ASCE MANUALS AND REPORTS ON ENGINEERING PRACTICE NO. 162

DESIGN AND CONSTRUCTION OF SOLAR PV STRUCTURES



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Design and Construction of Solar PV Structures

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MANUALS AND REPORTS ON ENGINEERING PRACTICE

(As developed by the ASCE Technical Procedures Committee, July 1930, and revised March 1935, February 1962, and April 1982)

A manual or report in this series consists of an orderly presentation of facts on a particular subject, supplemented by an analysis of limitations and applications of these facts. It contains information useful to the average engineer in his or her everyday work, rather than findings that may be useful only occasionally or rarely. It is not in any sense a "standard," however, nor is it so elementary or so conclusive as to provide a "rule of thumb" for nonengineers.

Furthermore, material in this series, in distinction from a paper (which expresses only one person's observations or opinions), is the work of a committee or group selected to assemble and express information on a specific topic. As often as practicable, the committee is under the direction of one or more of the Technical Divisions and Councils, and the product evolved has been subjected to review by the Executive Committee of the Division or Council. As a step in the process of this review, proposed manuscripts are often brought before the members of the Technical Divisions and Councils for comment, which may serve as the basis for improvement. When published, each manual shows the names of the committees by which it was compiled and indicates clearly the several processes through which it has passed in review, so that its merit may be definitely understood.

In February 1962 (and revised in April 1982), the Board of Direction voted to establish a series titled "Manuals and Reports on Engineering Practice" to include the manuals published and authorized to date, future Manuals of Professional Practice, and Reports on Engineering Practice. All such manual or report material of the Society would have been refereed in a manner approved by the Board Committee on Publications and would be bound, with applicable discussion, in books similar to past manuals. Numbering would be consecutive and would be a continuation of present manual numbers. In some cases of joint committee reports, bypassing of journal publications may be authorized.

A list of available Manuals of Practice can be found at https://ascelibrary.org/page/books/s-mop.

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PREFACE

This Manual of Practice was developed by a multidisciplinary team of structural and geotechnical engineers, wind and corrosion specialists, contractors, owners, developers, and racking manufacturers who are subject matter experts in the design, development, construction, operation, and maintenance of solar photovoltaic (PV) structures.

It is the first formal publication of its kind for the US solar PV industry and represents the inaugural publication of the ASCE-SEI Solar PV Structures Committee. This committee was formed in 2020 in response to the consensus widely held by many practicing professionals in the solar industry that there was a need for more formal industry design guidance. Prior to the publication of this Manual, only rooftop solar systems had some form of design guidance provided by a working committee of professionals.

This Manual provides comprehensive engineering and construction guidance for ground-mounted, rooftop, elevated (e.g., carport/canopy), and floating solar PV structures. It addresses key topics including design load development, structural and geotechnical engineering, corrosion assessment, wind load development, and construction quality control. By consolidating best practices, recording lessons learned, and incorporating the current state of the practice into one document, this Manual encourages the reliable design and development of solar PV structures, all while allowing the solar PV industry and its many stakeholders and owners to continue to grow, be innovative, and expand the contribution of clean energy generation to the electric grid.

Steven M. Gartner, P.E., M.ASCE, *Chair Emeritus*
ASCE-SEI Solar PV Structures Committee

CHAPTER 1
SOLAR PV STRUCTURES

1.1 INTRODUCTION

As the process of generating electricity continues to evolve from traditional nuclear fission and fossil fuel–based power plants to renewable sources of energy, new methods of design and construction are necessary for renewable energy to be developed and integrated. The rapid expansion of photovoltaic (PV) systems for the generation of electricity and the lack of uniformity in how these systems are being designed have demonstrated the need for guidance on how to reliably design and build high-performing structural systems. Solar PV construction ranges from residential roof top systems to large utility-scale, ground-mounted PV arrays consisting of millions of PV modules. Accordingly, each PV structural system requires novel approaches to their design and construction compared to that of traditional building structures. Because of the unique aspects of PV structural systems, this Manual of Practice (Manual) has been established so that all solar PV stakeholders will be able to develop PV systems that are both structurally reliable and consistent in producing electricity for owners and the communities that they serve throughout their expected service life. Solar project stakeholders include owners, developers, financial institutions, utility companies, Engineers of Record (EORs), original equipment manufacturers (OEMs), contractors, authorities having jurisdiction (AHJs), and any organization or individual that is involved with the development, design, assembly, construction, and operation and maintenance of a solar PV system.

Commentary

Photovoltaic systems and their supporting structures are typically developed and implemented by a main project team involving the following roles and responsibilities. The project team may also be supported by independent engineers, owner's engineers, and other parties responsible for peer review or representing financing interests, as arranged and contracted by the owner.

1. Owner: Responsible for project development and implementation, including financing and contracting for design, procured equipment, and installation services as well as gaining system approvals from local, state, and federal AHJs.
2. Authority Having Jurisdiction (AHJ): The existing regulatory body responsible for specific PV system approvals, as defined in the glossary of this Manual.
3. Engineer of Record (EOR): A registered professional engineer contracted to serve in responsible charge over the complete, or components of the, PV system, supported by other professionals and specialists needed to address specific PV system requirements (e.g., geotechnical, building evaluation, mounting system, civil, electrical, and structural engineers, who are then supported by corrosion and wind specialists, as well as other PV subject matter experts).
4. Installation Contractor: Contracted with the owner to furnish system equipment and materials and to install the PV system in accordance with documentation issued by the EOR for construction and PV system approvals and permits issued by the AHJ.

1.2 STATEMENT OF INTENT AND EXPECTED USE OF THIS MANUAL OF PRACTICE

This Manual has been developed to assist solar PV project stakeholders in the design and construction of solar PV structural systems. These systems utilize structures that range from residential and commercial rooftop racking and ballast structures, elevated structures that are traditionally called carports or canopy structural systems, small-, large-, and utility-scale, ground-mounted PV arrays utilizing fixed tilt racks and single- and dual-axis trackers, to floating solar structures. The size and generating capacities of solar PV systems are of a wide range. The solar PV industry usually considers a ground-mounted solar PV system to be large-scale if it has a capacity of at least 1 MW_{AC} (SEIA 2022) or at least 5 MW_{AC} as defined in National Electric Code Article 691 (NFPA 2023), whereas utility scale has usually fallen into the category of having a capacity of at least 5 MW_{AC} (Bolinger and Bolinger 2022). Rooftop and elevated systems

cover a large range as well but tend to be on the lower end of the capacity spectrum because most building roofs cover less than an acre to just over a couple of acres of PV modules. The ASCE/SEI Committee responsible for developing this Manual recognizes that not all solar PV systems require the same level of design and construction sophistication, but recommends that all rooftop, elevated, floating, and ground-mounted systems, regardless of system capacity, take into consideration the design and construction guidance that is provided in this Manual. This Manual is only intended for structural systems and their foundations that support PV modules and is not intended to be applied to other structural systems.

Although the information in this Manual is focused on the design of solar PV structures and written specifically to aid structural and geotechnical engineers, this information is also intended to assist all solar PV stakeholders in the design and development of PV power systems and facilities. The ASCE/SEI Committee responsible for developing this Manual strongly recommends that a structural and geotechnical analysis be performed by qualified and competent registered professional engineers who are experienced with the design of solar PV structures.

The information presented in this Manual is intended to be used with building code requirements and structural reference standards used in the United States. If the information in this Manual is used under the jurisdiction of a building code other than what has been adopted in the United States, then the EOR should reconcile their design methodology to be in accordance with that jurisdiction's building code(s), while still following the principles and design intent presented in this Manual.

Commentary

The level of engineering sophistication that is required to be employed to design, construct, and maintain a solar PV structure is dependent on many factors and, in many cases, is not well-defined by the solar PV industry. The Committee recognizes that not all solar PV structures require the same level of design and engineering sophistication. However, at this time, the Committee is recommending that the guidance provided in this Manual be considered for all types of solar PV structures. Photovoltaic systems principally involve the integration of structures and electrical equipment that gather and distribute solar PV generation; the focus of this Manual is on the structural aspects of each PV system, from PV module attachment to the PV rack through the PV structure down into the foundations.

No well-defined criterion exists to differentiate as to when a rigorous engineering effort is required and when the entire Manual is to be followed, or when partial or no incorporation of this Manual may be appropriate. In general, rooftop, ground-mounted, and floating residential solar PV structures that do not tie into the local electrical grid and are outside of local

AHJ/code requirements do not necessarily require an EOR to utilize this Manual, even though it can be beneficial to the PV system owner and their installation contractor to incorporate provisions of this Manual wherever possible. The owner of the PV system should manage risk by employing a competent EOR to design their solar PV structure or purchase a structure or racking system from an OEM that was designed by an EOR to meet the site-specific and service life requirements of the owner's system.

1.3 LIMITATIONS AND SCOPE

Members of the ASCE/SEI Solar PV Structures Committee prepared this Manual of Practice titled, "Design and Construction of Solar PV Structures." Although this Manual was produced using the best available resources, *ASCE makes no warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by ASCE or by the Solar PV Structures Committee*.

This Manual is intended to assist solar PV stakeholders in establishing project goals and execution strategies encompassing layout, risks, design, construction, operations, and maintenance. Due to the emphasis on the economy of design with many solar PV structures, this Manual is not intended to be prescriptive but rather to provide rational guidance so that design professionals can develop innovative and cost-effective solutions when designing solar PV structures. Rational design and development guidance is provided so that a reliable structural system can be developed. In addition, select aspects of solar PV structures, such as proprietary OEM-developed mounting systems, are not widely documented or well-understood at this time. The solar PV industry is a new industry relative to other power-generating industries and does not have decades of history to rely on or guidance from well-established codes and standards for best practices for design or construction. Currently, the experience to draw upon for guidance to designers is not extensive. The question often comes up: "How can a designer anticipate something is complex if the complexity comes from a phenomenon that is not well understood or even known?" If there is an aspect to the design that has not been studied or is not well-known, it should be approached with caution and the judicious use of professional engineering judgment until more knowledge can be developed.

Another goal of this Manual is to fill in the knowledge gaps that exist within the solar PV industry, and, for this first edition, to identify the areas that are not well-known in the industry and that need further study.

All aspects of solar PV structure design should be developed with care and caution until the industry matures, more lessons are learned, and the number of unknowns is reduced to a level where the incidence of failure is reduced to an acceptable level.

Each section of this Manual is made up of two parts—a guidance subsection followed by a commentary for that subsection. The guidance section is intended to make minimum recommendations for a consistent and reliable solar PV structure to be developed. The owner or EOR in responsible charge may require that the structure be designed to a higher standard than what is presented in each guidance section. The commentary is not intended to present a historical background of the development of this Manual, nor is it meant to provide a complete background of the research and studies that the committee used in developing design guidance. However, many references have been cited for those who want to perform their own study of the material. The commentary is intended to be used by competent individuals who can evaluate the limitations of the contents of this Manual and who will accept the responsibility for applying the guidance that is presented. Although this publication provides extensive design guidance, it is not intended to include a comprehensive literature review of all the topics covered nor the work of all subject matter experts. Such a comprehensive review is beyond the scope of this Manual, which is intended to inform engineering practice by bringing together various approaches implemented by current subject matter experts. The reader is expected to utilize their expert judgment to determine the applicability of any recommended method to the challenge at hand and to employ rational design methods in all work performed.

1.4 SOLAR PV STRUCTURES

Solar PV structures are structural systems intended to support solar PV modules for the design life of the system. In general, the design life of a solar PV system is often defined by the owner and is generally equal to the rated service life of the PV modules. Typically, racking systems made of cold-formed or structural steel and/or aluminum are utilized. However, this Manual is agnostic to the material used in design if the design professional utilizes rational engineering practices to design the structural system. These structural systems are usually considered to be both equipment and nonbuilding structures and are unoccupied by humans. They are not intended to shelter people during everyday conditions or during elevated environmental loads such as from wind, earthquake, flood, tornado, tsunami, or ice/snow. The level of safety to which these structural systems are to be designed varies on the basis of where they are located and how they may impact the community receiving the generated electricity.

In some cases, PV structures are incidentally occupied (i.e., human occupation is not the primary function of a PV structure such as in rooftop or elevated structures, even though people could be around or under the PV structure) and are expected to achieve the same life safety performance objective as the occupied building that is supporting them or a structure performing a similar function that does not have PV modules on its roof (i.e., a traditional carport with no PV modules). In other cases, such as ground-mounted and floating PV structures that have restrictions that prevent the public from gaining direct access to the PV structures, the design intent is not life safety but rather economic safety of the equipment and facility.

This Manual provides minimum recommendations for the design professional to establish a competent load path from the bottom of the solar PV module, through the module attachment fasteners into the superstructure, down through the substructure and into the soil. In a ground-mounted solar PV structure, the racking system (i.e., PV structure) is the superstructure, whereas the concrete ballast or pile foundations are the substructure. In rooftop PV structures, the racking system (i.e., PV structure) is the superstructure and the roof structure of the building supporting the racking system is considered the substructure. The columns, beams, and girts in a carport or canopy structure (i.e., an elevated PV structure) are the superstructure, whereas the foundation (if ground-mounted) or the top of the roof structure (if attached to the top of a parking ramp or a similar roof structure) is considered the substructure. Floating solar PV structures and their floats are considered the superstructure, whereas the anchors are considered the substructure or foundation. In all cases, the design professional is responsible for ensuring that the materials and component sizing of the superstructure and substructure are reliable and meet the owner's requirements throughout the defined design life of the PV system.

1.5 STRUCTURAL DESIGN OF SOLAR PV MODULES

Individual structural design of the solar PV module is the responsibility of the PV module original equipment manufacturer (OEM), including the design of the material that covers the solar cells (i.e., glass or other transparent material used), frame (if one exists), and attachment points on the module to secure the module to the PV racking structure (including hole diameter, material thickness, hole edge distance on the frame, and safe design load transfer to the fasteners).

PV module structural design by the module OEM should encompass all site-specific design loads including:

1. Static wind loads from the local building code or wind tunnel study,
2. Wind loads due to edge effects at the end of a racking system,

3. Snow loads (expected at the racking level, not ground snow loads),
4. Horizontal and vertical seismic loads,
5. Ice loads (including special considerations for floating systems),
6. Hail impact loads,
7. Wave action and loads (floating systems), and
8. Installation and maintenance live loads.

To allow for a reliable load path to be developed from each PV module to the PV supporting structure, the PV module OEM should provide the following information to the solar PV structure EOR in a module loading document so that PV module to PV structure connection fastener(s) can be designed by the PV structure EOR:

1. Module frame outside dimensions.
2. Weight of the module.
3. Type and thickness of top and bottom glass.
4. Type of frame material (i.e., including grade and material standard).
5. Cross section of the module frame.
6. Location of attachment points and fastener hole size for prepunched holes on the frame including the minimum number of points that are to be used to anchor the module to the PV structure.
7. Dimensions along the width and length of the module between attachment points on the frame.
8. Maximum ultimate tension for each attachment point on the module frame.
9. Maximum ultimate shear for each attachment point on the module frame.
10. Maximum allowed ($\pm$) pressure that the module can withstand and be operable after the load is removed. This pressure loading should account for the module being exposed to non-uniform pressure loads and a resulting internal moment across the module as will occur in a wind storm.
11. Minimum stiffness that the racking structure needs to be designed to have between PV module support points to prevent excessive deflection of the PV module during the ultimate wind speed (i.e., the site-specific unfactored wind speed from ASCE 7).
12. Any other special considerations (e.g., actions to avoid module displacement, flexure, or micro-crack risk under loads) including fatigue limits that the module components can withstand over the service life of the module.

The PV module OEM should either analytically design the structural system of the PV module or incorporate tests to determine the strength of the module. Although the module OEM should determine what criteria are to be used to determine when a module is considered to have

structurally failed when exposed to a loading condition and when it is considered to be structurally sound, a module is considered to have not failed if it is able to produce electricity after the loading event has occurred to the same level of power production it would have produced if the loading was not applied and if there are no cracks in its surface cover or in the solar cells once the load has been removed.

1. A static load rated capacity of the modules can be determined using UL 2703 (UL 2024), FM 4478 (FM 2025a), IEC 61215-1 and -2 (IEC 2021a and 2021b), or UL 61730-2 (UL 2022).
   (a) Since the solar industry currently only has rated capacities called out in consensus testing standards, the module OEM needs to demonstrate that the modules can resist the prescribed load effects that the applicable building code and ASCE 7 have outlined and the installation contractor needs to verify through coordination with the PV module OEM that the modules they are installing will have the strength to resist the design loads for the installation location.
   (b) In cases where the module is anchored to the racking structure with connections at the ends of two adjacent modules, it is important that at least two modules be loaded in the reference testing. In some cases, four or more modules may be jointly tested to affirm all racking components and attachment needs.
2. Hail resistance can be determined on the basis of UL 61730-2 (UL 2022), FM 4478 (FM 2025a), or IEC 61215 (IEC 2021a and 2021b). FM Data Sheet 1-34 (FM 2025c), *Hail Damage*, can be used to obtain hail exposure values for project locations in the United States.

If the module is designed for wind-borne debris due to its location in a hurricane-prone region, the following standards can be incorporated into the module design:

1. ASTM E1886 (ASTM 2019),
2. ASTM E1996 (ASTM 2020),
3. Florida Building Code TAS 201-94 (Florida Building Commission 1994a),
4. Florida Building Code TAS 202-94 (Florida Building Commission 1994b), and
5. Florida Building Code TAS 203-94 (Florida Building Commission 1994c).

If the module cannot resist wind-borne debris as defined by these tests, it is recommended that the modules be installed to minimize or eliminate their exposure to roof gravel or other local wind-borne debris source. Additional information, including safe separation distances, can be found in FM Data Sheet 1-28, *Wind Design* (FM 2025b).

If the module is to be designed for sandstorms, the following standards can be incorporated into the module design by the PV module OEM: (1) MIL-STD-810H (DOD 2022), and (2) IEC 60068-2-6 (IEC 2007).

Commentary

This Manual provides design recommendations for superstructures and substructures of typical solar PV structure types as of the release date of this Manual. This Manual does not address the structural design of PV modules because that requires specialized knowledge that is not typical for an EOR trained in building and nonbuilding structural systems.

Because PV modules can comprise up to 50% of the entire system cost (IFC 2015) to develop and build a solar PV facility, module durability and module structural design need continued improvement so that PV facilities can maintain an acceptable level of reliability as the industry evolves. Improvement can occur with more structural engineering being performed on the module framing systems rather than just relying on tests that anticipate module load effects during their service life. The tests (e.g., UL 2703, UL 61730-2, and FM 4478) that the PV module OEMs use are meant to provide load ratings (Section 4.2 of this Manual) and do not always match the design strengths that structural design codes and standards (e.g., IBC and ASCE 7) expect the PV structures to withstand. When this happens, shortfalls in performance may occur. Many gaps exist in the PV module structural design that need to be filled, including increased hail resistance, installation loads (e.g., as with larger format modules), and dynamic module responses to applied wind loads (e.g., from resonance when exposed to wind speeds lower than the extreme design wind speed). In addition to filling the design coordination gap, dynamic tests need to be developed for the module manufacturers to test to, as well as impact tests and static tests that reflect the type of loads that the modules will be exposed to during their service life. Until dynamic tests are developed by the solar PV industry that show if a fastener is at risk for vibration failure, fasteners that attach modules to solar PV structures should be designed to resist vibratory load effects and not be designed to only resist static loads. This includes not relying on friction-based fasteners or clips and only using fasteners that are proven through vibration testing to be resistant to coming loose and/or "walking off" when exposed to vibratory horizontal and vertical loads. Until the industry develops a vibration testing protocol for fasteners and modules, interim vibration tests should include testing frequencies of 0.5 Hz up to a minimum of at least 5 Hz but no more than 10 Hz.

When using Florida Building Code TAS 201-94, TAS 202-94, TAS 203-94 (Florida Building Commission 1994a, 1994b, 1994c), in addition to ASTM E1886 (ASTM 2019) and ASTM E1996 (ASTM 2020) to assess resistance to wind-borne debris, only laminated glass will pass such tests and not tempered or heat-strengthened glass used in PV modules. In the absence

of PV modules that meet the recommended test standards, one practical measure is to reduce the source of wind-borne debris in wind-borne debris regions in accordance with ASCE 7. Gravel or stone surfacing on roofs is not recommended near rooftop PV modules. Other methods to reduce such exposure include assuring that the design and construction for the roofing and wall cladding of adjacent structures are properly secured for expected wind speeds.

Testing should not be limited to static tensile tests of the module fastener itself. Rather, a dynamic test with a minimum test frequency of 0.5 Hz to 5 Hz should be performed using the PV modules and the fasteners to demonstrate that the vertical deflection and rotation of the PV module will not allow failure of or disengagement from the fasteners prior to reaching the design wind load. Where supports are provided between PV attachments, the test should use two or more PV modules to fully load the connections and supports. East–west facing arrays may require at least four PV modules to provide a realistic test.

Flexible or rigid rooftop PV modules may be secured/attached to the roof deck if precautions are made during the design. The roof deck should be designed for the additional wind pressures that the PV modules will transfer to the roof deck. Where rigid modules are secured to a mechanically fastened, single-ply roof system, testing should demonstrate that the wind load can be adequately transferred through the roof deck fasteners into the support structure or purlins below the deck. In many cases, more fasteners are needed to secure the roof deck to the structure.

Where PV modules are attached to standing seam metal roofs, one of the following should be done: (1) The attachments should be made at each deck rib, to follow the original wind load path of the roof assembly. (2) The roof assembly should be tested or analyzed to determine that the wind load transfer into the roof purlins will not compromise the roof deck or its internal clips.

Where rigid PV modules are attached to structurally insulated panels (SIPs) (either made of wood or metal), the attachment should be made through the SIP and into the purlin using self-drilling screws. Exception: Where the PV modules are proposed to be attached to the outer skin of the roof panels, testing should verify that failure of the roof (such as delamination of the outer panel skin) does not occur before reaching the target wind resistance.

Wind uplift resistance testing of PV modules and their fasteners to their support structure should be conducted and at a minimum should demonstrate that the PV modules and their fasteners are able to resist both static and dynamic design wind uplift pressures specific to the solar PV structural system.

Although it may not be practical to conduct wind uplift tests on the entire assembly, it is important that tests be conducted on PV modules and

their connections on ground-mounted structures. Similar concerns are there for roof-mounted PVs such that testing should not be limited to tensile tests of the connection itself. Uplift pressure tests should be done using the PV modules and the fasteners to demonstrate that the vertical deflection and rotation of the PV module will not allow failure of, or disengagement from, their fasteners prior to reaching the target wind load.

1.6 PEER REVIEW GUIDANCE

A peer review should be performed whenever an owner or AHJ requests for one to occur and whenever an innovative or new technology, material, or design methodology is incorporated into the design of a solar PV structure and/or its foundation system. This review should be done during or near the end of the design process and before the design is finalized. A peer review should not be carried out after the EOR submits sealed contract drawings and specifications or after the AHJ has reviewed and approved permits.

Commentary

Due to the unique nature of solar PV structures and because there is limited design guidance in the solar PV industry, peer reviews are recommended to make sure that the proper standard of care is being incorporated into any unique or innovative design or methodology where there is limited or no precedent in the solar industry. Although the owner and AHJ can request a peer review at any time, the owner is typically responsible for the costs associated with peer reviews. As an example, a foreign ground-mounted racking system OEM desired to enter the US solar PV marketplace, and the owner procuring the system was required by the AHJ to have a peer review completed by an independent engineer to verify whether both the level of safety and the installation were in accordance with the local building code. The peer reviewer determined that there were some shortfalls in racking design and that reinforcement was required to enable its use in the United States.

The peer review should be performed on all components of the structural system that make up the load path from the fasteners that attach the PV modules to the racking structure down to the soil supporting the foundation or to the rooftop structure that is supporting the rooftop racking system. This review should include, but not be limited to, the following items, unless the owner and AHJ agree to fewer items than what is listed:

1. Wind tunnel analysis including static, dynamic (w/ dynamic amplification factors), and aeroelastic.
2. Geotechnical recommendations.

3. Corrosion design recommendations.
4. PV racking system design (fixed tilt, tracker, rooftop, floating, elevated structure)
   (a) Superstructure design,
   (b) Substructure design,
   (c) Connections
      (i) Attachment of modules (e.g., module compatibility),
      (ii) Attachment of the racking system to the top of piles/foundations/rooftop/other,
      (iii) Interconnections within the racking system proper.

General peer review guidance is provided in Practice Note No. 24 (ACSE 2017), Policy Statement 351 (ASCE 2025), CASE 962-G (CASE 2013), and Peer Review in SE Practice (Malley 2022). These references also provide the roles of each participant and timing as to when the peer review should be performed during the design development.

REFERENCES

ACSE (Association of Consulting Structural Engineers). 2017. "Practice note No. 24—Structural peer reviews." https://www.acse.org.au/wp-content/uploads/2018/06/Practice-Paper-24-Peer-Reviews.pdf.

ASCE. 2025. "Policy statement 351—Peer review." https://www.asce.org/advocacy/policy-statements/ps351---peer-review/.

ASTM International. 2019. *Standard test method for performance of exterior windows, curtain walls, doors, and impact protective systems impacted by missile(s) and exposed to cyclic pressure differentials*, ASTM E1886. West Conshohocken, PA: ASTM.

ASTM. 2020. *Standard specification for performance of exterior windows, curtain walls, doors, and impact protective systems impacted by windborne debris in hurricanes*, ASTM E1996. West Conshohocken, PA: ASTM.

Bolinger, M., and G. Bolinger. 2022. "Land requirements for utility-scale PV: An empirical update on power and energy density." *IEEE J. Photovoltaics* 12 (2): 589–594.

CASE (Coalition of American Structural Engineers). 2013. *Guidelines for performing project specific peer review studies on structural projects*, CASE 962-G. Washington, DC: CASE.

DOD (US Department of Defense). 2022. *Environmental engineering considerations and laboratory tests*, MIL-STD-810H. Washington, DC: DOD.

Florida Building Commission. 1994a. TAS 201-94: *Impact test procedures*. Florida Building Code – Test Protocols for High-Velocity Hurricane Zone (HVHZ), Florida Building Commission, Tallahassee, FL.

Florida Building Commission. 1994b. TAS 202-94: *Criteria for testing impact and non-impact resistant building envelope components using uniform static air pressure*. Florida Building Code – Test Protocols for High-Velocity Hurricane Zone (HVHZ), Florida Building Commission, Tallahassee, FL.

Florida Building Commission. 1994c. TAS 203-94: *Criteria for testing products subject to cyclic wind pressure loading*. Florida Building Code – Test Protocols for High-Velocity Hurricane Zone (HVHZ), Florida Building Commission, Tallahassee, FL.

FM (Factory Mutual Insurance Company). 2025a. Examination Standard for Roof-Mounted Rigid Photovoltaic Module Systems, FM 4478. Johnston, RI: FM. https://www.fmapprovals.com/-/media/Feature/Approval-Standards/4478-pdf.pdf

FM. 2025b. "Wind design—Property loss prevention data sheets 1-28." Johnston, RI: FM. https://www.fm.com/resources/fm-data-sheets

FM. 2025c. "Hail damage—Property loss prevention data sheets 1-34." Johnston, RI: FM. https://www.fm.com/resources/fm-data-sheets

IEC (International Electrotechnical Commission). 2007. *Environmental testing—Part 2-6: Tests—Test Fc: Vibration (sinusoidal)*, IEC 60068-2-6. Geneva: IEC.

IEC. 2021a. *Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 1: Test requirements*, IEC 61215-1:2021. Geneva, Switzerland.

IEC. 2021b. *Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 2: Test procedures*, IEC 61215-2:2021. Geneva, Switzerland.

IFC (International Finance Corporation). 2015. "Utility-scale solar photovoltaic power plants: A project developer's guide." Washington, DC: IFC. https://www.ppiaf.org/documents/5191

Malley, J. O. 2022. "Peer Review in SE Practice." *Structure Magazine*. https://www.structuremag.org/article/peer-review-in-se-practice/

NFPA (National Fire Protection Association). 2023. "NFPA 70: National electrical code."

SEIA (Solar Energy Industries Association). 2022. "Major solar projects list." https://www.seia.org/research-resources/major-solar-projects-list.

UL (Underwriters Laboratories). 2022. *Photovoltaic (PV) module safety qualification—Part 2: Requirements for testing*, UL 61730-2. Northbrook, IL: UL.

UL. 2024. *Mounting systems, mounting devices, clamping/retention devices, and ground lugs for use with flat-plate photovoltaic modules and panels*, UL 2703. Northbrook, IL: UL.