Strength Comparison of Flat Roof Solar Panel Mounting Systems

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Abstract *— The trend of installing solar panels in residential buildings has been primarily driven by efforts to lower energy costs, signifying a notable shift towards embracing solar energy solutions. The market offers a wide range of structural mounting systems for solar panels. This paper concentrated on analyzed the most utilized mounting system for flat roofs and determining the strength capacity usage in a 160-mph wind speed hurricane event and compare the different installation patterns found in the existing installed mount systems in residential building around the island of Puerto Rico. The study underscores the overall reliability of the structural integrity while acknowledging deficiencies in one of the mounting systems employing the N=L installation pattern.*

Key Terms *— Aluminum, Solar Mount Installation, Solar Panel, Structural Analysis, Wind Load.*

INTRODUCTION

In Puerto Rico, the installation of photovoltaic solar systems in residential and commercial buildings has increased significantly in recent years. This growth is largely due to high energy costs associated with conventional electric grid services, which have led to a greater demand for solar energy solutions in both sectors. In the wake of hurricanes Irma (2017), Maria (2017), and Fiona (2022), the fragility of the existing electric grid infrastructure has become glaringly apparent. These natural disasters have led to substantial damage and prolonged periods of power restoration, emphasizing the need for more resilient energy sources.

The market is replete with numerous companies offering an assortment of electrical components and structural mounting frameworks for building integration. Among these, various structural frame and mounting system assemblies are constructed by different manufacturers to support solar panels. While there are several types of structures, such as ground-based and pitched roof frames, this paper will specifically concentrate on flat roof mounting system.

Mounting systems are commonly fabricated from materials like steel or aluminum, utilizing either standard section types or customized designs. This investigation has undertaken exploration and photographic documentation of diverse mounting systems in Puerto Rico to analyze their diverse installation patterns.

For this consideration, a comprehensive structural analysis has been conducted on three distinct flat roof mounting systems, named in this paper as Mounting System B, Mounting System U, and Mounting System H. This analysis leverages an existing photovoltaic project system to facilitate a like-to-like comparison among these design configurations.

The structural analysis was restricted to the Allowable Strength Design (ASD) method, focusing on evaluating the structural reliability of mounting systems under two different support installation patterns to determine their strength capacity against wind loads.

BACKGROUND

This project features an existing residential photovoltaic (PV) system as a reference for structural analysis. The system has a 5.49 kWAC / 6.75 kWDC solar photovoltaic grid-tied arrangement. The configuration includes 15 panel modules, specifically Boviet Solar BVM6612M-450S-H-HC-BF-DG (450W) units. These are organized into five distinct row-groups on the roof: two groups with four panels each, two groups with two panels each, and one group with three panels, distributed across various sections of the residential building.

The residential building, situated in Urb. Monte Alvernia, Guaynabo, features a single-level roof where the photovoltaic system is installed, 12 feet above ground level. The projected dimensions of the inclined PV panels for analysis purposes are 7 feet in length and 3.43 feet in width each solar panel. A 3D scanning picture is shown in Figure 1.

Figure 1
3D Scanning of Residential Building (Source: Verdifica PSC)

Commercially available flat roof mounts for PV systems are typically composed of three primary structural elements: the support columns (from now referred to as “legs”), the longitudinal support (from now referred to as “rail”), and the securing clamps. Figure 2 shows a side view of Mounting System B used in the referenced PV project.

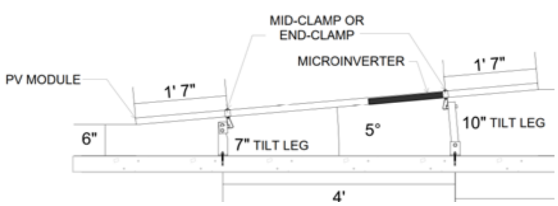

Figure 2
Side View of Mounting System B with Dimensions

Figure 3
Short Leg and Rail of Mounting System B

For this project, the existing structural mount installed at the site is designated as Mounting System B. A detailed image of the rail component is provided in Figure 3.

Mounting Systems

Manufacturers offer a range of structural components, varying from standard to heavy-duty specifications, to support solar panels on flat-roofed structures. However, within the solar energy industry, only a select few of these component types have gained widespread adoption due to factors like the three mounting systems selected for analysis.

In this context, three specific mounting systems have emerged as the most employed in flat roof installations across the island. These mounts are not only popular in terms of choice but also readily available in local stores, ensuring ease of access for both residential and commercial solar energy projects. These mounts, identified previously for the purpose of this research study as Mount System B, Mount System U, and Mount System H. Letters designation for the mounting systems refer to the section shape of the rail. Figures 4 to Figure 5 show an example of Mounting System U and Figure 6 show an example for Mounting System H.

Figure 4
Long Leg of Mounting System U

Figure 5
Mounting System U Rail Shape

Figure 6
Long Leg and Rail of Mounting System H

Given Puerto Rico's geographic position at approximately 18° latitude, the optimal orientation and angle for solar panels is achieved by facing the photovoltaic cell surface southward, inclined at an angle of 18° from the flat roof baseline. However, the default inclination for the mounting system selected in this project is 5° for Mounting System B and H and 10° default inclination for Mounting System U.

Leg Installation Patterns

The specific mount design utilized in the referenced project incorporates a unique leg arrangement, with five legs supporting four panels. This configuration is denoted as N+1=L, where N represents the number of solar panels and L the number of legs in the mount assembly. This is contrasted with a configuration where the number of legs equals the number of panels, expressed as N = L. An example in Figure 7 shows a N=L installation pattern and Figure 8 shows a N+1=L installation pattern.

Figure 7
Mount System U with N=L Installation Pattern

Across Puerto Rico, a diverse array of design configurations and structural assemblies for solar panel installations on residential buildings has been implemented. These installations frequently employ custom steel frames in conjunction with standardized components provided by manufacturers, optimizing both the installation process and structural integrity. In some cases, entirely custom steel frames are also utilized.

Figure 8
Mounting System H with N+1=L Installation Pattern

Other installation patterns like N-1=L were not evaluated in this analysis despite this installation can be found in residential buildings in Puerto Rico as illustrated in Figure 9.

Figure 9
Mount System with N-1=L (5 Solar Panels With 4 Legs)

METHODOLOGY

A thorough structural analysis was conducted to assess the capacities of various elements, using the PV system mentioned as a reference. This analysis facilitates a comparative evaluation of other mount systems that have been prominently utilized in recent years. The structural load analysis follows the guidelines of ASCE Standard 7-16, titled "Minimum Design Loads and Associated Criteria for Buildings and Other Structures" [1]. The specific structural mounting system in question is categorized under Section 29.4.3 of the ASCE 7-16 standard, which addresses "Rooftop Solar Panels for Buildings of All Heights with Flat Roofs or Gable or Hip Roofs with Slopes Less Than 7 degrees." However, the solar panels used in this project exceed the maximum panel length chord (length of solar panel) of 6.7 feet as stipulated in the section. Consequently, the procedure outlined in Section 29.4.3 for calculating applied loads is not applicable. The relevant section for this analysis is 29.4.1, titled "Rooftop Structure and Equipment for Buildings," falling under Chapter 29.4 "Design Wind Loads: Other Structures." This section provides the appropriate criteria for the structural analysis.

Focusing on Mounting System B, it features a leg configuration described as N+1=L. In this instance, with four solar panels, the mount contains five legs. For a detailed and precise analysis, the frame was modelled in STAAD.Pro structural software. This tool aided in determining the reaction forces for each structural element.

Given that the element of the structure is made of aluminum of non-typical section shape, the capacity calculations were based on the Aluminum Design Manual 2020 [2]. Additionally, any steel components were analyzed in accordance with the Steel Construction Manual, 14th Edition (AISC) [3].

Wind Load Parameters

In the requirement of wind load parameters, the structure falls under Risk Category II: "All Buildings and Other Structures," as per the ASCE 7-16. Utilizing Appendix P Microzone Wind Maps from Puerto Rico Code 2018 [4], which consider the location's topography without the necessity of calculating the topographic factor, the basic wind speed was established at 158 mph. For a more conservative analysis approach, this has been rounded up to 160 mph. Parameters are listed as follows:

- Wind Speed: V = 160 mph
- Wind directionality Factor: K_d = 0.95 (Rooftop)
- Exposure: B
- Topographic Factor: K_{zt} = 1
- Ground Elevation Factor: K_e = 1
- Gust Effect Factor: G = 0.85
- Average elevation: z = 12 ft
- Velocity Pressure Exposure Coefficient for Exposure: K_z = 0.57

Velocity pressure was calculated with (1) of Section 26.10-1 of ASCE 7-16:

$$q_z = 0.00256 K_z K_{zt} K_s K_d K_e V^2 \qquad (1)$$

The velocity pressure calculated is q_z = 35.49 psf.

Design Wind Loads

The load analysis for rooftop structures and equipment in this study follows Section 29.4.1 Rooftop Structures and Equipment for Buildings, focusing on calculating lateral and vertical forces. These forces are determined using Section 29.4-1 of ASCE 7-16 [1]:

$$F = q_z G C A_f \qquad (2)$$

where:

q_z = velocity pressure evaluated at height *z*
G = gust effect factor
C_f = force coefficient
A_f = projected area normal to the wind

Equation (2) is derived in resultant lateral force, F_h, illustrated in (3) and vertical uplift force, F_v, illustrated in (4), as follows:

$$F_h = q_h(GC_r)A_f \qquad (3)$$

$$F_v = q_h(GC_r)A_r \qquad (4)$$

where:

q_h = velocity pressure evaluated at the mean roof height of the building
A_f = vertical projected area of the rooftop structure or equipment on a plane normal to the direction of wind
A_r = horizontal projected area of rooftop structure or equipment
(GC_r) = product of gust effect factor and force coefficient specified in Section 29.4.1 of ASCE 7-16 for the resultant lateral force and vertical uplift force.

The product of gust effect factor (G) and force coefficients (C_r) are interpolated from values specified in Section 29.4.1 of ASCE 7-16. The value of (GC_r) is influenced by the building's lateral and roof areas for both horizontal and vertical plane axis projections. These projections are based on the dimensions of the four solar panels, which have a combined width of 13.82 ft (including a 3/8 inch clear spacing) and a length of 7 ft, resulting in a total area of 96.34 ft^2. The mount is designed with a 5° slope inclination, leading to calculated vertical and horizontal projected areas of 9.22 ft^2 and 96.34 ft^2, respectively. For the 10° slope of Mounting System U, the calculated vertical and horizontal projected area is 16.86 ft^2 and 95.63 ft^2, respectively. For the solar panel mounts with a 5° and 10° inclination the calculated uplift wind pressure results with similar values rounded to 47.5 psf for both inclinations. The lateral and uplift resultant wind loads were distributed equally per projected area among the clamps and applied as a point load to each clamp.

Structural Software Modeling

STAAD.pro, software for structural analysis and design, was utilized to model the mounting system, facilitating the determination of reactions and results from the applied loads. This software employs the stiffness method for linear elements and the finite element method for plates. A linear static analysis was employed in the model. All dimensions and joint connections in the model follow the specifications provided in the manufacturer's cutsheets, with frame mount legs spacings derived from project drawings. The sectional properties of elements (rails and legs) are based on the manufacturer's datasheets. Any other properties that are not provided directly in the cutsheet are logically deductive using principles of mechanics of materials.

The current mounting system design includes a leg for each clamp that is attached to the solar panels, as depicted in Figure 10. This mount consists of two distinct frames, which are interconnected using the solar panel's anodized aluminum alloy frame. In the STAAD.Pro software, these components are represented using angles that match those found in the software's aluminum standard shapes database. Figure 11 provides an illustrative example of how this modeling was realized in STAAD.Pro.

Figure 10
Mounting System B Long Leg Aligned with Clamp

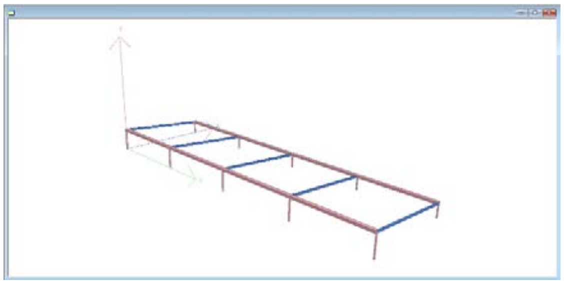

Figure 11
Render Model N+1=L

However, the structural elements of this mount assembly have unique shapes not included by the existing database in STAAD.Pro. As a result, their sectional properties are not available and must be manually entered into the software as external data.

According to the manufacturers cutsheet details for the three mounting systems, the aluminum alloy utilized is designated as 6005A-T61, with its material properties specified as follows:

- F_{ty} = tensile yield strength = 35 ksi
- F_{tu} = tensile ultimate strength = 38 ksi
- E = modulus of elasticity = 10,100 ksi

In the model, both lateral and uplift loads were uniformly distributed over each projected area and applied as point loads to the clamps, oriented along both vertical and horizontal axes. The scope of this structural analysis is exclusively on examining uplift wind loads in the worst-case scenario. This study is solely concentrated on Allowable Strength Design (ASD) method. This specific emphasis was chosen because all mounting systems manufacturers follow ASD method, but not all follow Load Resistance Factor Design (LRFD) method. Adopting ASD method as the standard analysis enables a consistent comparison between mounting systems from different manufacturers.

The design of the structure ensures that its allowable strength is equal to or surpasses the effects of the applied loads determined by the analysis. The ASD load analysis contains seven different load combinations. These mounting systems are particularly susceptible to high uplift wind loads and less to seismic loads. Of all the load combinations, only combinations 5, 6, and 7 include wind loads. For analyzing uplift wind load conditions, the most critical scenario for this structure is determined by load combination 7 (5), as follows:

$$0.6D+0.6W \tag{5}$$

where:

D = Dead load

W = Wind Load

Design Strength Capacities

The mounting systems discussed in this analysis are made from aluminum. This material shares several mechanical properties and behaviors with steel, though it differs in aspects such as weight, strength, and corrosion resistance. At this stage, the strength capacities of each element and component were meticulously calculated. The analysis of these strength capacities, including those of the elements and connections, was based on the guidelines provided in the Aluminum Design Manual 2020 [2], and complemented with the strength capacities specified in the manufacturer's cutsheets for Mounting System U.

The strength capacity of each element is indicated by the nominal strength, denoted as R_n, and is computed in accordance with the applicable provision of the manual. The manual outlines the requisite safety factor, Ω, for each structural component, enabling the calculation of the available strength determined as follows:

$$R_n / \Omega = \text{allowable strength} \tag{6}$$

Clamps attached the solar panels to the mount's rail. These fasteners' mechanical properties are described in ASTM A240/A240M [5]. Each fastener clamp has a diameter of 0.25 inches and is manufactured from 304 stainless steel. For determining the strength capacity of these bolts, the steel manual [3] was utilized, given that the aluminum manual [2] lacks specific guidelines for calculating the strength capacity of steel bolts. The shear and tension strengths of any other bolts were calculated in accordance with the provisions outlined in Section J3 of the steel manual [3].

Anchor Expansion Bolts

The drawings illustrate a standard application of expansion bolts to support the mounting system to the concrete floor. Typical anchoring detail the use of a Hilti KB3 3” X 3/8” stainless steel expansion bolt [6]. Employing a sealant is a typical and necessary practice in such installations. Due to the widespread industry use of this specific bolt type and the explicit naming of the manufacturer, the strength capacity was determined using the manufacturer's datasheet, following the conditions specified below:

- Roof slab material: Concrete
- Concrete strength: f'_c = 3000 psi (Assumed)
- Anchor embedment: 2.5 in
- Expansion bolt:
  - Tension strength: N_t = 1430 lb
  - Shear strength: V_n = 1570 lb

Legs Installation Pattern N=L

Moving forward in the scope of the analysis, a second model scenario, designated as N=L, was modeled for the three mounts. This model employs an arrangement where the rail is supported by a single leg per solar panel at the rails. The purpose of this arrangement is to compare the strength capacity usage of the three mounting systems discussed in the analysis. Specifically, this model places one leg centrally under each solar panel, reflecting a typical installation pattern used in the worst-case scenario in various residential buildings. Figure 12 illustrates a model in the software of the N=L installation pattern.

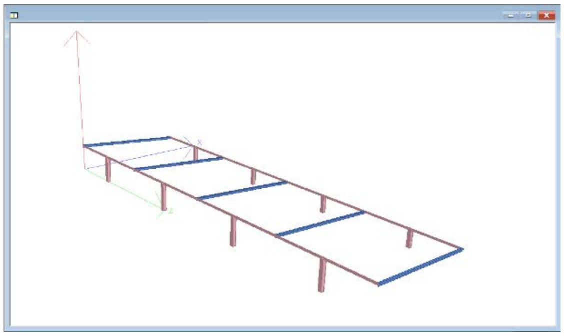

Figure 12
Render Model N = L

RESULTS AND DISCUSSION

The available strength for each structural component must meet the requirements of the chosen ASD load combination (5) expressed as the required strength, R_a, for uplift scenarios and the structural analysis shall satisfy:

$$R_a < R_n/\Omega \quad (7)$$

The subsequent table provides a detailed comparison of the reaction forces versus the available strength capacity of structural components in the three different mounting systems selected in this study. Table 1, 2 and 3 show the capacity usage for installation pattern N+1=L for the three mounting systems selected for analysis and Table 4, 5 and 6 shows the capacity usage for installation pattern N=L installation pattern.

Table 1
Mounting System B Strength Capacity Usage N+1=L

Element	Component	Ra/(Rn/Ω)
Clamp	Universal Fastener Clamp	35%
Long Leg	Bolts	26%
	Axial Tension	3%
	Slot Bearing Strength	14%
	U-Foot Tension	3%
	U-Foot Bearing Strength	11%
Short Leg	Axial Tension	5%
Anchor Bolt	Expansion Bolt	24%

Table 2
Mounting System U Strength Capacity Usage N+1=L

Element	Component	Ra/(Rn/Ω)
Clamp	Rail Mid Clamp	40%
	Rail End Clamp	33%
Long Leg	Assembled Tilt Back Leg	42%
Short Leg	Assembled Tilt Front Leg	41%
Anchor Bolt	Expansion Bolt	23%

Table 3
Mounting System H Strength Capacity Usage N+1=L

Element	Component	Ra/(Rn/Ω)
Clamp	Rail Clamp	35%
Legs	Bolt Leg	25%
	Slot Bearing Strength	11%
	Axial Tension	6%
Anchor Bolt	Expansion Bolt	23%

Table 4
Mounting System B Strength Capacity Usage N=L

Element	Component	Ra/(Rn/Ω)
Clamp	Universal Fastener Clamp	35%
Beam	Rail	63%
Long Leg	Bolts	27%
	Axial Tension	3%
	Slot Bearing Strength	20%
	U-Foot Tension	4%
	U-Foot Bearing Strength	13%
Short Leg	Axial Tension	5%
Anchor Bolt	Expansion Bolt	25%

Table 5
Mounting System U Strength Capacity Usage N=L

Element	Component	Ra/(Rn/Ω)
Clamp	Rail Mid Clamp	40%
	Rail End Clamp	33%
Beam	Rail	309%
Long Leg	Assembled Tilt Back Leg	47%
Short Leg	Assembled Tilt Front Leg	44%
Anchor Bolt	Expansion Bolt	25%

Table 6
Mounting System H Strength Capacity Usage N=L

Element	Component	Ra/(Rn/Ω)
Clamp	Rail Clamp	35%
Beam	Rail	46%
Legs	Bolt Leg	26%
	Slot Bearing Strength	12%
	Axial Tension	7%
Anchor Bolt	Expansion Bolt	24%

All mounting systems successfully met all manual provisions criteria $R_a < R_n/\Omega$ under the N+1=L installation pattern, evaluated at a wind speed of 160 mph. This assessment was conducted using ASCE 7-16 Section 29.4.1 [1], within the context of ASD method for uplift wind load cases. Notably, none of the mounting systems exceeded 50% of their strength capacity at this wind speed. Among them, Mounting System U exhibited the highest strength capacity usage, outpacing Mounting System B and H. The clamps were identified as the components with the highest strength capacity usage in Mounting Systems B and H. Conversely, for Mounting System U, the long leg was the component with the highest usage. It's also worth noting that the strength capacity usage of the expansion bolts remained consistent across all the mounting systems.

Mounting System B and H successfully met all manual provisions with the $R_a < R_n/\Omega$ strength criteria with the N=L installation pattern at 160 mph wind speed. However, Mounting System U exceeded its strength capacity for lateral-torsional buckling by 309%, making it the only frame unable to meet the strength criteria. For all three frames, the rails were the components with the highest strength capacity usage. The capacity usage of expansion bolts shows that the base reactions were slightly minimal differences between the two installation patterns.

CONCLUSION

In installations using the N+1=L leg pattern, all three mounting systems successfully met the strength criteria set forth in the aluminum manual [2], following the ASCE 7-16 load analysis from Section 29.4.1 for Rooftop Structure and Equipment for Buildings, specifically for wind speeds of 160 mph. In contrast, with the N=L pattern installation, Mounting System U failed to meet these strength criteria, whereas Mounting System B and H showed to meet strength criteria. Particularly, for installations using either N=L or N-1=L patterns, reinforcing the mounting systems by adding necessary legs near the clamps is a reliable solution. For systems with a small number of solar panels arrays, the N+1=L installation pattern is reliable for residential solar mounts. However, the participation and consulting of a structural engineer is crucial for any photovoltaic system installation to ensure compliance with contemporary engineering standards and codes.

With the increasing variety and demand for mounting systems, it is beneficial for future research to explore various options for commercial and industrial buildings under different scenario cases. While this current research does not focus on the maximum wind speed resistance of solar mounts, it is a highly recommended topic for future studies. Additionally, in the unfortunate event of another hurricane, it would be suggested to analyze an existing project that failed due to hurricane winds as a case study for further evaluation and improvement. This approach would provide valuable insights into enhancing the resilience of mounting systems against extreme weather conditions.

REFERENCES

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