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# Structural Feasibility Assessment of an Adjustable-Height Photovoltaic Mounting System Using Conceptual Design and Finite Element Simulation

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**Abstract**

The performance of photovoltaic (PV) systems is influenced not only by module efficiency but also by the flexibility and structural reliability of mounting systems, particularly those allowing height and tilt adjustments to accommodate site-specific and seasonal variations. While automatic tracking systems can increase energy yield, their high cost and mechanical complexity limit widespread adoption, underscoring the need for simpler, more economical alternatives. This study evaluates the structural feasibility of an adjustable-height PV mounting system that improves installation flexibility while maintaining mechanical integrity. A conceptual engineering design approach was employed to develop a modular mounting structure with a mechanical height-adjustment mechanism. Structural performance was assessed using finite element–based static simulations under gravitational loading representative of a commercial bifacial PV module. The evaluation focused on Von Mises stress distribution, total deformation, and safety factor as indicators of mechanical reliability at the conceptual design stage. The results indicate that maximum Von Mises stress remains well below the assumed material yield strength, while total deformation is negligible relative to overall structural dimensions. The calculated safety factor confirms an adequate structural safety margin, indicating that integrating a height adjustment mechanism does not compromise structural stability. The proposed mounting system demonstrates sufficient structural feasibility and mechanical simplicity for early-stage development, offering a practical, adaptable solution for ground-mounted and rooftop PV installations.



## 1. Introduction

The advancement of photovoltaic (PV) systems depends not only on improvements in cell efficiency but also on the design of mounting systems that allow adjustments in tilt and height to optimize solar radiation capture under varying site-specific and seasonal conditions [1]. Adjustable mounting configurations have been shown to increase energy yield and investment efficiency compared to fixed systems [2], particularly for small- to medium-scale applications [3, 4]. Studies on tilt optimization incorporating direct, diffuse, and ground-reflected radiation further demonstrate that periodic adjustment of mounting geometry can significantly increase annual energy production, highlighting the importance of adaptable, location-responsive mounting designs [5]. However, most existing solutions rely either on fixed structures or fully automatic tracking systems, which are often costly and mechanically complex [6]. This creates a clear need for mounting systems with moderate mechanical flexibility, capable of manual or semi-manual adjustment of tilt and height [7], that balance improved energy performance with cost-effectiveness, especially in sites with pronounced solar path variability or limited infrastructure [8, 9].

Recent studies identify two primary approaches in solar mounting system design, tilt angle optimization and elevation adjustment, to enhance solar radiation capture and thermal performance. Review studies emphasize that mounting structures significantly influence overall photovoltaic efficiency and balance-of-system (BOS) costs [10]. Experimental and modelling research shows that periodic tilt adjustment [11], including in bifacial systems [12], can increase annual energy yield while reducing module temperature through optimized combinations of tilt and elevation [13, 14]. In response, modular mounting designs with manual or semi-manual adjustment mechanisms have gained increasing attention due to their ability to provide operational flexibility without the complexity of fully automatic tracking systems [15]. From a techno-economic perspective [16], several studies report that manually adjustable tilt mechanisms can achieve a lower levelized cost of electricity (LCOE) than automatic trackers at certain scales [17, 18]. At the same time, low-cost and open-source designs further demonstrate the practical feasibility of such systems despite necessary trade-offs between cost and seasonal performance gains [19, 20].

Recent research highlights the influence of installation height on the thermal performance and energy output of photovoltaic systems, where increasing the clearance between the module and the underlying surface can reduce cell temperature and improve efficiency [21], particularly in bifacial configurations affected by surface albedo [22, 23]. Vertical and bifacial mounting configurations have been reported to maintain competitive energy yields while offering additional benefits such as reduced soiling and improved land-use efficiency [24, 25]. Studies on ground coverage ratio further provide important guidance for array layout optimization across different mounting configurations [26, 27]. However, structural safety assessments emphasize that mounting systems with variable height and elevation must carefully account for mechanical stability and wind-induced loads [28, 29]. Overall, the literature confirms that tilt angle and installation height are key design parameters in PV mounting systems [30, 31], whether addressed through analytical methods, numerical simulations [32, 33], or software-based optimization [34, 35], and that bifacial systems in particular can achieve significant performance gains when height is properly configured in combination with high-albedo ground conditions [36, 37].

Although previous studies have demonstrated that tilt angle and mounting height significantly influence the energy yield and thermal behaviour of photovoltaic systems, particularly for bifacial configurations, most existing research primarily emphasizes energy performance, thermal optimization, algorithmic modelling, or fully automatic tracking systems [38]. Consequently, the structural behaviour of simple and low-cost adjustable PV mounting systems has received comparatively limited attention, with many studies relying on qualitative descriptions or simplified analytical methods. Finite element–based evaluations addressing stress distribution, deformation behaviour, and safety factor associated with adjustable-height mechanisms are rarely reported. To address this gap, the present study proposes a simple, modular, adjustable-height photovoltaic mounting system. It evaluates its structural feasibility through finite-element–based static analysis at the conceptual design stage. The novelty of this study lies in providing a dedicated finite element–based structural feasibility assessment of a modular adjustable-height PV mounting system, with explicit emphasis on stress distribution, total deformation, and safety factor under gravitational loading. Accordingly, this study aims to assess the mechanical feasibility of the proposed system based on Von Mises stress, deformation, and safety factor criteria, establishing a consistent framework for early-stage structural evaluation and supporting further design refinement in future work.

## 2. Materials and Methods

### *2.1. Research Framework and Scope*

This study adopts a conceptual engineering design approach to develop and evaluate an initial design of an adjustable-height PV mounting system. The framework is intended to assess early-stage technical feasibility and fundamental structural behaviour by employing numerical simulation as a virtual experiment representing outdoor operating conditions. Finite element–based structural analysis is used to examine the system's mechanical response under assumed loading conditions, allowing efficient evaluation without physical prototyping at this stage. This methodological approach provides a systematic and reliable foundation for subsequent design refinement, prototype development, and real-world implementation, as summarized in Figure 1.

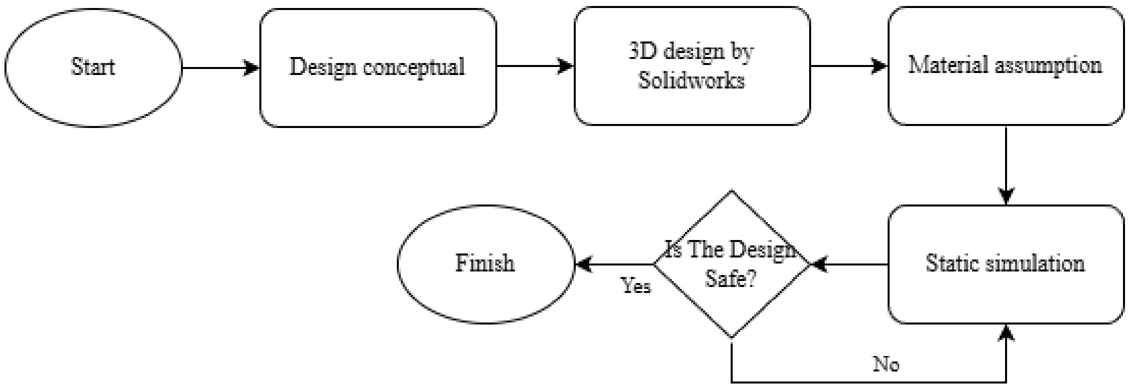


**Figure 1.** Research methodology flowchart.

**Table 1.** Conceptual design requirements and assumptions.

| Parameter | Description | Assumed Value | Justification |
|---|---|---|---|
| PV module type | Commercial crystalline silicon module | Bifacial module | Representative for small–medium PV |
| Module weight | Estimated module mass | 36 kg | Based on datasheet average |
| Height adjustment range | Vertical adjustment capability | — | Considerations regarding sunlight entering from above and below the PV module |
| Structural material | Main frame material | Galvanized steel | Common PV mounting material |
| Analysis scope | Structural evaluation | Static loading only | Conceptual-stage limitation |

*2.2. Design Objectives and Conceptual Requirements*

This stage focuses on defining the design objectives and conceptual requirements of the PV mounting system, with the primary goal of enabling mechanical height adjustment without compromising structural stability, simplicity, or analytical clarity. The height adjustment is intended to enhance installation flexibility, reduce potential shading, and improve air circulation around the module, which may, in turn, influence thermal performance. Conceptual requirements, summarized in Table 1, are derived from relevant literature and common mounting design practices, with key parameters such as module weight, frame configuration, and geometric constraints defined as realistic assumptions for small- to medium-scale PV applications. These assumptions serve as the basis for geometric modelling and structural evaluation at the conceptual design stage.

*2.3. Conceptual Mechanical Design and CAD Modelling*

Based on the defined design objectives, a simple, modular mounting structure with a mechanical height-adjustment mechanism was developed to allow vertical repositioning of the PV module without relying on complex tracking systems. This approach aims to balance mechanical flexibility with structural reliability at the conceptual stage. The proposed design was then modelled in three dimensions using CAD software to assess geometric feasibility, component integration, and primary load transfer paths, forming the basis for subsequent structural simulation and evaluation.

*2.4. Material Assumptions and Structural Idealization*

For analytical simplicity and consistency with industry practice, the structural components are assumed to be made of galvanized steel or structural aluminium commonly used in PV mounting systems. Key mechanical properties, including Young's modulus, Poisson's ratio, and yield strength, are adopted from standard literature and used as input for the structural simulation, as summarized in Table 2. In the finite element simulation, all structural components of the proposed adjustable PV mounting system are assumed to be manufactured from galvanized structural steel. The mechanical properties of galvanized steel, including a yield strength of 204 MPa, Young's modulus of 200 GPa, and Poisson's ratio of 0.3, are consistently applied in the stress evaluation and safety factor calculation.

To clarify the geometric configuration and structural arrangement of the proposed system, the adjustable-height PV mounting design is presented through multiple visual representations. Figure 2 illustrates the three-dimensional model from front, side, top, and isometric views, providing a comprehensive overview of the structural layout and component integration before numerical analysis. The front view highlights the vertical frame configuration and spacing between support legs, which are critical to overall structural stability. In contrast, the side view emphasizes the inclined support members and the tilt-setting mechanism that define the module's inclination. The top view shows the main frame arrangement and connection layout, ensuring uniform

**Table 2.** Assumed material properties used in structural simulation.

| Material | Young's Modulus (GPa) | Poisson's Ratio | Yield Strength (MPa) | Reference |
|---|---|---|---|---|
| Galvanized steel | 200 | 0.3 | 204 | [39] |

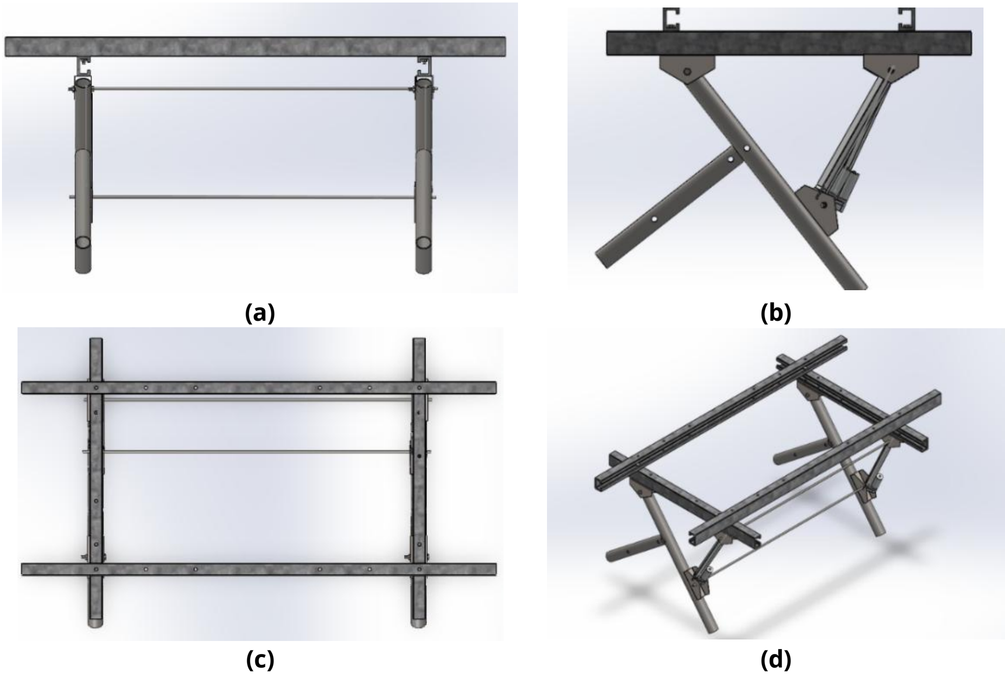

**Figure 2.** Multiple views of the proposed 3D SolidWorks mounting structure; a) Front view, b) Side view, c) Top view, and d) Isometric view.

**Table 3.** Main components of the proposed adjustable-height PV mounting system.

| Component | Material | Function |
|---|---|---|
| Base frame | Galvanized steel | Provides structural foundation and transfers applied loads |
| Support legs | Galvanized steel | Supports vertical loads and enables height adjustment |
| Height adjustment mechanism | Adjustable linkage mechanism | Allows vertical repositioning of the PV module |
| Connecting joints | Steel | Connects and integrates structural components |

load distribution across the structure, while the isometric view presents the integrated assembly of all structural components. Together, these views facilitate a clear understanding of the architectural design and support subsequent structural evaluation and fabrication considerations.

To further describe the structural configuration, the main components of the mounting system are summarized in Table 3: base frame, support legs, height adjustment mechanism, and connecting joints. This component-level overview confirms that the proposed design adopts a simple, modular architecture, providing a clear basis for structural simulation and feasibility assessment at the conceptual stage.

The base supports of the mounting structure were modeled as fully fixed boundary conditions. This assumption represents an idealized constraint condition commonly adopted in conceptual-stage finite element studies to isolate the structural response of the mounting system itself. Soil–structure interaction effects for ground-mounted installations and anchorage flexibility for rooftop systems were not explicitly modeled. As a result, the applied boundary conditions provide a simplified representation intended to establish an initial structural baseline rather than to replicate site-specific installation conditions.

The height adjustment mechanism is implemented as a simplified mechanical adjustment system at the conceptual design stage. No specific actuator type (e.g., hydraulic or electric) is explicitly modeled in the finite element analysis. Instead, the adjustment mechanism is represented by idealized connections that transfer gravitational loads to the supporting structure, enabling evaluation of the structural feasibility of the mounting system independently of actuation details.

### *2.5. Static Structural Simulation and Virtual Validation*

The conceptual design was evaluated using a finite element–based static structural analysis in SolidWorks to model the primary loads acting on the PV mounting system. Fixed support boundary conditions were applied at the base of the structure, and gravitational loading was applied to simulate the PV module's self-weight. Structural response was assessed through Von Mises stress distribution and total deformation to evaluate material yielding potential and structural stiffness. The safety factor was calculated as the ratio between the material yield strength ($\sigma_{yield}$) and the maximum simulated Von Mises stress ($\sigma_{v\ max}$), as defined in Equation (1), to confirm the structural feasibility of the proposed design.

$$SF = \frac{\sigma_{yield}}{\sigma_{v\ max}} \quad (1)$$

Where; $\sigma_{yield}$ is the yield stress material (MPa), $\sigma_{v\ max}$ is the max Von Mises stress from the FEM simulation results (MPa).

The safety factor evaluation in this study is intentionally limited to a single stress-based metric under gravitational loading. It is not intended to replace code-based structural verification procedures typically required for detailed engineering design.

## 3. Results and Discussion

This section presents the finite-element simulation results for the proposed adjustable-height PV mounting system under gravitational loading. The evaluation focuses on Von Mises stress distribution ($\sigma_{vmax}$), total deformation ($\delta_{max}$), and safety factor (SF). To evaluate the mechanical response and structural integrity of the proposed mounting system, a static structural simulation was performed as a numerical assessment of the conceptual design. Figure 3a shows that the self-weight of the bifacial photovoltaic module (36 kg) was applied as an equivalent gravitational load acting on the mounting structure. Instead of using concentrated point loads, the module weight was converted into a uniformly distributed load and applied along the supporting mounting rails at the module–frame contact regions. This approach represents a realistic load-transfer mechanism from the photovoltaic module to the mounting system via clamps and rail supports. The present structural analysis is intentionally limited to gravitational loading representing the self-weight of the photovoltaic module and supporting structure. Environmental loads such as wind uplift, seismic actions, and actuator-induced forces are not considered, as the objective of this study is to assess structural feasibility at the conceptual design stage rather than to perform a comprehensive code-compliant structural design.

The finite element mesh used in the simulation is presented in Figure 3b, with refined mesh density applied at joints and critical regions to accurately capture stress gradients. The structural model was discretized using three-dimensional solid elements. A refined mesh was applied at joints and in geometrically critical regions to accurately capture stress concentrations. In contrast, a coarser mesh was used in non-critical members to improve computational efficiency. The final finite element model consisted of approximately 723055 elements and 1204068 nodes.

The Von Mises stress ($\sigma_{vmax}$) distribution shown in Figure 3c indicates that the maximum stress is concentrated at the connection between the support legs and the main frame, with a peak value of $6.204 \times 10^7$ Pa (62.04 MPa). This value remains well below the assumed material yield strength of 204 MPa, indicating that the structure operates safely under the applied static load. Figure 3d presents the total deformation response, with the maximum displacement occurring at the upper support frame, approximately $2.21 \times 10^{-3}$ mm, demonstrating high structural stiffness and good geometric stability for a static PV mounting application.

The maximum total deformation ($\delta_{max}$) obtained from the finite element analysis is $2.21 \times 10^{-3}$ mm under gravitational loading corresponding to the self-weight of a 36 kg bifacial PV module. Although this deformation magnitude appears very small, it should be interpreted in the context of the simplified loading and boundary conditions adopted in this conceptual-stage study. Only gravitational loading was applied, and all support connections were idealized as fixed constraints, resulting in a relatively stiff structural response. The reported deformation, therefore, represents relative elastic displacement within the numerical model rather than an experimentally measurable deflection. This result is primarily used to confirm the absence of excessive flexibility under self-weight and does not represent serviceability limits under operational loads, such as wind or seismic actions.

The safety factor was evaluated as an indicator of the structural adequacy of the proposed adjustable-height mounting system under the assumed static loading conditions. Therefore, the reported safety factor is interpreted as a conservative indicator of structural feasibility at the early design stage rather than a code-compliant design criterion. A summary of the key simulation results, including maximum stress, maximum deformation, and safety factor, is provided in Table 4, confirming that the proposed design satisfies common safety criteria for static photovoltaic mounting structures.

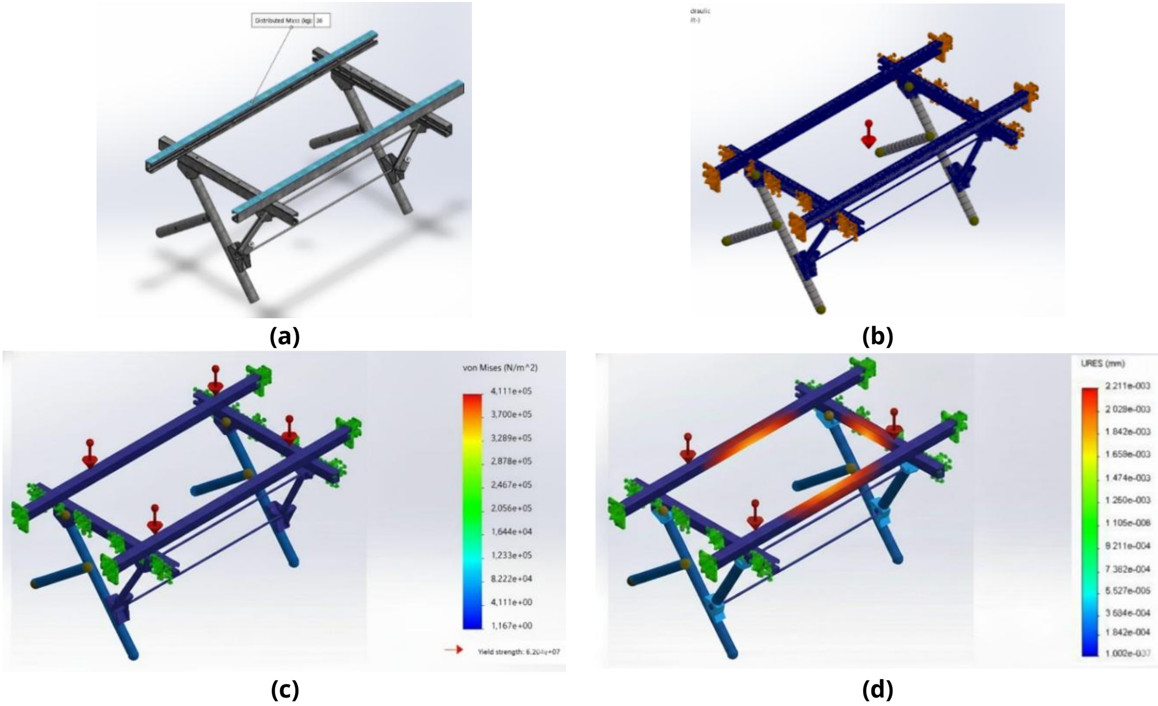


**Figure 3.** Static structural simulation results of the proposed solar panel mounting system; a) Applied boundary conditions and loading configuration, b) Finite element mesh generation, c) Von Mises stress distribution, and d) Total deformation under static gravitational loading.

**Table 4.** Summary of structural simulation results for the adjustable-height PV mounting system

| Simulation Parameter | Description | Value | Unit |
|---|---|---|---|
| Maximum Von Mises stress ($\sigma_{vmax}$) | The highest value is found in the base frame | 62.04 | MPa |
| Location of maximum deformation ($\delta_{max}$) | The highest value is found in the base frame | $2.21\times10^{-3}$ | mm |
| Assumed material yield strength ($\sigma_y$) | Yield strength of structural material | 204 | MPa |
| Calculated safety factor (SF) | Ratio of yield strength to maximum stress | 3.29 | — |

Based on the structural simulation results, three key aspects warrant discussion. The relationship among the three primary parameters: Von Mises stress ($\sigma_v$), maximum deformation ($\delta_{max}$), and safety factor (SF). The discussion of tilt angle and height in this study is limited to the predefined design requirements and does not constitute a parametric optimization analysis. The structural results obtained for the evaluated configuration indicate that the inclusion of adjustability features does not introduce excessive stress or deformation under self-weight loading; however, all responses remain within acceptable operational limits. This behaviour reflects a common structural trade-off observed in adjustable PV mounting systems, as reported in previous studies on manual tilt mechanisms and variable mounting structures [15–17]. Furthermore, the SolidWorks-based finite element simulation effectively captures load transfer paths and critical stress concentration regions, demonstrating the capability of the adopted approach to realistically represent static loading behaviour, as also applied in prior structural analyses of PV mounting and elevated PV structures [10, 28]. Overall, these findings confirm that the proposed mounting system successfully meets its two primary objectives: mechanical flexibility and structural safety, while providing a reliable platform for further PV performance assessment and field implementation.

From a practical perspective, the proposed adjustable-height PV mounting system provides a flexible and simple installation solution for ground-mounted and rooftop PV applications under space and environmental constraints [1, 5]. In this context, height-adjustable mounting systems enable site-specific adaptation without the complexity and cost of automatic tracking systems. The main contribution of this study is the development of a structurally evaluated conceptual design framework that complements prior research primarily focused on energy or economic performance, while establishing a technical basis for bifacial PV applications sensitive to geometric and environmental conditions [1, 5]. From a sustainability perspective, life-cycle assessment studies indicate that recycling strategies for monocrystalline PV modules in Indonesia can significantly reduce environmental impacts, underscoring the importance of aligning PV system design with long-term sustainability and end-of-life considerations [40]. Future work should incorporate dynamic and extreme wind load analysis, experimental prototype validation, and integrated energy–economic assessment to fully quantify the benefits of height adjustment [23].

## 4. Conclusions

This study evaluated the structural feasibility of a simple, modular, adjustable-height PV mounting system using finite-element–based static analysis under gravitational loading. First, the maximum Von Mises stress remains significantly below the material yield strength, indicating an adequate safety margin under the assumed static loading conditions. The simulation results indicate a maximum Von Mises stress ($\sigma_v$) of 62.04 MPa, which remains well below the assumed yield strength of galvanized steel (204 MPa). The corresponding safety factor (SF) is 3.29, indicating a conservative structural response at the conceptual design stage. Second, the observed total deformation is minimal, confirming sufficient structural stiffness and geometric stability despite the integration of a height adjustment mechanism. The maximum deformation ($\delta_{max}$) is $2.21 \times 10^{-3}$ mm, reflecting a stiff structural behaviour under self-weight loading. These quantified results confirm that the proposed mounting system satisfies basic structural feasibility requirements under the considered load case and provide a numerical baseline for further refinement and extended load-case evaluation in future studies. Third, the modular, mechanically simple design achieves an effective balance between adjustability and structural performance without the complexity of automatic tracking systems. Fourth, the modular, elevated configuration of the proposed mounting system may offer potential benefits in terms of shading reduction and thermal behaviour. These aspects were not evaluated in this study and should be investigated through dedicated thermal and energy performance analyses in future work. Overall, these results establish a robust technical foundation for further development, including design optimization, experimental validation through physical prototyping, and integrated evaluation of structural, energy, and economic performance.

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