Methodology for the Evaluation of Static Loads on Bifacial Modules Using a Test Bench

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Abstract

The increasing incidence of low-energy glass fracture in modern photovoltaic modules, particularly in large-area bifacial designs, poses a significant threat to long-term reliability. This trend is associated with recent design changes, including increased module dimensions and the adoption of thinner, heat-strengthened glass. To investigate the underlying structural behavior, this study presents an integrated approach combining experimental static load testing, using strategically placed strain gauges, with Finite Element Method (FEM) simulations. The results conclusively demonstrate that under a uniform load, the highest mechanical strains do not occur at the geometric center but are instead concentrated along the module's lateral longerons. This behavior is governed by the aluminum frame, which redistributes the load and transforms the glass-frame interface at the edges into the most structurally critical zones. This mechanism elucidates the field-observed fracture patterns that initiate at the module's edges and highlights the limitations of current certification protocols. The validated numerical model developed in this work serves as a predictive tool to support the design of more resilient modules and the revision of industry standards

Keywords: glass, strain gauges, stress, photovoltaic modules, solar.

1. Introduction

Photovoltaic solar energy has established itself as one of the leading renewable sources of electricity generation worldwide. In recent years, there has been significant growth in the adoption of photovoltaic systems, driven by technological advances in solar modules—such as the increase in module area and the reduction in glass thickness (VDMA, 2024). Although these innovations enhance energy efficiency, they may compromise the mechanical integrity of the modules, making them more susceptible to breakage, particularly in regions exposed to strong winds and adverse weather conditions (Markert et al., 2025; Silva et al., 2024).

Recent studies (Palmiotti et al., 2025; Silverman et al., 2024; Zuboy et al., 2024) suggest that, due to changes in the design and materials of photovoltaic modules, these components have also begun to function as structural elements, concentrating a significant portion of mechanical loads on the front glass. This has contributed to a rise in spontaneous glass fractures, even without extreme external events. The occurrence of such failures—without clear patterns regarding glass type or environmental conditions—has motivated the scientific community to investigate the root causes and propose solutions to improve the reliability of these devices. A recent study conducted at the Fotovoltaica-UFSC experimental plant found that approximately 50% of large-area bifacial modules exhibited glass failures after only nine months of operation despite the absence of severe weather events. Electron microscopy analysis revealed variations in glass thickness and defects at the frame-glass interface, such as voids or excess sealant material, which may act as stress concentrators and promote crack formation (Silva et al., 2024).

In both fixed systems and solar tracking structures, it is essential to evaluate the mechanical resistance of photovoltaic components under complex stresses, such as wind loads, temperature variations, and structural deformations. Therefore, the need for more robust testing methodologies that realistically simulate the stresses experienced by

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modules under field conditions becomes evident, ensuring their long-term durability and performance (Ma et al., 2023; Romer et al., 2024).

In this context, Palmiotti et al., 2025 emphasize that current testing methods are inadequate for predicting or mitigating the glass breakages observed in real-world installations. Thus, there is an urgent need to develop new testing methodologies capable of addressing more representative scenarios, including module installation on solar trackers and applying dynamic loads.

Therefore, this paper proposes the development of an experimental test bench for static load testing on large-area, bifacial glass-glass photovoltaic modules, aiming to identify the glass regions subjected to the highest stresses. To this end, strain gauges were positioned at strategic points to map the tensile and compressive strain fields. This approach represents a fundamental step towards more comprehensive investigations into load distribution and its relationship with crack formation, particularly for failures not associated with extreme weather events. The test bench was developed at the SENAI Institute for Innovation in Renewable Energies (ISI-ER) in Rio Grande do Norte, and the experimental data obtained were compared with numerical simulations using the Finite Element Method (FEM). The objective of this cross-validation is to enhance predictive models and support future improvements in certification and reliability protocols for photovoltaic modules.

2. Materials and methods

The experimental methodology of this study was based on the principles of the static mechanical load test, as described in the IEC 61215-2:2021 standard. Although this standard establishes a standardized procedure for photovoltaic module certification, in-field operating conditions are often more complex, involving dynamic and non-homogeneous loads arising from wind action, thermal variations, and mounting system influences (Beinert et al., 2023; Romer et al., 2024). Such conditions can induce localized stress concentrations that are not fully characterized by the standard test, thereby compromising the structural integrity and leading to failures such as glass cracking. Therefore, the present methodology focuses on the instrumentation of the module's glass to map this strain distribution under a controlled static load, serving as a fundamental investigation into the structural behavior that precedes failures observed in the field.

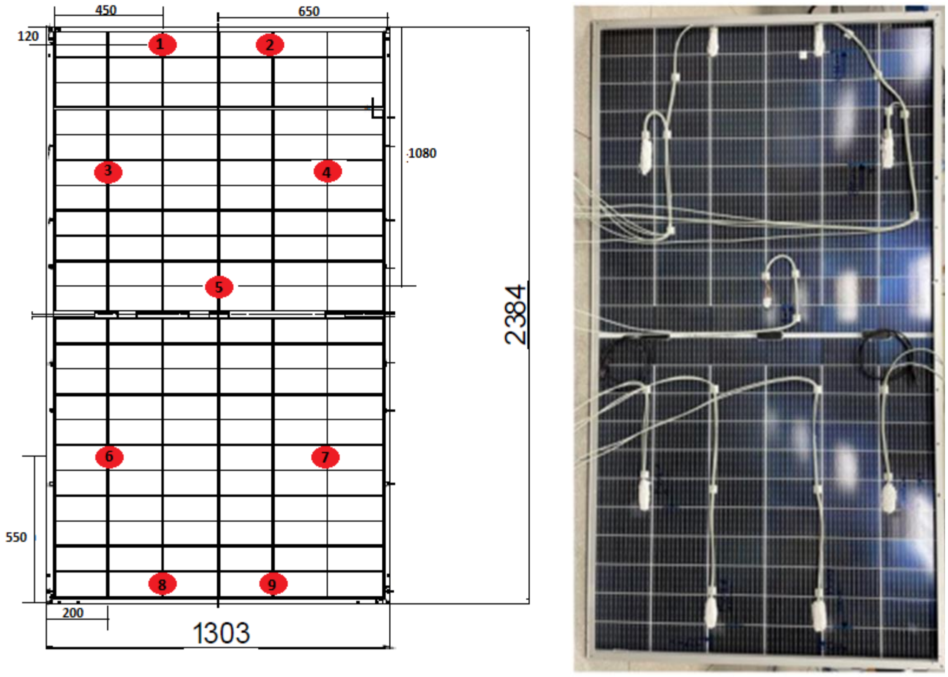
2.1. Photovoltaic Module

The photovoltaic module used in this study was a bifacial glass-on-glass module, model CS7N-645MB-AG, manufactured by Canadian Solar. The module measures 2384 x 1303 x 30 mm, with a laminate composed of two 2.0 mm thick glass sheets (heat strengthened glass) and a total mass of 34.5 kg.

2.2. Instrumentation with Strain Gauges

For strain mapping, triaxial strain gauge rosettes (model RY93-6/350 from HBM), with a nominal resistance of 350 Ω, were used. This configuration, featuring measurement grids oriented at 0°, 45°, and 90°, is ideal for the analysis of biaxial stress states where the principal directions are unknown. Furthermore, the selected model is self-temperature-compensated for materials with a thermal expansion coefficient similar to that of glass.

Nine rosettes were positioned (Figure 1a) and installed at strategic points on the rear surface of the glass (Figure 1b). This layout was designed to map the strain field distribution, enabling the identification of regions subjected to the highest tensile and compressive stresses, as well as critical zones of stress concentration.



(a) (b)

Figure 1: (a) Position of the strain guages and (b) Ilustration of the back of the bifacial module after instrumentarion

Prior to data acquisition, an instrumentation verification procedure was performed to ensure correct installation and functionality. This procedure included measuring the electrical resistance of each rosette grid, which was required to comply with the manufacturer's specification of 350 Ω ± 0.5% (Figure 2). Additionally, a continuity test was conducted to confirm the integrity of the electrical connections and the correct channel correspondence following the soldering process.

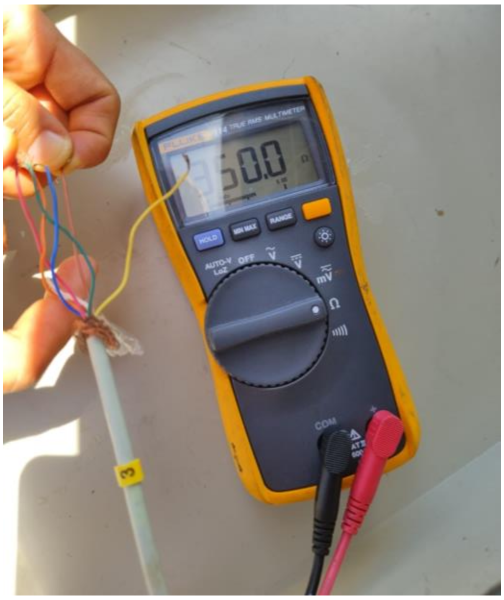


Figure 2: Checking the strain gauge electrical resistance reading

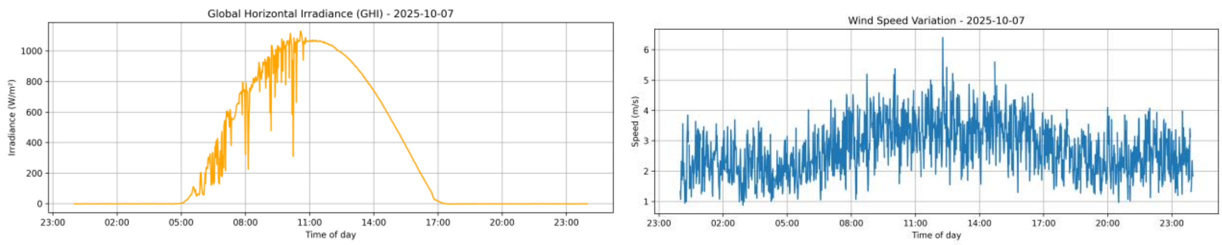
2.3. Data Acquisition System

Strain data acquisition was performed using an HBM system, comprising a QuantumX CX22W data logger and two QuantumX MX1615B bridge amplifier modules (Figure 3). The signals were sampled at a rate of 50 Hz, and the data were recorded in units of microstrain (με, or $\varepsilon \times 10^{-6}$), the standard unit for measuring low-magnitude strains. The HBM catmanAP software was used for test configuration, real-time monitoring, and data logging.

Figure 3: The HBM data acquisition system used in the test

2.4. Experimental Apparatus

The tests were conducted outdoors at the SENAI Institute for Innovation in Renewable Energy (ISI-ER) between 9:00 AM and 11:00 AM under clear sky conditions and low wind speeds (Figure 4). To mitigate the effects of thermal drift on the sensors, the strain gauges were balanced (zeroed) in the data acquisition system immediately before the start of each test.



(a) (b)

Figure 4: (a) Global Horizontal Irradiance (W/m²) and (b) Wind Speed Variation (m/s)

The static load was applied using 66 rectangular sand-filled molds, each with an average mass of 5.2 kg. This load was evenly distributed over the front surface of the module, resulting in a static pressure of 1084 Pa.

The test protocol followed these steps:

- Baseline: Data acquisition began with the module unloaded, recording signals for a period of 5 minutes to establish a stable baseline.
- Loading: The load was applied gradually, starting at the center of the module and progressing toward the ends to ensure uniformity.
- Load Monitoring: The module remained under full static load for a period of 1+1 hour (Figure 5). This extended measurement time, which exceeds the minimum of one hour recommended by the standard, was adopted to observe the material's response to deformation over time, including possible relaxation or creep phenomena.

The adopted methodological approach allows for the analysis of the impact of variables such as module design, mounting conditions, and structural interfaces on the mechanical load-bearing capacity. To this end, the experimental results are compared with a structural numerical simulation (FEM) developed in the Ansys software. This cross-validation has a dual objective: (1) to corroborate the laboratory-measured data and (2) to refine the numerical model so that it can be used as a reliable predictive tool. The synergy between the experiment and the simulation thus promotes a more comprehensive understanding of the photovoltaic module's structural response under critical load conditions.

(a) (b)

Figure 5: a) Side view of the static load test and (b) Illustration of the photovoltaic module under the effect of the distributed load

2.5. Computational Simulation with the Finite Element Method (FEM)

Assumptions and Simplifications

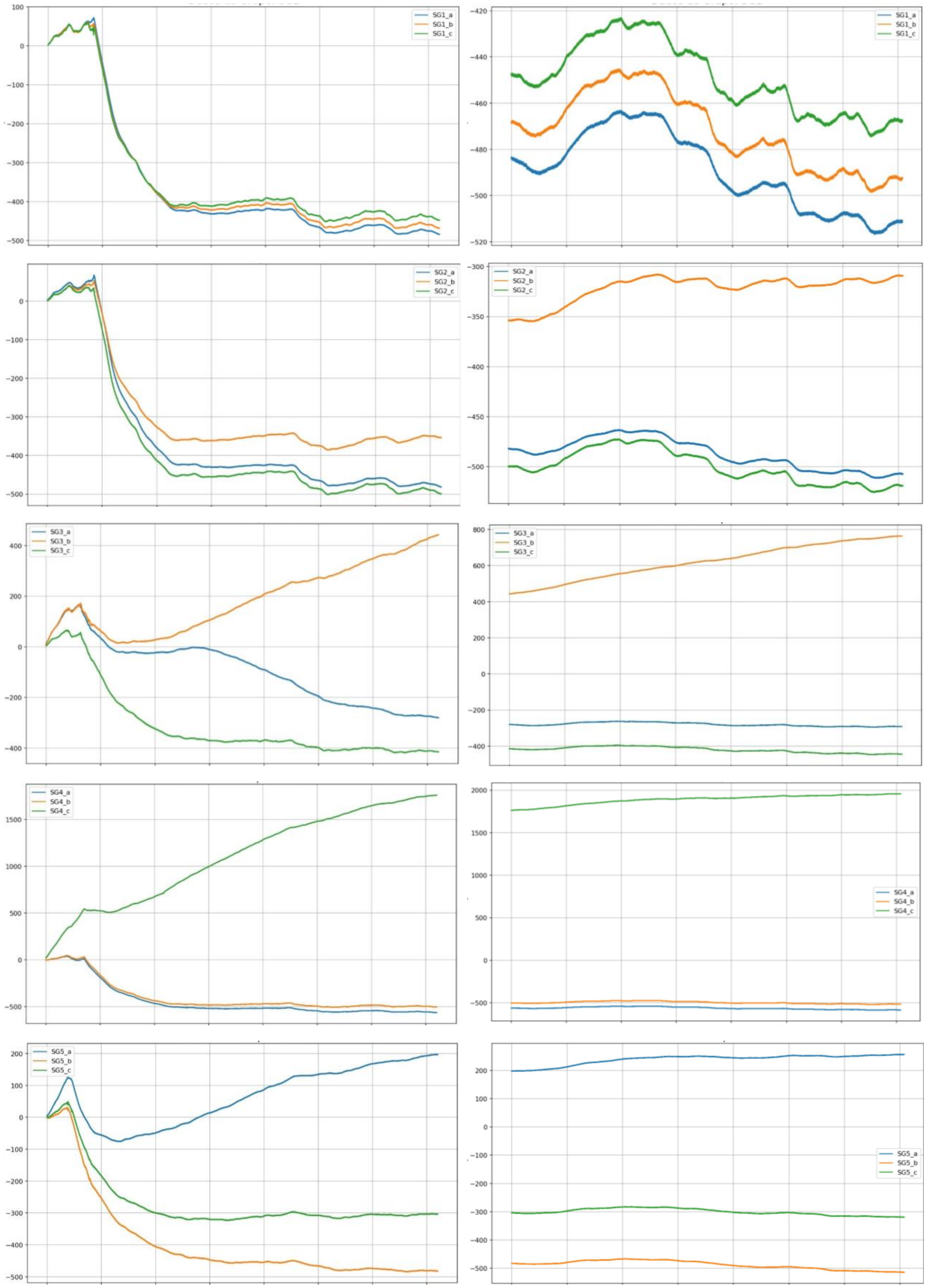
- Geometry: The aluminum frame's geometry was simplified based on the original profiles from the manufacturer's datasheet. The entire glass-silicon laminate was modeled as a single 5 mm thick soda-lime glass entity, assuming a perfect bond between layers and that the mechanical properties of the silicon and encapsulant layers are negligible compared to the glass.
- Mesh and Material Model: A tetrahedral mesh with a hybrid formulation was utilized, employing both linear and quadratic elements where appropriate. A linear elastic, isotropic, and temperature-dependent material model was implemented.
- Boundary Conditions: The mounting of the photovoltaic module was modeled by applying a fixed constraint to the typical contact areas on the bottom surface of the aluminum frame, located at 20% of the length from the lateral corners.
- Analysis Type: A steady-state, geometrically linear analysis with a linear strain approximation was used to solve the governing equations.
- Loads: A uniformly distributed surface load of 1085.4 Pa was imposed on the front surface, along with gravitational field forces, under ambient temperature conditions (25°C).
- Failure Criterion: The failure criterion for the materials was based on reaching the Ultimate Tensile Strength.

Material Properties

- Soda-Lime Glass: Density: 2465 kg/m³; Young's Modulus (E): 69.9 GPa; Poisson's Ratio (ν): 0.215; Yield Strength: 32.6 MPa; Ultimate Tensile Strength: 32.6 MPa
- Aluminum Frame Alloy: Density: 2770 kg/m³; Young's Modulus (E): 71 GPa; Poisson's Ratio (ν): 0.33; Yield Strength: 280 MPa; Ultimate Tensile Strength: 310 MPa

3. Results and Discussion

The strain distribution under static loading provides compelling evidence of the aluminum frame's crucial role in the module's overall structural rigidity. As detailed in Figure 6, the highest strains were not observed at the geometric center but were instead concentrated along the lateral longerons (strain gauges 3 and 4) near the mounting points – regions where displacement constraints induce higher strain gradients and, consequently, localized stress peaks. In contrast, the module's geometric center (strain gauge 5) showed significantly lower strain. This experimental finding is directly corroborated by the FEM simulation, which similarly predicted the highest principal stresses in these same edge regions. The synergy between the measured data and the numerical model reinforces the hypothesis that the aluminum frame—not the glass laminate alone—governs the mechanical response of the entire assembly.



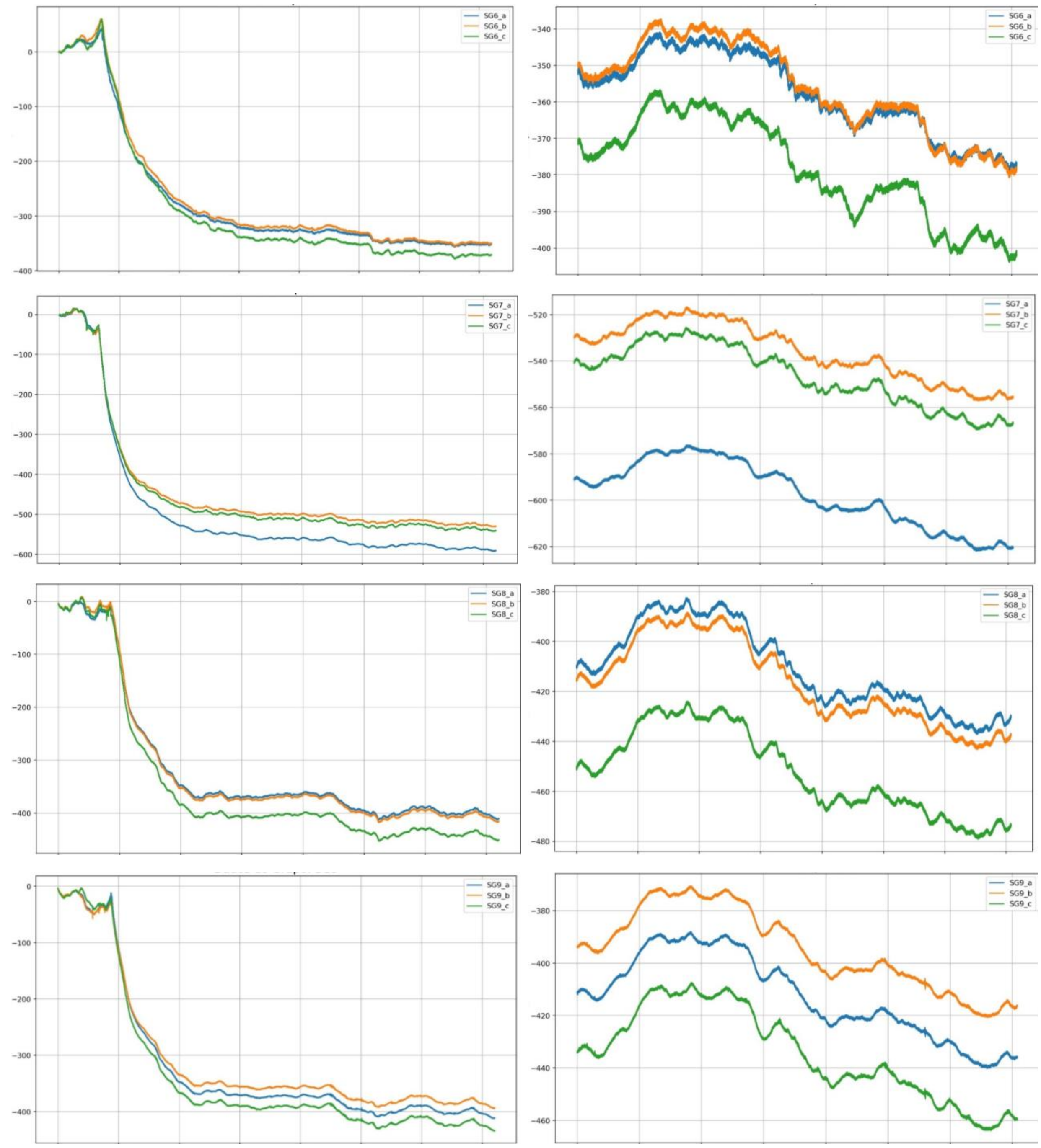


Figura 6: Mechanical deformations (με) measured by strain gauges; on the right side, the data scale is enlarged to observe the behavior of microdeformations when an additional hour of measurement was added to the test.

The numerical results, which focus on the behavior of the glass, offer a detailed view of the stress and displacement distribution. The analysis of the Maximum Principal Stress (Figure 7) reveals an excellent qualitative correlation with the measured data. The simulation predicts that the highest tensile stresses (~7.66 MPa) are concentrated on the lateral longerons of the glass, in direct agreement with the high microstrains experimentally recorded by the strain gauges positioned in these same regions. Both methods confirm that the module's center is a low-stress zone. This finding is of fundamental importance from the perspective of fracture mechanics, which postulates that regions of maximum stress are the preferential sites for microcrack nucleation. Thus, the simulation not only validates the experimental data but also identifies the glass's lateral longerons as the zones most susceptible to failure initiation under load, providing a crucial insight for the module's durability analysis.

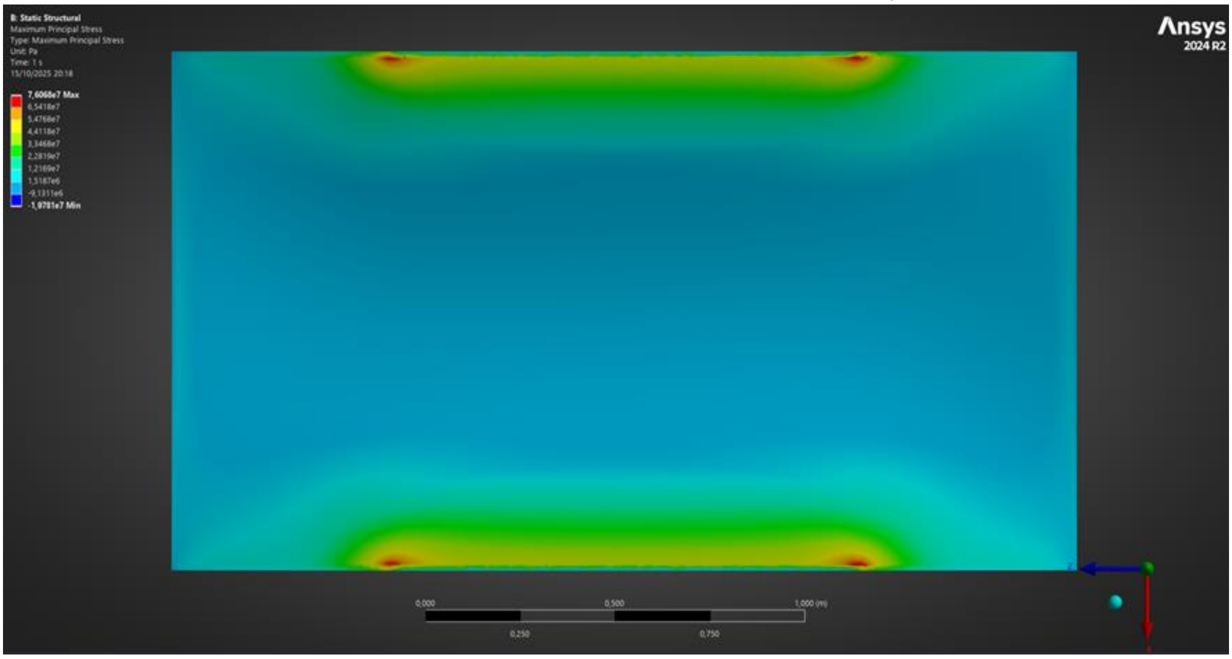


Figure 7: Distribution of maximum principal stress in the photovoltaic module

The fracture patterns (Figure 8) found in large-area bifacial modules by Azevedo et al. (2024) and Devir (2025) constitute the final physical validation for the numerical and experimental results. Low-energy cracks, resulting from cyclic environmental loads such as wind and thermal cycles, do not initiate randomly but rather at structurally critical locations (Silverman et al., 2024). The remarkable similarity between the crack nucleation sites and the zones of maximum principal stress predicted by the FEM simulation is conclusive. Both results demonstrate that the load redistribution imposed by the aluminum frame results in a stress concentration in the glass along the longerons, transforming these edges into the preferential sites for fracture initiation (Markert et al., 2025; Silva et al., 2024; Braga, et al., 2023).

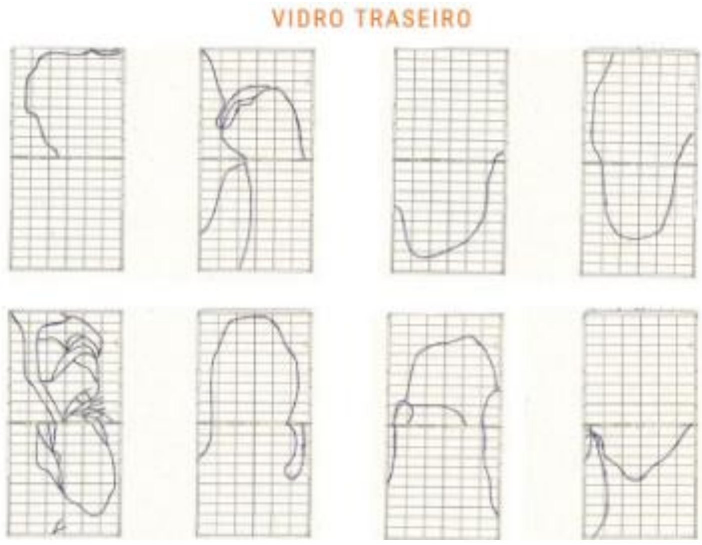


Figure 8: Pattern of cracks found in bifacial modules (Adapted from Azevedo et al., 2024)

Additionally, the Total Deformation plot (Figure 9) shows that the maximum physical displacement (4.78 mm) occurs at the geometric center of the panel. This result, while seemingly divergent at first, actually complements the analysis by distinguishing between displacement (deflection) and surface strain (stretching). While the center of the module exhibits the greatest displacement, the greatest material stretching occurs at the edges, due to the load transfer imposed by the frame's rigidity. This is in line with field crack patterns (Figure 8), which, as reported by Markert et al. (2025), single, extended cracks in the rear window, often oval in shape, are indicative of low-energy cracks under distributed loads.

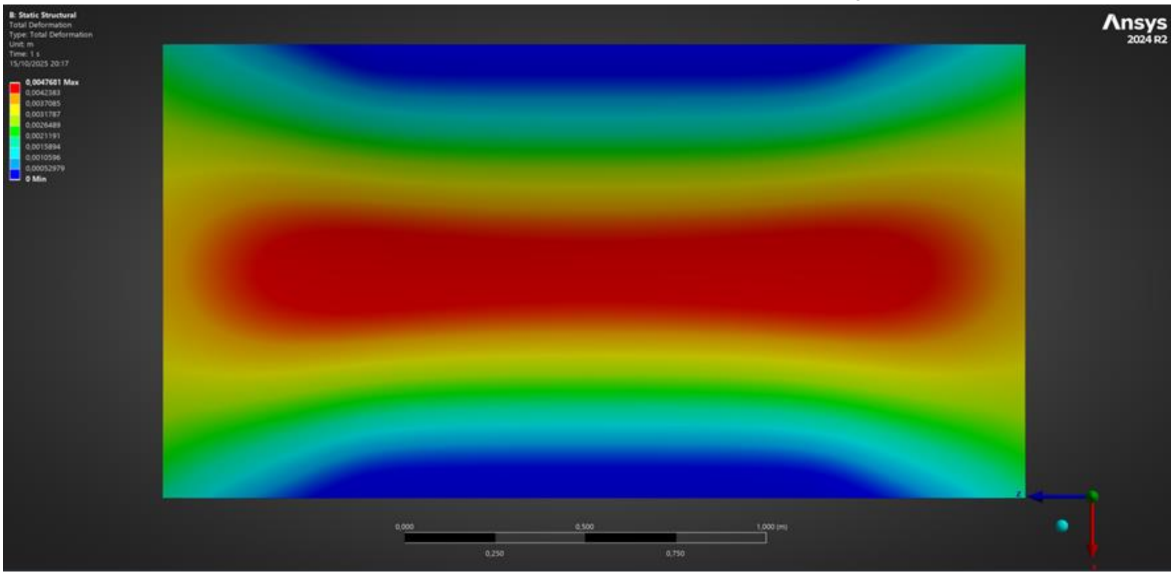


Figure 9: Distribution of total deformation in the photovoltaic module

However, the fundamental distinction must be reiterated: while the maximum physical displacement occurs at the geometric center, the greatest material stretching—and consequently, the highest tensile stress—is concentrated at the edges due to the load transfer imposed by the frame's rigidity. This mechanism provides a robust explanation for the continued increase in reported glass breakages in the field, as it identifies the longerons as the failure initiation point even under non-extreme operational loads that result in a centralized deflection pattern.

4. Conclusion

This study has demonstrated, through an integrated approach, that the structural response of large-area bifacial photovoltaic modules is governed by the interaction between the aluminum frame and the glass laminate. The investigation established a complete validation cycle: the experimental test quantified the highest strains on the lateral longerons; the Finite Element Method (FEM) simulation elucidated this phenomenon by mapping the stress concentration in these same regions; and the low-energy fracture patterns observed in the field (Azevedo et al., 2024; Devir, 2025; Markert et al., 2025) represent the physical consequence of this structural behavior.

It is evident that the module's deflection does not follow a simple plate model but rather a complex behavior where the load is redistributed to the edges. This mechanism provides a explanation for the increasing incidence of fractures in modern modules, which are larger, heavier, and utilize thinner, structurally weaker glass. This reinforces greater attention from the photovoltaic industry regarding module design and, mainly, the quality of materials and manufacturing processes used in the production line (RECT, 2024).

The contributions of this work are, therefore, the validation of a numerical model that can be used as a predictive tool and the provision of technical evidence to support the revision of certification protocols. Current standards like IEC 61215, while essential, do not adequately replicate this low-energy failure mode, making the development of more representative tests crucial. Ultimately, understanding this mechanism is fundamental for developing more resilient module designs and mounting systems, aiming to ensure the durability and bankability of future generations of photovoltaic power plants.

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