

Wind-Induced Dynamic Loading and PV Module Frame Fatigue: Lessons for Gulf Coast Resilience

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Abstract

Key Features

Large-format photovoltaic (PV) modules continue to expand across the U.S. Gulf Coast, a region characterized by recurrent exposure to high-wind, coastal storm events. While offering notable gains in power density and cost efficiency, these modules exhibit reduced structural rigidity and are increasingly vulnerable to cyclic fatigue and frame flange failure under hurricane-induced loading.

This study investigates the initiation and propagation of fatigue cracks within module frames subjected to dynamic wind loading typical of Gulf Coast storm profiles. Using nonlinear finite element analysis (FEA) calibrated to UL 61730 and ASCE 7-22 design parameters, we assess the mechanical behavior of aluminum frame geometries under sustained gust and reversal conditions.

Results indicate that standard 1.1 mm frame flanges can experience failure within minutes of peak cyclic loading, while integration of the RSW StormPlaSM SPO load-distribution element increases fatigue life by more than two orders of magnitude and reduces local stress concentrations by 33%.

These findings emphasize the urgent need to align PV mechanical testing protocols with regional wind risk profiles and to adopt hardware-based mitigation strategies for improved module resilience. The outcomes direct inform design standards, certification testing, and policy frameworks for durable solar infrastructure across hurricane-exposed U.S. territories.

Notable Hurricanes for the Gulf Coast Region

- Harvey – 2017 – Category 4
- Nate – 2017 – Category 1
- Michael – 2018 – Category 5
- Barry – 2019 – Category 1
- Hanna – 2020 – Category 1
- Laura – 2020 – Category 4
- Sally – 2020 – Category 2
- Delta – 2020 – Category 2
- Zeta – 2020 – Category 3
- Ida – 2021 – Category 4
- Ian – 2022 – Category 4
- Idalia – 2023 – Category 3
- Beryl – 2024 – Category 1
- Helene – 2024 – Category 4

Storms are taken from 2016 to the present – Category rating is taken at landfall

Gulf Coast Analog Site and Context

All Utility-Scale PV Projects (built through 2024)⁵



Deployment Size In The Region

As of 2024, the ERCOT and Southeast non-ISO markets represent the largest concentrations of utility-scale photovoltaic (PV) deployment in the United States. ERCOT added 7.6 GWAC and the Southeast non-ISO region added 4.7 GWAC in 2024 alone. Texas contributed the highest new capacity (7.7 GWAC), followed by Florida (3.2 GWAC). Cumulatively, ERCOT has deployed approximately 23 GWAC of utility-scale solar, while the Southeast non-ISO footprint accounts for an additional 21 GWAC.

This rapidly expanding portfolio across key Gulf Coast states underscores the critical need for enhanced mechanical resilience against hail, high winds, and hurricane exposure. As these installations age, low-cycle fatigue and cyclic frame deformation pose increasing reliability risks, particularly for large-format modules mounted on single-axis tracker systems exposed to dynamic loading. Ensuring the structural integrity of module frames and fastener assemblies in this growing fleet is therefore a central focus for future durability research and design standardization.

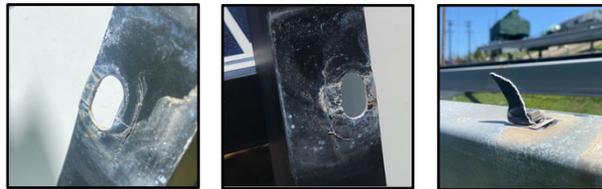
Worldwide Findings of Low Cycle Fatigue Failures



Low-cycle fatigue cracks & failures were found on modules after Category 5 Tropical Cyclone Ilsa hit the Pilbara region of Australia in April 2023.⁴

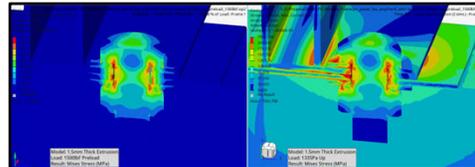


Kiwa PVEL showcases IEC62782 results as part of its 2024 Module Reliability Scorecard, validating that the non-linear FEA model matches both field empirical evidence and lab testing.

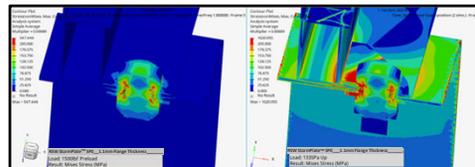


Low-cycle fatigue cracks were found on many remaining modules after Category 4 Hurricane Beryl in the Grenadines in 2024. Failures were found both on the low and high-pressure sides of the modules. Propagation led to failures and is the primary failure mode for module liberation. These findings were featured in Solar Under Storm II⁶.

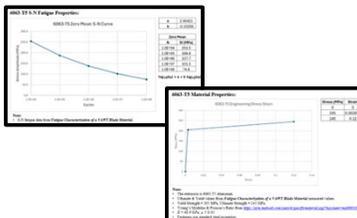
Finite Element Analysis



Industry typical M8 bolt stack-up utilizing a round washer at 1335Pa of test load (50% of the rated load of this panel) – Failure shows along the interior wall frame which was observed in the field (see photos above)



The RSW StormPlaSM SPO design was tested to distribute the load. FEA static results showed a 33% reduction in peak stress in the AL frame, drastically improving the frame performance and should (with further IEC61215 testing) improve overall module performance if the primary failure mode was frame buckling (which it often is)



- Material properties (6063-T5) and an appropriate S/N fatigue curve for the were selected.
- These properties combined enable non-linear FEA analysis of the fastener, washer selection and frame performance.
- As the frame deforms under load, stresses and forces change. It is important to capture these changes as the static FEA analysis showcased that the vast majority of IEC61215 testing would yield a module frame with permanent plastic deformation, even under 40-60% of the rated static load.
- This in-turn brings the question of "what determines a pass / fail for module performance in IEC 61215?". Electrical continuity considerations are primary in this regard.

Results

Fatigue Life 2 Elements from Edge A (Cycles)

Model	Applied Load		
	1068 Pa 40% Rated	1335 Pa 50% Rated	1602 Pa 60% Rated
1.1mm Thick Extrusion	198,427	14,730	607
1.5mm Thick Extrusion	2,298,817	283,000	38,958
RSW StormPla SM SPO 1.1mm Thick Extrusion	4,144,299	1,015,000	283,169

The 1.1mm thick frame flange showcased failure at approximately 607 cycles of load at 60% of it's rated load (1602 Pa). Assuming the wind comes from the worst case direction (rear) this could be achieved in the field in a matter of minutes.

The addition of the RSW StormPlaSM SPO in the analysis shows a great area of promise.

RSW StormPlaSM SPO showed a 450x increase in the number of cyclical loads compared to the 1.1mm thick frame utilizing industry-standard hardware stacks.

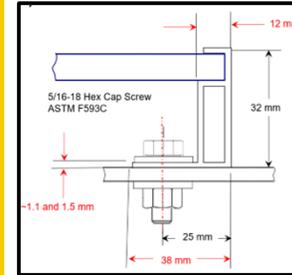
As modules evolve to become larger and have less rigidity, fastener selection needs to be tailored to the application. RSW StormPlaSM SPO is one example of how to better support these smaller frames against stress concentrations. Application specific mounting innovations and techniques like load distribution are key to reducing module liberations in the field.

Taking this analysis away from smaller-format modules under extremely high wind events is also alarming. The expected performance of a large format module under the same conditions would yield an expected failure frequency of 1000Pa (rather than 1335Pa) for an expected performance of under 1000 cycles. This is an industry wide problem, driven by module frame evolutions across all module platforms.

Multiple module frame flange thicknesses were assessed utilizing industry standard round washers to show the cyclical loading difference in simply increasing frame material. 1.1mm was measured in the field in the Grenadines. 1.5mm would constitute a 36% increase in material, estimated to cost approximately \$2.00 a module depending on module size (5000Wp). 1.5mm brings a meaningful improvement. However, the minimum cycle requirement for 20-year performance (acceptable) is yet to be determined.



The StormPlaSM SPO



Improving Codes & Standards

THE CHALLENGE:

LOW-CYCLE FATIGUE IN PV FRAMES

PV module frames are getting larger and thinner, but real-world environments expose them to dynamic wind loads, asymmetric pressures, and repeated stresses. Traditional static pressure ratings do not address the duty cycles that frames experience in the field. The result: premature fatigue failures, plastic deformation, and long-term liabilities for developers and owners.

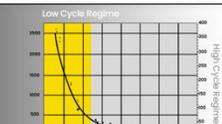
THE SOLUTION

THE PAPERCLIP PROTOCOLSM

Inspired by the university understood "paperclip test," the protocol demonstrates how repeated bending leads to fatigue and eventual breakage. This simple analogy opens the door to a standardized test method that isolates the onset of plastic deformation in PV module frames and defines it as a failure point. By combining low-cycle testing with established S/N curve science, the "Paperclip Protocol" provides a cross-comparable, parametric way to measure and rate frame durability across mounting methods and system designs.

GOALS OF THE PROTOCOL

- Identify the load level where plastic deformation begins in PV frames
- Establish both elastic test rating (before plastic deformation) and ultimate failure rating
- Provide a shorter, cost-effective fatigue test method compared to traditional high-cycle approaches
- Enable direct comparability across different racking and mounting solutions
- Emphasize that plastic deformation of the frame should be considered a failure



Series	Series	Series	Series	Series	Series
01	02	03	04	05	06
07	08	09	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36
37	38	39	40	41	42
43	44	45	46	47	48
49	50	51	52	53	54
55	56	57	58	59	60
61	62	63	64	65	66
67	68	69	70	71	72
73	74	75	76	77	78
79	80	81	82	83	84
85	86	87	88	89	90
91	92	93	94	95	96
97	98	99	100	101	102
103	104	105	106	107	108
109	110	111	112	113	114
115	116	117	118	119	120

Modco Module A Back-side load rating is an elastic test rating of 1800 and an ultimate test rating of 24000 Pa.

A FRAMEWORK FOR FUTURE DISCUSSION

This protocol is not the end point but the beginning of a broader conversation on cyclical loading in PV systems. It leverages ISO 3800 methodologies (like life and staircase testing) and adapts them to PV frames, offering a scalable path to standardization. Future work will refine load measurements, define measurement deformation thresholds, and integrate with International test protocols.

More Information

Resources:

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