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Maturing Rational Design Methodologies and Industry Consensus Engineering Standards: Critical Fastened Joints - Solar PV Industry

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Opportunities to Facilitate Industry Development; LCOE Reductions Increase Reliability by Improving Standards for Critical Structural Connections

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Maturing Rational Design Methodologies and Industry Consensus Engineering Standards: Critical Fastened Joints - Solar PV Industry

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The Guidance Document

The enclosed chapter on "Maturing Rational Design Methodologies and Industry Consensus Engineering Standards: Critical Fastened Joints - Solar PV Industry" is part of a compendium of free-standing chapters that taken together comprise the Guidance Document on Critical Structural Joints in solar PV racking systems. This chapter addresses the need for the development of industry led engineering consensus standards as has been done in other, more matured industries.

Chapters of Guidance Document:

- Fundamentals of Solar PV Bolted Joint Loosening and Prevention
- Gaps & Improvements for Utility-Scale Solar PV Mounting System Bolted Joints Tightening Methods, Tools & Fasteners
- Exploring Electrical Bonding in PV Structural Joints
- Proposed Specifications for Clearance Holes and Washers
- Maturing Rational Design Methodologies and Industry Consensus Engineering Standards: Critical Fastened Joints – Solar PV Industry
- Conclusions from 82 Failure Cases in Critical Structural Connections in Solar PV
- First Generation Efforts as Systems-Level Strength Testing of Solar PV Top-Down Clamps
- Cycling Demands on Solar Structural Joints under Wind Loading
- Deformation Analysis of Solar Structural Joints Under Wind Loading
- Large Format Modules & Legacy Assumptions

Executive Summary

Critical structural joints can be seen throughout a solar array and are called upon to secure modules and keep racking assembled and able to resist large demands from winds and snow loads. In the relatively new and fast-growing solar PV industry, the important role these hardware assemblies (e.g. clips, clamps, bolts, nuts, washers) play is not well understood by product designers. Failures with critical structural joints are surprisingly common and point to the need for maturing the engineering and assembly of these joints. The wide variety of design concepts Figures (1&2) demonstrate interesting and innovative ideas but are lacking the basics of fastener engineering seen in matured industries (e.g. transportation, buildings).

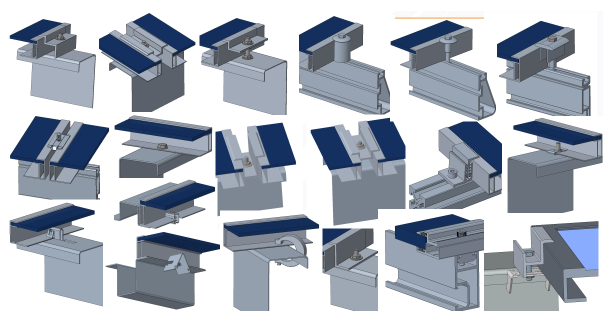


Figure 1 - Module Mounting Connections

Figure 2 - Solar mounting systems and the many connections

Complicating the maturing process for critical structural joints is that they are one component in rack supporting structures that exhibits a systems behavior; each component will affect the other and play a key role in maintaining structural integrity. When wind loads the surface of a module, the underlying racking members deflect and twist which in turn imparts forces back into the joints and into the mounted modules. Often, these supporting rack structures exhibit high deflections and low natural frequencies which amplify the demands placed into the joints even in moderate winds.

Current engineering practices and associated structural conventions view solar racking support structures as they would a high mass building that exhibit more static behaviors in wind events. Solar structures are unique from high mass buildings and require the development of solar specific industry engineering consensus standards.

Critical Structural Joints in the Larger Context of Mounting System Engineering

Mature industries are underpinned by a set of well-developed industry engineering consensus standards – documents that embody a set of minimally acceptable practices that protect both public safety and commercial interests. These documents are regularly updated through a rigorous, consensus-based committee process involving qualified industry professionals. Standards developing organizations (SDOs) host active professional committees that steadily promulgate new and updated revisions, making engineering standards living documents that evolve alongside technological development, knowledge acquisition, and changes in commercial needs. Changes in engineering standards are based on sound science, engineering principles, and data, which together form an underlying “rational design methodology.”

Mature industry engineering consensus standards serve a variety of important purposes. Stakeholders utilize them to design, engineer, procure, assemble, insure, and evaluate assets for potential investment and to assess potential legal liability. Among the stakeholders that rely on mature standards are investors, engineers, contractors, authorities having jurisdiction (AHJs), lawyers, insurance, asset owners, and public sector entities. Certain stakeholders perform a “gatekeeper” role, leveraging standards to protect industries and consumers from unqualified products and poor practices.

Today’s solar PV industry lacks such mature engineering consensus standards. Without them, engineers, contractors, AHJs, owners, and financial services companies cannot design, build, insure, and trade assets with a reasonable degree of certainty of asset performance, service life, or safety. Some gaps in standards relate specifically to the critical structural joints that are common across various types of solar PV installations (i.e., ground-mounted fixed and tracking, canopy, roof-mounted, and building-integrated). This uncertainty adds an unnecessary layer of friction, inefficiency, and cost to the widespread deployment of solar PV.

Today’s solar PV industry exhibits common signs of immaturity in terms of standards. Failures are far too common and basic minimum practice is not yet clearly defined by industry led consensus standards committees. There is need for industry led consensus standards which describe simplified design methodologies that are easily implementable by product designers. To develop these simplified methods, there needs to be the application of underlying rational design methodologies that are in turn underpinned by science-based experimental data and or relevant transferable knowledge. While some knowledge transfer opportunities exist, the unique nature of solar structures presents knowledge gaps that must be filled.

This Guidance Document chapter employs an evidence-based approach to highlight specific gaps in fundamental knowledge and the need for research to underpin rational design methodologies which in turn can result in matured engineering consensus standards for the solar photovoltaic (PV) industry. In addition to evidence-based gaps, there are two additional gaps that can be described as "self-apparent," meaning that there are obvious and irrefutable knowledge divergences. Maturing of solar consensus standards can occur through both knowledge transfer and the development of a rational design methodologies that industry committees produce if research is undertaken to address current knowledge gaps. This report not only highlights where research is needed but also refers readers to resources containing transferable knowledge and currently applicable standards.

Definitions

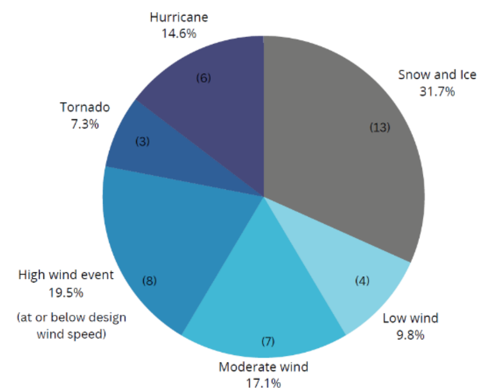
Term	Definition
alternative joints	Joints that fall outside of the main engineering standard, the Research Council on Structural Connections (RCSC) and are often not designed using a rational method based on known physical properties.
bonded joint	A joint that creates a low-resistance electrical connection between exposed conductive components within a PV mounting structure that are not intended to carry current.
codes	A consensus standard that has been adopted by a governing agency (i.e., authority having jurisdiction, or “AHJ”) and is legally enforceable. A consensus standard becomes a code when a governing authority, like a local government or regulatory body, formally adopts it and enacts it into law within its jurisdiction, making compliance with the standard mandatory and legally enforceable; essentially, the standard is “codified” and becomes part of the legal framework within that area, allowing for penalties if not followed. Codes generally represent minimum practices for safety and quality.
connection	A combination of structural elements and joints used to transmit forces between two or more members. The Research Council of Structural Connections (RCSC) uses the following definition: “An assembly of one or more joints that is used to transmit forces between two or more members.” (RCSC - Specification for Structural Joints Using High-Strength Bolts, Chicago IL, (June 11th 2020))
consensus standards	Sponsored by a Standards Development Organization (SDO) and is a standard developed through a rigorous committee consensus process comprised of professional engineers from industry.
critical structural joints	The assembly of components (e.g., fasteners, clips, washers, brackets, etc.) used to fasten structural joints in a PV system, including module attachment, racking and tracker interconnections, and attachment to underlying structures not otherwise covered by AISC 360-*22)*.
joint	Area where two or more ends, surfaces, or edges are attached. Categorized by type of fastener or weld used and method of force transfer. “Joint” is a common term used by both American Iron and Steel Institute (AISI) and American Institute of Steel Construction (ANSI/AISC 360-22), with definitions coordinated between the two standards developing organizations (SDOs).
maintenance-free solar PV joint	A joint capable of meeting its intended functional requirements for the intended design life, without maintenance.
rational design methodology	According to ASCE, “all structural systems, and the method of construction used to assemble each system, is to be based on a rational design methodology following well-established principles of mechanics and be evidence-based rather than following anecdotal opinions or experiences. This analysis is to result in a structural system that has developed a complete load path capable of transferring all loads from their point of origin down (i.e. wind loads acting on the solar PV module) into the supporting element such as the soil if the structure is free standing or floating, or the supporting roof structure if the structure is mounted to the top of a structure.”

	(ASCE – *The Method of Practice (MOP),* Chapter 4, Structural Design, Section 4.3, Rationality)
standard (consensus standard)	A set of guidelines and technical definitions that create "'how-to' instructions" for designers and manufacturers. Standards are developed in a collaborative process involving all interested parties. To achieve consensus, all views and objections must be considered, and a demonstrated effort must be made toward resolution. Compliance with standards is generally voluntary, since SDOs do not have legal enforcement authority. Consensus standards generally represent minimum practices for safety and quality.
standards developing organization (SDO)	Many different entities develop standards, including trade associations, professional societies, standards producers, consortia, companies, and government agencies. Collectively, these diverse entities are referred to as "standards developing organizations" (SDOs).
system-level stiffness	The ability of a complete PV racking system to resist wind, snow, and ice loading.
structural reliability	The ability of a structure to meet its functional requirements for the intended design life.
structural loading	Structural loading refers to the external forces, pressures, or environmental effects applied to a solar PV structure or its components. Common types of loading include dead loads (permanent), wind, snow and seismic.
structural demand	Structural demand is the internal force, stress, deformation, or displacement that develops within a structural element or system in response to applied loads. It represents the required performance or resistance a component must provide to safely carry the imposed structural loading. Examples include bending moments, shear forces, axial forces, and deflections calculated through structural analysis.
mounting system	All components; beams, joints, piles and foundations that make up a system designed to support solar modules.
fixed mounting system	A mounting system that is set a design tile and azimuth permanently.
tracking mounting system	A mounting system that can track the suns' movement across the sky during the day and in some cases can adjust for seasonal variations in the suns' position. Single axis trackers move in one dimension and track the sun's movement in a day and a single axis tracker can move in two axis and track both the daily and season movement of the sun.
elevated mounting system	A mounting system that can over span a ground, parking or water area that provides surface for solar modules and the ability to accommodate parking, equipment, pedestrian uses, storage and even bodies of water underneath.
solar PV joint capacity	The ability of a solar PV joint to resist loading demands.
traditional bolted joints	Those bolted joints that easily fall under RCSC guidance.

1. Critical Structural Connections and the Solar PV Industry

While the solar PV industry has made advancements in terms of developing engineering consensus standards, it has yet to reach a state of full maturity in key areas related to the unique structural and mechanical challenges found with PV mounting systems. Standards developing organizations (SDOs) and their professional industry committees are beginning to address these challenges, motivated by a growing body of evidence demonstrating the uniqueness of solar PV mounting structures that require consensus standards distinct from those used in buildings. Today, engineers and other key stakeholders apply standards largely designed for high-mass, static building structures to solar PV arrays, with poor outcomes.

Historically, change has occurred when industries experience pain and loss or worse, catastrophes. Such was the case with significant standards improvements in the wind industry. In the early 1990s, the wind industry in Europe and the United States employed insufficient design standards, resulting in breakdowns in major systems (e.g., blades, gearboxes, tower structures) over the 20-year design life (National Academies, 2011).



Today's solar PV industry is experiencing significant loss due to the structural integrity of its products. A research study from Lawrence Berkeley National Laboratory (LBNL) examined 83 cases of fastener failures in solar PV assemblies and found that only 22% of cases were clearly linked to severe wind events (i.e., hurricanes or tornadoes) – meaning that the majority of failures occurred at below, and in some cases well below, ASCE design wind speeds (Figure 3).

Figure 3. Fastener failures in solar PV assemblies

1.1 Systemic Implications of Immature Industry Engineering Consensus Standards Throughout the Lifecycle of Solar PV Systems

Consensus standards play important roles throughout the lifecycle of a structure, establishing a universal set of practices that guides decision-making and resolves any disputes or claims that may arise. These industry-led standards are needed to protect public safety, promote a healthy marketplace of products that are insurable, financeable and offer long term operations.

Helpfully, the Research Council on Structural Connections' (RSCS) main standard - *Specification for Structural Joints Using High-Strength Bolts* (RCSC 2020) provides important areas of transferable knowledge for some critical structural joints found in solar PV systems and describes the lifecycle phases of connections used in buildings applications in a manner that is a very relevant and analogous to solar. The RCSC Specification for Structural Joints

Using High-Strength Bolts is a critical standard that provides a framework for the reliable design, assembly, and inspection of bolted connections in steel structures. It standardizes the use of high-strength bolts, by defining acceptable joint types, bolt installation methods, required pretension levels, surface preparation, and inspection procedures. The specification plays a key role in the safety and structural integrity of buildings, bridges, towers, industrial facilities - by providing a rational design basis, supported by nearly a century of research and practice.

The RCSC manual shows five clear phases for critical structural connections used in buildings (Figure 4), with each relying on mature standards for success. For example, when things fail, the “Arbitration” phase relies on standards to properly ascribe responsibility.

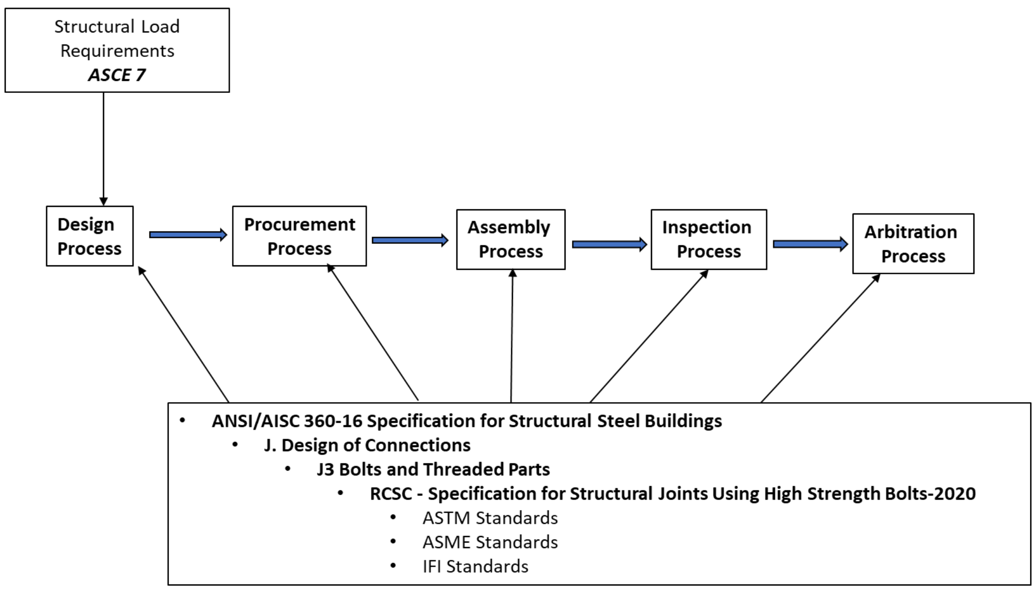


Figure 4. Matured standards support buildings across the five distinct phases of their lifecycle

Among solar industry experts interviewed for this study, a high level of frustration and confusion exists over why change is not occurring faster, and why unqualified mounting systems continue to be sold despite overwhelming evidence from field failures. The reason for this reluctance to change is that the solar industry does not yet have a minimum set of industry engineering consensus standards from which to operate. There is a need for a set of solar specific standards, apart from those used in buildings.

A key challenge facing the solar industry, therefore, is to move quickly to a set of matured standards that could eventually become code. This will require developing rational design methodologies, drawing from relevant transferable knowledge and science-based sources, and filling important research gaps to generate data.

1.1.1 CAPEX vs. OPEX and Unanticipated High LCOE

Another industry indicator for the need of PV specific engineering standards is the CAPEX-dominated (Figure 5) decision-making which has influenced the design and procurement of critical structural connections along with the other components. Without a minimum threshold for structural reliability established by matured standards, there effectively is no design floor, and CAPEX now dominates engineering and design decisions. Put another way, the industry now lacks price competition against a minimum practice that can result in a 30-plus-year design life. Many mounting systems fail at well below design wind speeds with chronic loosening of the critical structural joints seen which has in turn driven OPEX up dramatically for many asset owners.

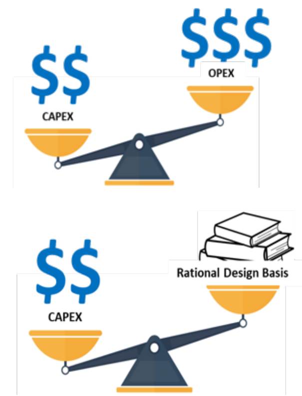


Figure 5. CAPEX, OPEX, RDB

Lowering CAPEX drives "critical decisions" about the design and assembly of solar PV structures more often than OPEX, currently. Periodic maintenance (retightening) of solar PV joints has become commonplace and accepted in this industry – but not in others. Unanticipated by owners are large OPEX costs leading to substantially increased LCOE.

Lowering CAPEX often influences critical decisions in the absence of a rational design methodology, test data, and safety and structural standards. Value engineering has resulted in lightweight structures and minimized structural sections (e.g., large-format modules) and significant failures.

1.2 Developing a Rational Design Methodology

Matured engineering consensus standards are underpinned by a body of engineering knowledge that is referred to as "rational," meaning grounded in evidence and science-based principles. In engineering, "rational design methodology" refers to an approach to design that is based on well-established scientific principles, mechanics, material properties, and logical analysis, rather than rules of thumb, empirical methods, or guesswork.

The ASCE Solar Structures Committee, in its recent guidance document (ASCE -The Manual of Practice, or "MOP"), has applied the concept of "rational design methodology" to solar structures and includes the following description.

> *All structural systems, and the method of construction used to assemble each system, is to be based on a **rational design methodology** following well-established principles of mechanics and be evidence-based rather than following anecdotal opinions or experiences. This analysis is to result in a structural system that has developed a complete load path capable of transferring all loads from their point of origin down (i.e. wind loads acting on the solar PV module) into the supporting element such as the soil if the structure is free standing or floating, or the supporting roof structure if the structure is mounted to the top of a structure.*

Mature engineering standards emerge out of a rational design methodology, which itself rests on a base of foundational knowledge (Figure 6). Foundational knowledge establishes evidence and defines what is "rational." For the solar PV industry, foundational knowledge includes transferable knowledge (engineering first principles); insight gained from the use of tools and techniques of computer modeling, wind tunnel tests and basic research; and failure data sources such as root cause analysis (RCA).

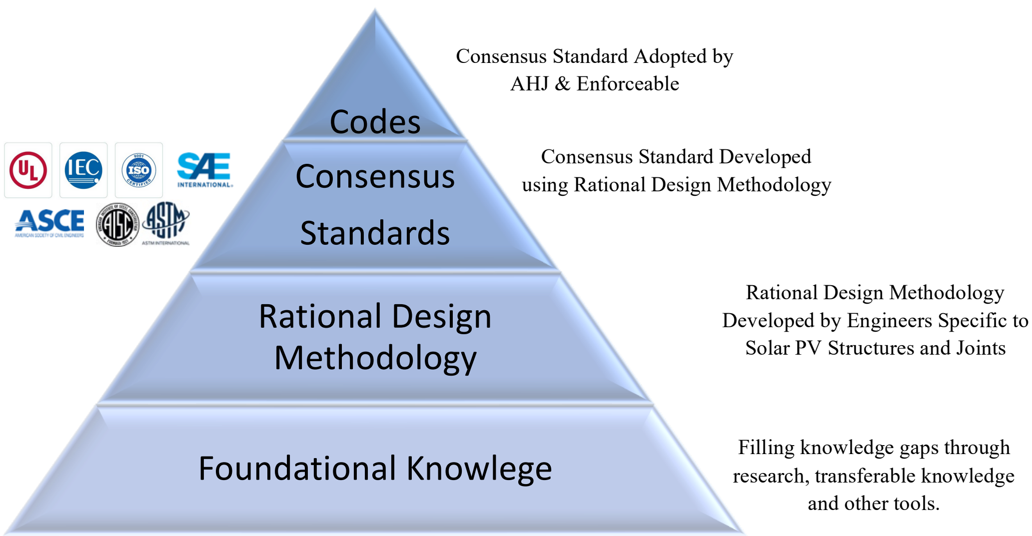


Figure 6. Codes and standards pyramid

1.3 Knowledge, Rational Design and Consensus Standards Gaps

1.3.1 The Six Core Gaps

This paper identifies and summarizes Six Core Gaps for the solar PV industry (
Table 1). Other, less urgent gaps are not addressed here. The first three gaps are very interdependent and interrelated. For example, testing (Gap #3) must incorporate the systems and dynamic effects seen in Gap #1; both would feed into Gap #2, design specifications.

Table 1. Six core code gaps for the solar PV industry

	GAP
#1	Critical Structural Connections, Systems Effects, and Dynamic & Cyclical Demands
#2	Lack of Design Specifications
#3	Strength Standards Paired with Relevant Testing
#4	Alternative Fasteners
#5	Self-Apparent Code Gaps
#6	Electrical Bonding Through Critical Structural Joints

2. Evidence of Gaps in Knowledge, Rational Design Methodologies and Industry Consensus Engineering Standards

Three sources of evidence support the existence of specific gaps: 1) interviews of seven industry experts; 2) a survey and structured interviews about 84 failure cases; and 3) "self-evident" gaps based on a survey of existing rack designs. Importantly, each of these three sources aligns with and corroborates each other.

Table 2 shows a summary of the evidence used to select and support five gaps in solar PV structural joints. The table indicates "yes" if direct evidence supported a code gap and "indirect" if a gap could be logically inferred. For example, Gap #1 (Critical Structural Connections, Systems Effects, and Dynamic & Cyclical Demands) can be easily inferred from the 84 case failure interviews.

Table 2. Summary of code gaps and evidence categories

Gap Category	**Structured Interviews (7 Industry Experts)**	**Survey & Structured Interviews (84 Failure Cases)**	**Self-Evident Failures**
(1) Critical Structural Joints, Systems Effects, and Dynamic & Cyclical Demands	Yes	Indirectly	Yes
(2) Lack of Design Specifications	Yes	Yes	Yes
(3) Strength Standards Paired with Relevant Testing	Yes	Indirectly	Yes
(4) Alternative small and unique fasteners	Yes	Yes	Yes
(5) Self-Apparent	Yes	Yes	Yes

2.1 Interviews with Seven Industry Experts

Interviews were conducted by George Kelly and Steve Hogan of the American Renewable Standards and Certification Association (ARESCA). Ten questions guided the interviews, and respondents were encouraged to elaborate on topics. Each question addressed a key topical area and was chosen to stimulate discussion (Table 3, left column). Interviews were recorded and transcribed, and responses were grouped into categories (Table 3, middle column). The categories were then narrowed down to gaps stemming from the interviews (Table 3, right column).

Table 3. Summary of interview questions, response categories, and resulting gaps identified

Interview Questions	Categories of Responses	Core Code Gaps Identified
1. What do you see as the principal issues affecting the structural reliability of module mounting systems (tracker, fixed rack and canopy)? 2. What issues do you see in structural reliability? 3. What are the principal causes of those structural reliability challenges? 4. Do you feel that 'system level stiffness' is properly addressed in the current standards? 5. If gaps exist, what SDO should address this issue?	1. Global observations 2. Design for movement/dynamics 3. Lack of consistent design guidance in PV standards 4. Training of installers/installation practices and tools 5. Testing topics a. Consistent testing of critical connections under dynamic conditions b. Wind tunnel testing 6. Standards for small, novel fastener hardware 7. Cost impacts	1. Critical Structural Connections, Systems effects, and dynamic and cyclical demands 2. Lack of design specifications 3. Strength standards paired with relevant testing 4. Non-traditional alternative small and unique fasteners 5. Self-Apparent 6. Electrical Bonding

6. Do you feel 'Solar PV Joint loads' is properly addressed in the current standards? 7. Do you feel 'Solar PV Joint capacity' is properly addressed in the current standards? 8. If a gap exists, what SDO should address this issue? 9. Are you willing to be quoted in an article regarding this topic? 10. If not, can we still use your input anonymously?	8. Appropriate standards developing organization (SDOs)	

Interviewees were chosen based on their prominence in the industry and according to the following selection criteria: 1) professional roles that would have given them first-hand knowledge of engineering practices, standards, and product testing; 2) organizations known to be actively involved with the pursuit of structural reliability; and 3) individuals with demonstrated leadership on structural reliability. Table 4 summarizes interview respondents industry demographics.

Table 4. Industry experts interviewed

Category	Number of Respondents
Rack manufacturer, product engineers	2
Rack manufacturer, safety/quality engineer	1
Standards developing organizations, standards manager	1
Industry association, standards manager	1
Nationally Recognized Test Labs, standards testing managers	2

The resulting standards and knowledge gaps with concurrence between respondents is shown in Table 5.

Table 5. Concurrence among experts: Identified standards gaps

Identified Standards Gaps	Respondent Concurrence
1) Critical Structural Connections, Systems effects, and dynamic and cyclical demands	All 7
2) Lack of Design Specifications	All 7
3) Strength Standards Paired with Relevant Testing	6
4) Alternative small and unique fasteners	All 7
5) Self-Apparent Gaps	4
6) Electrical Bonding	4

2.1.1 Key Observations from Expert Interviews

All respondents clearly and succinctly answered the interview questions and universally expressed concerns about the structural integrity of PV module mounting systems. All respondents cited current standards gaps as the primary reason why product designers are unable to produce racking systems that can withstand design wind speeds. This group of respondents expresses strong opinions that adequate standards (along with robust product testing) are essential to improving and maturing current practices.

Gap #1: Critical structural connections, system effects, and dynamic and cyclical demands

All respondents discussed this gap and included observations about the need for design practices, guided by standards, and testing that anticipate dynamics of solar structures. Key concerns included natural frequencies, self-excited vibrations, low-frequency resonances, and large structural deflections. These expert respondents unanimously agreed that critical structural connections are an integral part of the rack system, both affected by it and, in turn, affecting it. Fasteners see demands generated by the system of mounted modules, purlins, and sub-framing. Respondents raised these topics and identified dynamics causing strong cyclical loading events at the fastener, which may lead to fatigue, loss of preload, and eventual failure.

The topics experts raised in discussing this gap generally fell into two sub-categories: problematic issues not anticipated by product designers; and knowledge gaps in current engineering practices.

Gap 1 Sub Topic: Problematic issues not anticipated by product designers

Respondents universally commented on the issues that are not anticipated or designed for by current product engineers. The most-discussed factor was the dynamics of solar structures from several vantage points. They characterized solar PV structures as lightweight and flexible, making them susceptible to dynamic amplification phenomena such as aeroelastic flutter, vortex shedding, and other forms of self-excitation. These characteristics often result in large-amplitude displacements and torsional deformation of the frame components. Such dynamic behavior imposes complex, cyclic, and multi-axial loading on bolted and fastened joints—loading profiles that are often not considered in static design methodologies. Respondents noted that these compounded loading patterns can progressively degrade joint capacity, ultimately leading to loosening and mechanical failure.

Similarly, all respondents either explicitly pointed out or strongly inferred the presence of “systems effects,” whereby these large cyclical compound loading events degrade joint strength. These effects then lead to increasing bolted joint slip and deflection, which in turn escalates the cyclic loading on the connection, culminating in joint or frame failure.

Most respondents also pointed out the unanticipated load paths transmitting through connections into the PV modules themselves. Strong concern was expressed about what happens also to the module under these extreme cyclical loading events, and particularly around cracking the solar cells from stress concentrations and cyclical fatigue. Respondents also expressed clear concern and a need to protect the module.

Gap 1 Sub Topic: Knowledge gaps in current engineering practices

All respondents identified two main issues with current engineering practices: a dependence on static design conventions (borrowed from building engineering practices); and a lack of knowledge with respect to dynamics and systems effects. Based on respondent comments, important questions clearly must be addressed, such as,

- What global stiffness is required in a racking system to mitigate dynamic amplification?
- How much cyclic or compound loading can typical fasteners and modules sustain before failure?
- How should designers properly account for system-level behaviors in structural analysis?

One respondent raised concerns about the utility of wind tunnel testing, claiming that some existing testing is conducted poorly and may not accurately reveal the true dynamics of a given structure, particularly with rigid scale models.

Gap #2: Lack of design specifications

All respondents discussed topics related to minimally acceptable design guidance, which mature engineering consensus standards provide. The lack of clear standards for the design and engineering of solar structures is a major shared concern. Many of today's designs lack fastened joints that are engineered for the demands seen in field conditions over the lifecycle of a system, which may indicate a problematic lack of basic knowledge of fastened joint dynamics among product engineers. Specifically, the demands on a given joint for a given rack design were believed to be a key knowledge gap that must be addressed.

Gap 2 Sub Topic: Insufficiency of existing engineering consensus standards and the need for new approaches

All respondents expressed strong opinions that the existing design standards are not sufficiently mature for solar structures. All respondents also felt that solar-specific design standards must be developed. One respondent mentioned that racking products have widely divergent survivability outcomes when exposed to identical conditions, a phenomenon that can be seen after storms. All discussed the flexible and dynamic nature of racking systems as evidence of the need for solar-specific design standards.

Five respondents mentioned module-to-rack interface issues as needing further elucidation in standards as one respondent pointed out, module frames are often used as a structural element of the racking system (as module frames provide structural rigidity). Three respondents mentioned the siloing that occurs between rack and module manufacturers; because the interface is not well described in standards it is unclear which entity bears responsibility.

Gap 2 Sub Topic: Importance of industry engineering consensus standards

All respondents discussed the need for improved standards to guide the design community to an acceptable level of engineering practices. Five respondents pointed out that nothing in current standards clearly captures the dynamics of solar structures. There was a strong and universally held opinion that standards should be used to establish solar-specific engineering practices that can meaningfully improve outcomes.

<u>Gap 2 Sub Topic: Characterizing dynamic loading in engineering standards</u>
Six of the seven respondents recognized that the dynamic loading seen in solar structures is challenging to characterize, which in turn complicates standard development. These respondents referred to the lack of system stiffness as a key area needing to be addressed, as many designs on the market today hazardously assume that the module itself will provide the necessary stiffness.

<u>Gap 2 Sub Topic: The effects of standards on the lifecycle of an asset</u>
Three respondents commented on the implications that standards gaps have on the lifecycle of a system. One respondent mentioned that AHJs don't know what to inspect for, operators lack sufficient instructions to maintain racks, and when failures occur, it is very difficult to arbitrate a solution. With regard to arbitration, one respondent expressed a fear that "a few bad actors" could exploit engineering standard and knowledge gaps to intentionally sow confusion.

Gap #3: Strength standards paired with relevant testing

Testing in support of updated standards was a core theme discussed by six respondents. There were two areas of testing needs expressed by the respondents; 1) testing needed as a research tool to improve the rational design basis which in turn would support standards and 2) testing by industry lab that draw from a well-developed testing standard that allows engineers to design products of adequate strength.

One respondent mentioned that testing with solar-specific standards is needed to provide a "level playing field" so that racking companies can compete. Low-priced and poor-quality products would ultimately be eliminated from the bidding pool. One respondent disagreed, saying the task of product testing would be insurmountable.

According to one respondent who is actively involved with testing, requirements from certifying bodies are often vague and open to wide interpretation, and therefore a combination of UL, IEC, and IBC standards are often used. Six respondents discussed the need for testing that captures real-world loading conditions (e.g., wind dynamic, deflection, vibrational loosening, and uneven loads on the module face).

Six respondents mentioned testing of the mounted module, which relates to other comments made about the module-to-rack interface. Three respondents discussed current testing practices, which are intended to support UL 2703 compliance but are simply static sandbag tests on the face of a module. One respondent mentioned non-uniform module loading tests done for snow loads with no correlation to the fastened joint under dynamic wind loading.

One respondent suggested module manufacturers as an important stakeholder group that would benefit from improved testing. One module manufacturer no longer honors the "static sandbag" load tests of UL 2703 because it doesn't capture the true dynamic loading seen in field conditions.

The interviews gave a clear indication that testing must be standardized, capture dynamics and systems effects, and support the implementation of standards. One respondent referred to testing for dynamics as “performance testing,” meaning that expected demands must be integrated into a test. Two respondents mentioned adding a vibration test (to capture vibrational loosening that comes from joint slip) in addition to dynamic testing.

Gap 3 Sub Topic: The need for research

Regarding testing, one respondent mentioned the need for research to characterize the compound loading likely seen on bolted joints. With this knowledge, testing protocols could be developed that support standards. Another respondent mentioned the need to verify any new test that is devised; typically, this would involve research, which is an investment the industry would struggle with.

Gap 3 Sub Topic: Wind tunnel testing

Four respondents discussed wind tunnel testing limitations that result from the use of small, rigid, plastic models that lack the dynamics seen in real structures. One respondent discussed the high costs of such testing and the difficulty of capturing the full array of shapes and land topology seen in the field. One respondent discussed the importance of wind tunnel testing to gain dynamic amplification factors.

One respondent pointed out that in the solar PV industry, there is no testing convention that supports standards. As another put it: “There is complete freedom about, how is it exactly tested? In what direction? Is it a single load path? Is it a combined load? Is it a test to first yield? Is it test to plastic hinge? What is it?”

Gap 4. Traditional vs. Alternative Structural Joints

All respondents identified use of unique and alternative joints (defined below) as another area of significant concern how to determine the strength of these designs. Four of the respondents reflected on these fasteners as providing another area where solar was unique from other structures.

Background discussion on traditional versus alternative fasteners

Fastened joints in solar PV racking and module mounting systems can be grouped into either traditional or alternative fasteners. Traditional fastened joints, as a category, are covered by the Research Council on Structural Connections (RCSC) *Specification for Structural Joints Using High-Strength Bolts (RCSC 2020).* Generally, this includes bolts ½-inch and larger in diameter.

Traditional connections are commonly seen in rack assemblies. Figure 7 below provides examples of traditional connections commonly seen on solar PV racking.

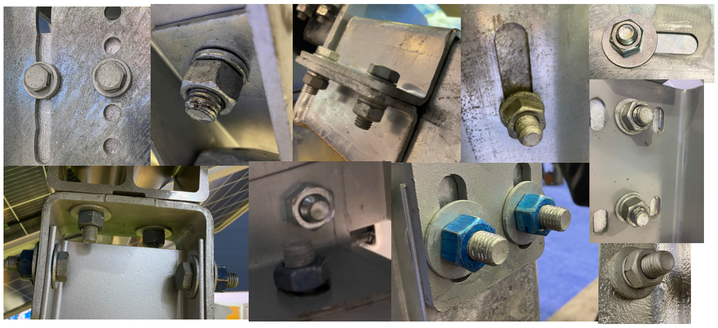


Figure 7. Traditional structural connections

These traditional fastened joints, while they should be designed using the RSCS specifications, currently are often not, as evidenced by the multitude of misapplications that can be seen from inspecting solar arrays in the field or at any tradeshow. Shown in Figure 7 above are several prime examples of the misuse of washers and slotted joints, just two very clear examples among several design issues often seen on mounting systems today. Both the Solar Structures Committee of the American Society of Civil Engineers (ASCE) and Underwriters Laboratory (UL) are promoting the application of the RSCS to mounting systems for fasteners and joints that fall under the definition of traditional structural connections.

Alternative Connections – Significant Standards (Or research supporting rational design basis) Gaps?

Beyond traditional connections are a wide variety of concepts that are used to mount modules and assemble solar PV mounting systems, and are considered alternative as they are conceived outside of basic rational design methodologies such as is described in the RCSC for traditional fasteners. These alternative joints in and of themselves representative of a serious gap in knowledge, rational design and standards. The definition of alternative comes from the fact that the fastener sizes and components (e.g. clips, clamps and cams) are unique to solar mounting systems and not addressed in the RCSC.

It is these alternative fasteners that are the source of most of the failures, as they are innovative but lack the well-established basic engineering design methods as detailed in the RCSC.

Some module mounting and mounting system designs sold today are far outside even basic engineering first principles; it is not uncommon to see rack joints comprised of non-structural hardware such as hose clamps, chain link fence brackets, and even door hinges. Most of the core gaps identified in
Table 1 relate to these unique connections. Figure 8 shows examples of alternative joints found on solar PV racking systems that are strikingly commonplace today. None of the examples shown in Figure 8 would have the strength capacity to resist even mild wind loading events.

Figure 8. Alternative Structural Joints

A research effort from the Lawrence Berkeley National Laboratory (LBNL) has conducted surveys of the trade floors at the Solar Energy Industries Association (SEIA) annual international trade conference, known as “RE+.” The research team conducted surveys in 2022, 2023, and 2024, and found many examples of alternative fasteners with serious design flaws. Across the three survey years, there was no appreciable improvement in practice.

The team compiled data from the 2022 event, conducting an audit of the solar PV racks and trackers on display at RE+ ‘22 (Ness et al., 2023). Specifically, the team looked at 19 different mounting system products and examined 92 critical structural joint designs. Of the 92 bolted joints examined, the team identified 83 areas of concern, many of which were quite serious and could potentially lead to significant financial loss and safety issues (i.e., for systems near pedestrians). Hardware found on display was cross referenced to product literature and was confirmed.

Gap 5. Self-Apparent Gaps

Four the respondents pointed out that some of the fastened joints contain hardware that is obviously not acceptable and not engineered. Section 2.3 explores these self-evident gaps in detail.

Gap 6. Electrical Bonding Gaps

Four of the respondents expressed concerns that solar PV module mounting fasteners could maintain electrical bonding over time. This topic was explored in detail in a section 2.3.3.3 below.

2.2 Interviews and surveys on 84 structural failures

A research team led by Lawrence Berkeley National Labs (LBNL) conducted structured phone interviews and surveys of 28 industry respondents covering 84 failure cases. The phone interviews were conducted using predetermined questions designed to uncover the circumstances behind the failures, including the engineering, construction, and installation practices used as well as the weather events at the time of failure. Other questions helped determine what failed and the results of the failure. Prior to the phone interviews, the team surveyed respondents to capture their general sentiments about failures with critical structural connections.

2.2.1 Survey Results

An online survey was used to capture basic information about each respondent before phone interviews took place. Twenty-five of 28 phone interviewees took the survey.

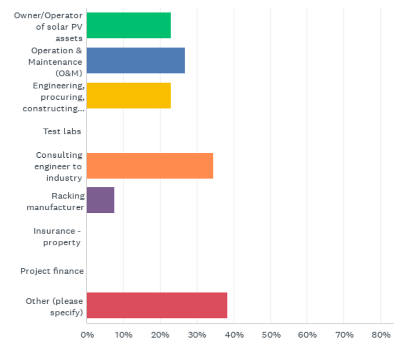


Figure 9. Respondents' professions

Stakeholders that own or operate systems (i.e., together, the Owner/Operators and Operations & Maintenance categories) were the largest stakeholder group (Figure). These respondents also have the most relevant and direct experience with failures.

Overall, survey respondents represented about 9.4 GW of systems located throughout the U.S. (Figure). As shown in Figure 11, survey respondents had overwhelmingly seen failures with fastened joints (92%).

Ninety percent of surveyed stakeholders view fastened joint failures in solar PV joints as a very important (70%) or a moderately important (20%) issue facing the industry.

Survey results also support the idea that structural failures are occurring often and with no correlation to geographical location, indicating no relationship to severe weather events. For example, the survey asked respondents to provide a fill-in answer to the question, *"Considering all systems you or your company manages or has consulted to; how many cases of fastened joint failures are you aware of?"* Instead of entering a number, some respondents said things like "too many to count," or "all systems," or ">100 systems."

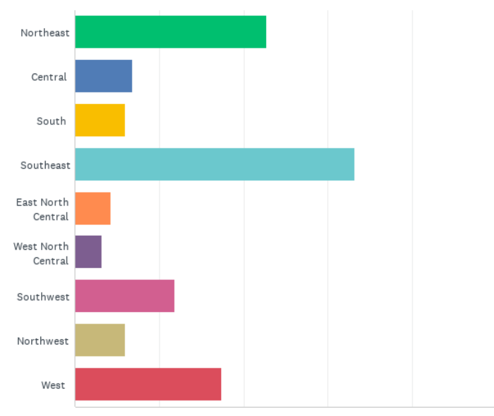


Figure 10. Geographical distribution of PV

2.2.2 Interview Results

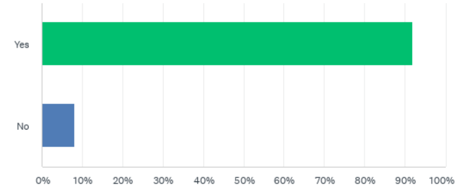


Figure 11. Respondents' direct experience with fastener failures

The team interviewed 28 respondents covering 84 instances of structural failure, a series of discussions that clearly indicated the existence of engineering gaps. During the interviews, respondents were asked to describe the weather events associated with fastened joint failures. Most failures occurred at or below design wind speeds – 46.4% of the time (Figure 12).

The interviews revealed that most failures of module mounting fasteners occurred with top-down clamps (33%) and through-bolted fasteners (30%) (Figure 13). Such failures of module-mounting hardware are indicative of the fact that these stacks fall well outside RCSC standards and should be considered "alternative."

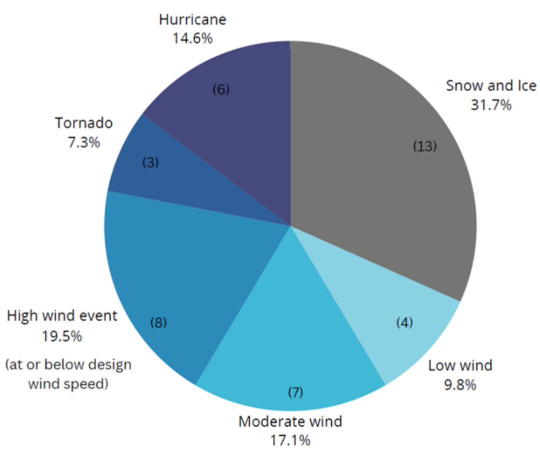


Figure 12. Weather at time of failure

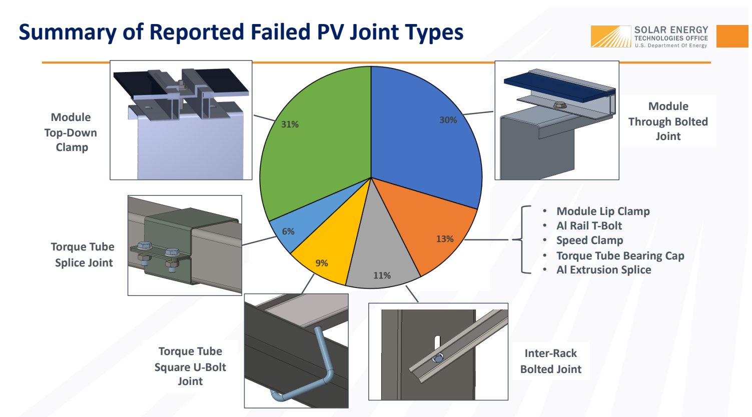


Figure 13. Breakdown of failed joints

2.3 Self-Evident Gaps

2.3.1 Prevalence of Nonstructural Joints

Inspecting module mounting fastening hardware and rack assembly joints on display at SEIA RE+ shows (years 2022-2025) reveal many clear examples of code and standards gaps. Examples of these gaps are also seen widely throughout racking product catalogs, at other trade shows, and during field visits.

Figure 14. Hose clamp used on torque tube

Figure 14 shows a hose clamp used to attach the torque tube to the table of modules and purlins. This picture was taken at RE+ 2022 in Anaheim, California, and the product was still on sale two years later, at RE+ 2024. The table purlins attached to the torque tube form a common friction joint, a joint that requires enough clamping force and friction in the joint to maintain the assembly under wind and snow loading. But a hose clamp is not designed to exert the needed clamping forces between the purlins and the torque tube, and therefore represents a gross misapplication.

Figure 15 shows another gross misapplication. This design uses a stamped steel clip-on nut, which is commonly used to affix license plates onto vehicles and other such low-demand, non-load-bearing applications. In this case, this simple low-strength nut is used to perform a role that requires a much higher strength fastener. Additionally, the joint concept is riddled with multiple other issues, strengthening the impression that no rational design basis was used in engineering this joint.

Figure 15. Clip-on nut used to mount torque

2.3.2 The Fastener Quality Act (FQA) and Problematic Fasteners

The Fastener Quality Act (FQA) (Public Law 101-592), a federal law passed in 1990, aims to reduce the risk of fastener failures and protect both public safety and commercial interests. The Act requires a large variety of fasteners to meet declared specifications and be inspected, tested (through an accredited lab), and certified using a consensus standard. Adherence to the FQA is common in other industries, but it is not prevalent in solar PV racking and module mounting systems. The FQA applies to threaded fasteners, nuts, and load-indicating washers, but not to the “alternative fasteners” of specialized clamps, brackets, and other unique hardware stacks commonly seen in solar PV systems.

To be identifiable and compliant with the FQA, bolts and nuts must be labeled with a manufacturer’s mark and then a consensus standard indicating its critical properties. Figure 16 shows two examples of stainless-steel fasteners that are properly marked.

Figure 16. Properly marked fasteners

Field inspections of solar PV racking systems reveal a “Wild West” of practices around fastener specifications, procurement, and field assembly. Collectively, these practices reveal large gaps in standards, with many violations of the FQA to which other industries strictly adhere and on which they rely for specifying, procuring, assembly, commissioning, and arbitrage (if failure occurs).

The results from the lack of fastener standards are commonly seen in solar PV module field installations are one or more of the following:

- Fasteners with no markings and no way to determine characteristics without lab testing.
- Fasteners partially marked but missing key pieces of information such as the maker's mark.
- Fasteners marked but of a low strength and chosen inappropriately for the joint demands seen.

The critical properties of fasteners used in the rack assembly and module mounting systems (e.g., dimensions, threads, head markings, finish, yield strength, tensile strength, and material properties) should be specified by the racking or tracker manufacturer unless a deviation is required to meet the fastener or assembly requirements defined in the module manufacturer's installation manual. These critical properties should be specified by rack manufacturer and in turn should translate to procurement and field assembly. This chain of events is normal for a matured industry but currently absent from the solar PV industry.

Fastener critical properties can be controlled through compliance with consensus standards developed by Standards Development Organizations such as ASTM International (ASTM), American Society of Mechanical Engineers (ASME), Society of Automotive Engineers (SAE), International Organization for Standardization (ISO), Deutsch Industrie Norm (DIN), Japanese Industrial Standard (JIS), or Industrial Fasteners Institute (IFI).

2.3.3 Insufficient marking on stainless fasteners

Stainless steel bolts and nuts marked "S30400" or "S31600" (Figure 17) are commonly seen on solar mounting systems and module mounting joints. However, these markings do not indicate compliance with a fastener consensus standard, and therefore cause the fastener to be non-compliant with the FQA.

These markings only indicate that the chemistry meets requirements for UNS S30400 or S31600 materials. The markings do not indicate whether the fastener was cold-worked or heat-treated, which are critical factors in determining fastener strength performance characteristics.

Figure 17. Stainless steel fastener marked "S30400"

Further, these bolts may contain a manufacturer's insignia, implying that the manufacturer is registered with the U.S. Patent and Trademark Office and has created a record of conformance demonstrating both compliance with consensus standards or specifications and traceability. Such an insignia indicates nothing about a fastener's strength capacity. Since these head markings do not reference a fastener consensus standard or indicate strength capacity, fasteners are not covered under FQA, and counterfeiting is not enforceable by the Office of Export Enforcement (OEE).

A list of approved fastener standards for bolts worth the solar industry's consideration can be found in the ANSI/AISC 360-22, rated by the American Society of Testing and Materials (ASTM) consensus standard.

Table 6: Common ASTM Fastener Standards Relevant to Solar Structures

Bolts	
ASTM A307 (Grade A & B)	ASTM F3043
ASTM A354	ASTM F3111
ASTM A449	ASTM F3125/F3125M

2.3.3.1 Missing manufacturer insignias

Bolts and nuts marked with “304” (Figure 18) or “316” are commonly seen in solar PV structures (Figure). These numbers do not indicate compliance with any consensus standard, and therefore cause the fastener to fall outside FQA rules.

The 304/316 markings do not assure the purchaser of any chemistry, strength, or performance characteristics. Again, the markings only imply (but do not verify) that the chemistry meets the requirements of UNS S30400 or S31600 material, rendering the FQA unenforceable and the fastener of questionable status.

Figure 18. Fastener marked “304”

Worse yet, such markings make it difficult for the OEE to enforce anti-counterfeiting rules. If fasteners like these are found as part of a failure investigation, inspectors have no direct way of verifying their characteristics, which complicates their work.

The “A2-70” marking on bolts and nuts (Figure 19) suggests the fastener complies with International Organization of Standards (ISO) 3506, meaning FQA protections would apply. However, it is common to consider these fasteners as suspect when they are stamped with a grade or class but lack a manufacturer’s mark. For example, if a need arises from an insurance carrier, an investor, or from arbitrage of a failure, further evaluation is needed to determine if the consensus standard requires a manufacturer marking, if the item meets standard requirements, or if the item is defective, counterfeit, or fraudulent. Answering some of these questions requires expensive lab testing of samples.

Figure 19. Fasteners marked “A2-70”

The fastener shown in Figure 19 is missing the manufacturer’s insignia and, therefore, does not meet ISO 3506 requirements. This could indicate the fastener is counterfeit and, if sold in the U.S., should be reported to the OEE.

2.3.3.2 Common use of low-strength bolts

Bolts marked properly with “307A” (Figure 20) comply with an ASTM standard for medium-strength bolts manufactured from heat-treated, low or medium-carbon steel. This specification defines a minimum tensile strength but not a yield strength, allowing the bolts to be manufactured more cheaply by eliminating one of the testing and certification criteria. The low cost of these bolts makes them more attractive to the solar PV industry, especially since they can be hot-dip galvanized.

These bolts are meant to be used in light structures, secondary or bracing members, platforms, and catwalks in which the loads are primarily small and static in nature, and where the strength of the connection is not a critical factor.

Figure 20. Low-strength 307A bolts

A 307A bolt is relatively low-strength and lacks a defined pretension requirement, since yield or proof strength is not defined in the ASTM standard. According to AISC 360-22, these bolts should only be tightened to the snug-tight condition (where the plies of the connected elements are brought together) and should only be used in bearing-type connections.

A common misconception is that solar PV structures are statically loaded, and therefore that shear loads can be transferred through bolted joints using direct load bearing through the bolt (versus through friction grip in the joint). However, multiple researchers have concluded that loading in solar PV individual bolted joints is highly dynamic. Worse yet, low system stiffness and other factors amplify loading in solar PV bolted joints, resulting in dynamic shear and tension/compression load combinations.

Although using snug-tightened 307A bolts in dynamically loaded solar PV bolted joints does not align with AISC 360-22 guidance, it is nonetheless commonly done and potentially problematic. Since the bolts can only be snug-tightened, the shear load carried in the joint results in joint slip, as well as direct load bearing on the bolt shank. Joints that repeatedly slip are at a high risk of joint loosening and bolt fatigue. Since the bolts can only be snug-tightened, the resulting pre-tension in the bolt and bolted joint capacity to resist joint opening cannot be quantified.

With today's standards gaps, solar PV mounting systems and tracker manufacturers are not prevented from specifying ASTM 307A bolts. Alternative low or medium-strength bolts that should be required by the industry include SAE J429, Grade 2 or Grade 5; ASTM F3125, Grade A325-Type 1; or ASTM A449-Type 1.

2.3.3.3 Improvement Opportunities for Industry Standards: Electrical Bonding in PV Structural Bolted Joints

The solar photovoltaic (PV) industry is capital-intensive, so strong incentives exist to lower expenditures (CAPEX). Value engineering efforts have been applied to solar PV mounting systems to reduce weight, material costs, installation time, and labor costs. Since a utility-scale project contains millions of solar PV bolted joints, joint design and assembly have been the focus of value engineering efforts. As a result of this value engineering, module attachment, and mounting system joints frequently have two functions: acting as both a structural and electrical bonded joint, a.k.a. a 'structural-bonded joint.' This joint configuration is now common in residential, commercial, and utility-scale module mounting systems (Wiser, Bolinger, & Seel, 2020).

Structural bonded joints are essential components in the load path connecting the solar PV module to the ground (see Figure 2). The joints also create an equipotential (low resistance) electrical connection (bond) between exposed conductive components of the PV mounting system to reduce the risk of electric shocks when an electrical fault current passes through the mounting structure. Structural bonded joints are widely used in the solar PV industry because of their simplicity and low cost, compared to using separate bonding jumper cables, which are more time-consuming to assemble.

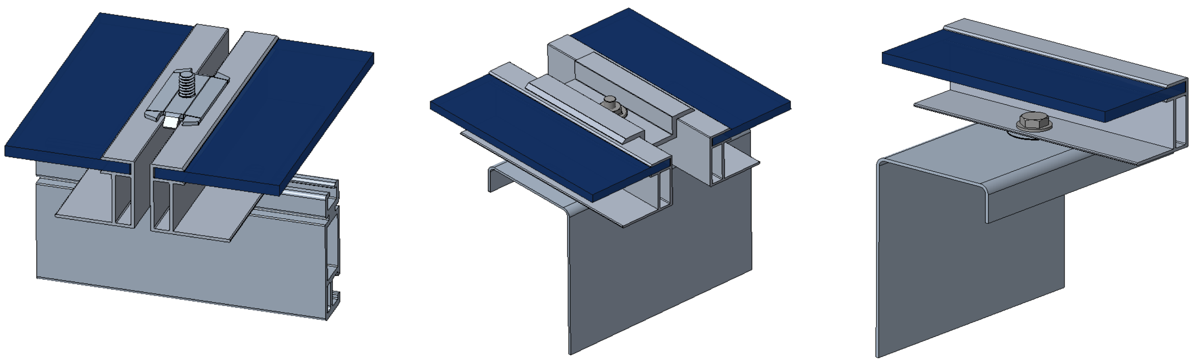


Figure 21. Examples of Solar PV Structural - Bonded Joints

Despite their seemingly simple nature, the physics of structural joints and electrical conduction through bonded joints are surprisingly complex. Electrical resistance in these joints depends on various factors, including material selection, assembly methods, clamp load, corrosion, and applied structural loading. Moreover, these joints are exposed to environmental conditions throughout the mounting structural operational lifespan, which can lead to degradation or loss of electrical bonds due to corrosion and loosening.

2.3.3.4 Aging of PV Structural Joints: Impacts on Electrical Bonding and Grounding

The rate at which structural joints in a PV system degrade depends on many factors, including the design of the modules and mounting hardware, the overall system layout, and the specific environmental conditions at the site. Given these variables, it is essential to continue research, monitor the performance of systems in the field, and address shortcomings in current standards. and industry practices.

Loosening or failures of structurally bonded joints in PV mounting systems made from conductive materials, such as steel and aluminum, can increase electrical resistance across connections. These joints must be electrically bonded in accordance with the U.S. National Electrical Code (NEC). The integrity of structural joints is critical; even a few loose joints can lead to catastrophic failures. Conversely, many failed joints are required to disrupt the grounding path, as multiple grounding paths exist in PV systems. A structurally sound joint is likely a reliable electrical bond. Field tests on the equipment ground path across different PV structures would confirm this link.

The aging of structural bonded joints in PV mounting systems is influenced by module and mounting system design, site-specific layout, and local environmental conditions. These interacting factors underscore the need for ongoing research, field performance evaluations, and a thorough review of existing standards, and industry practices to ensure the long-term reliability of these bonded joints.

2.3.3.5 Interim Measures for Enhancing Structural Bonding Standards in PV Installations

Defining specific changes to product-level standards to address the degradation of structural bonded connections may not be feasible or justified without additional testing, but incremental revisions to UL2703 could be an effective interim measure. Some suggestions for consideration in short-term improvement are listed here.

- Clarify UL2703 Bonding Resistance Test: Revise UL 2703 to clarify that the bonding resistance test in Section 13 is intended to verify a low-resistance electrical path through structural bonded joints in the tested mounting system, provided those joints are properly tightened. The test does not evaluate bonding performance under field conditions where joints may become loose.

- Clarify Selection of Corrosion Resistance Materials in UL2703: The selection of 'unprotected materials' used in PV mounting systems should be dependent on the intended atmospheric corrosivity categories C1 (very low) to C5 (very high) according to ISO 9223. For instance, 6000 Series aluminum may be considered inherently corrosion-resistant in most conditions, but not in C5 environments.

3. Resolving Gaps – Maturing Solar PV Industry Critical Structural Connections

3.1 Current Efforts – Addressing Gaps: Summary

There are two active committee consensus standards efforts, one under ASCE and a second under UL. There is a third effort that is pending under the International Electrotechnical Commission (IEC). (Figure 22)

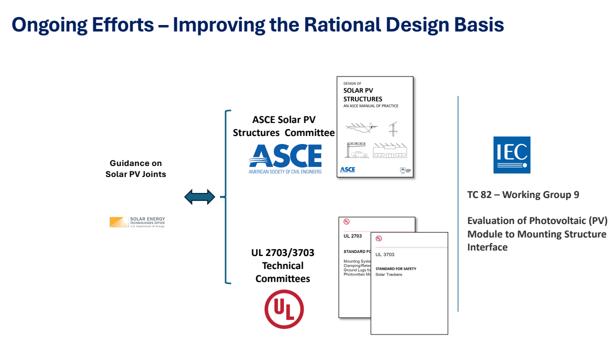


Figure 22 - Consensus Standards Work Current

3.1.1 The American Society of Civil Engineers, Solar Structures Committee – The Manual of Practice (Table 7)

The American Society of Civil Engineers (ASCE), Solar Structures Committee is releasing engineering guidance focusing on design principles to incorporate these wind dynamics. The dynamic behavior is generally understood to result from the unique characteristics of solar arrays as relatively lightweight, flexible bluff bodies subjected to powerful turbulence patterns (vortex shedding) that flow from array rows. The results are cycles of deflection. There are planned for future revisions of the MOP and Table 7 summarizes the current guidance language included in this first version.

Table 7: Critical Structural Connections Engineering Guidance Included in ASCE, Solar Structures Committee – Methods of Practice (MOP)

Topic	Guidance Provided
Controlling Pretension in Clamped Friction Joints	• Establishes applicability to all critical connections • Design to Pretension and not to generic torque values ‘torque call outs’ • Torque wrenches are adjusted to achieve pretension in the field • Fasteners must be tightened in a manner that results in a known and controlled range of pretension.
Confirming use of AISC 360-22 - RCSC where applicable	• For threaded fasteners ½’ in diameter or larger in bearing, pre-tensioned bearing or pretensioned slip-critical connections.
Installation of pretensioned high strength bolts, ½’ larger	• Describes five (5) methods currently recognized by RCSC.
Small than ½’ diameter fasteners	• ‘EOR is to rationally design the connection, including the fasteners, using fastener design strengths based on either testing of individual fasteners, full scale connection testing, or a consensus document that provides guidance for the design of connections specifically for solar PV structures.’
Individual fastener testing	• Use of a third-party testing agency (not fastener manufacturer) • Test results supersede other strength ratings
Full scale connection assembly testing	• Option 1. Use of International Building Code (IBC) Section 1702 (modified). • Option 2. The North American Specification for the Design of Cold-Formed Steel Structural Members, American Iron and Steel Institute (AISI), Chapter F (modified). • Option 3. The Aluminum Design Manual, The Aluminum Association, Appendix 1 of Part I Specification for Aluminum Structures (modified)

3.1.2 Underwriters’ Laboratory – UL 2703 Updates – May 2025

In May of 2025, UL voted to approve updates to **UL 2703 -** Mounting Systems, Mounting

Devices, Clamping/Retention Devices, and Ground Lugs for Use with Flat-Plate Photovoltaic Modules and Panels (UL 2703 Ed. 1-2015): Sections 2 (Glossary), 6 (Construction), 22 (Short Time Current Test) and 26 (Installation, assembly instructions) and important appendices to UL 2703. The updates represent very significant advancements in applying rational design principles in the critical structural connections for solar racking and module mounting.

3.1.2.1 UL 2703 Changes Approved by Section

Section 2 – Glossary Updates

1. Added the definition "critical structural connections" similar to the definition used in this chapter for "critical structural connections"
2. Added the definition "critical bonding fastener" to denote fasteners that are relied upon for structural and electrical bonding simultaneously.
3. Added the definition for "lock bolts" which allows this important technology to achieve UL 2703 approvals.

Important impacts from glossary updates: Brings needed attention to connections that play critical roles in the structural integrity and electrical bonding of racking systems.

Section 6.0 – Specification of critical properties

1. Resolves concerns about incomplete or missing specifications for key connections, which can lead to variable fastener quality and compromised structural, electrical and corrosion performance

Important impacts from specification updates: Bring to full industry awareness the need to specify fastener properties, (e.g. sizes, finishes, alloys) that are determinants of success. Industry stakeholder given the vocabulary and principles to specify, procure and evaluate fasteners.

Section 6.5 – Joints with separating loads

1. Introduces the principle that clamping forces must resist separating loads in consideration of safety factors. Updates allow for either a calculation or experimental method given manufacturers options to meet this requirement.

Important impacts from separating load requirements: Applies a rational design method as is used successfully in other industries to solar critical and bonding joints that can lead to more predicable outcomes. Represents important engineering knowledge transfer into the solar industry.

Section 6.6 – Joints with shear loads

1. Requires racking engineers to specify estimate shear loads on the greater of either the minimum design load (prescribed in Section 21.4) or manufacturer's product load rating.

Important impacts from shear load requirements: Requires engineers to consider friction coefficients between treated steel (treated for corrosion resistance) and anodized aluminum (common module frame metal choice) instead of plain steel. This will result in more conservative designs.

Section 26.1 – Instructions

1. Provides important instructions in support of changes to Sections 6.0, 6.5, 6.6.

Important impacts from updated instructions: Requires that engineers clearly communicate specifications to other key stakeholders such as assemblers and O&M crews. Bring to industry consciousness the importance of technical communications with industry stakeholders. Will force engineer to take important factors into consideration that are currently either not addresses at all or inconsistently so.

Section Appendices

1. Provides detailed methodologies in support of the other updated sections on engineering calculations on such topics as clamp loads. Related to that important reference sections are provided on common fastener specifications and material properties.

Important impacts from updated appendices: moves engineering practices along to using rational design methods based on known joint and fastener properties. Provides detailed calculation methods and information resources.

3.1.3 Pending IEC – TC 82 (Solar PV Energy Systems) – Evaluation of Photovoltaic (PV) Module to Mounting Structure Interface

The TC 82 committee developed an extensive draft document titled *'Evaluation of Photovoltaic (PV) Module to Mounting Structure Interface'* which focuses solely on module mounting hardware. Currently, there is some indication that this effort might be reinvigorated and moved forward.

3.1.4 Summary Table – Current Efforts to Address Standards Gaps

Table 8 is a compilation of current proposed changes from standards committees. The table provides a quick glance at current committee efforts are addressing the gaps identified here. The current standards work is categorized as 1) substantially improved (SI), 2) which require research to provide basic knowledge (R) and 3) those gaps not addressed (NAD). A clear conclusion from the table shows a few things with some gaps gaining substantial improvement (SI), there is a clear need for research (R) to address knowledge gaps. Addressing knowledge gaps is foundational and will allow committee work to proceed. A second conclusion is centered on significant gaps (e.g. testing matched to standards) that are not address. Development of product level testing gained from the kind of current research-grade testing starting at Lawrence Berkeley Laboratory and UC Berkeley is widely recognized by industry experts as a key area of work.

Current Standards Update and Develoment Efforts To Address Gaps	Key Codes and Standards Gaps					
Current Codes and Standards Efforts	1. Critical Structural Connections; Systems Effects, Dynamic and Cyclical Demands	2. Lack of Design Specifications	3. Strength Standards Paired with Relevant Testing	4. Alternative Fasteners	5. Others	Details
UL 2703 Revisions - 2025						
Section 6.2A - Critical Fasteners, Critical Properties Disclosure	SI & R	SI & R	NAD	SI & R	NAD	Requires designer to utilize consensus standards to identify fastener critical material properties. Non-traditional components would not be covered here.
Section 6.5 - Fatique Failures Cyclical Loading	SI & R	SI & R	NAD	SI & R	NAD	Introduces meaningul cyclical loading considerations but yet to introduce systems-level loading and complex demands on criitcal fasteners.
Section 6.5.1 - Calculation Method - Joints in Tension & Separating Loads	SI & R	SI & R	NAD	SI & R	NAD	Calculation methods based on transferable knowledge.
Section 6.5.2 - Experimental Methods - Joints in Tension & Separating Loads	SI & R	SI & R	SI & R	SI & R	NAD	Provision allows for designer to apply experimental methods.
Section 6.6 - Joints in Shear	SI & R	SI & R	NAD	SI & R	NAD	Calculation methods based on transferable knowledge.
ASCE Manual of Practice (MOP)						
Controlling Pretension in Clamped Friction Joints	NAD	SI & R	NAD	SI & R	NAD	Does Four Things 1) Requires contolled pretension in all "Critical" joints 2) Torque values cannot be taken from generic tables and must be calculated using rational methods 3) Torque wrenches must be field adjusted 4) Fastener must be tightened in a manner that delivers a known range of pretension values.
Confirming use of AISC 360 - RCSC where applicable	SI & R	SI & R	SI & R	NAD	NAD	Applies to Traditional Structural Connections found in solar PV racking but not "Non-Traditional" varieties.
Installation of high strength bolts > 1/2" in diameter	NAD	SI & R	SI & R	NAD	NAD	Described the five approved methods shown in the RCSC.
Installation of Small than ½" diameter fasteners	NAD	SI & R	NAD	SI & R	NAD	"Engineer of record (EOR) is to rationally design the connection, including the fasteners, using fastener design strengths based on either testing of individual fasteners, full scale connection testing, or a consensus document that provides guidance for the design of connections specifically for solar PV structures."
Individual fastener testing	NAD	SI & R	SI & R	SI & R	NAD	1)Use of a third-party testing agency (not fastener manufacturer) must be used. 2)Test results supersede other strength ratings.
Full scale connection assembly testing	SI & R	SI & R	SI & R	SI & R	NAD	Provides three full scale testing options: 1) Option 1. Use of International Building Code (IBC) Section 1702 (modified) 2) The North American Specification for the Design of Cold-Formed Steel Structural Members, American Iron and Steel Institute (AISI), Chapter F (modified) 3) The Aluminum Design Manual, The Aluminum Association, Appendix 1 of Part I Specification for Aluminum Structures (modified)

Key - Current Efforts to Address Gaps	
SI	Significant Improvement but More Revisions Needed
R	Research Needed - Knowledge GAPS Exist
NAD	Not Addressed
E	Early Discussion
M	Matured Substantially - More Revisions May Occur
NA	Not Applicable

Table 8. Impact of current code committee work

3.2 Current Efforts – Systems Level Module Mounting Connections Testing

Under a research project funded by the Department of Energy, Solar Energy Technology Office (SETO), the research team has developed a first-generation systems level critical fastener testing rack (Figure 23).

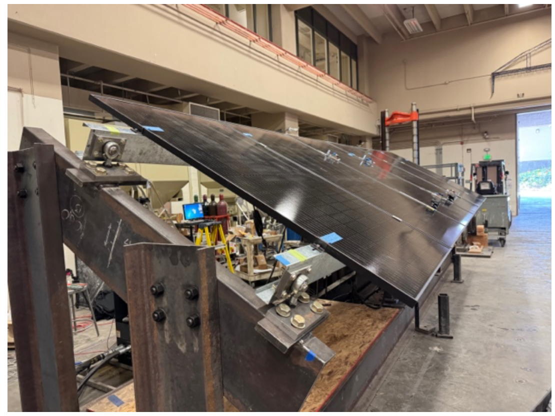


Figure 23. Systems Level Test Rack

This first-generation test rack is based on common framing configurations for a four-post fixed ground mount system. It is designed to test module mounting hardware for both top-down and through bolted joint hardware setup as seen in Figure 24.

The test rack has specifically been designed to replicate how PV system components interact under realistic wind loads and to test how those loads impact the entire PV structural system (not just the modules). It was developed under U.S. Department of Energy's Solar Energy Technologies Office (SETO)

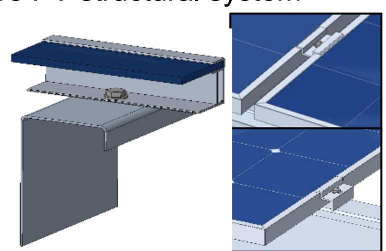


Figure 24. Top down and through bolt module mounting testing

The test rack is designed to impart systems-level loading into the module mounting fastener stacks by actuation of the underlying purlins and using two mode shapes, deflection cycles that simulate wind directions and speeds common to a Texas location with moderate winds.

Test cycles that include frequency, deflection and mode shapes were developed using a computation fluid dynamics modeling (CFD) and finite element analysis (FEA) (Figure 25).

This is the first start in systems-level testing and needs to be expanded to include other common framing configurations for both fixed rack and tracking systems.

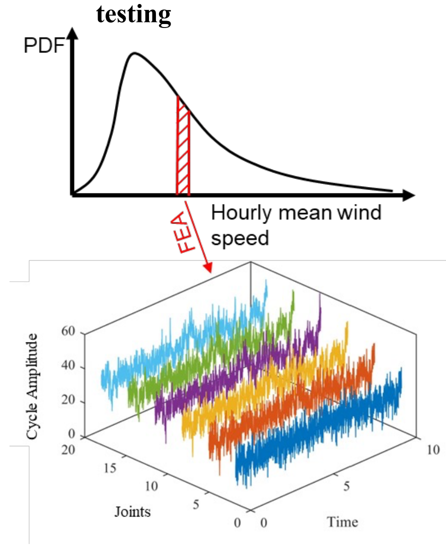


Figure 25. Deflection and cycles used in testing

4. Research Needs: Developing Rational Design Methods and Addressing Knowledge Gaps

4.1 Gaps #1 and #3: Critical Structural Connections; System Effects, Dynamics and Cyclical Demands and Need for Relevant Strength Testing Tied to Standards

Solar PV racking systems exhibit highly dynamic and cyclical behavior in wind. This behavior is seen from computational fluid dynamic (CFD), wind tunnel testing, field failure inspections, pluck testing and captured on video.

When array frame members deflect and torsional bend (torque tubes) each assembled item (modules, mounting rails and purlins) impart demands into critical connections that are not anticipated by designers. These demands are far higher, compound (combining levering, shear and tensile loads) and cyclical. Module frames, rails and purlins bend and twist (torsional) which appears to apply high demands that are likely a combination of shear, tensile and levering loads. These loading phenomena should be understood as 'system effects,' where each component interacts with others and collectively affects the overall integrity of the solar rack. The idea that these complex loading events are not anticipated by product designers who have largely relied on irrelevant building standards and in some cases are based on no engineering conventions at all. Though changing, the only standard widely used (UL 2703) is based on static design principles with an associated over-simplified test 'the sandbag test'

Under current design conventions, wind pressures and the resulting forces on the face or back of a module are thought to simply resolve themselves into fasteners, then into racking rails, frame elements and then down into foundation piles. But a growing body of field evidence show much more dynamic and interrelated systems effects between fastened joints and rack system. For example, when a structure reaches a low resonate frequency with large cyclical deflections, huge forces lever on fastened joints and mounted modules, resulting in degradation of the joint which in turn leads to greater movement in the structure with eventual cascading failures. If degraded in strength, the loosened joints will in turn change the characteristics of the rack most likely reducing stiffness and shifting the natural frequency lower.

There is a gap in current code that properly encompasses both the dynamic behavior of racking and the demands placed on the fastened joints; the interplay between the rack system and its fastened joints. To fully characterize these demands, a combination of lab testing (validated by field testing) needs to be undertaken for the most common frame archetypes.

4.2 Need for Developing low-cost, product-level testing and modeling methods – module mounting

Using the knowledge gained from lab testing, meaningful standards and accompanying product-level test racks can be developed and sold by testing equipment companies to industry labs that currently support solar racking and module manufacturers.

Rack designers and the independent test labs that certify products need meaningful yet affordable ways to strength test fastener concepts that reflect realistic demands, given the whole rack design (including the mounted module). Currently, the systems-level and dynamic demands seen by rack and module mounting joints are not understood and represent an area of research need and a significant knowledge gap.

Testing is needed that can cover the wide variety of frame archetypes (Figure 26) and critical connection types.

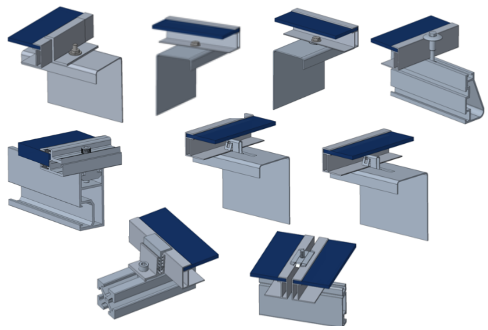


Figure 26. Examples of module mounting hardware

Figure 27. PSE Test Rack Example

Once this knowledge gap is filled, there is interest on the part of UL to create a standard that includes testing procedures. Once testing procedures are developed, companies that manufacture testing equipment (Figure 27) can then sell products to the solar PV independent test labs supporting the rack industry. Other key stakeholders rely on these industry test labs to assess investments and insurance risks. Figure 28 shows a suggested and simplified roadmap to achieving the goal of meaningful product level testing.

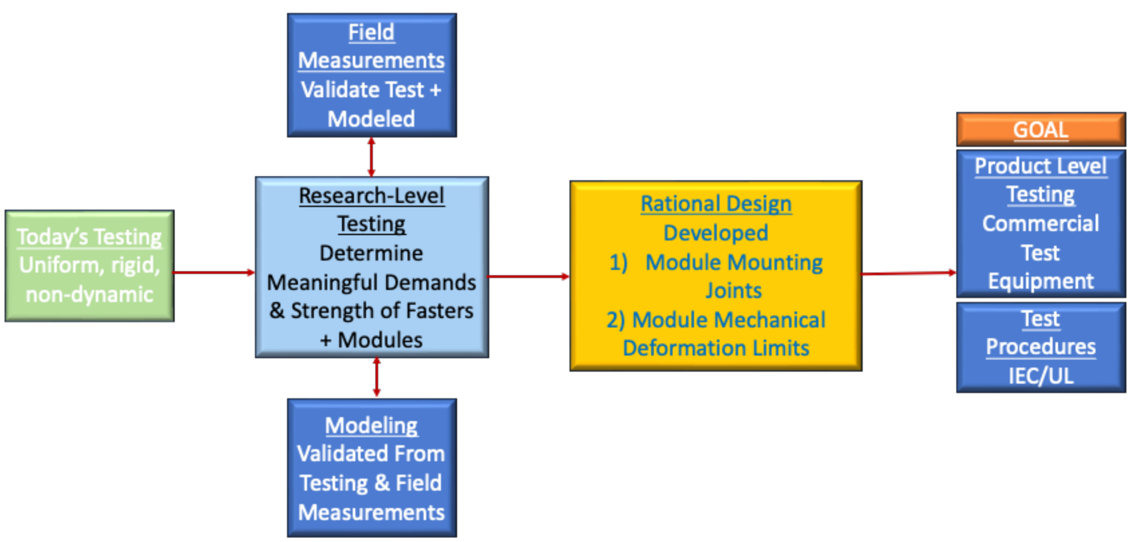


Figure 28. Moving to product level testing with accompanying standard

4.3 Need for Design Specifications

Threaded fasteners smaller than ½' diameter and the clamps, clips, and brackets are not covered in building code embodied by the Research Council on Structural Connections (RCSC), *Specifications for Structural Joints Using High Strength Bolts* (RCSC 2020). Nearly all of the fastener sizes used in module mounting and some varieties seen in racking systems are smaller than ½' and therefore the solar industry lacks a primary code. The implications are far reaching, covering all aspects of specification, engineering, procurement, operations, and failure arbitration.

1. Fastener Quality Act (FQA): Related to this issue of no core code is that fasteners are specified to fall under the Fastener Quality Act (FQA) which ensure that each fastener is marked to identify a manufacturer (registered entity in the U.S. Patent and Trademark office), conformance to a consensus standard or specification, and following upon these designations some kind of traceability.

2. Systems-Level Effects: Solar PV fastened joints are part of a rack system and are subject to forces resulting from dynamic movement that is just now becoming recognized. Solar racking systems are lightweight, flexible and subject to self-excitation which amplifies and delivers compound forces to fastened joints. The powerful cyclical demands on fastened joints are not yet understood enough to be part of the engineering lexicon for solar PV racking systems.

4.4 Addressing Small Alternative Fasteners

According to the ASCE Manual of Practice for Solar PV Structures, connections that are not designed in accordance with AISC 360-22 and the RCSC, including fasteners and faying surfaces made of materials other than what is listed in Section 1.5 of the RCSC, are considered to be *alternative structural connections* and are to be designed in accordance with one of the following:

1. If the connection is to be made of standard structural bolt sizes specified in the RCSC but are made of materials from a consensus standard other than ASTM (i.e., DIN, Eurocode, or similar consensus standard), then the connection should be designed in accordance with Section 2.12 of the RCSC.

2. If the connection is to be made of nonstandard structural bolt sizes that are not specified in the RCSC, screws, or any nonstandard structural fastener to attach any connection assembly or components of a solar PV structure (i.e. including, but not limited to, the module attachments to the racking structure, slip joints holding torque tubes to the top of their piles, module support brackets, bracing of fixed tilt racking structures, pin connections), the EOR is to rationally design the connection, including the fasteners, using fastener design strengths based on either testing of individual fasteners, full scale connection testing, or a consensus document that provides guidance for the design of connections specifically for solar PV structures.

5. References

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Fastener Quality Act (FAQ) - The Office of Export Enforcement (OEE) enforces the FQA on behalf of the Commerce Department's National Institute of Standards and Technologies (NIST). To report an FQA violation, call the OEE Hotline at 1-800-424-2980 or by submitting an enforcement lead/tip.
If you have a general question about the FQA, contact NIST by telephone at 301-975-4011 or by email at fqa@nist.gov. Fastener Quality Act (FQA)