What's going wrong?

Problematic

fastener selection and joint design on display at RE+

Researchers:

Jon Ness, president, Matrix Engineering Consultants
Gerald Robinson, principal investigator, LBNL
Tracy Becker, associate professor, UC Berkeley
James Elsworth, mechanical engineer, NREL
Holden Murphy, engineering student, Matrix Engineering

Mature industries are characterized by well-developed engineering practices, standards, quality management processes and highly reliable systems. The solar PV industry has generally not achieved this level of maturity in its structures and fastener technology.

During the 2022 RE+ event in Anaheim California, this past September, a research team walked the Exhibit Hall and found many stark examples of industry immaturity. The team performed an informal survey and spotted common misspecification and, in two cases, particularly extreme examples of misapplications. In one example, the team spotted car headliner fasteners, and with the second, a chain link fence component — both non-structural but called upon to maintain structural integrity.

The importance of fasteners within PV racking and tracker systems is often overlooked by system designers. Although composed of relatively simple and inexpensive components, fasteners play a critical role in the structural reliability of PV systems.

Joint engineering practices and standards in structural steel and transportation industries have matured over the past century and become widely adopted. As a result, failures of fastened joints (or bolted joints) in buildings and transportation are now rare. In comparison, the solar PV industry is relatively young and lacks the depth of engineering practices and standards of other industries. Loose, missing or broken bolts in solar are surprisingly common. When it happens, modules can become damaged, detached, or even worse, systems can collapse. All of these can increase maintenance costs, reduce system performance, or worst of all, create life-safety risks.

Industry audit underway

A project funded by the Department of Energy, Solar Energy Technology Office (DOE-SETO) is researching this very topic. The research team is made up of a mix of subject matter experts from academia and industry. Among other things, the team is working to find areas of transferable engineering knowledge from other industries.

The team recently conducted an audit of the solar PV racks and trackers on display at RE+ '22. The team looked at 19 different racking products and examined 92 bolted 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 (for systems near pedestrians).

Applying a traditional Failure Modes Effects Analysis (FMEA) framework, the likely failure effects resulting from the bolted joints examined at RE + are summarized in Table 1 below. Note that most of the failure effects can be classified as "serious" in terms of potential financial and life-safety impacts.

Following are two examples of fasteners found on the racks and trackers at RE+ '22, which have been shown to either be ineffective or problematic in other industries.

Locking fastener myth

The team found that many trackers and racking systems widely used helical spring washers (or lock washers) in module attachments and inter-rack connections (**see Fig. 1**). These lock washers were chosen based on a misguided belief that they will lock the nut/bolt to the joint and prevent loosening.

Unfortunately, the body of evidence from both experience and experimental results in the transportation industry is that lock washers do not prevent self-loosening. Instead, they have been shown to speed up the rate of loosening in many cases. Lock washers have been virtually eliminated for use in automobiles for these reasons.

Alternatives to the helical spring washer, such as thread lockers and wedge lock washers, have been shown to be more effective at preventing self-loosening and are widely used in rail and the automotive industry.

Nylon risks

The team also found the widespread use of nylon insert prevailing torque nuts, (or nylon lock nuts), as seen in **Fig. 2**. Although relatively inexpensive and effective at preventing the fastener from falling out, nylon lock nuts are not effective at keeping the bolted joint tight.

Worse yet, the unique properties of nylon can result in failures if not properly

Table I. Summary of possible failure effects — 92 bolted joint survey from RE + 2022

Failure Effect	Details
Component detached	Individual component such as a module becomes liberated.
System structural capacity reduced	Structural capacity degrades over time (relaxation, self-loosens and corrodes). System vulnerable to wind load events.
System structural capacity lost	Single point failure triggers cascading failures and eventual system collapse.
Low system stiffness	System prone to large deformations and uncontrolled joint loading and failure. Can lead to cascading failure scenarios and or damage to modules or components.

Figure 1: Helical spring washers (or lock washers) have been shown to be ineffective at preventing joint loosening. Photo: SETO research team

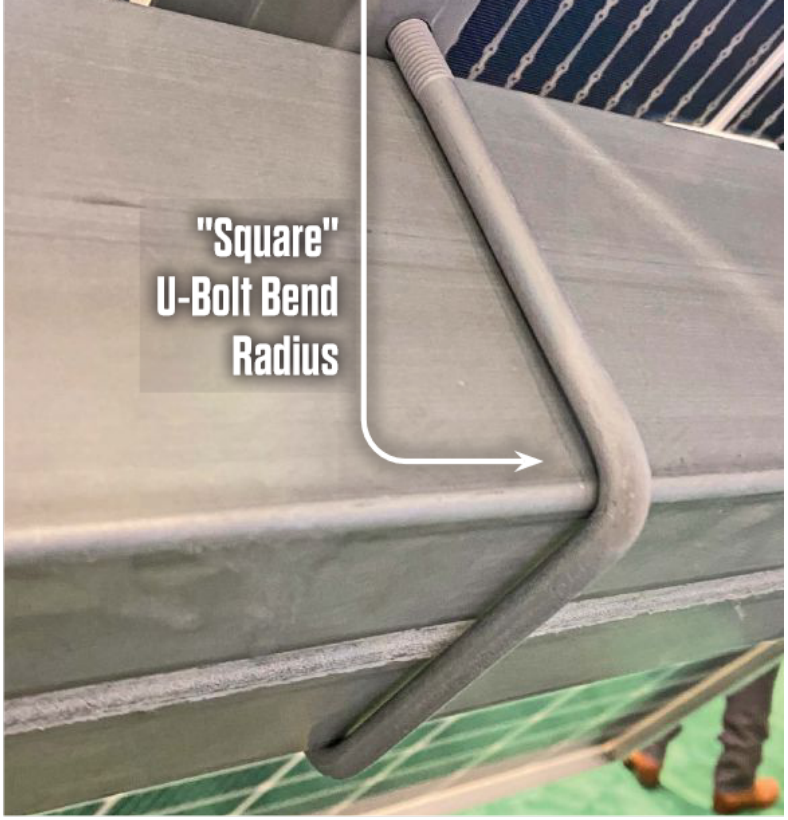

Figure 3: Square u-bolts are at risk of fracture if not properly specified and manufactured. Photo: SETO research team

specified and assembled in the field. Nylon inserts are sensitive to and degrade from temperature, moisture and ultraviolet ra diation (UV) exposure. Complicating cold weather installations, nylon degrades and becomes brittle at low temperatures and humidity, which can make them difficult to install successfully.

In some cases, the nylon rings crack, chip or are pushed out during assembly, making them ineffective. Another concern is the nylon becomes brittle when exposed to ultra-violet (UV), making them ineffective unless blockers or stabilizers are added to the nylon.

And lastly, nylon lock nuts are often mated with stainless steel bolts. Unfortunately, galling often occurs during the assembly of stainless steel, especially if the threads have not been lubricated. This is especially true for nylon lock nuts.

When specifying nylon lock nuts, be sure to require UV-resistant nylon and require that a pre-applied lubricant such as wax be applied to the nut to reduce the likelihood of galling during assembly.

To reduce the risk of the nylon, insert cracking or push-out when assembling in low temperatures, and be sure to keep the nuts warm before use. Alternatively, skip the nylon lock nut altogether and instead specify a device that is rated to resist self-loosening under conditions of long-term exterior exposure.

U-Bolts, fatigue fracture failures

The team found that at least five manufacturers useing u-bolts with square corners to join inter-rack and tracker connections (see Fig. 3). Although square u-bolts create a relatively simple low-cost joint, they are at risk of fatigue fractures at the bend radius if not properly specified and manufactured.

The design of a square u-bolt is a delicate compromise between the design requirements and manufacturability. A full explanation of these compromises is outside the scope of this article, but in short, the fit between the u-bolt and the clamped structural rectangular tube must be as tight as possible for the joint to effectively transfer load. This tight fit can

> Of the 92 bolted joints examined, the team identified 83 areas of concern

only be achieved by making the u-bolt corner bend radius the same or smaller than the outside radius of the structural tube.

Unfortunately, bending the u-bolt to this radius often results in "necking" of the bolt diameter in the radius and in some cases tool marks. Both necking and tool marks create stress concentrations and can trigger fatigue fractures.

Another common issue occurs when high-strength materials are specified that require the u-bolt material to be heat treated. A manufacturing best practice is to heat treat the u-bolt after it is bent into the U shape. Since this process can be expensive and problematic, some manufacturers heat-treat the u-bolt before bending it. This shortcut saves time and money, but forming the u-bolt after heat-treat often causes the bent areas to become brittle and prone to fracture during assembly or while in service.

The use of square u-bolts to reliably join structural components is possible, but only if properly specified and manufactured under rigorous process control standards. This is widely understood and practiced in the automotive industry.

Just the beginnning

The RE+'22 show floor at RE+ was packed full of innovative solar PV racking and tracker structures, but basic bolted joint engineering was absent. The research team that contributed this piece will be producing guidance materials and offering some training over the next year.

Industry stakeholders struggling with bolted joint challenges are invited to contact the research team; Gerald Robinson, principal investigator, Lawrence Berkeley National Laboratory, at gtrobinson@lbl.gov.

Figure 2: The use of nylon lock nuts can be problematic in solar pv joints unless they are properly specified.