STRUCTURAL SEISMIC REQUIREMENTS AND COMMENTARY FOR ROOFTOP SOLAR PHOTOVOLTAIC SYSTEMS

Prepared by

SEAOC Solar Photovoltaic Systems Committee

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STRUCTURAL ENGINEERS ASSOCIATION OF CALIFORNIA
1020 12th Street, Suite 303
Sacramento, CA 95814
Phone: (916) 447-1198
Fax: (916) 444-1501
Email: info@seaoc.org
http://www.seaoc.org

Structural Seismic Requirements and Commentary for Rooftop Solar Photovoltaic Systems

This document was written by the SEAOC Solar Photovoltaic Systems Committee, a subcommittee of the SEAOC Wind Committee. The document was reviewed by the SEAOC Seismology Committee.

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Preface

This document was developed by the Structural Engineering Association of California's (SEAOC) Solar Photovoltaic Systems Committee, a subcommittee of the SEAOC Wind Committee. [to be completed: purpose of committee, need for requirements, process followed, acknowledgements]

Requirements and Commentary

1. Structural performance objectives

Consistent with the intent of the IBC 2009 (Section 101.3), PV panels and their structural support systems shall be designed to provide life-safety performance in the Design Basis Earthquake and the design wind. Life-safety performance means that systems are expected not to create a hazard to life, for example as a result of breaking free from the roof, sliding off the roof's edge, exceeding the downward load-carrying capacity of the roof, or damaging skylights, electrical systems, or other rooftop features or equipment in a way that threatens life-safety. For life-safety performance, damage, structural yielding, and movement are acceptable, as long as they do not pose a threat to human life.

Commentary: The Design Basis Earthquake in ASCE 7-10 has a return period of approximately 500 years, and design wind loads are based on a return period of approximately 300 years for Risk Category I structures, 700 years Risk Category II, and 1700 years Risk Category IV (i.e. the importance factor is built into the return period for wind). For more frequent events (e.g., events with a 50-year return period), it may be desirable to design the system to remain operational; these requirements do not cover but do not preclude using more stringent design criteria.

2. Types of systems

For the purposes of these structural requirements, rooftop PV panel support systems shall be classified as follows:

- **Unattached (ballast-only) systems** are not attached to the roof structure. Resistance to wind and seismic forces is provided by weight and friction.
- **Attached roof-bearing systems** are attached to the roof structure at one or more attachment points, but they also bear on the roof at support points that may or may not occur at the same locations as attachment points. The load path for upward forces is different from that for downward forces. These systems may include additional weights (ballast) as well.
- **Fully-framed systems** (stanchion systems) are structural frames that are attached to the roof structure such that the load path is the same for both upward and downward forces.

Systems not covered by the definitions above are outside the scope of these provisions.

Commentary: Attached systems can include those with flexible tethers as well as more rigid attachments. Both types of attachments are to be designed per Section 4: Attachment Requirements.

3. Building seismic-force-resisting system

For PV systems added to an existing building, the seismic-force-resisting system of the building shall be checked per the requirements of Chapter 34 of IBC 2009.

Commentary: Per Sections 3403.4 and 3404.4 of IBC 2009, if the added mass of the PV system does not increase the seismic mass tributary to any lateral-force-resisting structural element by more than 10%, the seismic-force-resisting system of the building is permitted to remain unaltered.

4. Attachment requirements

PV support systems that are attached to the roof structure shall be designed to resist the lateral seismic force F_p specified in ASCE 7-05 Chapter 13. For attached roof-bearing systems, friction not to exceed $(0.9\mu_s - 0.2S_{DS})W_{pf}$, is permitted to resist the lateral force F_p where W_{pf} is the component weight providing normal force at the roof bearing locations, and μ_s is the coefficient of friction at the bearing interface. The resistance from friction is permitted to contribute in combination with the design lateral strength of attachments to resist F_p.

Unattached (ballast-only) systems are permitted when all of the following conditions are met:

- The maximum roof slope at the location of the array is less than or equal to 7 degrees (12.3 percent).
- The height above the roof surface to the center of mass of the solar array is less than the smaller of 36 inches and half the least plan dimension of the supporting base of the array.
- The system is designed to accommodate the seismic displacement determined by one of the following procedures:
    - Prescriptive design seismic displacement
    - Nonlinear response history analysis
    - Shake table testing

5. Design to accommodate seismic displacement

For unattached (ballast-only) systems, accommodation of seismic displacement shall be afforded by providing the following minimum separations to allow sliding:

Condition	Minimum Separation
Between separate solar arrays	$0.5\Delta_{MPV}$
Between a solar array and a fixed object on the roof	Δ_{MPV}
Between a solar array and a roof edge with a qualifying parapet	Δ_{MPV}
Between a solar array and a roof edge without a qualifying parapet.	$1.4\Delta_{MPV}$

Where Δ_{MPV} is the design seismic displacement of the array relative to the roof, as computed per the requirements herein. For the purposes of this requirement, a parapet is “qualifying” if the top of the parapet is not less than 6 inches above the center of mass of the solar array, and also not less than 24 inches above the adjacent roof surface.

Commentary: The factor of 0.5, based on judgment, accounts for the likelihood that movement of adjacent arrays will tend to be synchronous and that collisions between arrays do not necessarily represent a life-safety hazard. The factor of 1.4 is added, by judgment, to provide extra protection against the life safety hazard of an array sliding off the edge of a roof. A qualifying parapet (and the roof slope change that may be adjacent to it) is assumed to partly reduce the probability of an array sliding off the roof justifying the use of Δ_{MPV} rather than $1.4\Delta_{MPV}$. Calculation of the parapet’s lateral strength to resist the array movement is not required by this document.

Each separate array shall be adequately interconnected as an integral unit such that for any vertical section through the array, the members and connections shall have a design strength to resist a total horizontal force across the section, in both tension and compression, equal to $0.1W_1$

Where

W_1 = the total weight of the array, including ballast, on the side of the section that has smaller weight.

The horizontal force shall be applied to the array at the level of the roof surface. The force $0.1W_1$ shall be distributed in proportion to the weight that makes up W_1. The computation of strength across the section shall account for any eccentricity of forces.

Elements of the system that are not interconnected as specified shall be considered structurally separate and shall be provided with the required minimum separation.

Electrical systems and other items attached to arrays shall be designed to accommodate the required minimum separation in a manner that meets code life-safety performance.

Commentary: This document provides only structural requirements. The design must also meet applicable requirements of the governing electrical standards.

The minimum clearance around solar arrays shall be the larger of the seismic separation defined herein and minimum separation clearances required for fire-fighting access.

Commentary: Section 605 of the International Fire Code (ICC 2012) provides requirements for firefighting access pathways on rooftops with solar arrays, based on the recommendations in CAL FIRE-OSFM (2008). For commercial and large residential flat roofs (which are the roof type on which unattached arrays are feasible) requirements include 4 ft to 6 ft clearance around the perimeter of the roof, maximum array dimensions of 150 feet between access pathways, and minimum clearances around skylights, roof hatches, and standpipes.

Note that the clearance around solar arrays is the larger of the two requirements for seismic and fire-fighting access. The separation distances do not need to be added together.

6. Prescriptive design seismic displacement

Δ_{MPV} is permitted to be determined by the prescriptive procedure below if all of the following conditions are met:

- I_p per ASCE 7-05 Chapter 13 is equal to 1.0 for the solar array and for all rooftop equipment adjacent to the solar array.
- The maximum roof slope at the location of the array is less than or equal to 3 degrees (5.24 percent).
- The manufacturer provides friction test results, per the requirements herein, which establish a coefficient of friction between the PV support system and the roof surface of not less than 0.4. For Seismic Design Categories A, B, or C, friction test results need not be provided if the roof surface consists of mineral-surfaced cap sheet, single-ply membrane, or sprayed foam membrane, and is not gravel, wood, or metal.

Δ_{MPV} shall be taken as follows:

Seismic Design Δ_{MPV}

Category	
A, B, C	6 inches
D, E, F	$[(S_{DS} - 0.4)^2]$ * 60 inches, but not less than 6 inches

Commentary: The prescriptive design seismic displacement values conservatively bound nonlinear analysis results for solar arrays on common roofing materials. The PV Committee concluded that limits on S_{DS} or building height are not needed as a prerequisite to using the prescriptive design seismic displacement.

7. Friction testing

The coefficient of friction used in these requirements shall be determined by experimental testing of the interface between the PV support system and the roofing surface it bears on. Friction tests shall be carried out for the general type of roof bearing surface used for the project under the expected worst-case conditions, such as wet conditions versus dry conditions. The tests shall conform to applicable requirements of ASTM G115, including the report format of section 11. An independent testing agency shall perform or validate the friction tests and provide a report with the results.

The friction tests shall be conducted using a sled that realistically represents, at full scale, the PV panel support system, including materials of the friction interface and the flexibility of the support system under lateral sliding. The normal force on the friction surface shall be representative of that in typical installations. Lateral force shall be applied to the sled at the approximate location of the array mass, using displacement controlled loading that adequately captures variations in resistive force. The loading shall be applied at a velocity of between xxx and xxx inches per second. If stick-slip behavior is observed, the velocity shall be adjusted to minimize this behavior. Continuous electronic recording shall be used to measure the lateral resistance. A minimum of three tests shall be conducted, with each test moving the sled a minimum of three inches under continuous movement. The force used to calculate the friction coefficient shall be the average force measured while the sled is under continuous movement. The friction tests shall be carried out for the general type of roofing used for the project.

Commentary: Because friction coefficient is not necessarily constant with normal force or velocity, the normal force is to be representative of typical installations and the velocity is to be less than or equal to that expected for earthquake movement. A higher velocity of loading could over-predict frictional resistance. Lateral force is to be applied under displacement control to be able to measure the effective dynamic friction under movement. Force-controlled loading, including inclined plane tests, only captures the static friction coefficient and does not qualify. [note important requirements from G115]

Friction tests are to be applicable to the general type of roofing used for the project, such as a mineral-surfaced cap sheet or a type of single-ply membrane material such as EPDM, TPO, or PVC. It is not envisioned that different tests would be required for different brands of roofing or for small differences in roofing type or condition.

For solar arrays on buildings assigned to Seismic Design Category D, E, or F where rooftops are subject to significant potential for frost or ice that is likely to reduce friction between the solar array and the roof, the building official at their discretion may require increased minimum separation, further analysis, or attachment to the roof.

Commentary: A number of factors affect the potential that frost on a roof surface will be present at the same time that a rare earthquake occurs, and that such frost increases the sliding displacement of an array. These factors include:

-the potential for frost to occur on a roof based on the climate at the site, whether the building is heated, and how well the roof is insulated,

-the number of hours per day and days per year that frost is present,

-whether solar modules occur above, and shield from frost, the roof surface around the support bases of the PV array

-[other considerations, probability, etc]

The PV Committee is not aware of any research specifically addressing (a) the potential for frost or freezing of this type, (b) the effect of frost on the friction behavior of various roof surfaces, or (c) the likelihood that such frost forms underneath or sufficiently adjacent to solar panel feet as to compromise displacement resistance. Section C10.2 of ASCE 7-10 describes some of the phenomena related to the formation of frost, freezing rain, and ice

8. Nonlinear response history analysis or shake table testing

The design seismic displacement corresponding to the Design Basis Earthquake shall be determined by nonlinear response history analysis or shake table testing using input motions consistent with ASCE 7-05 Chapter 13 design forces for non-structural components on a roof.

The analysis or test shall use a suite of not less than three appropriate roof motions, spectrally matched to broadband design spectra per AC 156 Section 6.5.1. Each roof motion shall have a total duration of at least 30 seconds and shall contain at least 20 seconds of strong shaking per AC 156 Section 6.5.2 The spectrum shall vary linearly with component period T in the increasing portion of the acceleration-sensitive region, and shall be proportional to $1/T$ in the velocity-sensitive region. A three-dimensional analysis model or experiment shall be used, and the roof motions shall include two horizontal components and one vertical component.

The analysis model or experimental test shall account for friction between the system and the roof surface, and the slope of the roof. The friction coefficient used in analysis shall be based on testing per the requirements herein.

If at least seven roof motions are used, the design seismic displacement is permitted to be taken as 1.1 times the *average* of the peak displacement values (in any direction) from the analyses or tests. If fewer than seven roof motions are used, the design seismic displacement shall be taken as 1.1 times the *maximum* of the peak displacement values from the analyses or tests. Roof motions shall have a minimum duration per AC 156 consistent with the expected Design Basis Earthquake motions at the site.

Resulting values for Δ_{MPV} shall not be less than 50% of the values specified in Section 6, unless lower values are validated by independent Peer Review.

Commentary: Nonstructural components on elevated floors or roofs of buildings experience earthquake shaking that is different from the corresponding ground-level shaking. Roof-level shaking is filtered through the building so it tends to cause greater spectral acceleration at the natural period(s) of vibration of the building and smaller accelerations at other periods. The target spectra defined in AC 156 are broadband spectra, meaning that they envelope potential peaks in spectral acceleration over a broad range of periods of vibration, representing a range of different buildings where nonstructural components could be located.

In lieu of spectrally matching (frequency scaling) motions to a broadband roof spectrum, it may also be acceptable to apply appropriately scaled Design Basis Earthquake ground motions to the base of a building analysis model that includes the model of the solar array on the roof. In such a case the properties of the building analysis model shall be appropriately bracketed to cover a range of possible building dynamic properties and behavior.

Because friction resistance depends on normal force, vertical earthquake accelerations can also affect the horizontal movement of unattached components, so inclusion of a vertical component is required.

The factor of 1.1 used in defining the design seismic displacement is to account for the random uncertainty of response for a single given roof motion. This uncertainty is assumed to be larger for sticking/sliding response than it is for other types of non-linear response considered in structural engineering. The factor is chosen by judgment.

References

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International Code Council (ICC), 2009, *International Building Code*, Country Club Hills, Illinois.

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International Code Council (ICC), 2012b, *International Fire Code*, Country Club Hills, Illinois.

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Appendix A: Affected Building Code Sections

ASCE 7-10

Section 1.2.1 Definitions
Add the following, as defined in this document:
Unattached (ballast-only) solar photovoltaic systems
Attached solar photovoltaic systems
Fully-framed solar photovoltaic systems

Section 13.4 Nonstructural Component Anchorage
Add the following exception:
Exception: Unattached (ballast-only) rooftop solar photovoltaic systems are permitted where the conditions of Section 13.7 are met.

Section 13.7 Unattached (Ballast-Only) Rooftop Solar Photovoltaic Systems *[new section]*
Add the requirements as detailed in this document.