Dynamic Mechanical Load Testing of PV Module Connections: From Qualification to Capacity Characterization

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Abstract

Background & Purpose

Dynamic Mechanical Load (DML) testing and static load testing according to IEC 61215 are widely used to qualify photovoltaic modules for mechanical durability. These protocols establish minimum compliance thresholds through fixed-amplitude cyclic loading and limited static load cycles. While effective for certification, they do not quantify fatigue capacity, characterize nonlinear joint loosening, or define performance margins under realistic environmental loading conditions.

PV mounting systems subject modules to variable-amplitude cyclic stresses that vary by project and can approach or exceed standardized DML levels. Field investigations following major wind events have identified fatigue crack initiation and propagation at module hardware mounting points, indicating that cyclic capacity, rather than static strength alone, governs long-term survivability. These observations highlight a gap between the assumptions underlying qualification testing and in-field demand.

This study evaluates a performance-based testing approach using increasing amplitude cyclic loading of modules mounted in representative tracker configurations. Loading amplitudes were progressively increased beyond standard DML levels to identify crack initiation thresholds, the onset of plastic deformation, fastener relaxation behavior, and changes in joint stiffness.

Results demonstrate a nonlinear fatigue response and reveal significant differences in capacity between mounting configurations that are indistinguishable under fixed-amplitude qualification testing. A capacity-based dynamic mechanical characterization approach is proposed to complement existing standards by defining performance envelopes rather than relying solely on minimum compliance criteria.

Targeted Audience

- Project Developers
- Independent Power Producers (IPPs)
- Engineering, Procurement & Construction (EPC
- Independent Engineering Firms (IE's)
- Structural Engineering Consultants
- Wind Engineering Consultants
- PV Module Manufacturers
- Module Frame Suppliers
- Solar Racking Manufacturers
- Single-Axis Tracker Manufacturers
- Third-Party Testing Laboratories
- Standards Committees (IEC, UL, ASCE)
- Insurance Companies and Underwriters
- Lenders, Tax Equity Investors
- Infrastructure Funds
- Owner's Engineers

Limits of Current DML Testing

Utility-Scale PV - Current State of the Art

Dynamic Mechanical Load testing under IEC TS 62782, and incorporated into IEC 61215 revisions, applies 1,000 cycles at a fixed amplitude of 1,000 Pa. This protocol serves as a screening tool to identify gross dynamic weaknesses. However, the selected amplitude is not directly tied to a module's static load rating under IEC 61215 and is often substantially lower than the module's certified design load.

As a result, DML testing may verify survivability under moderate cyclic demands (e.g., 50mph winds) while providing limited insight into actual fatigue capacity. A module tested at 3,600 Pa static load and further evaluated at 1,000 Pa dynamic load may be leaving a significant portion of its structural envelope unexplored. The test establishes minimum cyclical loading compliance rather than quantifying an actual capacity.

Additionally, DML testing applies a uniform pressure across the module surface. In field installations, particularly on single-axis trackers, wind loading is rarely uniform. Tilt angle, row position, and aerodynamic effects produce highly uneven and varying pressure distributions. This nonuniform loading can significantly increase stresses at mounting locations compared with those predicted under uniform loading. As a result, a module that performs adequately under uniform cyclic pressure has only moderate predictive value for modules under realistic, uneven wind loading conditions. An example of one direct effect of assuming uniform loading is a tendency for projects to use shorter module rails. However, it can be shown that the actual, unbalanced loading on module fasteners can be double what is tested in these short rail configurations.

Finally, fatigue response in bolted aluminum and steel assemblies is highly nonlinear. Scaling fatigue life from one pressure amplitude to another is highly configuration-dependent and not realistic in practice. A 1,000Pa for a 1,000-cycle test does not well characterize progressive bolt loosening, fretting wear, or the overall cyclical failure mechanisms that govern long-term performance.

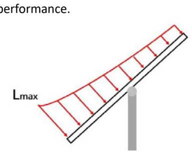
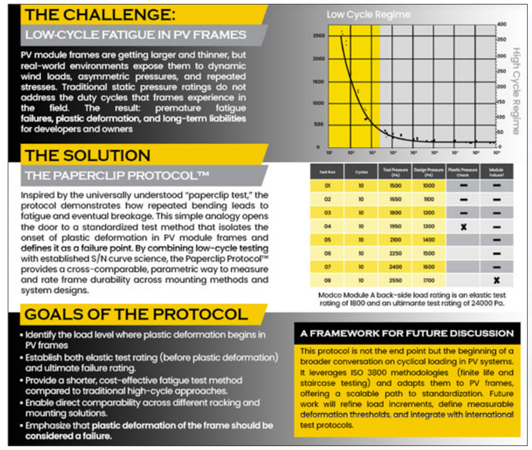


*Image courtesy of Canadian Solar: CS_Installation-Manual_PV-Modules_EN-v3.1-EN

Originally Proposed Capacity-Based DML Framework



Experimental Program

Test Setup	Cycle Testing Protocol	Pre/Post Characteristics
Test 1 (T1) "Flat Washer" Long Rails	- 1000 Cycles at +/-1000Pa - 1000 Cycles at **+/-1500Pa** (If passed at +/-1000Pa) - 1000 Cycles at **+/-2000Pa** (If passed at +/-1500Pa) - 1000 Cycles at **+/-2500Pa** (If passed at +/-2000Pa)	MQT 01 Visual Inspection
Test 2 (T2) "Flat Washer" Short Rails	- 1000 Cycles at +/-1000Pa - 1000 Cycles at **+/-1250Pa** (If passed at +/-1000Pa) - 1000 Cycles at **+/-1500Pa** (If passed at +/-1250Pa) - 1000 Cycles at **+/-1750Pa** (If passed at +/-1500Pa)	MQT 01 Visual Inspection

Each configuration followed a controlled stepwise loading protocol. Modules were first subjected to 1,000 cycles at ±1,000 Pa. If no failure criteria were observed, the same specimen advanced sequentially to 1,000 cycles at ±1,500 Pa*, then ±2,000 Pa, and finally ±2,500 Pa. This progressive step-up approach was designed to determine the maximum cyclic pressure amplitude survivable for 1,000 cycles within each mounting configuration, rather than limiting evaluation to a single fixed-amplitude demand as prescribed in standard DML testing.

Visual inspections were conducted before and after each loading stage to document frame deformation, mounting interface behavior, fastener relaxation, fretting wear, crack initiation, and any other emerging damage mechanisms. Test outcomes are therefore reported as a capacity metric, defined as the highest cyclic pressure amplitude that successfully completed 1,000 cycles while satisfying all inspection criteria.

Because fatigue response is highly nonlinear with respect to stress amplitude, and approximately linear with cycle count within a fixed amplitude regime, the highest pressure capable of sustaining 1,000 cycles is proposed as the most meaningful indicator of dynamic performance capacity. Notably, both test specimens successfully completed 1,000 cycles at ±1,000 Pa, meeting current DML compliance thresholds, yet exhibited differentiated performance at elevated amplitudes.

*T1 used 500Pa increments. T2 used 250Pa increments based on anticipated maximum rating achievable.

Results: Nonlinear Fatigue & Interface Behavior

Metric	T1 ("Flat Washer") Long Rail	T2 ("Flat Washer") Short Rail
Frame Deflection	Visible - Minor	Visible - Significant
Fretting Wear	Significant	Moderate
Bolt Loosening	Yes	Yes
Highest Cycle Passed	1000 cycles @ 2500Pa*	240 cycles @ 1,250Pa
Static Pressure Test Rating	3,600Pa uplift	2,100Pa uplift

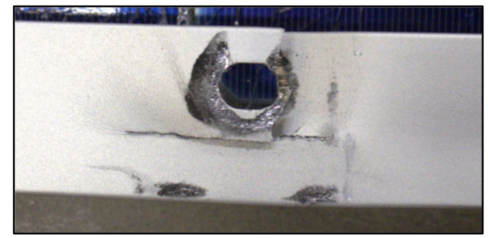


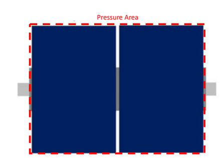
Photo 1: Frame Fatigue Failure and Fretting Wear Observed in T2 Testing

*Highest Pressure That the Current Machine Can Dynamically Test

System Design & Standards Recommendations

Lessons Learned From Testing

1. **Changing the dynamic rating of test panels to the highest pressure that can pass IEC 61215 criteria after 1,000 cycles is the cleanest approach to a performance standard**. It leverages existing test methods, equipment, and standards.
2. **Dynamic testing should include the same 1.5 test/design safety factors as static testing**. Because dynamic loading is nonlinear, this provides critical resilience to real-world cyclical loading.
3. **Non-uniform loading should also be tested** (test both uniform and non-uniform cases and take the lowest rating). Testing the pressure distribution that results in the highest fastener loading is a reasonable approach to approximating real-world performance. For example, on 1P single-axis tracker systems, this would be the distribution that returns the highest moment at the torque tube.
4. **Identification of frame plastic deformation is too subjective as a test criterion**. Ultimately, accounting for both unbalanced module loading and the 1.5 test/design safety factor should eliminate concerns about plastic deformation in real-world applications.
5. **Module testing should ideally be done for 2 modules together**.
   - Current testing is performed on a single module, effectively halving the rail loading of shared rails.
6. **Joint relaxation, junction box contact with the racking system & glass contact with the racking system are commonplace at higher loadings and should be considered mechanical loading test failures (both cyclical & static)**.
7. **Representative structures to the field install should be required for certification to any load** (cyclical & static).
7. In addition to complete frame failure in T2, measurable bolt relaxation and fretting wear were observed, indicating early degradation preceding module detachment.



Ideal Future Testing Setup – If not longer
Minimum Future Testing Setup Proposal

More Information

Resources:

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5. Seel, J., Mulvaney Kemp, J., Cheyette, A., Gorman, W., Darghouth, N., Robson, D., Rand, J., & Jeong, S. (2025). *U.S. Utility-Scale Solar, 2025 Edition: Analysis of Empirical Plant-level Data from U.S. Ground-mounted PV, PV+battery, and CSP Plants (exceeding 5 MWAC)* [Slide Deck]. Lawrence Berkeley National Laboratory.
6. Burgess, C., Stone, L., & Elkin, D. (2025, June 10). *Solar Under Storm III: Updated best practices for hurricane-resilient ground-mount solar PV systems*. Rocky Mountain Institute.

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