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Exploring Electrical Bonding in PV Structural Joints

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Exploring Electrical Bonding in PV Structural Joints

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Table of Contents

Table of Figures

List of Tables

Glossary

Term	Definition
Structural Joint	A joint that is a critical element of the structural load path between the solar PV module and the earth.
Bonded Joint	A joint that creates an equipotential (low resistance) electrical connection between exposed conductive components of the PV mounting system. Bonded joints reduce the risk of electric shocks when an electrical fault current passes through the mounting system.
Structural-Bonded Joint	A joint is a critical element of the structural load path between the solar PV module and the earth **and** a low-resistance electrical connection between exposed conductive components within a PV mounting system.
Electrically Bonded Structure	A structure where all the exposed conductive components are connected to establish electrical continuity and conductivity, essentially creating a single, low-impedance path for fault current to flow in case of a ground fault
Types of Solar PV Structural-Bonded Joints	**Inherently Conductive:** Structural-bonded joints that are inherently electrically conductive. For example, a structural joint consisting of two purlins coated with ASTM A653 G90 is considered inherently conductive. **Inherently Non-Conductive:** Structural-bonded joints that require an electrical bonding device to penetrate nonconductive coatings, such as anodization or paint, to pass either the UL 1703 or UL2703 bonding resistance test.
Contact Resistance ($R_{contact}$)	Contact resistance refers to the electrical resistance between two conductive materials due to an interruption or barrier that impedes the free flow of electrical current. This resistance encompasses constriction, film, and spread (bulk) resistance.
Constriction Resistance (C_R)	The electrical resistance that occurs when an electrical current passes through the small contact points between two solid surfaces.
Film Resistance (F_R)	Electrical resistance arises when current passes through non-conductive materials, such as oxides, dirt, or other contaminants on contact surfaces.
Spread Resistance (S_R)	Spread resistance occurs when an electric current spreads out from a point of contact into a larger area of conductive material. This type of resistance is significant when current flows through a small contact area into a bulk material.
Bulk Resistance (B_R)	Inherent resistance of a material to the flow of electric current through its bulk or volume. It is a fundamental property of the material itself, determined by resistivity and material dimensions.
Resistivity	A fundamental property of a material indicates how strongly it resists the flow of electric current. The resistivity of a material is defined as the electrical resistance per unit length and unit cross-sectional area.

1. Introduction

1.1 Structural Bonded Joints in Solar PV Mounting Systems

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).

1.2 Importance and Functionality of Structural Bonded Joints

Structural bonded joints are essential components in the load path connecting the solar PV module to the ground (see
Figure 1). The joints also create an equipotential (low-resistance) electrical connection (bond) between the exposed conductive components of the PV mounting system, reducing the risk of electric shock 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.

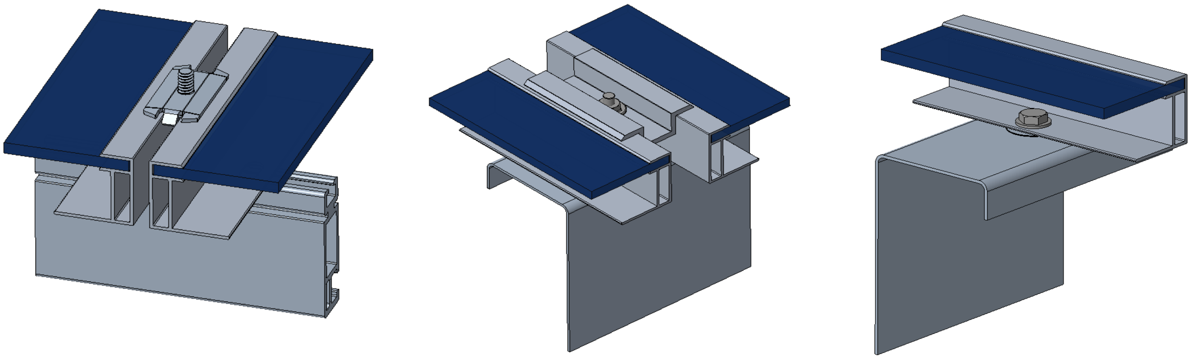

Figure 1: Examples of Solar PV Structural - Bonded Joints

1.3 Challenges and Requirements

Structural bonded joints must reliably withstand static loads (dead and snow) and dynamic loads (wind) applied to the mounting system. These joints must also create a low-resistance path for fault current in the event of a ground fault. This chapter examines these critical joints and the challenges of maintaining electrical conduction throughout the mounting system's lifetime.

1.4 Complexity and Environmental Impact

Despite their seemingly simple nature, the physics of structural joints and electrical conduction through bonded joints is 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 operational lifespan of the mounting structure, which can lead to corrosion and loosening, resulting in degradation or loss of electrical bonds.

1.5 Standards and Maintenance

While NEC, IEC, and UL standards guide system design, construction, materials, assembly, and qualification testing for bonded joints, they do not comprehensively address the maintenance or performance of structural bonded joints through the operational lifespan of the mounting system. Although UL2703 includes a post-salt spray bonding resistance test to simulate environmental exposure and aging, this test is not exhaustive. It does not account for other concurrent environmental and loading conditions.

1.6 Research Findings on Solar PV Structural Joint Failures

A research team funded by the Department of Energy, Solar Energy Technologies Office (DOE-SETO) conducted structured interviews with diverse stakeholders in the photovoltaic (PV) industry to gather valuable insights into the characteristics, prevalence, and cost impacts of solar PV joint failures, including loosening. The team interviewed over 28 respondents, providing a comprehensive understanding of the structural reliability of solar PV joints in 17,000 systems with over 94 GW of capacity. The survey revealed several key findings, including the surprisingly common occurrence of fastener loosening. Of the 80 reported solar PV joint failures, nearly 44% were attributed to loosening. Interestingly, the team found installer errors accounted for only a small fraction (13%) of the failure causes, while a relatively substantial portion (37%) stemmed from design-related issues.

Evidence further suggests that some PV structural joints, including PV structural-bonded joints, may be chronically loose, particularly those involving module through-bolted joints and top-down clamps.

1.7 Effect of Structural Bonded Joint Loosening

Anecdotal evidence from failure investigations indicates that loose structural bonded joints have increased electrical resistance, intermittent resistance values, or, in some cases, complete loss of the electrical bond. Since solar PV systems commonly have multiple grounding paths, multiple failed structural bonded joints would need to occur in a mounting structure to interrupt the grounding path. However, it could be assumed that the widespread or chronic loosening of structurally bonded joints could significantly affect the electrical bonding integrity of the system.

This paper hypothesizes that the loosening of structural bonded joints can result in increased electrical resistance and potential loss of bond for two reasons.
The loss of clamp load directly increases the constriction resistance in structural bonded joints.
The loss of clamp load allows the structural bonded joints to gap, exposing the electrical conduction path to the environment and allowing the development of non-conductive corrosion products or films.

Controlled field tests on the equipment ground path across different PV systems would likely confirm this link, which is an area that needs additional research. Further targeted research on the aging of structural bonds, considering dynamic loading, normal and chronic loosening, and cyclical dry and wet conditions, is crucial for a deeper understanding of this potential issue. Until such tests and research are completed, and standards are developed, the industry should follow the known best practices for the design, assembly, and maintenance of structural bonded joints.

2. Fundamentals of Electrically Bonded Joints

2.1 Electrically Bonded Joints – Basic Theory & Concepts

This section focuses on the basic theory and equations related to the electrical bonding of direct current (DC) faults in PV mounting systems. Although the same equations apply to alternating current (AC) circuits, the terminology and application differ slightly. Current transmission through a bonded joint is directly proportional to the voltage across it and inversely proportional to its resistance, as expressed by Ohm's Law:

Equation 1: Current (ADC) = Voltage (VDC) / Resistance (Ω)

Achieving an initial low-resistance electrical, structural bonded joint can be challenging because multiple factors, including joint materials, surface finishes, non-conductive films on the surfaces, and contact pressure, influence the total electrical resistance across a bonded joint. (Berillo, 2009).
Figure 2 **and**

Figure 3 illustrate electrical current transmission across the joint and the increased meshing of material asperities with increased clamp force.

These factors are captured in

Equation 2: $R_{BJ\ Tot} = R_B + R_C + R_S + R_F$

Where:

$R_{BJ\ Tot}$ = Total resistance across a bonded joint (Ω)
R_B = Bulk resistance (Ω)
R_C = Constriction resistance (Ω)
R_S = Spread resistance (Ω)
R_F = Film resistance (Ω)

It is important to note that **bulk resistance (R_B)** and **spread resistance (R_s)** are inherent to the joint material selection and interface design. In contrast, **constriction resistance (R_c)** and **film resistance (R_F)** are dynamic and may change over time due to factors such as clamp force (loosening) and film buildup (corrosion or contamination) (Berillo, 2009), (Bowen, 2020)

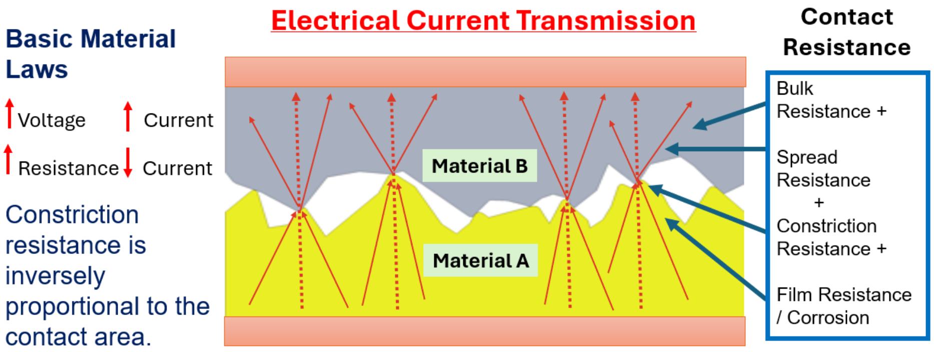

Figure 2: Electrical Current Transmission Across an Interface – Loose Bonded Joint

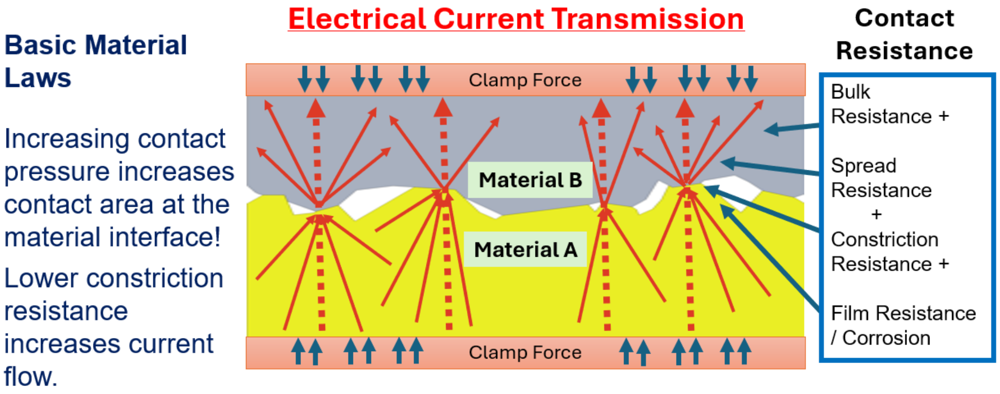

Figure 3: Electrical Current Transmission Across an Interface – Tight Bonded Joint

2.1.1 Bulk Resistance (R_B)

Bulk resistance refers to the inherent resistance to the flow of electric current through the clamped components in a bonded joint. This resistance primarily depends on the intrinsic resistivity of the clamped components, the cross-sectional area, and the length of the current path. The bulk resistance remains unchanged when the temperature is uniform throughout the entire material, without fluctuations or gradients.

The bulk resistivity of the common materials used in solar PV mounting systems varies widely (see Error! Reference source not found.Error! Reference source not found.).

Table 1: Electrical Bulk Resistivity for Common Materials in Solar PV Mounting Systems

Material	Electrical Resistivity (ρ) ($\times 10^{-8}$ Ω*m)
Structural Steel	10 – 100
Hot Galvanizing Coating (Zn)	5 – 7
Aluminum (6000 Series)	2.80 – 5.00
Stainless Steel (300 Series)	72 – 74

The bulk resistance (R_B) through a component can be estimated using

Equation 2:

Equation 2: RB = (ρ x L) / A

Where:
R_B = Bulk Resistance (Ω)
ρ = Material Electrical Resistivity (Ω*m)
L = Length of conduction path (m) through the bulk material
A = Area of conduction path (m^2) through the bulk material.

2.1.2 Constriction Resistance (R_C)

Constriction resistance occurs because the actual effective contact area between the joint surfaces is significantly smaller than the total contact area. The components of a structural-bonded joint—fasteners and their threads, joint plates, and washers—may appear to have smooth surfaces. However, at the microscopic level, the surfaces are rough, covered with ridges, grooves, mountains, and valleys (asperities). As a result, the joint surfaces only touch at microscopic contact areas. These areas of microscopic contact are called asperity spots, or 'a-spots' in electrical joint theory. When electrical current passes through these joints, the electrical conduction is constricted through these 'a-spots.' This constriction effect results in an uneven current distribution across the contact area, leading to higher overall resistance (Bowen, 2020).

When the joint is tightened, the asperities are forced into contact, resulting in high, localized compressive stresses and the plastic flattening (yielding) of the microscopic features. This enlarges the 'a-spot' areas and reduces electrical resistance. Should the joint loosen, the 'a-spot' areas will decrease due to elastic spring back or loss of contact, and the electrical resistance will increase accordingly. (Berillo, 2009), (Bowen, 2020).

The constriction resistance (R_c) through a component can be calculated using Error! Reference source not found..

Equation 4: $R_c = \rho / (2 \times a)$

Where:
R_C = Constriction resistance (Ω)
ρ = Material Electrical Resistivity (Ω*m)
a = Representative radius of an equivalent circle contact (m)

Note: The calculation of constriction resistance is based on individual contact points, known as ‘A-Spots,’ on the material interface. To determine the total constriction resistance across the interface, the individual constriction resistances of all contact spots (A-Spots) are considered in parallel.

2.1.3 Spread Resistance (R_S)

Spread resistance arises at the interface where current transitions from a point of contact into a larger area. This resistance is influenced by the geometry of the contact area, material properties, and the quality of the contact interface. Factors such as contact pressure, surface roughness, and contaminants or films on the contact surfaces can cause variations in spread resistance. The spread resistance (R_s) through a component can be estimated using Error! Reference source not found..

Equation 5: $R_s = \rho / (4 \times a)$
Where:

Rs = Spread resistance (Ω)
ρ = Material Electrical Resistivity (Ω*m)
a = Radii of representative circular area of the asperity contact (m)

Note: The calculation of spread resistance is based on individual contact points, known as ‘A-Spots,’ on the material interface. To determine the total spread resistance across the interface, the individual spread resistances of all contact spots (A-Spots) are considered in parallel.

2.1.4 Film Resistance

Environmental exposure can lead to corrosion. Most commonly, corrosion occurs through oxidation, meaning the metal loses electrons to oxygen in the environment, forming an oxide as a byproduct. Oxidation typically forms thin films on metal surfaces. The film resistance of an oxide film depends on the electrical resistivity and thickness of the film (see **Table 2**). In extreme cases, an oxide film can act as an insulator.

Table 2: Electrical Film Resistivity for Corrosion Products of Common Materials in Solar PV Mounting Systems

Base Material	Base Material	Electrical Resistivity (Ω*m)

	Oxides	
Structural Steel	Fe_20_3	1x10^{3} – 1x10^{5}
	Fe_20_4	0.3×10^{-3}
Hot Galvanizing Coating (Zn)	$ZnCO_3$	Electrical Insulator (Very High)
Aluminum (Series 6000)	Al_20_3	1x10^{14}
Stainless Steel (300 Series)	Cr_2O_3	1x10^{8} - 1x10^{10}
	Fe_20_3	1x10^{3} – 1x10^{5}
	Fe_20_4	0.3×10^{-3}
	NiO	1x10^{2} – 1x10^{3}

The film resistance (Rf) through a material interface can be calculated using **Equation 6.**

Equation 6: Rf = (ρ_f x t) /A

Where:
R_f = Film resistance (Ω)
ρ_f = Film Electrical Resistivity (Ω*m)
t = Thickness of the film (m)
A = Area of contact (m2)

Note: The calculation of film resistance is based on individual contact points, known as 'A-Spots,' on the material interface. To determine the total film resistance across the interface, the individual film resistance of all contact spots (A-Spots) is considered in parallel.

2.2 Inherent Conductive and Non-Conductive Materials and Coatings

The inherent electrical conductivity of structural joint components and their coating can complicate the electrical bonding.

Some materials and coatings, such as ASTM A653 G90 (hot-dip galvanizing), are inherently conductive. Electrical bonding of steel components with a G90 coating can be as simple as cleaning the surfaces to remove oxidation and bolting the joint with a clamp load high enough to pass the bonding resistance test (see UL 1703/UL 61730/2703 Bonding Path Resistance Tests). Other coatings, such as anodized aluminum, are inherently non-conductive and require an electrical bonding device that pierces the coating and establishes the electrical bond.

2.3 Electrical Bonding and Safety in Solar PV Systems

The integrity and reliability of electrical bonds are vital in photovoltaic (PV) systems. Degradation of these bonds can lead to stray electrical fault currents, resulting in unintended paths and potential safety concerns (Ball, Zgonena, & Flueckiger, 2013).

2.3.1 Practical Example of Bonded Joint Resistance

Error! Reference source not found. illustrates the installation of a utility-scale, single-axis solar tracker in which the PV modules are attached and bonded using through-hole, bolted joints. A bonding device that pierces the non-conductive anodized coating achieves the electrical bond between the aluminum PV module lip and the supporting G90 zinc-coated rail.

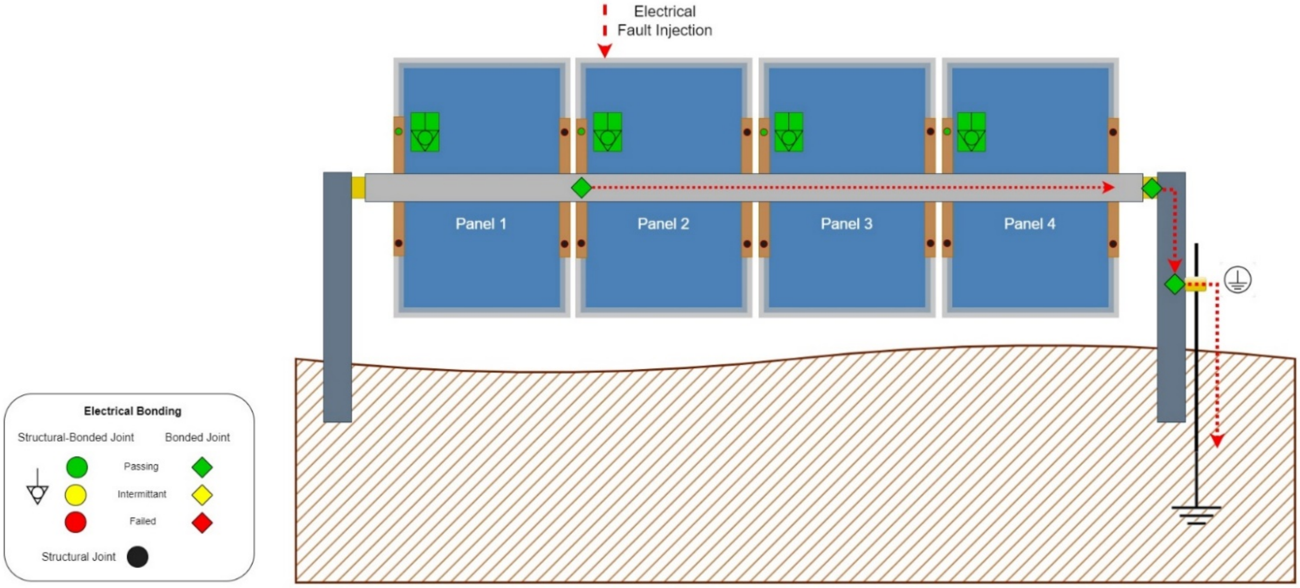

Figure 5 depicts the fault current ground path through various solar module support interfaces. Assuming all structural and electrical bolted joints meet the specified standards, an electrical fault current will pass through a structural bonded joint if it remains tight and can take multiple routes to the electrical ground connection.

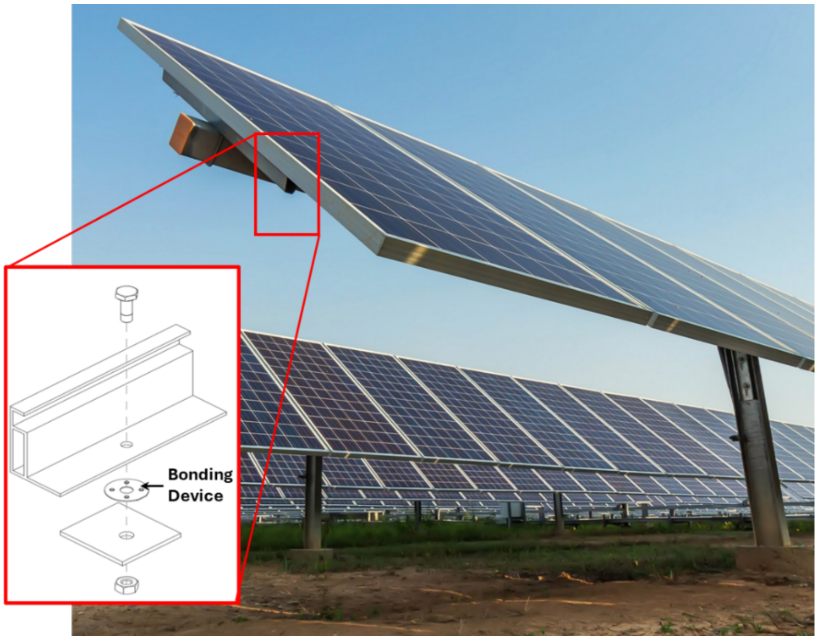

Figure 4: Utility Scale Solar Array Tracker Installation –Utilizing a Through-Bolt System

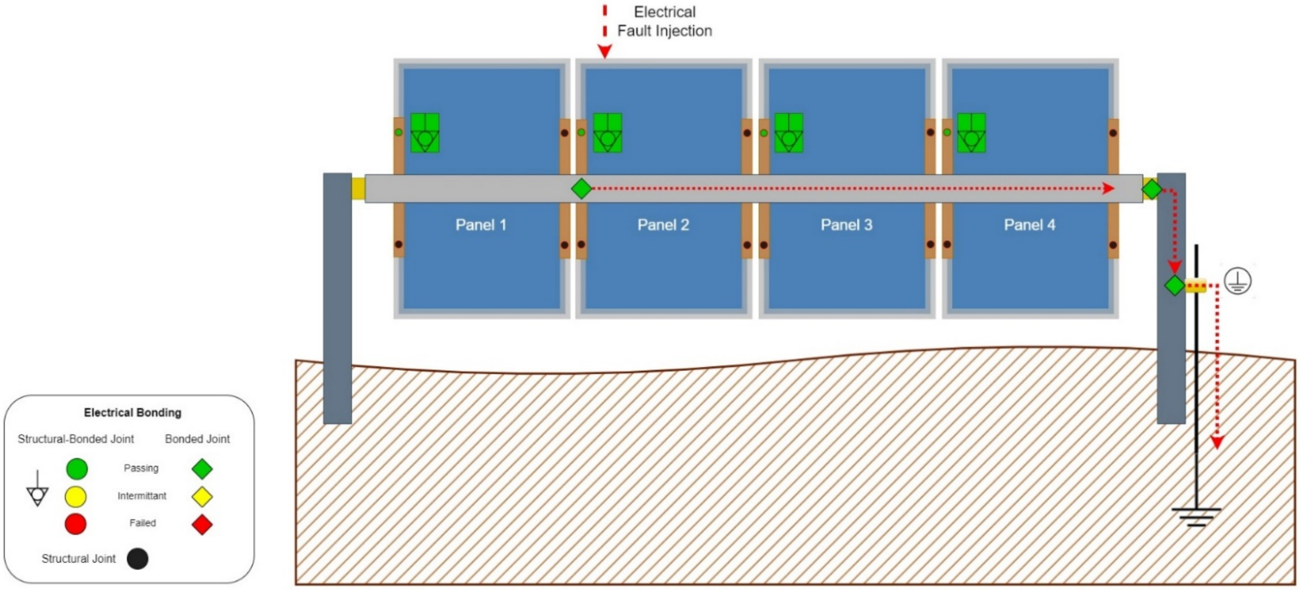

Figure 5: PV Tracker Array with Passing Electrical Bonding

In contrast,

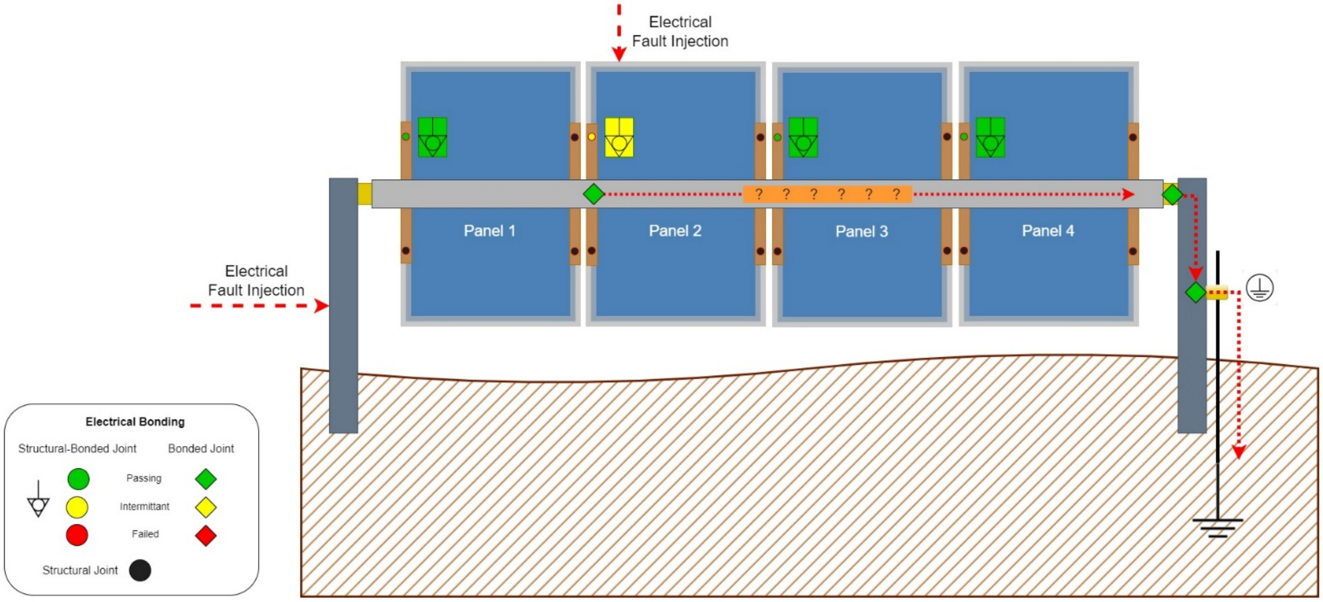

Figure 6 shows that intermittent bonding, caused by factors such as looseness, corrosion, or the presence of a film, can inhibit or intermittently break the electrical fault grounding path. This disruption can lead to increased resistance at the bonding interface, potentially causing overheating and further degradation of the connection. Finally, ***Figure* 7** highlights that when resistance is sufficiently high, current will not flow, compromising the electrical bond and grounding path to the earth-ground connection (EGC). This high resistance can result from loosening, poor maintenance, or environmental factors, jeopardizing the safety and reliability of the electrical system (Bowen, 2020).

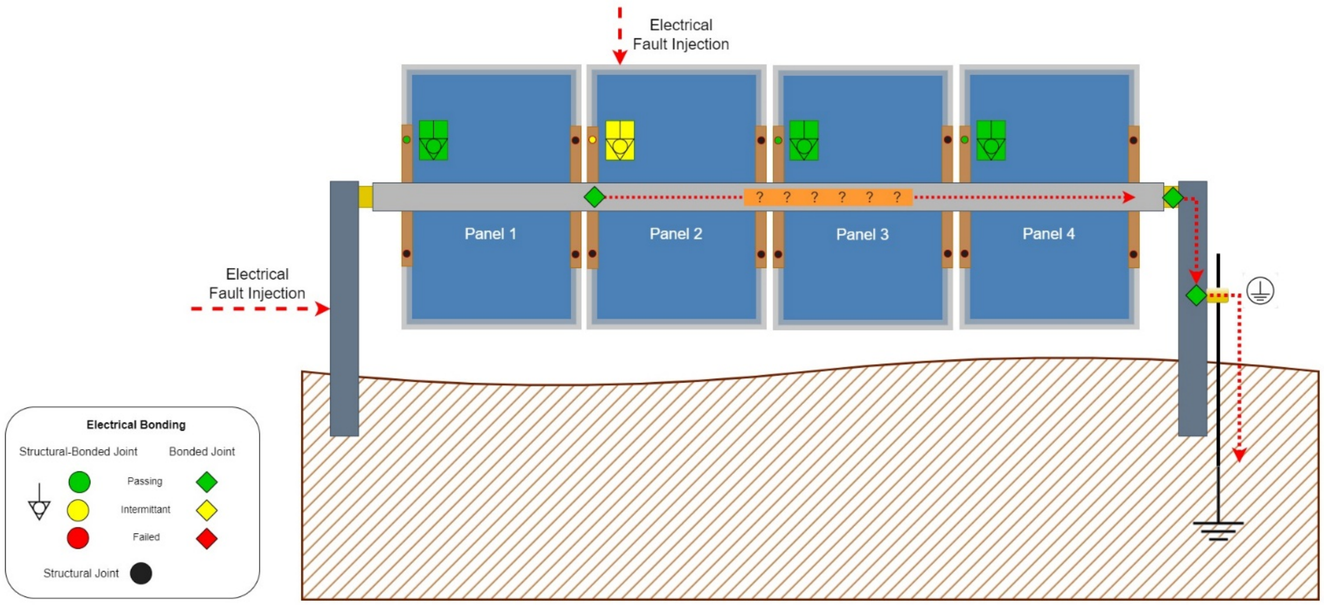

Figure 6: PV Tracker Array with Intermittent Electrical Bonding

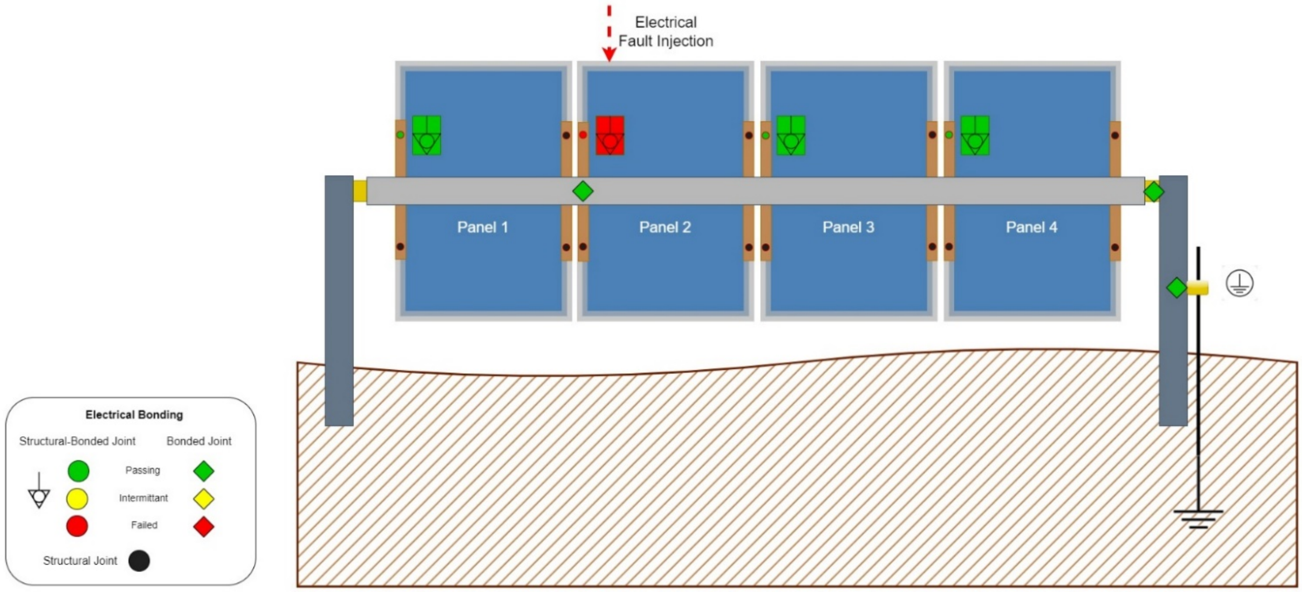

Figure 7: PV Tracker Array with Failed Electrical Bonding

2.3.2 UL 1703/UL 61730/2703 Bonding Path Resistance Tests

The bonding path resistance tests specified in UL 1703/UL 61730 and UL 2703 are essential for ensuring the safety and reliability of photovoltaic (PV) systems. These standards cover both DC and AC circuits. The test criteria are based on DC because measuring resistance in a grounding connection is simpler, eliminating the influence of inductive and capacitive reactance that occurs with AC in high-current potential fault situations.

According to UL 1703, PV module bonding requirements mandate that aluminum module frames be bonded at one or more locations using a bonding device that pierces the anodized coating. According to UL 1703, Sect. 25.1, the resistance between the grounding terminal/lead and any accessible conductive part must not exceed 0.1 Ω.

Similarly, UL 2703, Sect. 13.1 specifies that the resistance between grounding or bonding junctions must also not exceed 0.1 Ω. Maintaining this low bonding resistance is crucial for effective grounding and bonding, which helps prevent electrical shock hazards. This resistance level ensures that fault currents can be safely conducted to the ground, thereby reducing the risk of electric shock (UL 61730, 2021); (UL2703, 2021); (UL 1703, 2021).

A higher resistance in the bonding path may lead to overheating at the bonded joint during a PV module fault condition. Furthermore, this resistance requirement aligns with the National Electrical Code (NEC) and other safety standards, ensuring that photovoltaic systems are installed and operated safely and reliably. (Ball, Zgonena, & Flueckiger, 2013)
The bonding path resistance test involves passing a direct current equal to twice the fuse ampere rating specified for the PV module through the bonded joint. The resistance is then calculated using Ohm's Law, based on the measured voltage drop between the grounding terminal or lead and a point within ½ inch of the current injection point. The test is completed both before and immediately following the humidity cycling tests in all three standards, UL 1703, UL 61730, and UL 2703.

The following outlines the method to determine the bonding resistance across a joint using the UL 1703/2703 bonding resistance test:

1. **Preparation**: Ensure that the photovoltaic (PV) module and all bonding Joints are thoroughly cleaned and free from corrosion or debris.

2. **Measurement Setup**: Use a digital low-resistance ohmmeter (DLRO) or a similar device designed for low-resistance measurements. Connecting the test leads to the specific points where bonding resistance is to be measured. This ensures accurate and reliable readings of the bonding resistance at the designated locations.

3. **Current Injection:** Inject a current equal to 2x the fuse amperage rating specified. The current shall pass between the grounding terminal/lead and the conductive part. Note that typically, the DLRO produces the current injection.

4. **Two-Point Measurement**: Connect the leads to two points along the fault current ground path for a basic assessment. The measuring point must be within 12.7 mm (1/2") of the point of current injection. Calculate the impedance using Ohm's Law ($Z = V/I$). **Note:** $Z = R$ (resistance) in DC circuits.

5. **Four-Point Measurement**: For enhanced accuracy, particularly over longer distances, employ a four-point measurement method. This involves two current-carrying leads and

two voltage-sensing leads. The current is injected through the outer leads, and the voltage drop is measured across the inner leads, thereby minimizing the influence of lead resistance on the measurement.

6. **Verification**: Conduct the measurement at multiple points to ensure consistency and verify that all bonded joints meet the required resistance threshold. The testing shall be conducted on at least three unconditioned samples without pretreatment or environmental conditioning before testing.

2.3.3 Electrical Fault Detection Using Continuous System Monitoring

Electrical ground fault detection systems are designed to identify ground faults, not bonding failures. Consequently, electrical bonding failures can go undetected by these systems. It should also be noted that utility-scale photovoltaic (PV) installations typically lack automatic detection systems for monitoring electrical bonding, which can lead to undetected failures and pose potential safety risks. Additionally, these installations, which are usually ground-mounted and not located on buildings, do not generally incorporate rapid shutdown devices. Being situated in remote areas reduces the risk for emergency responders and the public, and the design and layout of utility-scale systems allow for different safety protocols.

In summary, the electrical resistance through structural bonded joints in utility-scale installations is generally not monitored. The structural bonded joints are typically completed visually or through simple torque checks. Bonding resistance testing is not commonly conducted as part of the normal O&M of utility-scale installations, either.

3. Key Influences of Electrical Conductivity of Structural Bonded Joints

Electrical resistance through structural bonded joints depends on numerous factors, including material selection, assembly methods, clamp load, corrosion, and structural loading. These joints are exposed to environmental conditions throughout the life of the mounting structure, which can lead to corrosion and loosening, increasing the resistance across the bonded joint. In extreme cases, corrosion and loosening can result in the complete loss of the electrical bond (Ball, Zgonena, & Flueckiger, 2013), (Kovalov, 2021).

3.1 Loose Solar PV Bolted Joints are Surprisingly Common

Solar PV bolted joint loosening behavior (i.e., loss of clamp load) is surprisingly complex and often not fully understood. Depending on the design, loosening may be a ‘one-time event’ early in the mounting system’s life, but it can be chronic in extreme cases.

Research has revealed two fundamental types of loosening in bolted joints: relaxation loosening (non-rotational) and self-loosening (rotational). Solar PV bolted joints commonly experience both types of loosening. Understanding these distinctions is crucial for addressing the true causes of bolted joint loosening in PV mounting systems.

3.1.1 Relaxation Loosening

Relaxation is a general loosening process in which the initial pretension in the bolt (and the clamp load in the joint) decreases over time without rotation between the internal and external threads. This type of loosening is often called non-rotational loosening. Solar PV bolted joint relaxation loosening can occur through at least four distinct mechanisms. The first two, embedment and differential thermal expansion/contraction, are normal (expected) and should be accounted for in the design process. The second two, joint yield and fretting wear, are problematic and should be avoided altogether.

3.1.2 Self-Loosening

Self-loosening is a specific loosening process that affects solar PV bolted joints that are repeatedly overloaded in shear and repeatedly slip. When self-loosening occurs, the initial clamp load in the joint decreases over time due to rotational loosening between the nut and bolt.

A detailed explanation of relaxation, self-loosening, and their prevention is provided in *Fundamentals of Solar PV Bolted Joint Loosening and Prevention* (Ness and Robinson, 2026).

Industry Misunderstanding: “Fastened joints loosen due to vibration”
Research has revealed two fundamental types of loosening in bolted joints: relaxation loosening (non-rotational) and self-loosening (rotational). Solar PV bolted joints commonly experience both types of loosening. While vibration can influence both relaxation and self-loosening, it is not the root cause of either type.

3.2 PV Mounting Systems: Dynamically Loaded & Flexible

Solar photovoltaic (PV) mounting systems are lightweight and flexible compared to traditional structures like bridges and buildings. The systems can experience significant deflections and movement under dynamic wind loading. Such deflections and movement can amplify the loading experienced at individual joints within the structure (including the structural bonded joints). It is widely recognized that loading resulting in localized yielding or repeated joint slip, will cause joint loosening (Koekemoer, Johann Richard Bredell, & Reinecke, 2024), (Chen, Zhu, Shu, & Li, 2023).

3.3 Thermal Cycling – Repeated Joint Slip

Solar PV mounting systems are exposed to large temperature swings on a seasonal and daily basis (thermal cycling), which can result in repeated expansions and contractions across the structure or within the joints.

Expansion and contraction within the mounting system can result in repeated joint slip, which will cause loosening due to fretting wear or self-loosening unless special care is taken during the design process.

3.4 Aluminum Oxide – A Non-Conductive Barrier to Corrosion (and Bonding)

Aluminum can be easily extruded into complex shapes that are lightweight and corrosion-resistant. It is an excellent choice for solar PV mounting systems and module frames. Aluminum does have some disadvantages, however.

When aluminum is anodized, a thicker layer of protective aluminum oxide is formed through an electrochemical process. The anodized coating on aluminum PV module frames and aluminum mounting systems is typically around 10µm to 15µm thick. This coating significantly improves corrosion resistance compared to untreated aluminum and creates a non-conductive 'film' because of its thickness and resistivity. (The film resistance (R_F) through an anodized coating can be calculated using Equation 6) The resistance through this layer exceeds the limit allowed by the UL bonding resistance test. To pass the test, the anodized layer must be removed or pierced with a bonding device.

Bonding devices are commonly manufactured from stainless steel, a metal higher on the galvanic series than aluminum. Due to the difference in electrochemical potential between stainless steel and aluminum, the aluminum will sacrifice itself (corrode) to protect the stainless-steel bonding device if the joint is moist. If assembled correctly, the bonding device embeds itself in the aluminum, which self-seals to form a structural bonded joint with low electrical resistance and resistance to oxidation and galvanic corrosion. If that same structural bonded joint is loose and not sealed, the joint will likely have either high or intermittent resistance values.

The naturally occurring aluminum oxide layer (a.k.a. passivation layer) is typically around 4 nanometers thick. While this thin layer does not automatically indicate poor electrical conductivity, it is still important to pierce or remove these oxides before assembling the bonded joint to ensure optimal conductivity.

In some instances, PV module frames are bonded using jumper cables. This process involves scraping, gouging, or cutting through the anodized layer to enable electrical conduction between the cable lug and the module frame. However, if the joint is not sealed, the exposed bare aluminum is susceptible to environmental exposure, leading to accelerated oxidation compared to a sealed joint. This oxidation can increase the electrical resistance of the joint.

3.4.1 Use of an Improvised Bonding Device – The Star Washer

To meet the NEC’s grounding and bonding requirements, contractors have used external tooth washers (star washers) as bonding devices for solar PV modules (see ***Figure 8***).

When tightened, the star washer’s sharp protrusions pierce the nonconductive, anodized surfaces to establish an electrical connection. Although mounting system manufacturers generally do not approve of this method, some electrical inspectors permit its use. Star washers are inexpensive, but field experience has shown they can be problematic in structurally bonded joints.

Matrix Engineering investigated a failure at a 5 MW site where PV modules were bonded using star washers. The site’s O&M manager reported that PV modules would detach during moderate wind events, and the module attachment bolts would not stay tight, even after repeated tightening. A closer examination revealed that star washers were placed between the module and the mounting structure to create the electrical bond.

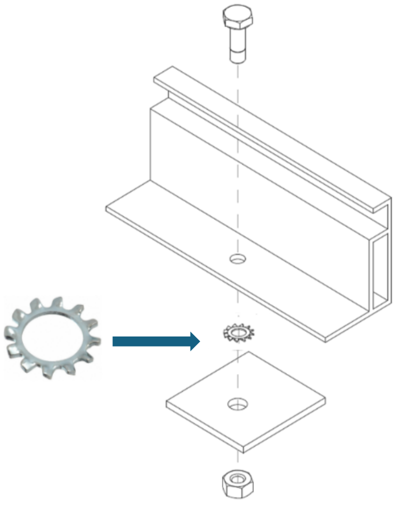

Figure 8: Problematic Star Washer Placement in Module Through-Bolted Structural Bonded Joint

A root cause analysis determined that star washers were the cause of the loose joints and subsequent module detachments. Examination of the failed joints showed compressive yield under the star washer protrusions. It was concluded that bolt pretension and applied loads were concentrated at the small contact area of the star washer protrusions, causing the module frame to yield after tightening. (See Figure 9: Disassembled Module Through Bolted Joint Bonded with Star Washer**Figure 9**). The through-bolted joint, bonded with star washers, would relax, even if repeatedly retightened. This conclusion was verified through laboratory testing.

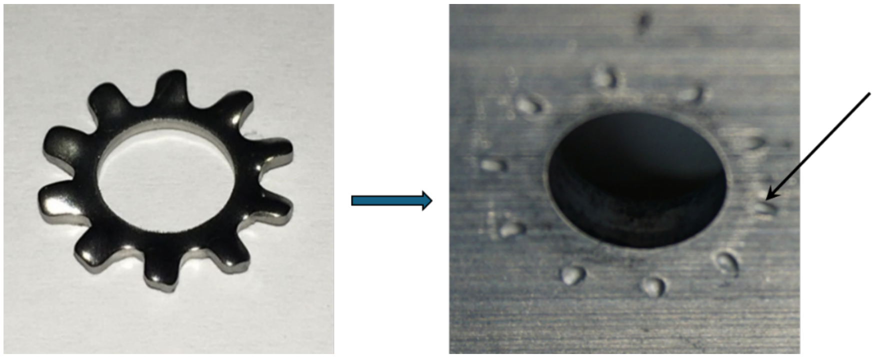

Figure 9: Disassembled Module Through Bolted Joint Bonded with Star Washer

Based on this work, it was concluded that the only solution was to replace the star washers with WEEB®-DSK14 washers, the mounting system manufacturer’s approved method (certified under UL2703). WEEB® washers pierce the anodized coating on the aluminum like star washers, but their protrusions are much sharper. As a result, the protrusions sink deeply into the module frame until the full washer comes into contact, distributing bolt pretension and applied loads over a larger area, preventing additional relaxation.

Following the repairs, the O&M manager reported that the joints remained tight, even after several high-wind events.

Industry Misunderstanding: "Star washers can be used to bond structural joints."
Star washers are suitable bonding devices for PV non-structural bonded joints, where they can effectively maintain electrical continuity. However, they are not recommended for structural bonded joints, as they are prone to loosening due to compressive yielding under dynamic loading.

3.4.1.1 Lab Testing WEEB® vs. Star Washers (Contribution by Burndy) (Burndy, Hubbell, 2016)

Short-Time Current Testing
To demonstrate the advantages of the WEEB® washer bonding device over star washers, a comparative analysis was conducted in accordance with UL 467: Standard for Safety Grounding and Bonding Equipment. Short-time current testing, recognized as one of the most rigorous test sequences, was employed to assess connection resiliency relative to system ratings based on the upper limits of the conductor size (IEEE, 2014).

The energy applied in each test sequence was designed to simulate a fault current just below the fuse rating of the conductor. Utilizing #6 wire ratings, tests were conducted with WEEB® and star washers installed on anodized aluminum and powder-coated steel structures, paired with zinc-plated copper lugs of comparable ratings and sizes.

Additionally, tests incorporated oxide-inhibiting compounds Burndy® Penetrox™ E (Pen-E) and Sanchem NO-OX-ID® (No-Ox), which are intended to protect connections from corrosion without compromising electrical integrity by sealing out moisture to prevent galvanic corrosion (Di Troia & Zahlman, 2010).

Figure 11 illustrates a failed connection with a star washer, while ***Figure 11:*** Short-Time Current Test (WEEB®) depicts a successful connection that sustained the specified current for the test duration with the WEEB® Washer (Burndy, Hubbell, 2016). During this test, the thermal energy generated by an electrical current passing through the bonded joint over a specified period was calculated using I^2t conversions (current squared through time). This method assesses the ability of the bonded joint to withstand short-term overcurrent conditions without failing (IEC, 2013).

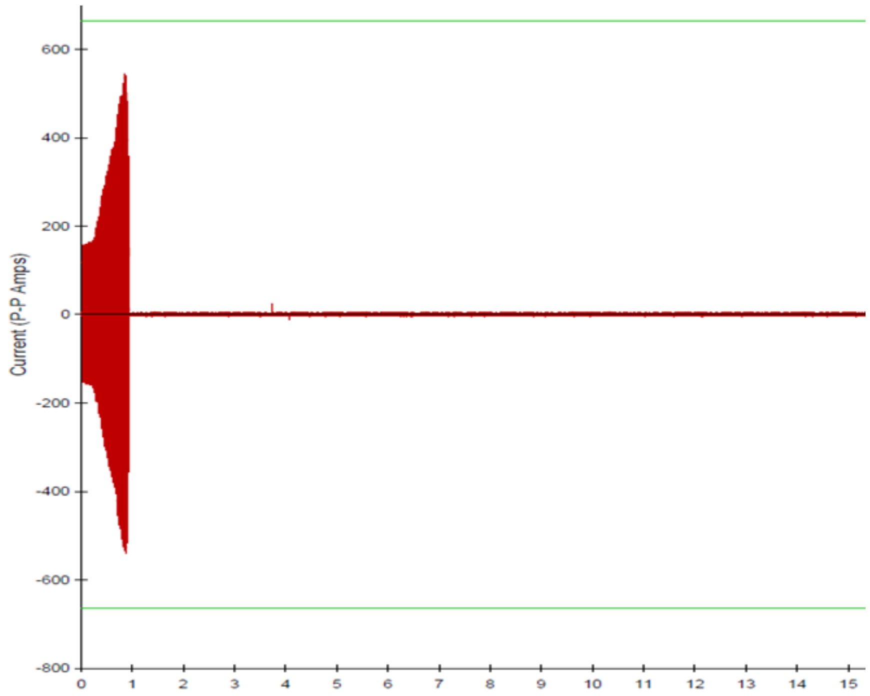

Figure 10: Short-Time Current Test (Star Washer) (Burndy, Hubbell, 2016)

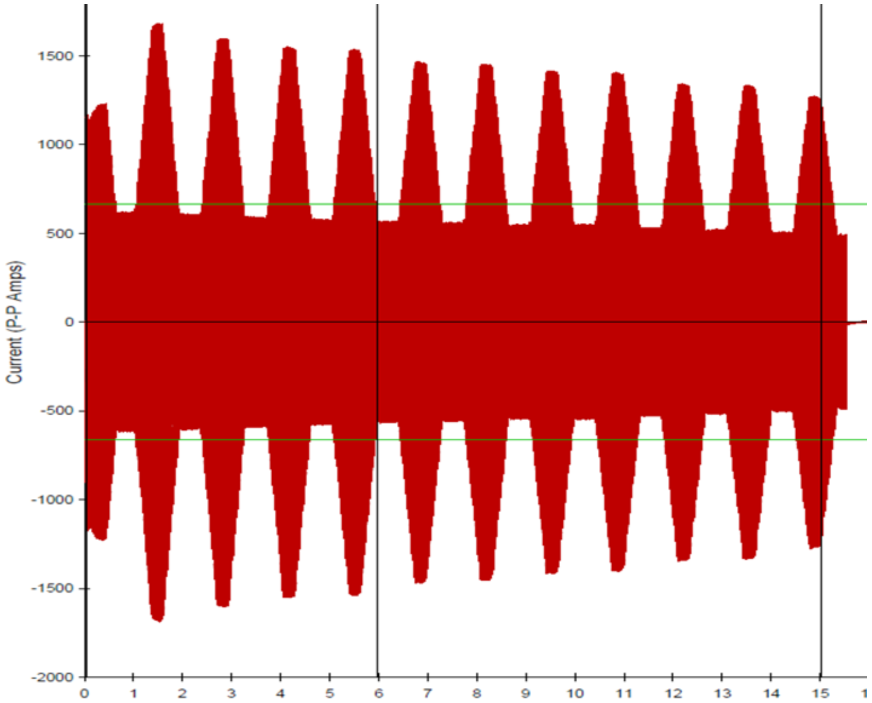

Figure 11: Short-Time Current Test (WEEB®) (Burndy, Hubbell, 2016)

Burndy's analysis of Short-Time test results for WEEB® and star washers (bare, with Pen-E, and with No-Ox) revealed that most samples achieved passing results. All WEEB® washer samples passed, whereas two of the three-star washer samples with No-Ox failed to carry the current. One sample failed to create continuity before the test, and both exhibited no continuity post-testing.

Resistance readings were recorded before and after testing. Initial readings reflect the connection quality at installation, while post-test readings indicate reliability following electrical stress. Burndy determined that WEEB® washer groups exhibited lower average resistances compared to star washer groups.

Figure 12 illustrates comparable initial resistance across the test groups. However, post-test measurements revealed significant differences: star washer resistance increased markedly, whereas WEEB® washer resistance decreased, indicating a better response to thermal cycling.

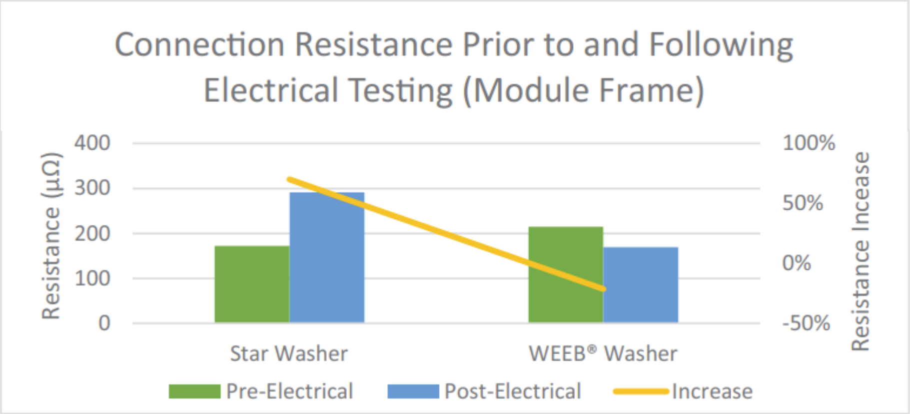

Figure 12: Resistance measurements from short-time current testing on anodized aluminum (Burndy, Hubbell, 2016)

3.4.1.2 Resistance in Corrosive Environments

In 2015, Burndy conducted a 500-hour salt fog test in accordance with ASTM B117. Resistance readings were taken before the test and at 165-hour intervals. These measurements provide insights into the performance of connections in corrosive environments (ASTM, 2015).

Figure 13 illustrate the progression of resistance over 500 hours. All samples exhibited increased resistance over time, indicating bonding degradation. The rate and consistency of this increase reflect the durability of the bonded joint.

Refer to ***Table 2*** for a detailed description of the bonding device test samples and their installation order. No structural loading was performed during this test. The hardware was tightened to the specified torque and placed in the salt spray chamber.

Table 2: PV Electrical Bonding Device Comparison Testing (Burndy, 2015)

UUT	Bonding Device	Size	Material	Installation Order
1	Star Washer	5/16”	18-8 Stainless Steel	Bolt / Anodized Aluminum Frame / UUT / G90 Galvanized Steel / Nut

2	Star Washer	5/16”	18-8 Stainless Steel	Bolt / UUT / Anodized Aluminum Frame / G90 Galvanized Steel / UUT / Nut
3	Serrated Flange Nut	1/4"	18-8 Stainless Steel	Bolt / Anodized Aluminum Frame / G90 Galvanized Steel / UUT
4	WEEB 9.5L		304 Stainless Steel	Bolt / Anodized Aluminum Frame / UUT / G90 Galvanized Steel / Nut
5	WEEB UIR		304 Stainless Steel	Bolt / Anodized Aluminum Frame / UUT / G90 Galvanized Steel / Nut

WEEB® washer samples showed consistent increases in resistance, enabling reliable maintenance planning. Conversely, star washer samples showed erratic resistance readings, complicating maintenance schedules. Notably, a star washer placed between anodized aluminum and galvanized steel exhibited a significant increase in resistance after 300 hours. This inconsistency highlights the unreliability of star washers compared to WEEB® washers.

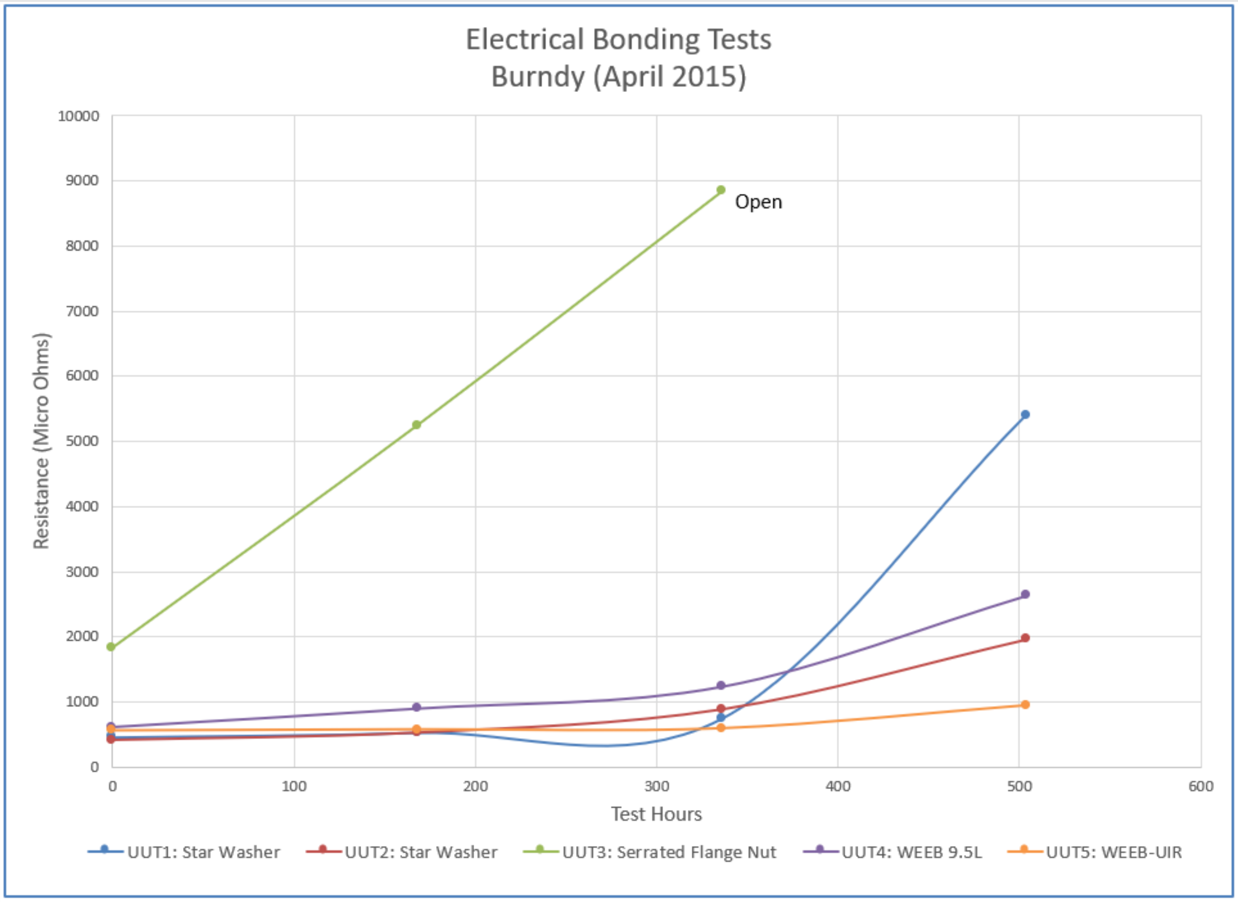

Figure 13: Resistance measurements through salt fog testing, coated steel samples (Burndy, 2015)

4. Design Tips for Reliable Structural Bonded Joints

Achieving reliable structural bonded joints through the operational lifespan of the PV mounting system begins with a ‘rational’ design. Here are a few design tips to ensure reliable structural bonded joints.

1. **Only use Listed Bonding Devices:**
    - Follow the PV module and mounting system installation manuals for the correct bonding method for the module frame.
    - The National Electrical Code (NEC) specifies that products must be listed for their intended applications. Adhering to these requirements ensures compatibility and safety. Two common standards for bonding devices are UL 467 and UL 2703. UL 2703 addresses mounting systems, mounting devices, clamping/retention devices, and ground lugs for use with flat-plate photovoltaic modules and panels (UL Solutions, 2015).
    - Ensure that any listed bonding device is positioned between the module frame and the supporting structure to serve as an electrical conduction path. Avoid placing bonding devices under the head of a bolt or nut in a structural bonded joint, as this results in electrical bonding through the fastener rather than the joint.
    - Properly engineered and listed bonding devices should achieve self-sealing upon joint tightening, thereby eliminating the need for additional sealants.

2. **Consider Joint Relaxation in the Selection of Fasteners and Bonding Devices:** [See: *Fundamentals of Solar PV Bolted Joint Loosening and Prevention* (Ness and Robinson, 2026)].
    - Consider implementing Belleville washers or similar components. These washers can maintain clamp load even if the structural bonded joint experiences embedment or dimensional changes due to differential thermal expansion or contraction, thereby maintaining low contact resistance and delaying corrosion in the joint interface.
    - Whenever possible, design structural bonded joints using fasteners with a longer grip length (less stiff bolt) to minimize relaxation in the fastener system.

3. **Select Materials Appropriate for the Environment:**
    - Consider environmental factors such as moisture, temperature fluctuations, and UV exposure.
    - Design the system to protect the interface of structural bonded joints from the environment, using protective coatings or enclosures where necessary.
    - Use compatible materials to prevent galvanic corrosion. Ensure that connectors and fasteners are made from materials that do not react adversely with PV module frames and racking systems.

4. **Plan for Maintenance Access:**
    - Design the system with maintenance considerations in mind. Ensure that all bonded joints are easily accessible for inspection and maintenance. This facilitates the identification and correction of issues with bonded joints before they become significant problems.

5. Assembly Tips for Reliable Structural Bonded Joints

Ensuring reliable bonding in solar photovoltaic (PV) systems is essential for safety and optimal performance. The following are a few key assembly practices to maintain the reliability of structural bonded joints:

1. **Clean, Dry, and Inspect Joint Surfaces Before Assembly:**
    - Thoroughly clean the surfaces of the joints to remove dirt, contaminants, and oxidation. If necessary, use appropriate cleaning agents to ensure optimal electrical conductivity.
    - Ensure the joint surfaces are completely dry before assembly.
    - Check the joint surfaces for any signs of corrosion. If corrosion is present, clean it off completely before proceeding to ensure reliable grounding and long-term stability.

2. **Ensure Proper Assembly and Contact:**
    - Assemble the joints, ensuring the clean and dry surfaces make proper contact. This maximizes electrical conductivity and minimizes resistance.
    - For all bolts and connectors, strictly adhere to the manufacturer’s torque specifications. Using incorrect torque, whether over-tightening or under-tightening, can lead to bonding failures. Utilize calibrated torque tools to ensure that joints are secured correctly.
    - After assembly, visually inspect structural bonded joints to ensure they are assembled correctly and perform spot quality checks on electrical bonding using continuity and ground resistance tests.

3. **Use Proper Tools and Follow Guidelines:**
    - Ensure that all tools and equipment used for assembly are appropriate for the task and in good condition. Adhere to the manufacturer's instructions and guidelines for assembly and bonding. This ensures that all components are installed correctly and safely.

6. O&M Tips for Reliable Structural Bonded Joints

Ensuring reliable bonding in solar photovoltaic (PV) systems is essential for safety and optimal performance. The following are a few key operations and maintenance (O&M) practices to maintain the reliability of structural bonded joints:

1. **Regular Inspections & Retightening:**
   - Conduct comprehensive and periodic inspections of structural bonded joints.
   - Inspections should look for evidence of structural bonded joint loosening, corrosion, wear, or physical damage that could compromise the electrical bond.
   - Loose structural bonded joints should be retightened. If feasible, conduct the UL 1703/2703 bonding resistance test on the retightened joint to ensure the electrical bond resistance does not exceed 0.1 Ω.

Industry Misunderstanding: "Torque audits always provide an accurate indication of the clamp load in existing bolted joints in field installations."
Torque auditing, especially if done months after the initial assembly, may not be a reliable indication of the clamp load in a bolted joint and, therefore, not a good indication of the electrical resistance of the structural bonded joint.

2. **Component Replacement:**
   - Develop a regular maintenance schedule to replace bonding devices in structural bonded joints prone to chronic loosening. Such loosening may cause damage to the bonding device and compromise the bond.
   - Keep an inventory of spare parts to facilitate quick replacements and minimize downtime.

3. **Documentation and Training:**
   - Keep detailed records of all inspections, maintenance activities, and any issues identified. This documentation is vital for tracking the history and performance of structural bonded joints.
   - Ensure that all personnel maintaining the PV system are adequately trained in bonding techniques and safety protocols. Proper training helps prevent human errors that could compromise system reliability.

7. Topics Meriting Additional Research

Understanding how electrical structural bonded joints age is crucial to ensuring the long-term reliability and performance of photovoltaic (PV) systems. Here are some key areas of research that could fill knowledge gaps and improve the reliability of structural bonded joints.

7.1 Monitoring Structural Bonding Integrity: From Assembly to End of Life

Understanding the state of an electrically bonded joint at the time of assembly is crucial for predicting its long-term performance. Research should focus on initial assessments of joint integrity, including electrical resistance, mechanical stability, and environmental resilience, as well as the quality of assembly practices. Establishing a baseline at the time of installation allows for tracking performance changes over time and under various conditions. This ongoing research is important for identifying early indicators of degradation, informing maintenance schedules, and improving design standards to enhance the longevity and reliability of PV systems. Ultimately, this knowledge can lead to safer and more efficient solar energy installations, reducing downtime and maintenance costs.

Collecting and analyzing field data from existing PV installations throughout their lifecycle, from installation through mid-cycle life, can provide valuable insights into real-world aging processes and help validate laboratory findings. These tests should focus on measuring the resistance in the equipment ground path across different PV systems, accounting for loosening and corrosion. Additionally, further investigation into bare steel piles should be considered.

7.2 Refining Existing Laboratory Testing Procedures

Further research is needed to refine laboratory testing procedures that more accurately simulate long-term aging of the structural bonded joints due to dynamic loading **and** humidity cycling. Such tests should also account for normal relaxation loosening. These advancements in testing will allow for a more accurate estimation of the service life of structural connections, which is essential for maintaining electrical bonding integrity. Despite considerable time and resource commitment, investing in this research will reduce risk in the rapidly growing and competitive solar industry.

7.3 Researching Optimal Maintenance Practices and Schedules

Regular inspections and maintenance to identify deterioration in structural and electrical connections are also crucial. Currently, practices vary significantly across the industry. Determining the optimal maintenance schedule is essential for balancing cost-effectiveness and durability. Research is needed to establish best practices for maintenance intervals and procedures that ensure longevity and safety while being economically viable. This balance is key to maintaining PV system integrity over time and will drive design improvements and updates to standards.

7.4 Researching Advanced Monitoring Techniques

Researching advanced monitoring techniques, such as real-time resistance measurement and non-destructive testing methods, can help detect early signs of increased resistance in structural bonded joints. Encouraging the adoption of such smart monitoring systems to detect early signs of bond degradation and alert maintenance personnel could also significantly extend the operational lifespan of electrical bonds. However, integrating smart technology may face resistance due to initial costs and ongoing maintenance needs.

8. Improvement Opportunities for Industry Standards

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

The rate of degradation of structural joints in a PV system depends on many factors, including the module and mounting hardware design, the overall system layout, and the specific environmental conditions at the site. Given these variables, it is essential to continue research, monitor system performance in the field, and address shortcomings in current codes, 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 codes, standards, and industry practices to ensure the long-term reliability of these bonded joints.

8.2 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.

8.2.1 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.

8.2.2 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.

9. Conclusions

This investigation underscores the critical role that electrical bonding in PV structural joints plays in maintaining the structural integrity and electrical safety across the lifespan of photovoltaic installations. The industry benefits from cost-effective, dual-purpose structural-bonded joints.

However, their design is complex. Material properties, environmental exposure, mechanical loading, and installation practices all influence performance. These factors create ongoing challenges for long-term reliability.

Field evidence shows that joint loosening, corrosion, and intermittent conductivity are more prevalent than commonly assumed, with potential consequences for grounding reliability and system safety.

Current standards, such as UL 2703, define important baseline testing. But the standard does not fully capture the combined effects of dynamic loading, thermal cycling, corrosion, and chronic loosening experienced in real-world conditions. Maintenance practices also vary widely across the industry, with limited adoption of bonding resistance verification as part of routine O&M. The absence of standardized, long-term monitoring methods leaves a potential gap in the industry's ability to identify and address undetected loss in bonding before it impacts system safety.

To bridge these gaps, further targeted research is critical. Priority areas for research include refining laboratory tests to replicate in-field aging mechanisms better, collecting lifecycle performance data from operating systems, and developing advanced monitoring technologies for early detection of bond degradation. In parallel, investigations into optimal maintenance intervals and the economic trade-offs of various inspection regimes are also needed to balance cost with system longevity and safety.

As utility-scale PV deployment accelerates, the industry should not rely solely on initial installation quality to ensure decades of reliable operation. Advancing our understanding of how structural bonded joints degrade and can be effectively maintained will improve electrical safety.

While current practices provide a functional baseline, the opportunity—and the need—for deeper research is clear. In the interim, strengthening standards and integrating field-validated best practices will be important to ensure that PV structural-bonded joints remain both structurally sound and electrically dependable from commissioning to end-of-life.

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