bending strength effect), plotted as a function of roof slope. This would reduce the expected DCRs for a given roof slope while shifting the crossing point where DCR=1.00 to steeper roof slopes.

The numbering hierarchy of the A2.9 tables are as follows:

Figure A2.9

- .1 = load on every 2nd rafter (n=2)
- .2 = load on every 3rd rafter (n=3)
  - .1 = 24" o.c. rafter spacing
  - .2 = 16" o.c. rafter spacing
    - (a) sheathing = 1/2" plywood, Cr = 1.15
    - (b) sheathing = 7/16" OSB, Cr = 1.05

The East Bay Green Corridor's (EBGC) Structural Check List Table 2 (Maximum Horizontal Anchor Spacing) is based on conditions similar to, but slightly more conservative than, the A2.9._._(a) Figures. These figures cover Solar PV arrays with anchors at every second and third rafter, on rafters at 16" and 24" on center, and with the assumptions of Wind Exposure B, roof mean height = 30 feet, sheathing = 1/2" nominal (15"/32" actual) plywood, and Cr = 1.05. The EBGC Structural Check List Table 2 is based on the slightly more conservative assumption of a mean roof height of 50 feet instead of 30 feet.

The State Solar Permitting Guidebook's Toolkit Structural Criteria Table 1 (Anchor Maximum Horizontal Spacing) is based on conditions similar to, but more conservative than, the A2.9._._(b) Figures. These figures cover Solar PV arrays with anchors at every second and third rafter, on rafters at 16" and 24" on center, and with the assumptions of Wind Exposure B, roof mean height = 30 feet, sheathing = 1/2" nominal (15"/32" actual) plywood, and Cr = 1.05. The Structural Criteria's Table 1 is actually based on the more conservative assumptions of Wind Exposure C (instead of B) and mean roof height of 40 feet (instead of 30 feet). The Structural Criteria's Table 1 also covers Solar Thermal arrays in addition to Solar PV arrays.

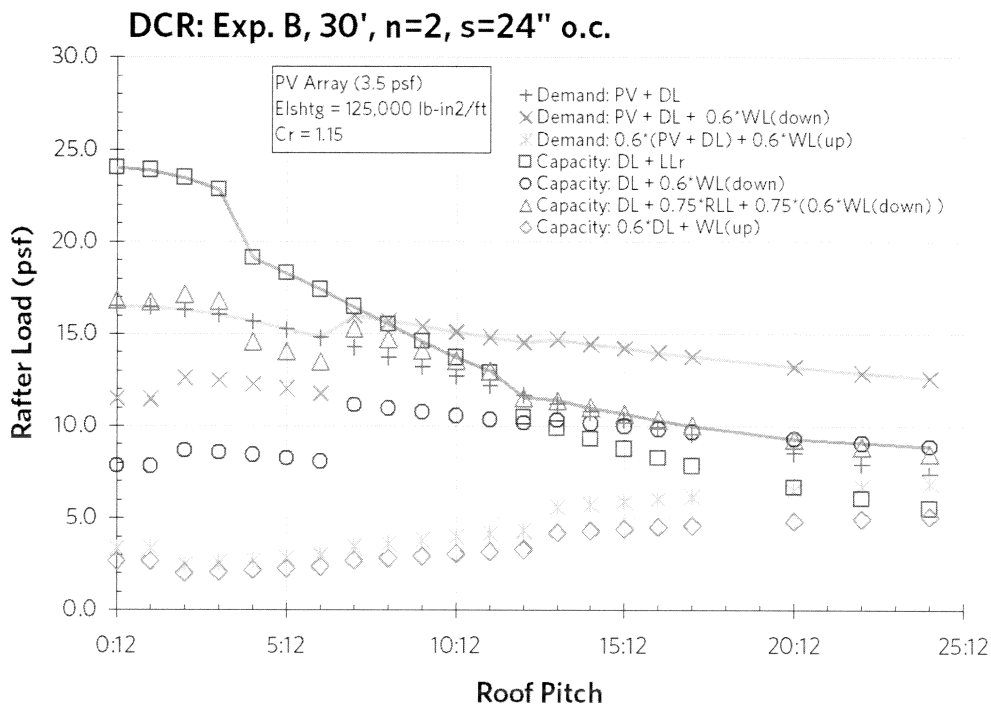


Figure A2.9.1.1(a). Demand and capacity normalized loads, anchors at every 2nd rafter, rafters spaced at 24" o.c., using East Bay Green Corridor assumptions for sheathing thickness and Cr.

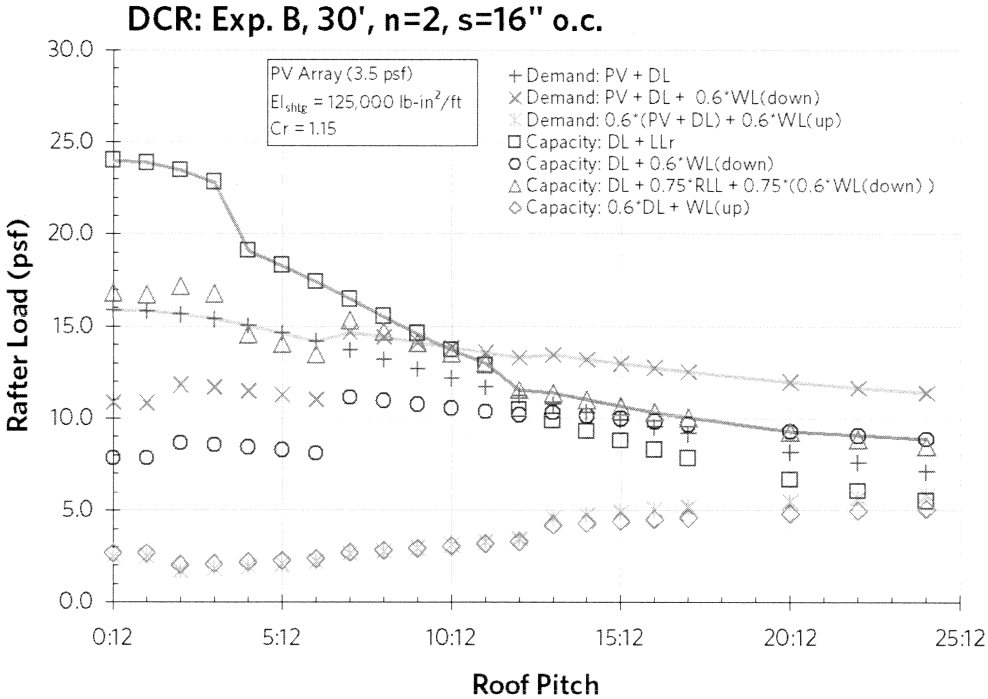


Figure A2.9.1.2(a). Demand and capacity normalized loads, anchors at every 2nd rafter, rafters spaced at 16" o.c., using East Bay Green Corridor assumptions for sheathing thickness and Cr.

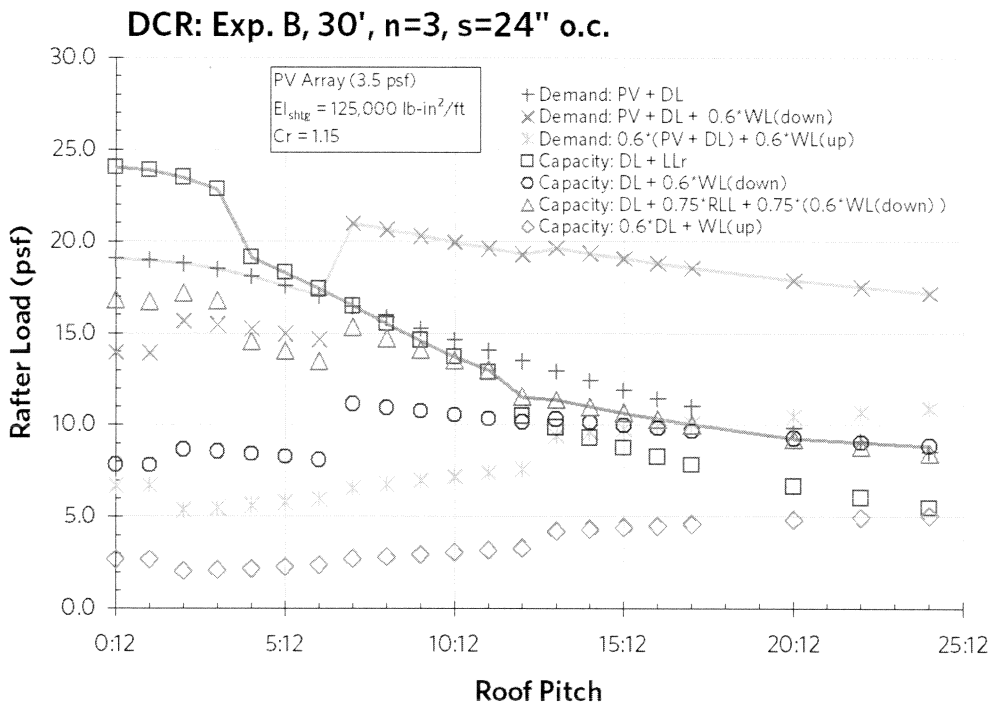


Figure A2.9.1.2(a). Demand and capacity normalized loads, anchors at every 3rd rafter, rafters spaced at 24" o.c., using East Bay Green Corridor assumptions for sheathing thickness and Cr.

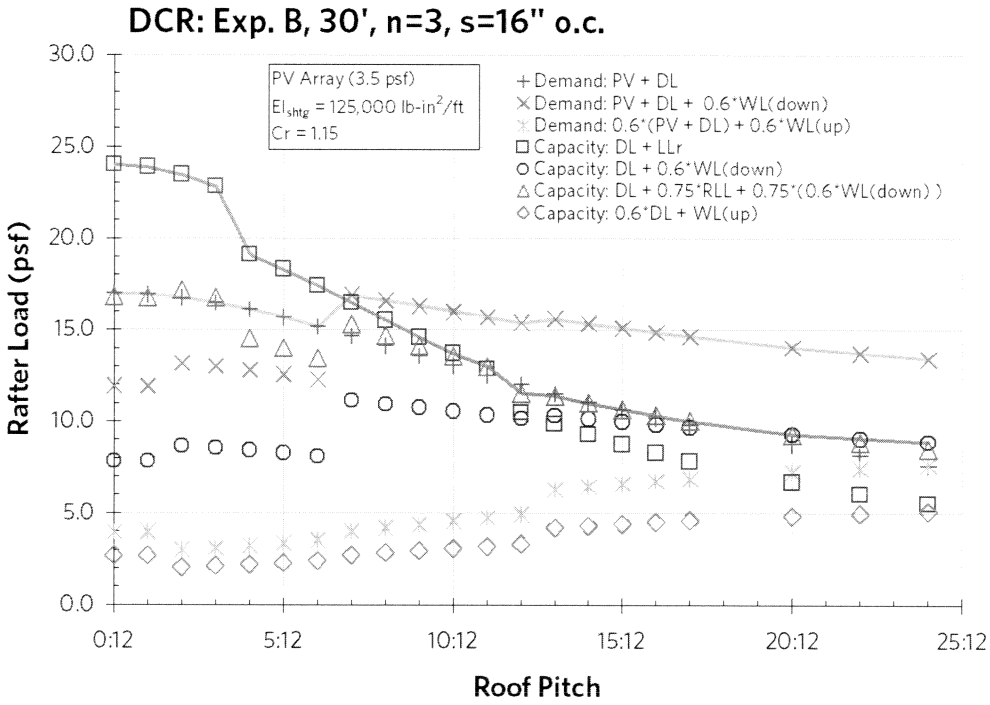


Figure A2.9.2.2(a). Demand and capacity normalized loads, anchors at every 3rd rafter, rafters spaced at 16" o.c., using East Bay Green Corridor assumptions for sheathing thickness and Cr.

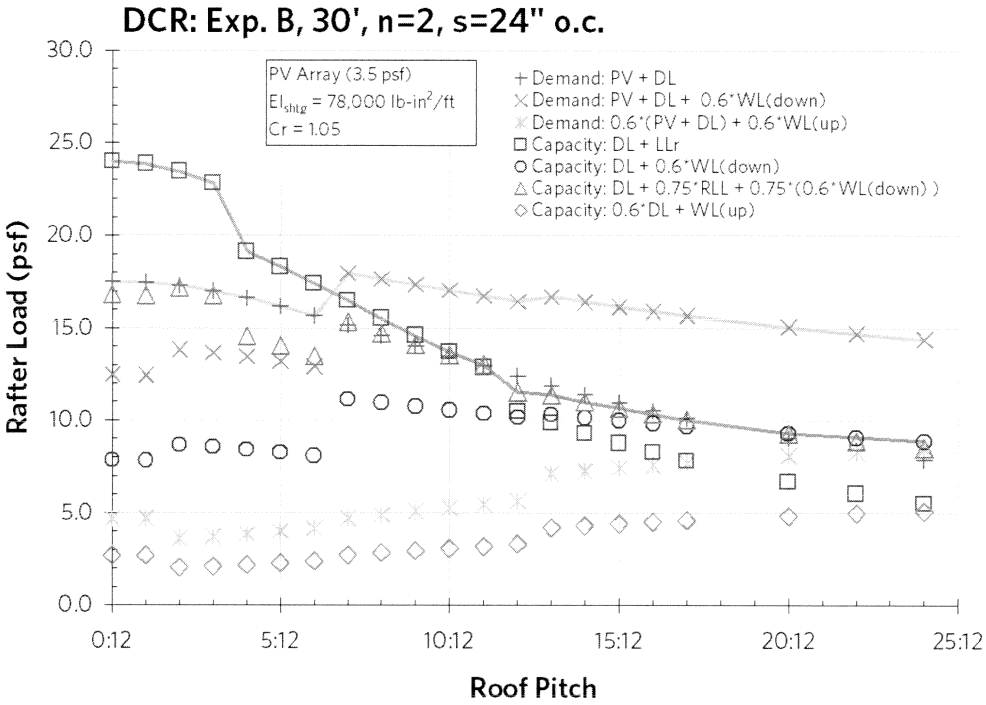


Figure A2.9.1.1(b). Demand and capacity normalized loads, anchors at every 2nd rafter, rafters spaced at 24" o.c., using California's Solar Permitting Guidebook's Toolkit Structural Criteria assumptions for sheathing thickness and Cr.

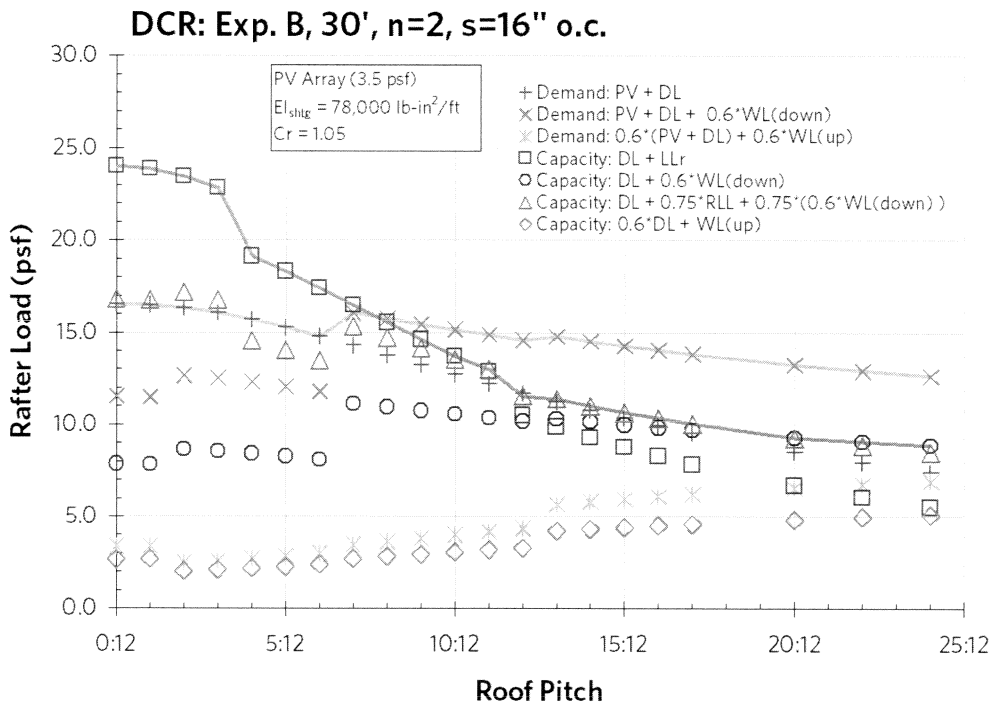


Figure A2.9.1.2(b). Demand and capacity normalized loads, anchors at every 2nd rafter, rafters spaced at 16" o.c., using California's Solar Permitting Guidebook's Toolkit Structural Criteria assumptions for sheathing thickness and Cr.

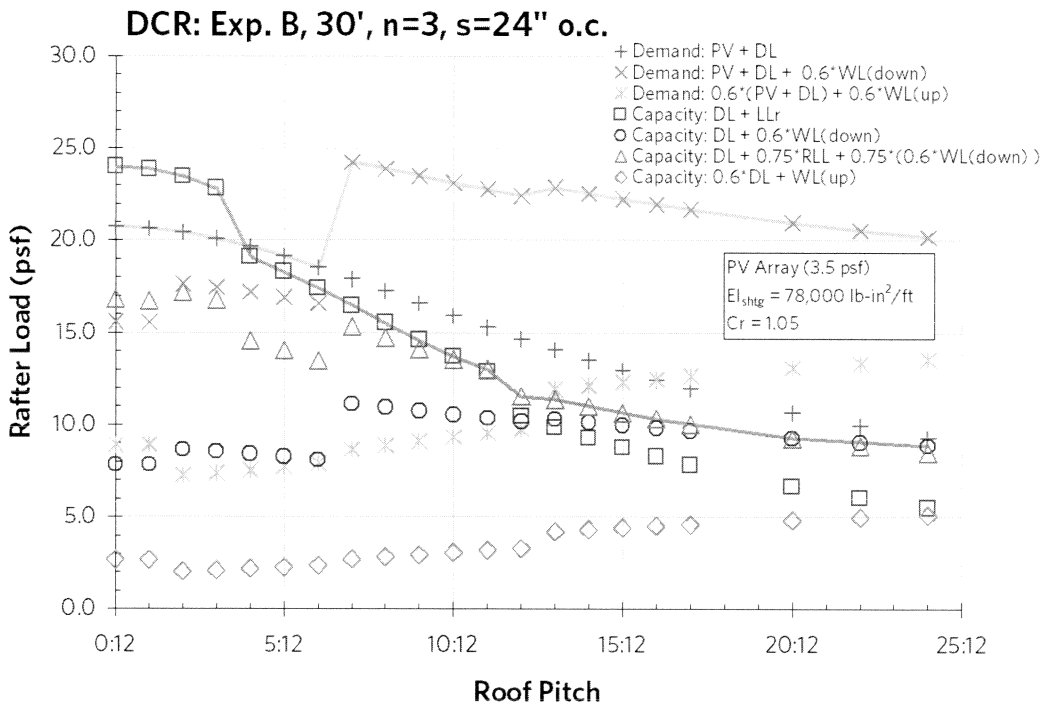


Figure A2.9.2.1(b). Demand and capacity normalized loads, anchors at every 3rd rafter, rafters spaced at 24" o.c., using California's Solar Permitting Guidebook's Toolkit Structural Criteria assumptions for sheathing thickness and Cr.

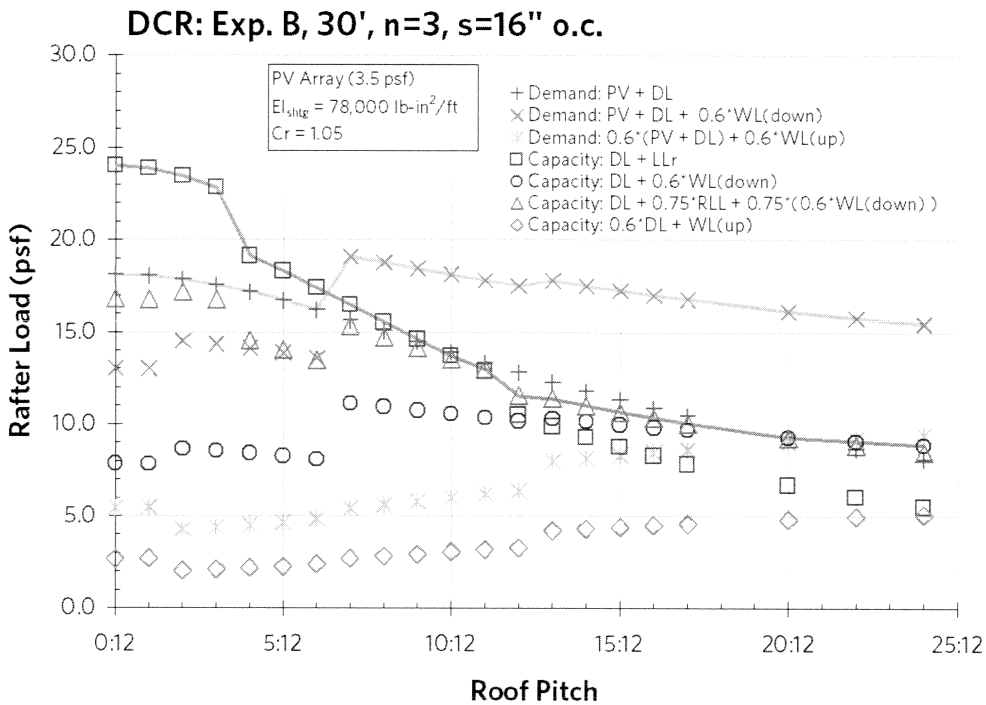


Figure A2.9.2.2(b). Demand and capacity normalized loads, anchors at every 3rd rafter, rafters spaced at 16" o.c., using California's Solar Permitting Guidebook's Toolkit Structural Criteria assumptions for sheathing thickness and Cr.

2.F.5. Statistical Analysis of the Conservatism of EBGC and State Assumptions

The analysis behind Table 1 (maximum horizontal anchor spacing) is based on a series of assumptions that determine where most installations fall in relation to code compliance (Demand Capacity Ratio, DCR = 1.00). If these assumptions are consistently unconservative, a significant fraction of installations could, upon further analysis, be shown to not comply with code (though would likely still be relatively safe). On the other hand, a series of overly conservative assumptions can create a situation where the vast majority of installations are needlessly conservative and therefore unnecessarily costly, just to address an extremely rare and unusual combination of conditions.

The statistical analysis below provides a sense of the level of conservatism for the both the original East Bay Green Corridor's Structural Check List, and the State Toolkit's Structural Criteria. Table A2.12 lists assumptions in six categories used in developing the anchor maximum horizontal spacing tables for the East Bay Green Corridor (EBGC) project and the State's Solar Permitting Guidebook. Those categories of assumptions are:

1. Thickness of sheathing (7/16" OSB, 15/32" OSB or Plywood, 1x sheathing)
2. Array loading pattern along rafter (anchors at midspan, third points or uniform)
3. Lumber spacing and size increments, assuming the original design was optimized, reflecting the best combination of rafter spacing and size to keep the demand/capacity ratio as close to one as possible without exceeding one.
4. Demand reduction from an array's partial coverage of rafter length, considering the portion of arrays that do not fully extend from eave to ridge.
5. Wind exposure (B, C or D).
6. Roof mean height (20, 30, 40 or 50 feet).

In each category, the EBGC and State analyses made assumptions that are located along a range of possible assumptions normalized capacity/demand ratios, with each possible choice also having a corresponding estimated frequency of occurrence. For instance, the first category (sheathing) has three sheathing thickness choices, with corresponding normalized capacity/demand ratios and estimated frequencies. The CLSF for 7/16" sheathing is 1.33, and normalized to CLSF=1.47 for the more common 15/32" sheathing, the normalized capacity/demand ratio (termed the NCDR "multiplier") is 1.33/1.47 = 0.90.

For the state environment, based on interviews with lumber wholesalers, the fraction of dwellings with 7/16" roof sheathing is estimated to be about 30% of tract home developments in the central valley, and about 15% of single and two-family dwellings statewide, while for EBGC, with older housing stock and fewer low-end tract homes, the estimated frequency of 7/16" OSB is lower. Likewise, the state, with large developments in the central valley, is assumed to have more Exposure C conditions with dwellings adjacent large open fields, compared to EBGC, with most dwellings in urban/suburban areas with Exposure B terrain

surface roughness. Because the estimated relative proportions of sheathing thicknesses and Wind Exposures for the state differ from the East Bay region, the state as a whole has a statistical "environment" that differs from the EBGC.

The number of choices in the six assumption categories are 3,3,4,5,3 and 4 respectively, so the number of possible combinations of NCDR probabilities is (3)(3)(4)(5)(3)(4) = 2,160. For each of the 2,160 combinations, the product of the six NCDR multipliers is calculated, along with the corresponding product of six frequencies. Within discrete increments of NCDR product multipliers, the corresponding frequency products are summed. The result is a histogram that roughly approximates a normal distribution. Along this histogram, the product of the six NCDR multipliers can be located, for both the EBCG and State assumptions, and the area under the lower bound tail can be compared to the total area under the histogram to calculate the expected percentage of projects that do not comply with code. For the set of State assumptions, compared to the State environment, the estimated frequency of code noncompliance for solar arrays installed on roofs is less than 0.2% (2 out of 1,000 dwellings), while the East Bay Green Corridor structural checklist may result in code noncompliant designs 5% of the time.

It is important to note that the code has large factors of safety, so the probability of code noncompliance is many times greater than the probability of damage or collapse. To put this in perspective, 5% of visually-graded timber columns are weaker than code-expected strengths (Breyer, Fridley, Cobeen and Pollack). This means that one out of twenty columns in large wood-framed warehouses and "big box" stores are "understrength", yet because of large factors of safety in the building code, collapse is exceedingly rare. From this perspective, the assumptions behind the EBGC Structural Check List that create a 5% lower bound tail are probably appropriate, while the assumptions behind the State Structural Criteria that create a 0.2% lower bound tail may be overly conservative.

Table A2.12. Maximum Horizontal Anchor Spacing Table's Basis Within Range of Assumptions, Normalized to 1.00 = Typical or Average

East Bay Green Corridor (EBGC)
State of California Toolkit Structural Document
Both (unchanged from EBGC)

1. Concentrated Load Sharing Factor Sheathing Thickness

CLSF, sheathing thickness (example: anchor spacing=3 rsp)

Thickness	CLSF	Normalized	State Est. % Freq	EBGC Est. % Freq
7/16" OSB	1.33	0.90	15%	5%
15/32" OSB	1.47	1.00	70%	50%
19/32" OSB	1.67	1.14	15%	45%

2. CLSF, Moment Distribution Assumption

			Est. % Freq
Midspan Pt Load	1.51	0.94	15%
Third Pt. Loads	1.60	1.00	70%
Uniform Load	1.73	1.08	15%

3. DCR, lumber incremental size

See Table A2.4	Rel. Strength	Mean DCR	Mean CDR		Est. % Freq
2x4@16 to 2x6@24	0.61	0.81	1.24	1.04	14%
2x4@24 to 2x4@24	0.67	0.84	1.20	1.00	57%
2x6@24 to 2x6@16	0.67	0.84	1.20	1.00	57%
2x8@24 to 2x8@16	0.67	0.84	1.20	1.00	57%
2x10@24 to 2x10@16	0.67	0.84	1.20	1.00	57%
2x6@16 to 2x8@24	0.86	0.93	1.08	0.90	14%
sqrt(1.00/.90)		0.95	1.05	0.88	
2x8@16 to 2x10@24	0.92	0.96	1.04	0.87	14%

Table continued, next page

4. Demand Reduction from partial roof coverage (3 ft from ridge)

Panel Coverage	Relative Moment	1/Mr	Normalized to 15'	Est. % Freq
8 ft - 3 ft to ridge (63% cover)	0.74	1.35	1.24	20%
12 ft - 3 ft to ridge (75% cover)	0.88	1.14	1.05	30%
15 ft - 3 ft to ridge (80% cover)	0.92	1.09	1.00	30%
18 ft - 3 ft to ridge (83% cover)	0.95	1.05	0.97	10%
sqrt(1.00/.90)	0.95	1.05	0.97	
Full Coverage	1.00	1.00	0.92	10%

5. Wind Exposure Assumption			State Est. % Freq	EBGC Est. % Freq
Exosure B	1.00	1.00	78%	88%
Exposure C	1.40	0.71	25%	10%
Exposure D	1.66	0.60	2%	2%

6. Mean Roof Height Assumption			Est. % Freq
20 feet, 1 story	0.90	1.11	45%
30 feet, tall 2 story	1.00	1.00	30%
40 feet. 3 story	1.09	0.92	10%
50 feet, tall 3 story	1.16	0.86	5%

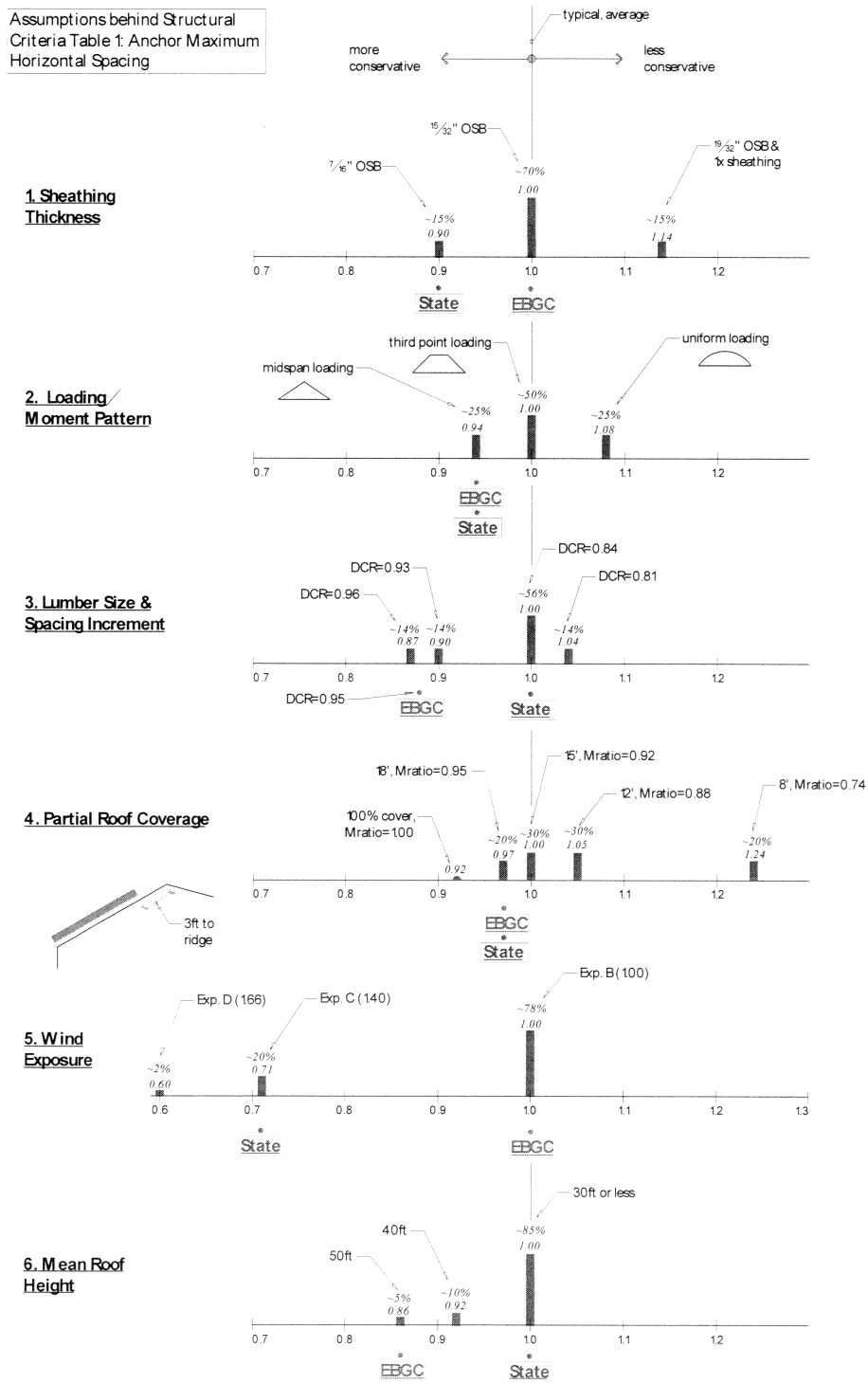


Figure A2.10: Assumptions behind the Structural Criteria's Table 1 considered in the statistical analysis shown in figure A2.12.

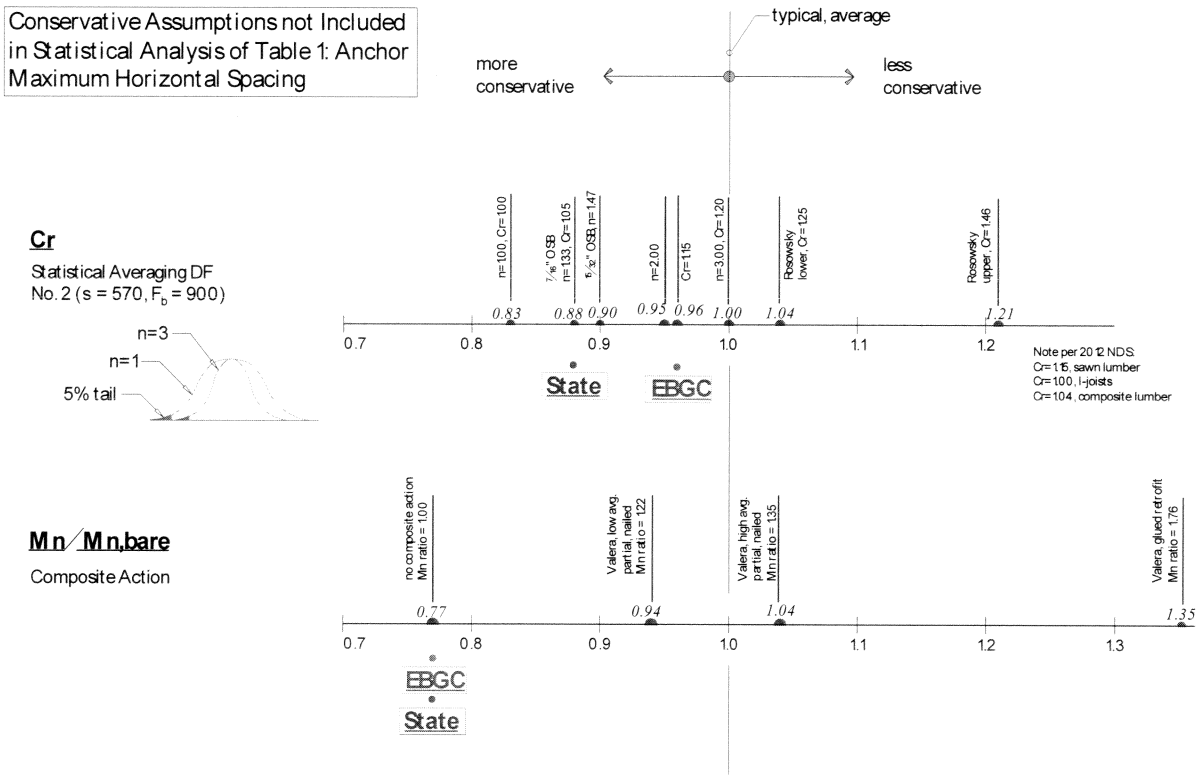


Figure A2.10: Conservative assumptions regarding Cr=1.05 and no partial composite action that are part of the basis of the Structural Criteria's Table 1, but are not considered in the statistical analysis shown in figure A2.12.

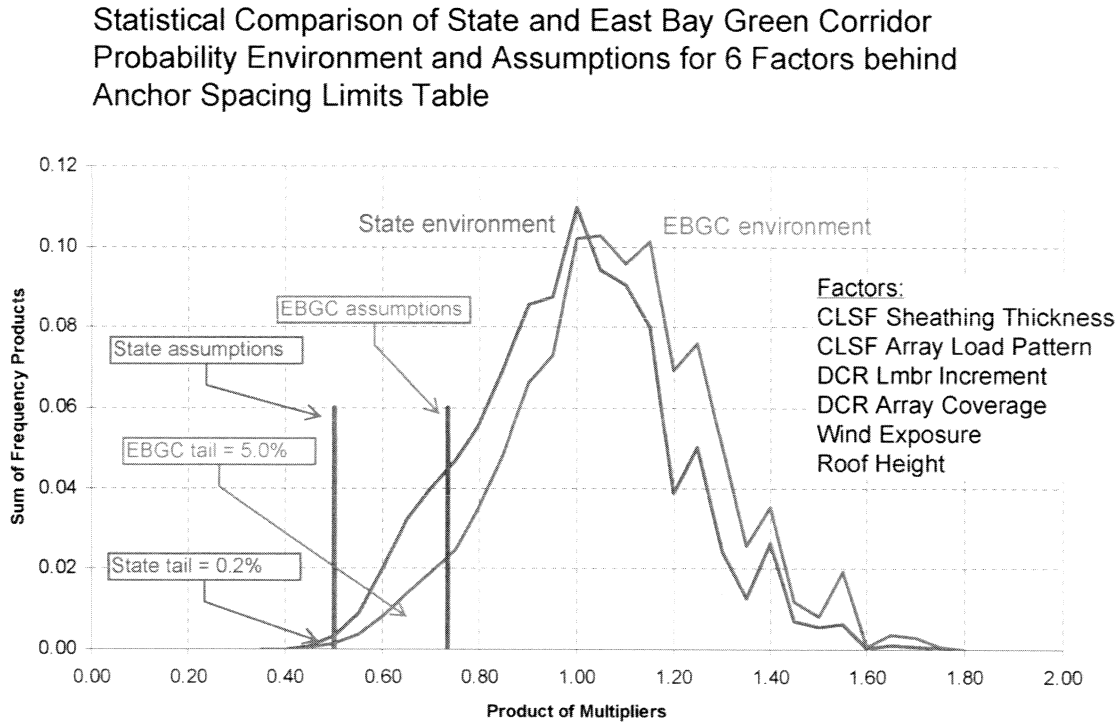


Figure A2.12: Statistical analysis of the likelihood that solar array installations based on the Anchor Maximum Horizontal Spacing tables (EBGC Table 2, State Table 1) will result in designs that do not comply with the building code. The analysis suggests that following State criteria will result in code noncompliant designs less than 0.2% (2 out of 1,000) of the time, while the East Bay Green Corridor structural checklist may result in code noncompliant designs 5% of the time. It is important to note that the code has large factors of safety, so the probability of code noncompliance is many times greater than the probability of damage or collapse.

2.G. Wind Uplift Checks

Most solar support component manufacturers' code compliance manuals set appropriate limits on wind uplift tributary areas, and define acceptable fasteners, including screw diameter and minimum embedment depth into the rafter.

2.G.1. Alternative Tables in Lieu of Manufacturer's Guidelines: The following section provides an alternative conservative approach if the installer does not use pre-designed solar support component systems, or does not follow the manufacturers' code compliance guidelines.

Tabulated anchor tributary areas are based on the following assumptions:

- PV system self weight (including modules and mounting hardware) is assumed to be 3.5 psf.

- Anchor point is assumed to be fastened by one or more 5/16" lag screws with a minimum penetration of 2½" installed in the middle third of a 2x roof rafter.
- The rafter has a specific gravity of 0.42 (e.g. Spruce-Pine-Fir) or greater (e.g. Hem-Fir, Close-grain Redwood, Douglas-Fir), and therefore applies to almost all framing lumber used on the west coast.
- Allowable load increases due to load duration are included.
- Service conditions are dry and below 100°F.
- Building importance factor for wind = 1.0 in all cases.
- The building is not located in an area prone to significant wind speed up effects (topographic factor K_{zt} = 1.0).
- Wind loads are determined from ASCE 7-10 modified for an internal pressure coefficient GCpi = 0. The 16 psf minimum design wind load is ignored.
- The maximum panel cantilever is L/3 where L is the distance of the cantilever backspan.

In addition to the assumptions above, the lag screw withdrawal capacity was reduced by a factor of 1.4 to account for two effects:

1. Prying effects that are sometimes found in anchorage details, and
2. Rafter off-center effects, to cover mis-installation where the lag screw is not installed within the required middle third (1/2") strip along the center of the 2x rafter that is assumed by NDS (1.5d edge distance = 1.5 x 5/16" = 0.47"). 5/16" diameter lag or self-drilling screws can sometimes be installed even closer than 1.5d to the rafter edge without resulting in loss of torque ("spinning in the hole") that would alert the installer to a mis-located screw.

Tables A2.13 also allows for the following modification factors if an anchor is not fastened down by a 5/16" diameter lag screw embedded at least 2½" into a roof rafter:

a. Multiply tributary areas by 0.80 for 2" threaded embedment for 5/16" lag screws.
b. Multiply tributary areas by 0.67 for 1/4" diameter self-drilling screws with 2½" threaded embedment, and by 0.54 factor for 1/4" diameter self-drilling screws with 2" threaded embedment.
c. If two fasteners are used per anchor, tributary areas shall not exceed those shown in the table, but do not need to be reduced per notes b and c.

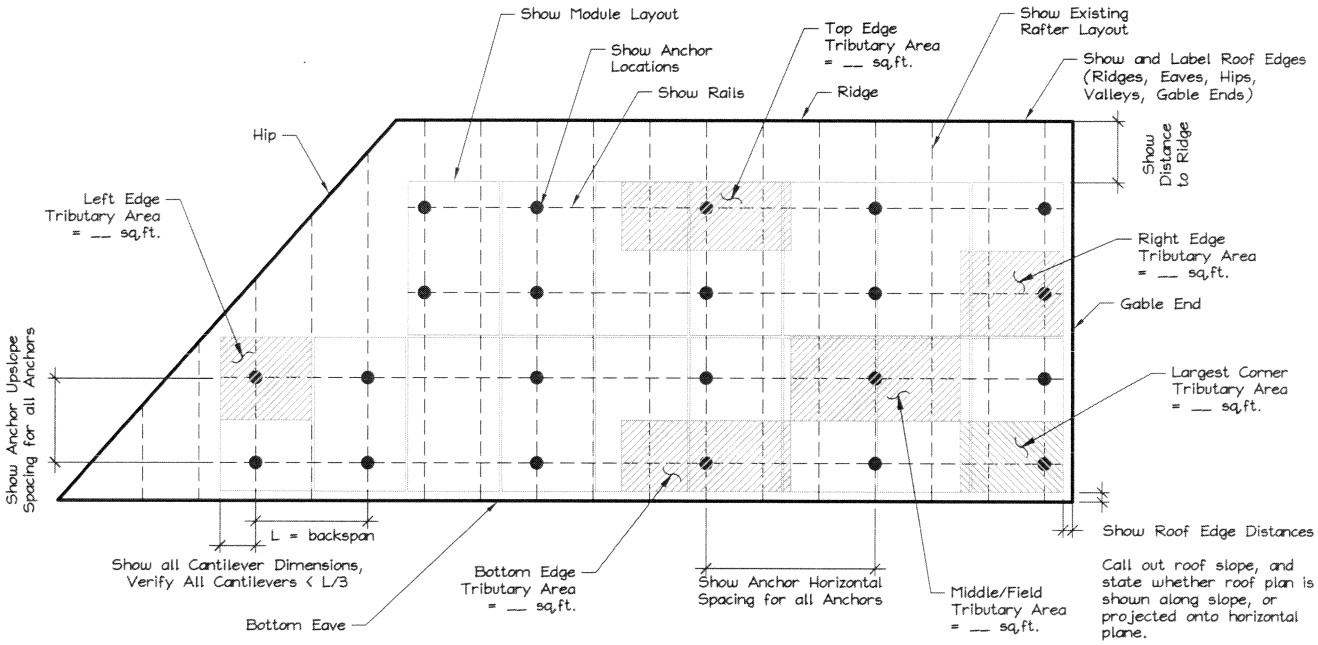


Figure A2.13. Sample Photovoltaic Module and Anchor Layout Diagram.

Table A2.13. Maximum Tributary Area per Anchor (Square Feet)

Mean Roof Height (feet)	Roof Pitch	Roof Zone	Exposure Category		
			B	C	D
30	Flat to 6:12	1 (Interior / Field)	34	25	21
		2 (Edge)	19	13	11
		3 (Corner)	12	8	7
	7:12 to 9:12	1 (Interior / Field)	25	25	22
		2 (Edge)	25	21	17
		3 (Corner)	25	21	17
	10:12 to 12:12	1 (Interior / Field)	21	21	21
		2 (Edge)	21	21	17
		3 (Corner)	21	21	17
40	Flat to 6:12	1 (Interior / Field)	32	23	19
		2 (Edge)	17	12	10
		3 (Corner)	11	8	7
	7:12 to 9:12	1 (Interior / Field)	25	24	19
		2 (Edge)	25	19	16
		3 (Corner)	25	19	16
	10:12 to 12:12	1 (Interior / Field)	21	21	19
		2 (Edge)	21	19	16
		3 (Corner)	21	19	16
50	Flat to 6:12	1 (Interior / Field)	30	22	18
		2 (Edge)	16	12	10
		3 (Corner)	10	7	6
	7:12 to 9:12	1 (Interior / Field)	25	23	18
		2 (Edge)	25	18	15
		3 (Corner)	25	18	15
	10:12 to 12:12	1 (Interior / Field)	21	21	18
		2 (Edge)	21	18	15
		3 (Corner)	21	18	15

See Table Notes, Next Page

Table Notes:

1. Mean roof height is the distance from average grade to midway between roof eave and ridge.
2. Table assumes 110 mph design wind speed (ASCE 7-10) and zero snow load.
3. Tabulated tributary areas are based on the following anchorage assumptions:
   a. Anchor is fastened by one 5/16" diameter lag screw with minimum threaded penetration of 2½" into the rafter, not including sheathing. Install in a pre-drilled 3/16" diameter hole to prevent splitting.
   b. Anchor withdrawal and lateral capacities are multiplied by 0.5 to account for possible misalignment with rafter centerline.
   c. Table applies to any wood with a specific gravity of 0.42 (e.g. Spruce-Pine-Fir) or greater (e.g. Hem-Fir, Close-grain Redwood, Douglas-Fir), and therefore applies to almost all framing lumber used on the west coast.
4. Modify the tabulated tributary areas for the conditions described below:
   a. Multiply tributary areas by 0.80 factor for 2" threaded embedment.
   b. Multiply tributary areas by 0.67 factor for 1/4" diameter self-drilling screws with 2.5" threaded embedment, and by 0.54 factor for 2" threaded embedment.
   c. If two fasteners are used per anchor, tributary areas shall not exceed those shown in the table above, but do not need to be reduced per notes 4.a and 4.b.
5. The installer is responsible for determining that support components and hardware can span between anchor points.
6. In the following notes, "roof edge" is defined as a ridge, hip, gable end or eave. "Gap distance" is the distance between surface of roof and underside of module.
   a. At roof edges where modules are within one gap distance to roof edge, multiply edge and corner areas by one half.
   b. At roof edges where modules are within two gap distances to roof edge, multiply edge and corner areas by two-thirds.

2.G.2. Distance to Edge of Roof Requirements: Wind tunnel studies show that as wind passes over a roof edge, it creates a high-velocity shear layer that bends toward the roof plane as it crosses over a building wall-roof edge interface (see Figure A3.2). The angle of this shear layer in relation to the roof plane varies with time, and is affected by the angle between the wall-and-roof planes, or at hips and ridges, the angle between two roof planes. Solar module edges that align with the roof edge are within the shear layer, effectively turning the edge of the modules into roof overhangs. As the modules are pulled back away from the roof edge, their tendency to catch the shear layer updraft is reduced. According to Dr. David Banks (e-mail 3/18/2013), if "gap" is defined as the distance from the roof surface to the underside of the module, then the module should be set back about two gap lengths from any roof edge to ensure the module is outside the shear layer zone. ICC AC 428 addresses this effect by simply requiring that all modules be set back 10" from all roof edges. This may be conservative for gaps less than 5 inches.

An alternative way of addressing this effect is to reduce the Table A2.13 maximum edge and corner tributary areas if the high velocity roof edge zone is encroached upon. The overhang / shear layer effect can be conservatively taken into account by doubling assumed uplift pressures (i.e. halving the allowed edge tributary area per anchor) if the module is within one gap distance to a roof edge (ridge, hip or eave), and by assuming uplift pressures are increased by 50 % (i.e. multiplying by two-thirds the allowed edge tributary area per anchor) if the

module perimeter is between one and two gap distances to a roof edge. Further wind tunnel studies may be appropriate to quantify how much wind uplift is increased on a flush-mounted array when module edges encroach into the shear layer within two gap distances to a roof edge.

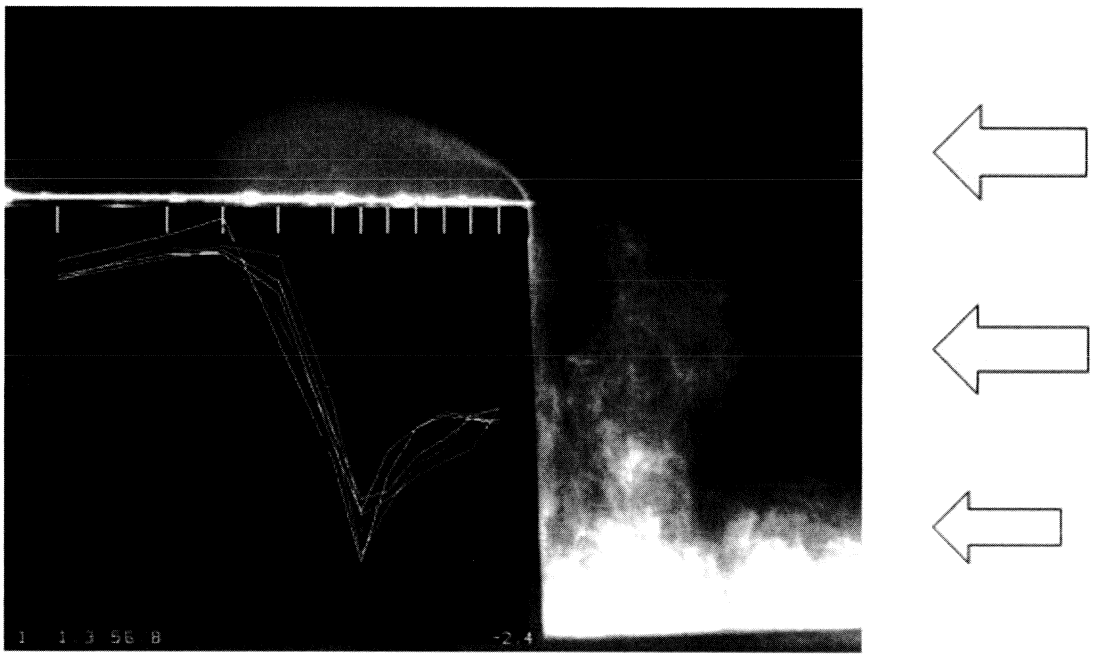


Figure A3.2. Wind tunnel study showing high velocity shear layer near a roof edge, courtesy of Dr. David Banks. Dr. Banks explains: *"This image is from my dissertation, and it is actually a still shot from an image sequence; the movie shows that the shear layer flaps up and down a fair bit. This is why we recommended V:2H. The position/shape of the shear layer will differ for roofs with eaves and high slopes, so I would be careful about drawing too many general conclusions from this sharp corner, low-rise, flat roof study."*

Part 3. Unusual Wind Conditions

3.1 Typical "Exposure B" Conditions: Most areas within cities and suburbs are ASCE 7-10 "Exposure B", with trees and buildings upwind of most subject buildings that break up surface winds and ameliorate wind pressures.

3.2 Nearshore "Exposure D" Conditions: It is important to recognize that buildings immediately adjacent coastal waters are subject to "Exposure D" conditions. Per ASCE 7-10, shorelines facing bodies of water broader than about one mile (5,000 feet) are defined as Exposure D. This special wind zone extends inland at least 200 yards. Exposure C extends an additional 300 yards until transitioning to Exposure B if local terrain is rough (urban, suburban or wooded).

3.3 Topographic Effects Equivalent to Exposures C and D: Likewise, buildings near the crest of the coastal hills and ridge lines are subject to topographic wind "speed-up" effects described in ASCE 7-10 that can significantly increase design wind pressures. Calculating topographic speed up effects directly for a specific site has two drawbacks:

The topographic effect calculation is complex and best determined by a licensed engineer,

The topographic effect, even if calculated, cannot be input into the standard anchor spacing and wind uplift tributary area tables developed for this project.

One way to address special topographic effects is to increase the design wind speed to approximate topographic effects. This approach is used in the California Residential Code's Table R301.2.1.5.1. Note that wind speeds shown in that table reference back to ASCE 7-05, with a base design speed of 85 mph, instead of ASCE 7-10 with a base design wind speed of 110 mph. Table R301.2.1.5.1 of the CRC was used to define the hill slope limits (15% max. slope for Exposure B, 5% max. slope for Exposure C) that are described in Part 0, Region and Site Checks, of this document.

Another way to address special topographic conditions in Exposure B areas is to approximate topographic effects by translating them to equivalent Exposures C and D. Table A3.1 shows the wind pressure increases for Exposures C and D in relation to Exposure B.

Table A3.1. Exposures C and D Relationship to Exposure B

Roof Mean Height	K_z Exp B.	K_z Exp. C	K_z Exp D.	Ratio Exp C/B	Ratio Exp D/B
50 ft	0.81	1.09	1.24	1.35	1.53
40 ft	0.76	1.04	1.20	1.37	1.58
30 ft	0.70	0.98	1.13	1.40	1.61

Using Google Map's terrain feature, a topographic section was cut through the Berkeley hills at Marin Avenue as an example of a typical section through the west side of the east bay hills. The ridge crest at the top of Marin Avenue is at an elevation of approximately 1,020 feet. The calculated topographic wind speed-up effect, K_{zt}, is approximately:

- 1.9 at elevation 1,000 feet (near crest of ridge)
- 1.6 at elevation 800 feet
- 1.4 at elevation 600 feet

The ridge crest along the Berkeley and Oakland hills ranges from 1,000 to 1,600 feet, with most areas abutting ridge crests in the 1,000 to 1,400 feet range. A rough "rule of thumb" might be:

- elevations within 200 feet of ridge crest elevation = Exposure D
- elevations between 200 and 400 feet from ridge crest elevation = Exposure C

Ideally, this rule of thumb would be verified by each city's Chief Building Official, or better yet, replaced by city maps showing areas of equivalent wind Exposure categories. It's interesting to note that preliminary calculations suggest that some areas near the crest of the east bay hills actually exceed Exposure D equivalent wind pressures (a topographic effect of about 1.9 versus the Exposure D / B ratio of about 1.6.

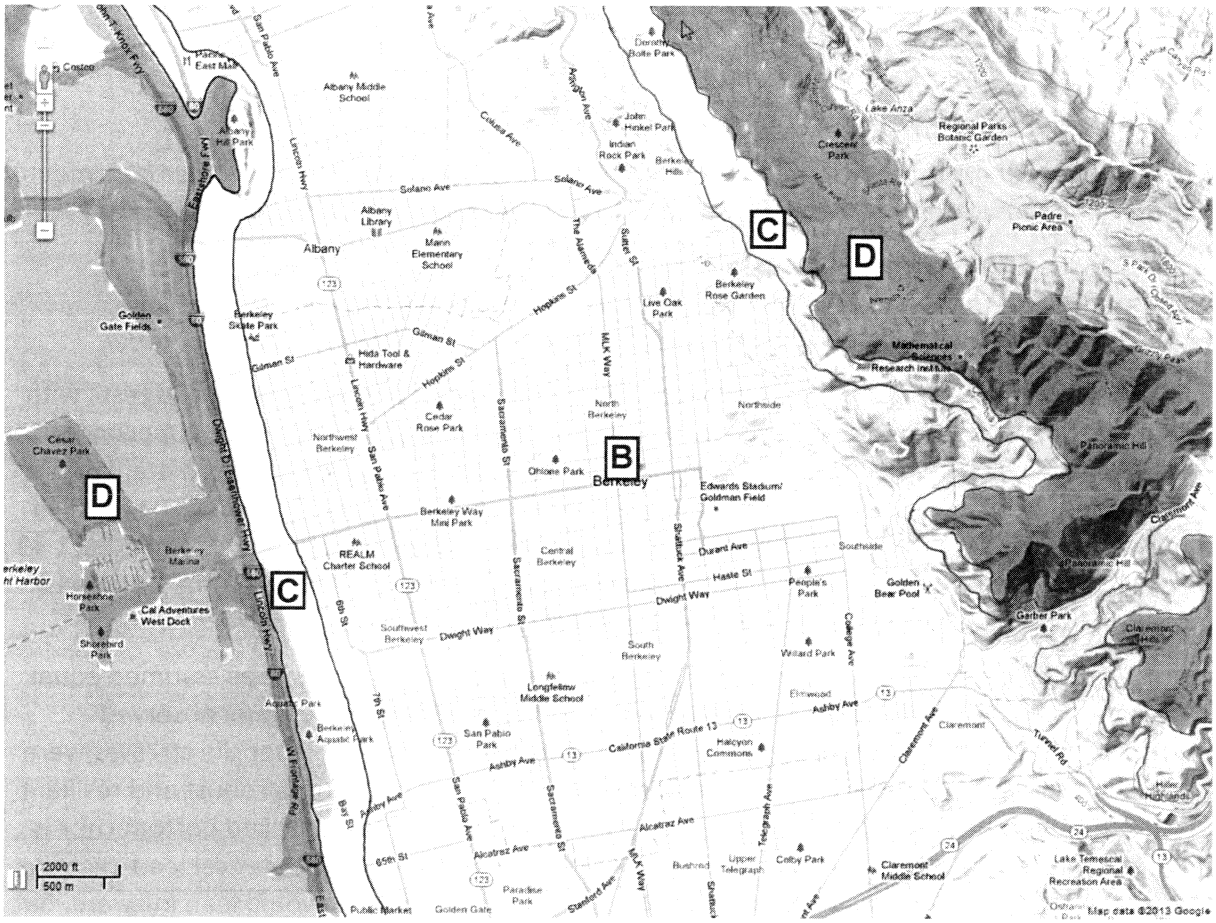


Figure A4.1. Approximate extent of special wind condition areas along part of the East Bay Green Corridor (Albany/Berkeley/North Oakland/Emeryville area shown). Wind Exposure D and C occur along the edge of San Francisco Bay, with a fetch of more than a mile across open water. Along the coastal side of the east bay hills, topographic effects for these Exposure B areas are translated into *equivalent* Exposures C and D.

Part 4. Frequently Asked Questions

4.1 Wood Allowable Stress Code Changes

With the big changes to the wood code in the 1990s, didn't wood allowable values become considerably more conservative? Weren't allowable wood stresses unreasonably high in the old days?

The Commentary to the 1997 National Design Specification (NDS) provides an excellent overview of the history of allowable stresses for visually graded lumber.

In 1991 allowable bending stress, F_b, changed from being based on clear grain wood tests with strength reductions for knots, to "in-grade testing" (an 8 year effort where 70,000 specimens were destructively tested). In general, allowable bending stresses stayed approximately the same or slightly increased, especially for the shallower member sizes (2x4s and 2x6s) typical of many rafters, and especially when the ratio of new-to-old wind load duration factors (1.60/1.33 = 1.20) is taken into account. Allowable bending stress, F_b, is the basis of the Table 1 analysis, and should not be confused with allowable tensile stress, F_t.

In the 1962 and earlier editions of the NDS, the allowable tensile stress, F_t, was assumed equal to bending stress, F_b. This was re-evaluated in the 1960s, precipitated by many observed failures in the tensile bottom chords of large bowstring trusses. Allowable tensile stresses were essentially halved. One of the reasons engineers are confident that wood is robust and resilient is that many structural engineering offices were called in to repair fully cracked bottom chords of long span bowstring trusses. Typically, despite the truss's loss of all theoretical load-carrying capacity, the roof would simply sag and the supporting posts and walls would lean outward, but the roof would not collapse.

4.2 Seismic Roof Mass

What about the impact of the increased roof mass from the PV array on the expected seismic performance of the residence?

The re-roofing allowance that's been in the code since 1979 (and implicit before that) essentially allows a reroof overlay over the entire roof, and typically weighs between 2 to 4 psf (20 yr roof = approx 2 to 2.5 psf; 40 or 50 yr roof = approx 3.5 to 4 psf). Most code officials allow this without requiring calculations showing sufficient lateral strength, and there have been few problems from allowing these overlays. This appears to be the case even though the increase in inertial mass (and subsequent shears at the top story) might be 4 psf / 20 psf = 20%, although typical installations are closer to 3 psf / 25 psf = 12%. Note that the denominator includes the weight of the roof, ceiling and top half of the walls of a one-story building. For multistory buildings, the code static-equivalent triangular lateral force distribution will further "dilute" (reduce) the shear increase percentage. Even if the 10% rule of Chapter 34 is slightly

exceeded, wood-framed one- and two-family dwellings are typically very resistant to seismic collapse once obvious weak spots like unsheathed cripple walls are addressed.

It's important to note, then, that a typical reroof overlay places greater seismic demands on a building's lateral system than a typical PV system. Typical case: PV system weighs 3.5 psf, and covers 80% of the south facing gable roof. In a single story building, the global increase in lateral loads to the building would be: 3.5 psf x 40% / 20 psf = 7 % (less than the 10% trigger in Chapter 34). Plan torsion effects may make loads to individual elements slightly greater than 7%, but still likely to be less than 10%. If the building was more than one story tall, multistory effects would further dilute (reduce) the percentage increase in loads.

4.3 Asymmetric Loading

Is there reason to be concerned about unexpected stresses on north rafters from asymmetric loading on the roof by a solar array placed only on the south side?

For truss-type roofs, including roofs with non-bearing ridge members and collar or attic-floor joist ties, the panels on the south roof will put the north rafters under a slight compressive load. However, this effect is so small as to be essentially negligible. Back-of-the-envelope example: 24 ft wide roof, 6:12 slope, with 12 ft south horizontal span and 12 ft north horizontal span, with the roof rafters and attic floor joists forming a simple triangular truss. A 4 psf load on the south span will create a vertical reaction of 13.4 plf at the north wall, and place the north rafters under a 30 plf axial load. Assuming 2x6 rafters at 24" o.c., this creates an axial stress of 30plf x 2 ft / (1.5" x 5.5") = 7 psi. Even if the rafters are anchored at 6 ft, the roof sheathing will tend to distribute this axial stress uniformly across all three rafters on the north side, especially by mid-span where axial + bending interaction would control. Even if the roof sheathing didn't redistribute the axial loads, an axial stress of 3 x 7 psi = 21 psi on a single north rafter is also essentially negligible.

Part 5. Applicability to Other Regions of California and United States

5.1 High Snow and Wind Load Regions

The Solar Permitting Initiative's Structural Criteria has been specifically designed to apply to most regions of California. Most of California has the lowest design wind speed in the country (110 mph per ASCE 7-10), and has zero snow loads. The Structural Criteria can also apply to special wind regions (115-130 mph) under Wind Exposure B conditions. While the majority of the country does have ASCE 7-10 design wind speeds of 110 or 115 mph, major areas of the eastern and southeastern seaboard, as well as Hawaii, have significantly higher wind speeds based on hurricane forces, with design wind speeds often in the 120 to 150 mph range, and as high as 190 mph at the southern tip of Florida. It is important to note that design wind pressure is proportional to the square of design wind speed, so the difference in design wind pressure between the 110 mph wind speeds typical for California and a design wind speed of 140 mph typically found along the eastern seaboard is a factor of 1.62 (roughly a sixty percent increase). Likewise, areas where roof snow loads exceed roof live loads also create significantly greater concentrated loads on roof rafters than those considered for zero snow load areas of California. In regions of high wind and snow loads, staggering rows of anchors, in order to create a quasi-uniform loading pattern, quickly becomes the preferred solution. More studies are needed to identify where the transition occurs between anchoring to every third rafter with no staggered rows, to staggering rows to fasten two out of every three rafters, to anchoring to every second or third rafter along a single row, with every subsequent row of anchors staggered as one moves up the roof (quasi-uniform loading).

5.2 Comparison with the Solar ABCs: The Solar ABCs (www.solarabcs.org/permitting) offers an even simpler structural criteria against which California's Expedited Structural Permitting Process Structural Criteria can be compared. The Solar ABCs prevents substructure overloading by controlling the maximum load per anchor (or "stand-off" in Solar ABC parlance). The maximum load of 45 lbs. per anchor corresponds to a panel tributary area of 9 to 15 square feet, depending on whether the panels weigh 3 psf (typical case) or 5 psf (the latter is the Solar ABCs maximum allowed array density). These are conservatively small tributary area limits at low slopes (note that Table A2.13 allows tributary areas up to 34 square feet), and potentially un-conservatively large tributary area limits at steeper slopes. Horizontal anchor spacing and staggered rows of anchors are not explicitly addressed, so economical anchor layouts typically allowed in solar support component manufacturer's code compliance manuals often cannot be achieved using the Solar ABCs.

To increase the flexibility and robustness of the Solar ABCs, we believe California's Structural Criteria's Table 1 (maximum horizontal anchor spacing limits) might be a useful supplement to the Solar ABCs. Table A2.13 in this appendix may also be a useful supplement to the Solar ABCs for cases when a manufacturer's pre-designed solar support system is not used. Tables 1 and A2.13 in their current form are only appropriate for regions with a modest wind design speed

(110 mph per ASCE 7-10) and zero snow loads, but could be expanded in the future to address regions of higher wind and snow loads.

5.3 City of Los Angeles Expedited Solar Permitting and Similar Ordinances:

As stated in the introduction to California's Solar Permitting Guidebook Toolkit Structural Document, the document is intended for jurisdictions without an expedited process for residential solar structural permitting, and is not intended to replace or supplant procedures for jurisdictions with an expedited process already in place. The City of Los Angeles' P/GI 2014-027 *Guidelines for Plan Check and Permit Requirements for Solar Energy Systems* is a good example. These guidelines exempt solar installations from structural permitting if five simple requirements are met. They are articles D.1 through D.5:

1. Solar energy device is roof mounted and does not exceed the existing building height at the highest point.
2. The solar energy device system weight does not exceed four pounds per square foot (4 psf).
3. The solar energy device is installed within 24" of the roof immediately below.
4. The maximum concentrated load imposed by a solar energy device support onto the roof structure is a maximum of 60 pounds (0.18 kN); and
5. For wood construction, the maximum spacing for supports of the solar energy devices shall be 48" on center, and shall be anchored to solid roof rafters or to solid blocking with a minimum of one 5/16" diameter lag screw embedded a minimum of 2.5" or as recommended by the manufacturer, whichever is more stringent. For other types of construction, the support shall be approved by the Department.

If the City of Los Angeles, or other jurisdictions with similar rulings, would like to incorporate the Toolkit Structural Document, it might consider the following simple amendments *(in blue italicized text)* to articles D.4 and D.5:

4. The maximum concentrated load imposed *by the self weight of* a solar energy device support onto the roof structure is a maximum of 60 pounds (0.18 kN); and
5. For wood construction, the maximum spacing for supports of the solar energy devices shall be 48" on center, and shall be anchored to solid roof rafters or to solid blocking with a minimum of one 5/16" diameter lag screw embedded a minimum of 2.5" or as recommended by the manufacturer, whichever is more stringent.

    a. For flush-mounted solar energy devices meeting all the requirements of the 2014 California Expedited Solar Permitting Toolkit Structural Document, maximum support spacing may be as much as 72" in the cross-slope (perpendicular to rafter) direction, under the conditions allowed in that Document.

6. For other types of construction, the support shall be approved by the Department.

Part 6. Research Topics

6.1 Wind Uplift

Research by Dr. Gregory Kopp at the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario, Canada, suggests that "air permeable cladding" such as solar arrays may, in certain configurations, have substantially lower wind uplift loads than ASCE 7-10 as interpreted by ICC AC-428 would suggest. For arrays with at least a 2 cm (3/4") gap between modules, reduction factors may be as low as fifty percent. The results of this research is being discussed in several national and international code committees, and may be incorporated in future editions of ASCE 7.

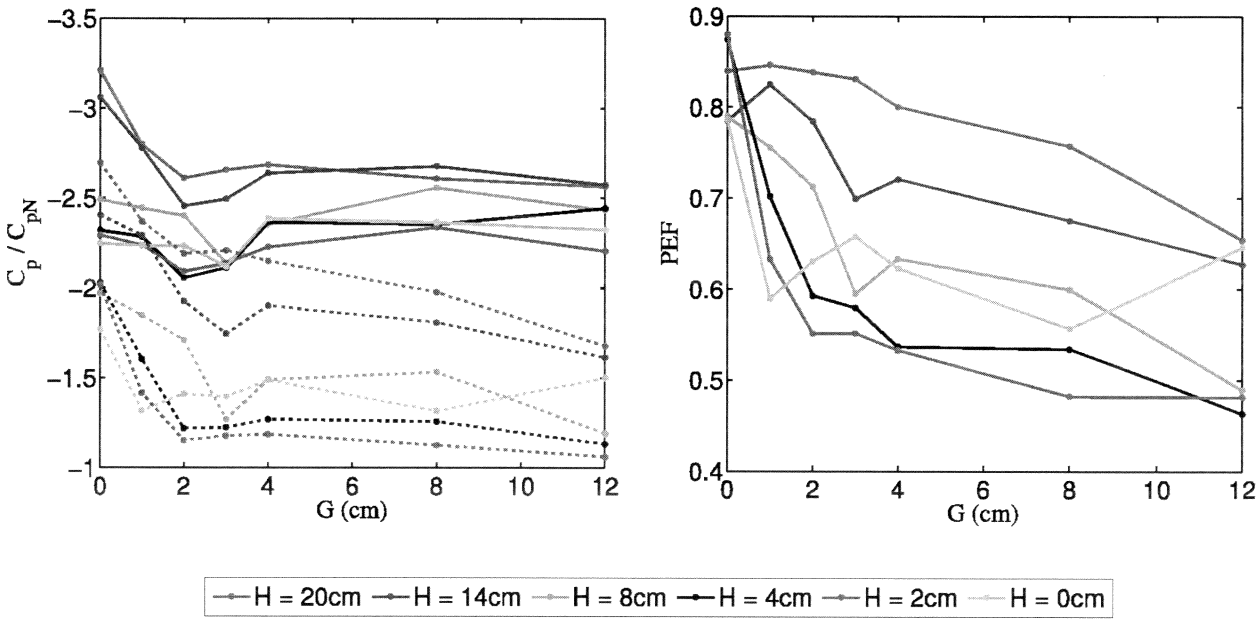


Figure A7.1. Preliminary research results for flush-mounted "air permeable cladding" such as solar arrays mounted on sloping roofs of low rise buildings. PEF, Pressure Equalization Factor, is the ratio of actual to code-predicted wind uplift pressures, and represents a reduction factor from current code values. G is the gap between modules and H is the height of the modules off the roof, that is, the distance from top of roof to underside of modules.

6.2 Dynamic Resonance:

There has been some discussion in the wind research community that some solar arrays may have structural vibration frequencies that match wind flutter at certain wind speeds. Such resonant vibration could substantially amplify wind uplift pressures.

6.3 Wood-Framed Residential Roof Downward Load Capacity:

Dr. Stephan Dwyer of Sandia National Laboratories has been investigating the actual downward load capacity of typical residential wood-framed roofs. Preliminary results suggest that residential wood roofs have substantially greater capacity than that suggested by code. This reserve capacity is probably due to load sharing, catenary membrane action and composite member action between the roof sheathing and rafters, and other effects.

6.4 Manufactured Plated Wood Trusses

Manufactured plated wood trusses differ from simple span roof rafters in several significant ways. Wood trusses typically span the full width of the building, rather than from eave to ridge. They consist of individual members interconnected by plate connectors. Manufactured wood trusses are typically design/build elements; in addition to the dead plus live load combination, manufacturers also design the top chords to resist the 250 pound live load of a worker standing midway between panel points, which imposes bending in addition to axial compression. The concentrated load from the anchor of a solar array will usually be less than 250 pounds, even considering downward wind effects, so problems are not anticipated when anchoring to truss top chords between panel points.

Back-of-the-envelope calculations suggest that trusses are stiffer than common rafters, so the concentrated load sharing factor should be somewhat lower than that for common rafters. For this reason, for manufactured wood trusses, footnote 3 in Table 1 reduces the anchor maximum horizontal spacing to 4'-0". Footnote 3 also requires that anchors in adjacent rows be staggered, thereby creating a quasi-uniform load distribution that removes any reliance on load redistribution and the concentrated load sharing factor C_{LSF}.

One truss connector company, Mitek, recommends that, at least for new trusses, solar array lag screws should be fastened to blocking between trusses instead of to the truss's 2x top chord. The concern seems to be about 5/16" lag screws installed close to plate connectors at top chords, where negative moments may create high tension stresses along the top surface of the top chord. In general, until more research is conducted, solar installers may want to avoid fastening lag screws directly into or close to truss panel points, where plate connectors occur.

6.5 Lag Screw Edge Distance Under Seismic Loads

5/16" lag screws into 2x rafters meet the 1.5 diameter edge distance requirement for loads parallel to rafter (i.e. downslope loads), but technically do not meet the 4 diameter edge distance requirement for minor seismic loads perpendicular to the rafter. Because of the light weight of solar panels, seismic design forces are quite modest (2-4 psf), an order of magnitude less than many wind and snow design loads (20-40psf).

For new public school construction, Oakland DSA review engineers have required 5/16" lag screws be installed into blocking between 2x truss top chords rather than into the truss top chord itself. Their concern is that under seismic lateral loads acting cross-slope (east/west), the code required edge distance of 4d is not met, and splitting could occur.

For existing construction, a 5/16" stainless steel or hot-dipped galvanized lag screw fastened into 2x rafters is the industry standard, and fastening instead into blocking between rafters is costly and often not feasible. One author is aware of tests by at least two solar support component manufacturers that have tested loading in this direction. Cross-grain splitting has not been observed, probably because of the interaction between the anchor, the lag screw, the sheathing and the rafter. Shear appears to primarily be taken out through friction and bearing into the sheathing, with the lag into the rafter primarily acting in prying/pull-out rather than shear. Under severe seismic shaking, even if some cross-grain splitting occurred, a failure of an array sliding off a roof is unlikely because modules are interconnected and fastened to the roof at a large number of points, providing significant redundancy.

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UL 2703. Underwriters Laboratories Inc. November 2012. *Outline of Investigation for Mounting Systems, Mounting Devices, Clamping/Retention Devices and Ground Lugs for Use with Flat-Plate Photovoltaic Modules and Panels.*

Part 8. Contacts and Acknowledgements

8.1 Contacts:

This document was authored by John Wolfe and Andrew Wagner, with input and help from many others. Technical questions regarding California's Solar Permitting Guidebook's Toolkit Structural Criteria and Structural Technical Appendix may be addressed to John Wolfe.

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2013 CBC Update

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2014 California Solar Permitting Guidebook's Toolkit Structural Document

Under the leadership of the Governor's Office of Planning and Research, the advice of its task force on solar permitting, and the assistance of the Center for Sustainable Energy, the planners of the second edition of the California Solar Permitting Guidebook decided to incorporate more structural information, based on the East Bay Green Corridor's model. The effort was funded through the US Department of Energy's Sunshot Initiative, with significant volunteer contributions from task force members and stakeholders.

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James A. Adams SE, EZ Tech
Steve Bauer SE, Unirac

Joe Cain PE, DNV GL
Richard Hanson PE, Solar City
James Lai SE, Chair, SEAOC Wind Committee
Joe Maffei SE, Maffei Structural Engineering, Chair, SEAOC Solar PV Committee
Jeremy Rogelstad PE, ZEP Solar
Norm Scheel SE, Normal Scheel Structural Engineer
Andrew Wagner PE, Tipping Structural Engineers
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