GAMECHANGE SOLAR
REPOWERING THE PLANET

Designing for Extreme Wind

Understanding Fatigue Loading on Purlins for Single Axis Trackers

May, 2025

GameChange Solar

230 East Ave., Suite 100

Norwalk, CT 06855 USA

www.gamechangesolar.com

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Executive Summary

Solar power plants are increasingly being designed and installed in hurricane-prone and otherwise high wind speed locations. The structure supporting PV modules on these plants must sustain significant levels of repeated wind loads. Over time the cycling of wind load accumulates as fatigue load. A study commissioned by GameChange Solar and performed by CPP Wind Engineering Consultants shows that fatigue loading at a site during an example hurricane reached over 8,000 cycles at pressures up to 1,400 Pa.

Current testing and design standards for fatigue loading on single-axis trackers are either insufficient compared to the cycles and pressures determined by CPP or cannot accurately model the complex assembly of purlin, module frame, and module glass. Systems designed in accordance with these standards may fail under real-world loading conditions.

GameChange Solar proposes a novel fatigue loading test procedure, which more accurately reflects pressures, cycle quantities, and loading conditions experienced during long duration wind events. This provides a powerful tool for designing tracker systems and PV modules for the damaging effects of hurricanes.

About the Authors

Scott Van Pelt

Chief Engineer

Scott oversees the customer facing engineering team at GameChange Solar. In this role, he is responsible for the execution, accuracy, and timeliness of all of GameChange Solar's technical deliverables.

He is a Professional Engineer licensed in two dozen states and has acted as the Structural Engineer of Record for more than 10 GW of installed solar capacity. With more than a decade of experience in the renewable energy space, Scott currently serves on the UL 2703 and UL 3703 committees and Technical Committee 82 regarding Solar Photovoltaic Energy Systems.

Scott graduated Summa Cum Laude from Lehigh University with degrees in Civil Engineering and Finance.

Nathaniel Healy

Genius Tracker Product Director

Nat Healy is the Product Manager for GameChange Solar's Genius Tracker products. Starting as a Structural Engineer, he has overseen the design, installation, and commissioning of over 4 GW of solar racking and trackers across six continents.

In his role as Product Director, he works directly with the Business Development, R&D, and Engineering staff to facilitate collaboration and promote continued learning on products and industry trends.

Passionate about education, Nat leads internal and external workshops to both train and learn directly from clients, field installers, and internal teams around the world.

Nat graduated from Dartmouth College, with a B.Eng. in Mechanical Engineering.

1. Introduction

As solar photovoltaics become an increasingly popular means of generating clean energy, solar power plants are being proposed in hurricane-prone and otherwise high wind speed locations with increasing frequency. Additionally, as PV module sizes have grown in recent years, the total wind force acting on each PV module has increased, further intensifying the force moving through the structural connections supporting it.

The wind load applied to the surface of the module, given a certain wind speed, is relatively well understood due to the prevalence of boundary layer wind tunnel testing performed by racking and tracker manufacturers throughout the industry. It is worth noting that, as shown in the results of these wind tunnel tests, the wind does not apply pressure to the module evenly. The windward side of the module typically receives a much higher wind pressure during each wind gust, as shown in Figure 1.

The magnitude of this pressure is also well understood. The design wind speed for a location is either determined through review of maps in local building codes or through site-specific studies, such as those per ASCE7-22 section 26.5.3. In either case, the design wind speed corresponds to the speed of a single three-second wind gust, which is not likely to be exceeded in a specific time interval. In the U.S. code environment, this typically corresponds to a mean return interval of 300, 700, or 1,700 years for Risk Categories 1, 2, and 3, respectively, and provides a known level

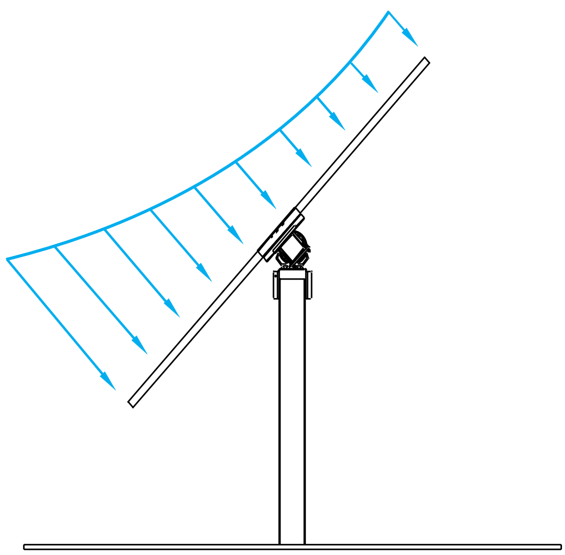


FIGURE 1:
Uneven Wind Loading on a Single Axis Tracker

of reliability to the project owner and their insurer.

As an industry, what remains less understood is the magnitude and frequency of fatigue loads on the modules, such as those during a hurricane. Fatigue failure is the formation and propagation of cracks due to repetitive or cyclical loading. The cyclic loads are typically significantly below the threshold that would result in material yielding. Hurricanes can impart high gust wind speeds for extended time periods, resulting in cyclical loading consisting of many load cycles at high amplitudes on the structural components of the tracker. Each cycle causes a crack to propagate a little bit farther, ultimately resulting in the failure of the part.

Of specific concern for fatigue failure is the connection between the purlin (sometimes referred to as a support rail, clamp, or MIB) to the torque tube, which rotates the PV modules from east to west throughout the day. Purlins are often made of galvanized cold-formed steel in a hat, a.k.a. omega, shape. A purlin design common in the industry, without any reinforcement, is shown in Figure 2. This will be hereafter referred to in this report as Purlin Design A.

The gauge of steel should be optimized to provide a solution that is both economical and provides the desired level of reliability. Thinner materials make this connection particularly susceptible to fatigue failure.

This paper provides a means to determine the magnitude and frequency of fatigue loading and addresses potential advantages and pitfalls of determining the structural capacity of a racking system to resist the fatigue loads using code and standard formulae, finite element modeling, and full-scale testing.

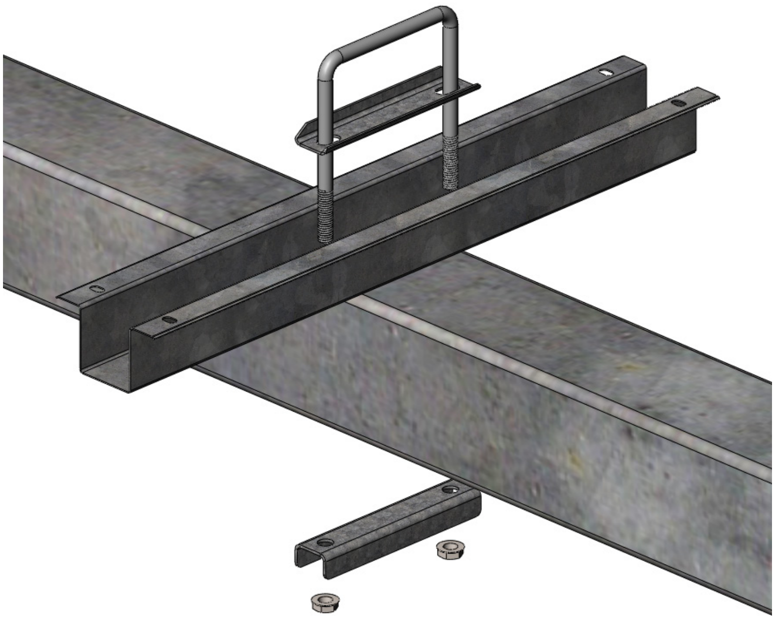


FIGURE 2:

Exploded View of Example Purlin to Torque Tube Connection (Purlin Design A shown)

1.1 Expected Magnitude and Cycle Count of Fatigue Loads

As mentioned previously, hurricanes can impart particularly significant fatigue-style loading. To better understand fatigue loading experienced by a single axis tracker during hurricanes, GameChange worked with CPP, a leading boundary layer wind tunnel consulting firm. Using wind conditions from a site during an example hurricane combined with wind tunnel data, CPP performed a rain-flow analysis to determine cycles and pressures on the windward half of the module (see Figure 3).

Hurricane Ian which made landfall in Florida in 2022 was chosen as the example hurricane. This storm had hurricane-force winds extending up to 45 miles from the center of the storm. At the time, Ian was tied for the fifth strongest hurricane on record to hit the contiguous United States. This included wind gusts up to 110 mph near Sarasota Bradenton International Airport. The data from the meteorological tower at the airport provided a high-resolution data set on which the analysis could be based.

The results of the study show that the sample site likely experienced over 8,000 cycles with pressures up to 1,400 Pa with over 1,700 cycles at amplitudes over 600 Pa. The full CPP study is available on request.

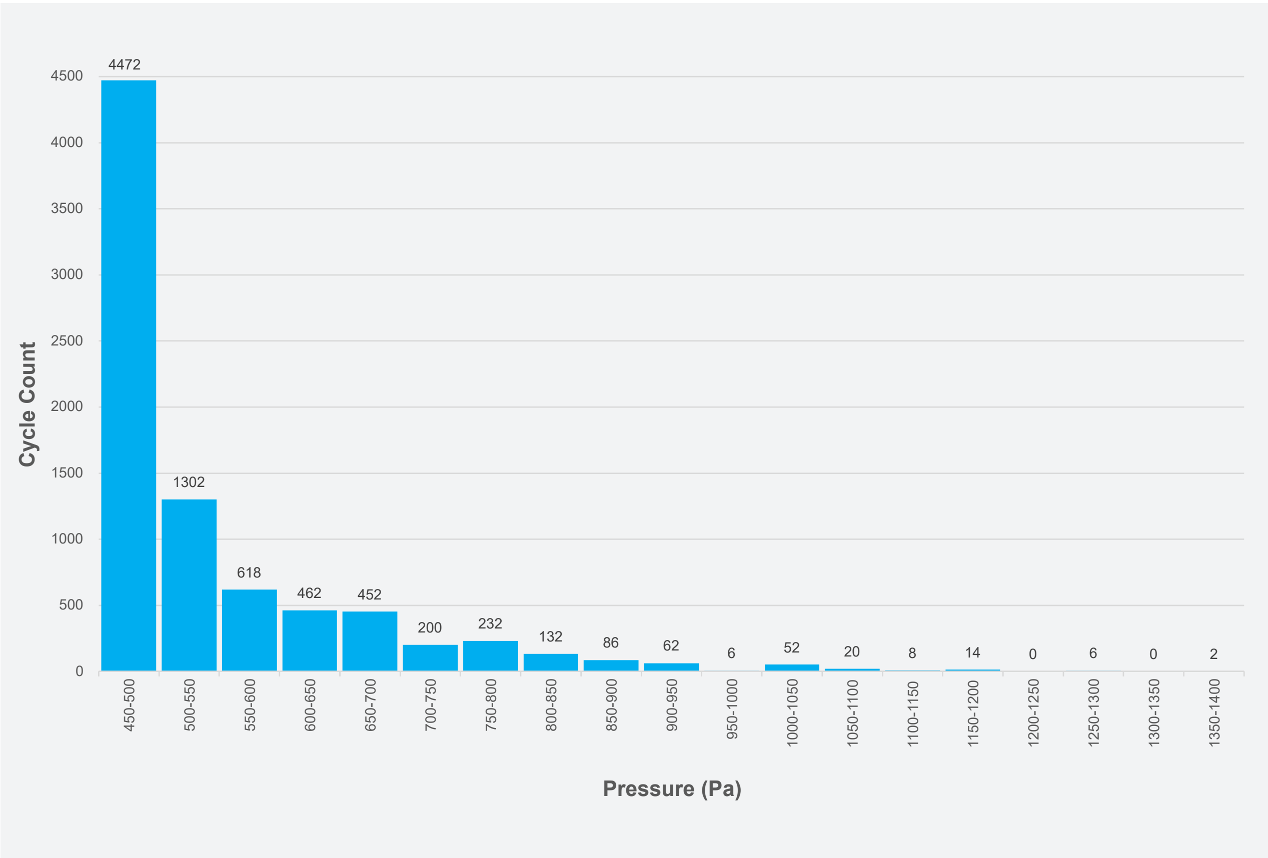


FIGURE 3:

CPP Analysis Pressures on Module Leading Edge vs Cycle Counts for Sample Site During Hurricane Ian

2.0 Are Current Means to Address Fatigue Sufficient?

2.1 Mechanical Load Test Standards

Currently, there are test standards for cyclic loading of PV modules, one typical example being IEC 62782. This standard calls for the PV module to be mounted on support rails, connected using appropriate mounting means (clips/clamps and any kind of fastener), and then subjected to a uniform 1,000 Pa [20.9 psf] load.

As reflected in the testing below, full-scale tests should be performed on an assembly consisting of both the PV module and the supporting purlin. Testing an assembly instead of just an individual purlin more accurately accounts for the load path of the wind pressure through the module and the contribution of the stiffness of the PV module frame. This reduces the risk of overly or underly conservative test results. This load is cycled on and off 3 to 7 times per minute for 1,000 cycles. However, testing sponsored by GameChange Solar and performed by RETC shows that the IEC 62782 standard is insufficient.

Figure 4 shows an example purlin design, referred to in this report as Purlin Design A, after testing in strict conformance to IEC 62782. These purlins are Grade 80, 21-gauge steel, meeting the requirements of ASTM A653. The purlins supported the PV module using bolts at the 400 mm mounting hole locations in the module frame. There is no reinforcement between the purlin and the supporting torque tube. As shown in Figure 4, no cracks were visible after the IEC test; therefore, crack propagation due to fatigue loading was not flagged as a concern.

Purlins of the same design, Purlin Design A, were tested using the same equipment and loading frequency as IEC 62782 but with a higher cycle count to better align with the cycle count established in the CPP study. After only 2,000 cycles at 625 Pa, crack propagations were observed at multiple locations in the purlin, as shown in Figure 5. This cycle count is less than the total cycle count that is expected during a hurricane per the CPP analysis.

It is important to note that the purlins in these tests were not the only source of failure. During the testing, other samples shown in Figure 6 exhibited cracking of the aluminum module frame under cyclical loading. As such, it's critical to analyze the full assembly of module, hardware, and purlin to identify potential failures.

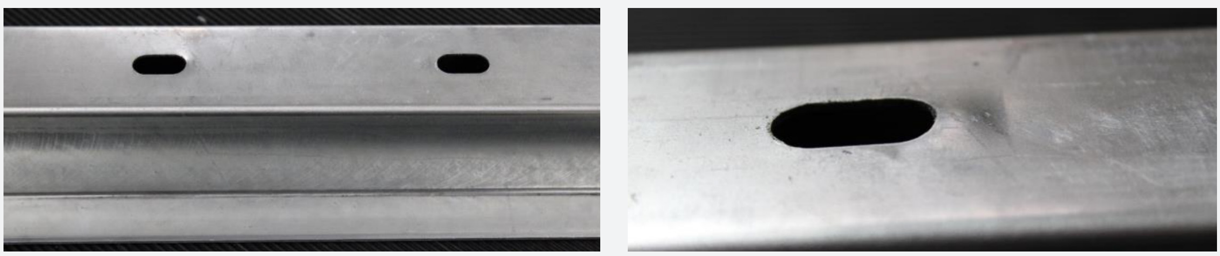


FIGURE 4:
Purlin Design A After IEC 62782 Testing

In summary, the purlins tested per IEC 62782 showed no signs of failure, but those tested under simulated hurricane loading showed obvious signs of crack propagation and structural failure. Thus, IEC 62782 is not an appropriate means to determine the fatigue capacity of purlin systems installed in hurricane-prone locations, and fatigue failure could result in on-site damage.

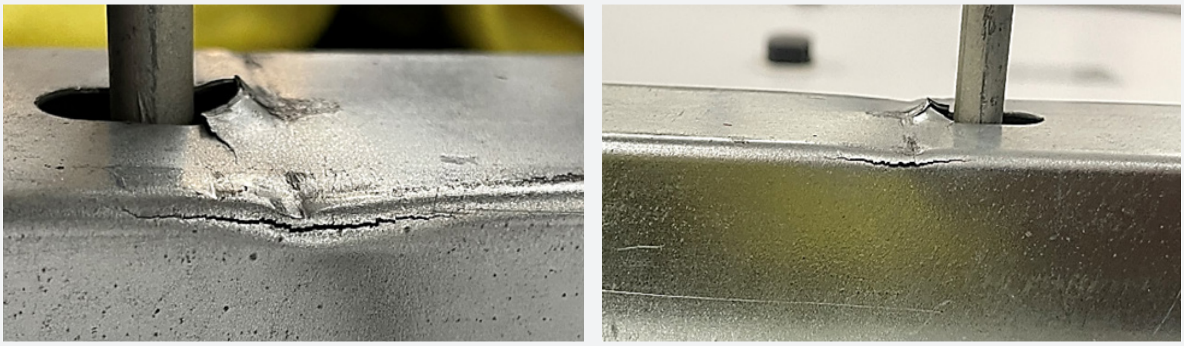


FIGURE 5:

Purlin After Enhanced Cyclical Testing to Replicate Hurricane Loading

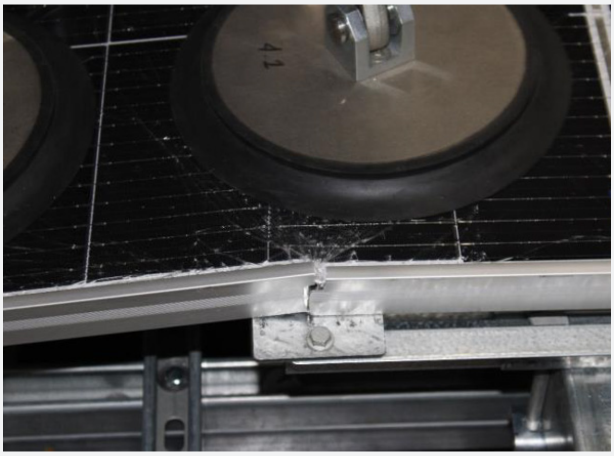


FIGURE 6:

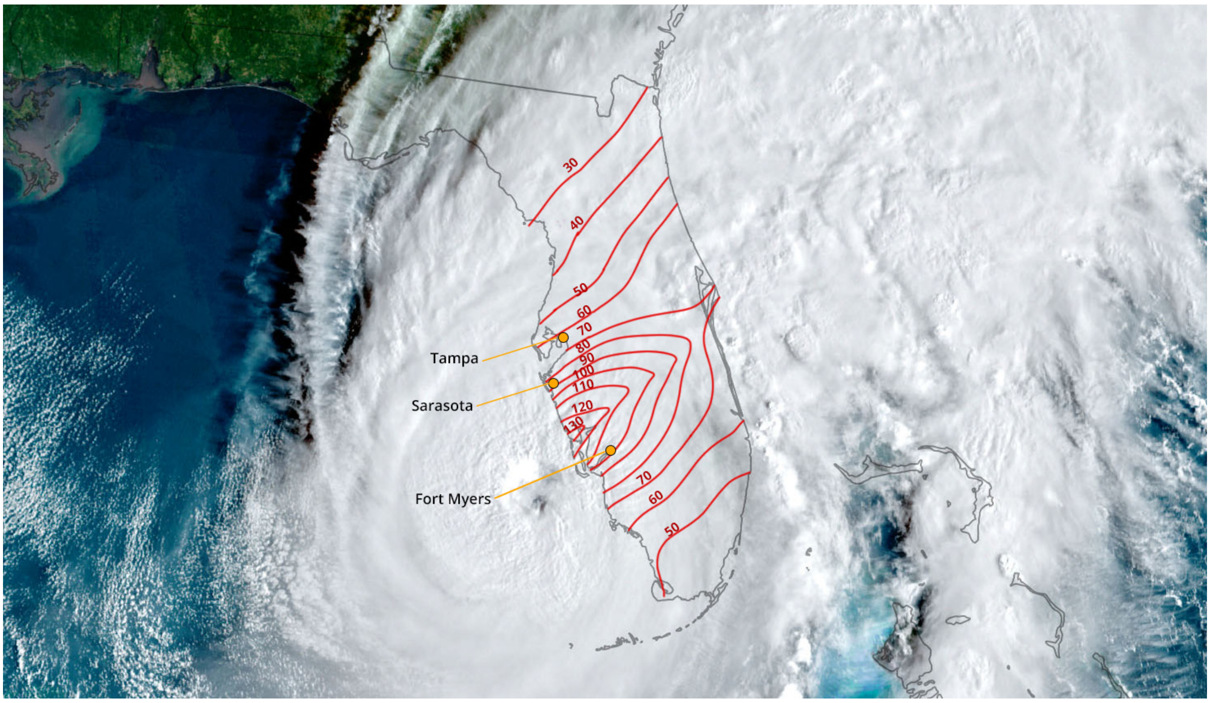
Purlin and Module Assembly after Cyclical Testing, Showing Failure of the Module Aluminum Frame

2.2 Fatigue Equations in Design Standards

Various standards exist throughout the world to address the design of cold-formed steel parts, which typically cover the purlins that connect the PV module to the torque tube. In the U.S., the applicable standard is S100, published by the American Iron and Steel Institute (AISI). Fatigue loading of cold-formed steel parts is addressed in section M of the 2016 edition of this standard. The expectation is that the purlin can be idealized as a cantilevered beam extending from a fixed connection with the torque tube to calculate stresses in the purlin to compare to a maximum design stress range calculated in accordance with the tables and equations in the standard.

Per Table M1-1 of AISI S100, the purlins qualify as Stress Category 1, which applies to "As received base metal and components with as rolled surfaces, including sheared edges and cold-formed corners." From Equation M3-1 of S100, the theoretical Design Stress Range, i.e. the stress of each cycle that would be required to cause failure for a component enduring 8,000 cycles is 158 ksi. This accounts for a component meeting the requirements of Stress Category 1 and a cycle count in line with CPP's simulated hurricane loading, The 158 ksi theoretical stress far exceeds the maximum stress in the purlins calculated from the static analysis of the design level wind gust. In other words, the AISI S100 calculation concludes that the part would fail in the first cycle and never survive a repetitive fatigue style load. As such this calculation is overly conservative when applied to single-axis tracker purlin design.

One clear reason that AISI S100 is highlighted as not accurate for this application is that it primarily governs parts of a single material, as opposed to the complex assembly of steel, aluminum, glass, and others that make up a purlin and module connection. While AISI S100 can accurately model cyclical loading of a purely steel part, like a torque tube, it is not applicable to module and purlin testing and design.



Map Showing Wind Speeds Experienced During Hurricane Ian in Florida, 2022. (*Wind speed contours, in mph, per Applied Research Associates Inc. (ARA) estimates. Satellite image of Hurricane Ian: source NASA Earth Observatory.)*

2.3 Finite Element Modeling

While 3D Finite Element Analysis (FEA) is a very useful design tool for structural and mechanical engineers alike, the analysis is designed to identify ductile-type failures, such as the yielding of a steel structural component. Current software solutions, including Ansys, do not show adequate correlation to test data when identifying brittle failure modes.

Furthermore, the connection in question is particularly difficult to model using FEA as the modeler must account for the residual stresses from cold forming the steel, galvanizing the steel, and the preload in the bolt (the force applied to the joint members by torquing the bolts).

As an example, Figure 7 shows the von Mises stresses of an FEA model of the same Purlin Design A under loading that resulted in failure described in section 2.1 above. This includes a downward pressure of 625 Pa on the module, corresponding to the load on interior modules during an 86 mph wind event. The analysis was run using the engineering software Solidworks. As demontrated, the maximum stresses are on the order of 50 ksi, well below the 80 ksi yield stress of the material.

The FEA model would not predict the failure of the part due to fatigue. However, as shown in the second mechanical test of Purlin Design A, the part does not have enough capacity to survive the expected 8,000 cycles. Thus, this method of analysis does not accurately highlight the risk of purlin failure under fatigue loading during a hurricane.

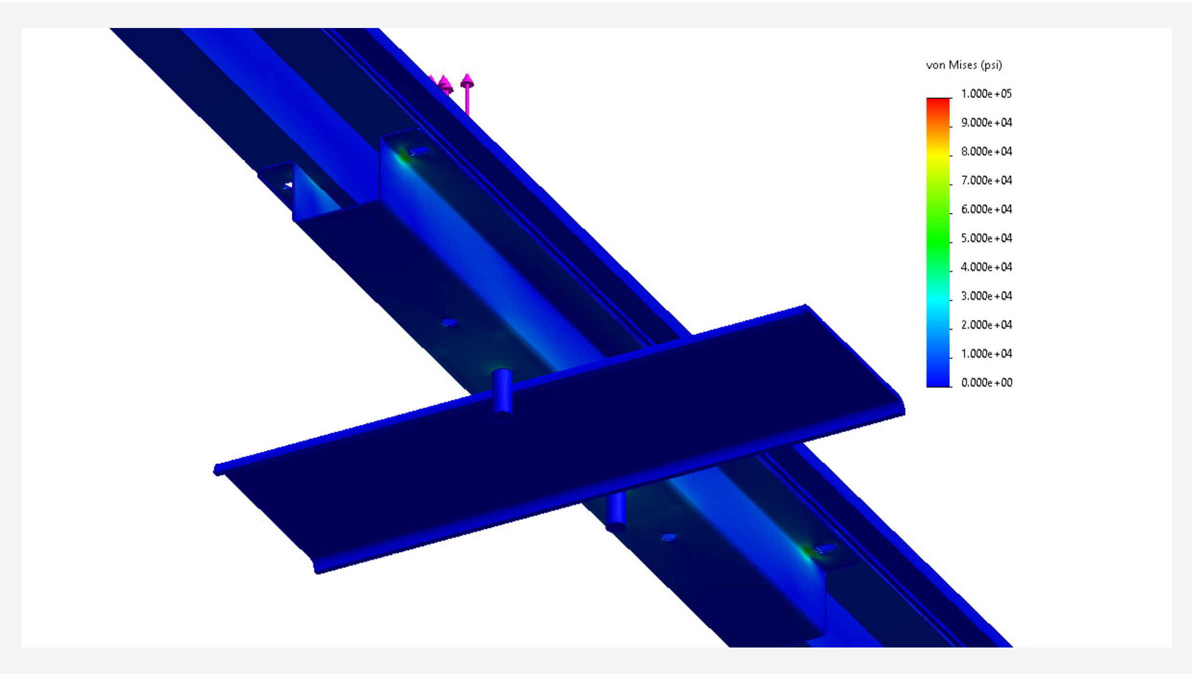


FIGURE 7:

Purlin Internal Stresses per FEA

3.0 Proposed Test Programs

3.1 Fatigue Loading Approach

The proposed design methodology relies heavily on full-scale testing, as existing analytical means are inaccurate, as described above. The proposed test procedure covers a service level, fatigue load sequence. It should be noted that the strength level static loading procedure per section 4.16 of IEC 61215 should still be followed in addition to this proposed procedure.

Ideally, this procedure is performed on a test rig large enough to hold two modules, so that the purlin between those two modules is accurately loaded according to real-world conditions. If only one module is used, each purlin would only experience loading corresponding to one connected module, not representing the majority of purlins, which are connected to two modules. If the test rig is only large enough for a single module, the pressure on the module shall be doubled to match the loading conditions of a purlin shared between two modules.

Five rounds of dynamic mechanical load (DML) tests are performed. Each round of DML has a set cycle count with pressures scaled to the expected on-site pressure. Three to seven cycles are applied per minute, as the current IEC 62782 standard dictates. Each DML cycle consists of one load pulling on the front of the module glass then a return to neutral position, thus simulating an uplift wind gust on the rear side of the module. Due to the cyclonic nature of hurricanes, wind direction may change throughout the event, inducing loading on either the front, back, or both sides of the module. Uplift loading is used as the most conservative loading scenario.

The cycle counts and base pressures derived from the CPP analysis described in Section 3.1 are shown in Figure 8. These cycle counts and pressures come from consolidating the wide range of CPP data into just three load levels and cycle counts, allowing for easier programming and testing of the DML machines. Each cycle range is increased by a factor of 1.2 to account for other wind loading, beyond just a single the simulated hurricane, the system will receive during its design life. For example, the CPP analysis in Figure 3 shows over 6,000 cycles at pressures at or below 600 Pa. These are consolidated into the two rounds of 600 Pa at 4,000 cycles each.

Project-specific pressures can be scaled off these base pressures by taking the squared ratio of the project design wind speed over the CPP report wind speed of 110 mph. For example, a project with a design wind speed of 120 mph would use 714 Pa for the first round of testing (714 Pa = 600 Pa * [120 mph/110 mph]^2).

Pressure (Pa)		
Interior	Perimeter	Cycle Count
600	1200	4000
1000	2000	1000
1400	2800	100
1000	2000	1000
600	1200	4000

FIGURE 8:

DML Cycle Counts and Pressures based on CPP Analysis at 110 mph Wind Speed

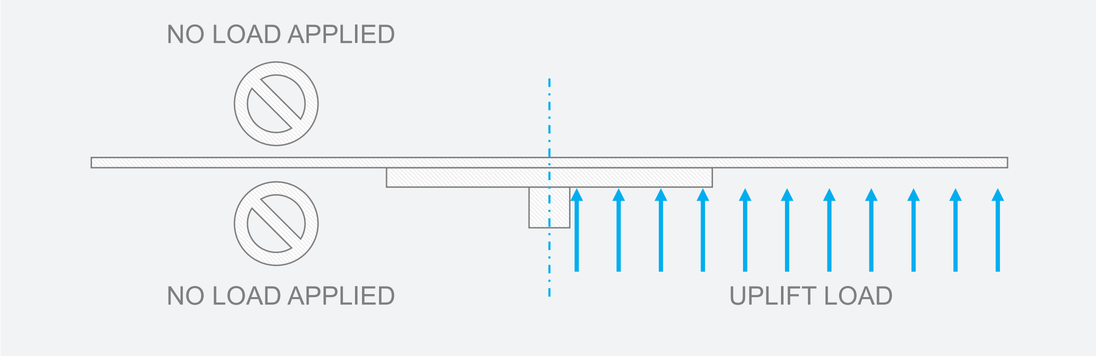


FIGURE 9:

Unbalanced Dynamic Mechanical Load

The load is only applied to one side of the module (see Figure 9), thus mimicking the unbalanced nature of wind loading observed during wind tunnel testing and on-site loading (referenced in Figure 1). All other test criteria for the DML are to match IEC 62782.

At the end of the test sequence, the parts are inspected for any signs of damage. Failure criteria shall be aligned with UL 2703 Section 21.6, wherein "there shall be no visual permanent deformation that may adversely affect system safety or compliance." Minor plastic deformations or "dimples" of cold-formed steel components are acceptable, as they do not adversely affect safety or compliance. Cracking or micro fissures visible to the naked eye (greater than 1 mm in length) and propagating through the entire thickness of the purlin shall be considered adversely affecting compliance and thus constitute a failure.

3.2 Example Test Results

GameChange Solar sponsored testing was performed at RETC per the above test procedure. The testing was conducted for a site with a design wind speed of 107 mph in hurricane-prone Florida. The full test report is available on request, and a summary of the results is as follows.

To determine the expected fatigue loading for this site, the 300-year return interval design wind speed of 107 mph was converted to a 50-year return interval service level wind speed of 90 mph. This conversion is intended to more accurately match the tested wind speed to the project's design life, which is 35 years, as described in AISI S100 Chapter M. The approach laid out in Section 3.1 determined the test pressures by taking the squared ratio of the 110 mph wind speed from the CPP report to the 90 mph test wind speed (see Figure 10).

Pressure (Pa)		
Interior	**Perimeter**	**Cycle Count**
400	690	4000
670	1160	1000
800	1380	100
670	1160	1000
400	690	4000

FIGURE 10:

DML Cycle Counts and Pressures for a Test at 90 mph Wind Speed

The purlin design used in the example test has an improved connection between the purlin and torque tube compared to Purlin Design A and is referred to herein as Purlin Design B. Purlin Design B is the standard preassembled purlin design provided by GameChange Solar.

These purlins are Grade 80, 18-gauge steel, meeting the requirements of ASTM A653. The purlins supported the PV module using bolts at the 400 mm mounting hole locations in the module frame.

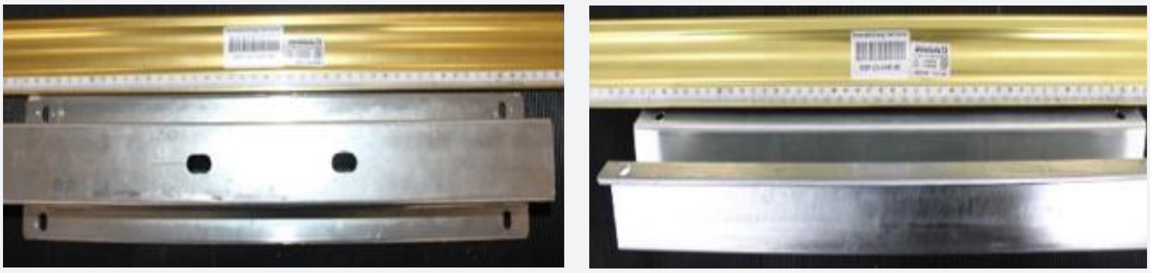


FIGURE 11:

Purlin Design B after Fatigue Load Testing

Figure 11 shows the condition of a purlin after the service level, fatigue load paths described above. The post-test inspection revealed no deformation and no cracks present. Therefore, the behavior of the purlin is expected to remain ductile, and fatigue failure is not expected even during a hurricane wind event.

By mandating the test approach described in section 3.1, a project owner, financier, and design engineer can be confident that the proposed hardware configuration has sufficient capacity to resist the low cycle fatigue loads associated with a hurricane or other major storm.

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www.gamechangesolar.com/contact

Headquarters
230 East Avenue, Suite 100
Norwalk, CT 06855
Phone: +1 (203) 769-3900
Email: outreach@gamechangesolar.com

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