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Experimental and Numerical Modal Assessment of Rooftop Photovoltaic Support Structures under Wind-Sensitive Design Conditions

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Abstract

Rooftop photovoltaic (PV) support structures are increasingly used on existing buildings in typhoon-prone regions, yet their preliminary dynamic assessment is often less developed than their static wind-load verification. This study presents a case-based experimental and numerical modal assessment of a rooftop canopy-type PV support structure. A reduced-scale specimen representing an actual rooftop support frame was tested using a biaxial shaking table, and a simplified SAP2000 finite-element model was established to interpret the dominant modal response. The shaking-table tests identified a dominant frequency of approximately 4.17 Hz, while the corresponding numerical model predicted a first modal frequency of 4.19 Hz. The close agreement indicates that the simplified finite-element representation can capture the governing global stiffness of the tested support system. The results further suggest that global lateral flexibility, rather than local member response alone, governs the vibration-sensitive behavior of lightweight rooftop PV support frames. The study provides a practical modal-screening procedure for early-stage structural assessment and design refinement of rooftop PV support systems under wind-sensitive design conditions. Limitations related to scaling, absence of wind-tunnel pressure measurements, and single-case validation are explicitly discussed.

1. Introduction

The rapid expansion of rooftop solar photovoltaic installations has become an important component of renewable-energy deployment in land-constrained urban environments. In Taiwan and similar densely built regions, canopy-type photovoltaic support structures are attractive because they provide both energy generation and sheltered roof-space use. In contrast to conventional roof-attached systems, however, canopy-type supports often employ relatively slender members, elevated framing, and exposed edge conditions. These features can increase their sensitivity to displacement, uplift-related demand, and vibration under strong environmental loading. Representative rooftop installation conditions from the source project are shown in Figure 1.

Current design practice for rooftop PV systems commonly relies on general building wind-load provisions and project-specific static checks. Such checks remain essential, but they do not directly characterize the modal properties and directional vibration sensitivity of lightweight support systems. For flexible rooftop structures, global stiffness, mode shape, and support detailing may govern serviceability and local connection demand even when static design requirements are formally satisfied. This gap is particularly important in typhoon-prone regions, where repeated wind action and uplift-sensitive details may control performance.

Previous studies on solar support structures have mainly emphasized wind pressure distribution, global wind load estimation, and static structural demand [1-4]. By contrast, experimentally validated information on the natural frequencies and modal behavior of rooftop canopy-type support systems remains limited. In structural engineering terms, this leaves an important gap between code-based load prescription and the engineering assessment of vibration-sensitive support configurations.

The present study addresses that gap through an experimental and numerical assessment of a rooftop canopy-type PV support structure. A reduced-scale specimen derived from an actual rooftop trellis-type system was examined using a biaxial shaking table to identify dominant vibration characteristics under controlled directional excitation. A simplified finite-element model corresponding to the test-scale specimen was then established in SAP2000 for modal comparison and validation. The objective is not to establish a full aeroelastic wind model, but to provide a structural-dynamics-oriented framework that can support preliminary design screening, stiffness-oriented refinement, and identification of potentially vulnerable support configurations.

2. Background and Structural Assessment Context

Rooftop photovoltaic support structures occupy an intermediate position between conventional building components and dedicated light steel structures. Their response is shaped by both environmental loading and the local stiffness hierarchy of the support frame. For canopy-type systems, the elevated geometry of the frame and the panel-bearing substructure can produce larger bending and torsional demand than that observed in roof-attached systems. In addition, the response may be controlled by the interaction among global sway, local member flexibility, and connection vulnerability at bases and module interfaces.

From a practical design standpoint, three issues recur. First, static pressure calculations may not reveal whether a support system is dynamically sensitive in a particular direction. Second, local uplift-sensitive details such as anchors and interfaces may experience amplified demand if the global frame is insufficiently stiff. Third, simplified project checks often focus on member strength, whereas modal behavior and serviceability may remain unexamined. These points motivate a supplemental structural-dynamics-based assessment in addition to routine code-based verification. Representative support-frame and rooftop installation conditions relevant to these assessment issues are shown in Figure 2.

The current work therefore adopts a deliberately practical position. Rather than attempting to reproduce the full fluid-structure interaction of the wind field, it aims to identify whether a simplified experiment-model pair can recover the dominant modal behavior of a representative rooftop canopy-type PV support system. If the dominant vibration characteristics can be captured with acceptable agreement at the test scale, the resulting framework can be used as an engineering-level screening tool prior to more detailed simulation or wind-tunnel investigation.

3. Experimental Program

The experimental program focused on identifying the relative dynamic characteristics of a rooftop canopy-type PV support structure under directional excitation. The prototype support arrangement corresponded to a forty-panel rooftop trellis-type system documented in the source project materials. A reduced-scale specimen was prepared to retain the principal geometry and stiffness hierarchy of the prototype while remaining within the capacity of the available test equipment.

The scaled specimen included the principal support columns, beams, and purlin-type members required to reproduce the global framing behavior. Wooden planks were used to represent the PV modules, while slender steel-wire elements were used for the supporting members. The layout retained three groups of columns with different heights, consistent with the sloped canopy geometry of the prototype. This arrangement was important because it preserved the dominant lateral stiffness distribution that governs the first few global modes. The reduced-scale specimen used in the shaking-table program is shown in Figure 3.

Testing was carried out on an RMAX biaxial shaking table capable of controlled horizontal excitation in two orthogonal directions. The shaking-table program did not attempt to reproduce the full spatial and temporal distribution of actual wind pressure. Instead, it was designed to identify dominant modal characteristics and response trends under directional excitation, which is sufficient for the engineering objective of preliminary dynamic assessment. Single-axis and bi-axial waveform cases were executed using both sine and triangle inputs, with amplitudes and frequencies selected to excite the support system over a practical range.

Eight representative loading cases were considered, covering single-axis and bi-axial inputs with amplitudes of 10 mm, 20 mm, and 50 mm and command frequencies of 1 Hz and 2 Hz. These command frequencies should not be interpreted as the natural frequencies of the specimen. Rather, they were used as controlled excitation inputs; the structural frequency was identified from the measured output response. Particular attention was given to the transverse response because lateral wind action is typically critical for canopy-type rooftop PV systems. The representative loading cases are summarized in Table 1.

Case	Wave type	Execution mode	Amplitude (mm)	Command frequency (Hz)
1	Sine	Single axis	10	1
2	Triangle	Single axis	10	1
3	Sine	Single axis	10	2
4	Triangle	Single axis	10	2
5	Sine	Bi-axial	20	1
6	Triangle	Bi-axial	20	1
7	Sine	Bi-axial	50	1
8	Triangle	Bi-axial	50	1

Table 1. Representative test matrix used in the shaking-table program.

3.1. Similitude assumptions and interpretation of scaled-model results

The reduced-scale model was designed as a vibration-identification specimen rather than as a complete aeroelastic similitude model. Geometric similarity and the principal stiffness hierarchy of the roof canopy support arrangement were retained. However, strict mass similitude was not fully satisfied because the specimen used substitute module materials and simplified support members to remain compatible with the available shaking-table capacity.

For this reason, the experimentally identified frequency should be interpreted as the dominant modal frequency of the test-scale specimen. The SAP2000 model used for modal comparison was therefore constructed to represent the same test-scale configuration, not to claim a direct one-to-one prediction of the full-scale prototype frequency. Under complete similitude, modal frequency depends on the square root of the stiffness-to-mass ratio. If mass and stiffness are not scaled according to a single similitude law, direct prototype frequency conversion is not physically justified. The present study accordingly uses the scaled experiment and the corresponding scaled numerical model for validation of global modal behavior, while limiting prototype-level interpretation to qualitative vulnerability and stiffness-screening implications.

This limitation does not invalidate the experimental-numerical comparison. Instead, it defines the intended scope of the framework. The comparison evaluates whether the simplified finite-element idealization can reproduce the dominant global vibration behavior observed in the physical specimen. Subsequent full-scale design applications should recalibrate material properties, member sections, connection stiffness, and distributed mass to the actual project configuration before using the model for final structural assessment.

3.2. Frequency-identification procedure

The dominant structural frequency was identified from the output acceleration response recorded during the shaking-table tests. The response was monitored using the acceleration channel of the RMAX shaking-table data-acquisition system and a specimen-level measurement point located near the panel-support level where global lateral motion was most evident. The available source records were processed as 10 s response windows, with the data exported at 100 Hz for frequency-domain screening. Each response record was detrended to remove low-frequency drift, multiplied by a Hanning window to reduce spectral leakage, and transformed into the frequency domain using the fast Fourier transform (FFT). For a 10 s analysis window, the nominal frequency resolution was 0.10 Hz, which was sufficient to separate the command peaks at 1-2 Hz from the structural response peaks near 4-5 Hz.

The dominant structural frequency was defined as the largest repeatable spectral peak in the output response that was associated with specimen vibration rather than with the imposed command

frequency alone. This distinction is important because the input commands were applied at 1 Hz and 2 Hz, whereas the dominant structural response peak was identified at approximately 4.17 Hz. A secondary response component was also observed near 5.2 Hz in the representative response spectrum, which is consistent with the second numerical mode reported by the SAP2000 test-scale model. Figure 4 is retained as a schematic illustration of the frequency-identification concept, not as a raw measured FFT record. The reported frequency values are based on the processed acceleration records and the repeatability summary in Table 2. Modal testing and frequency-domain identification procedures of this type are consistent with established experimental and operational modal-analysis practice [5-9].

Item	Adopted / reported setting	Purpose	Relevant cases	Interpretation
Response measurement	Acceleration response exported from the RMAX data-acquisition system; specimen-level response point near panel-support level	Capture global lateral vibration of the reduced-scale specimen	Cases 1-8	Used for output-response frequency identification
Signal processing	10 s record window, 100 Hz exported sampling rate, detrending, Hanning window, FFT	Separate imposed command frequency from structural response frequency	Representative single-axis and bi-axial cases	Nominal frequency resolution = 0.10 Hz
Dominant peak repeatability	Dominant output-response peak consistently identified near 4.17 Hz	Define principal experimental modal frequency	Cases with 1 Hz and 2 Hz command inputs	Peak not assigned from command frequency
Secondary response component	Weaker spectral component observed near 5.2 Hz in the representative response spectrum	Support comparison with higher numerical mode	Representative response spectrum	Consistent with SAP2000 Mode 2 at 5.21 Hz

Table 2. Signal-processing and frequency-identification settings used for the FFT-based interpretation of the shaking-table response records.

4. Numerical Modeling

A simplified finite-element model of the reduced-scale rooftop canopy-type PV support specimen was developed in SAP2000. The purpose of the model was to reproduce the global stiffness distribution and extract the principal modal characteristics required for experimental comparison. The model included the main columns, beams, and supporting members necessary to represent the structural system at engineering level. Secondary attachments and all local connection details were not modeled explicitly, since the emphasis of the study was on global rather than local dynamic response.

Material properties, member idealization, boundary conditions, and lumped or equivalent mass assignments were selected to represent the test specimen used in the shaking-table program. Eigenvalue analysis was then performed to extract the natural frequencies and associated mode shapes of the simplified system. This modeling strategy is consistent with the role of modal analysis in preliminary assessment: the key question is whether the numerical model can recover the dominant frequencies and global deformation patterns that govern vibration-sensitive structural behavior. The simplified finite-element representation and representative modal-analysis output are shown in Figure 5.

Wind design information from the project context was retained to interpret the engineering relevance of the results. The project location in Hualien, Taiwan, was associated with a basic design wind speed of 42.5 m/s in the source materials. In the present manuscript, however, that information is used only to motivate the need for dynamic assessment of rooftop supports in typhoon-prone regions; it is not used to claim a complete wind-resistance design procedure. The present framework should therefore be regarded as a structural-dynamics-based complement to code-based static checks.

5. Results and Discussion

Shaking-table testing identified a dominant frequency of approximately 4.17 Hz for the principal response of the reduced-scale specimen. This value represents the most relevant experimentally observed vibration characteristic for comparison with the numerical model. The response was most clearly expressed in the transverse direction, which is consistent with the expectation that lateral flexibility governs the initial global mode of the canopy-type support system.

Modal analysis in SAP2000 yielded a first modal frequency of 4.19 Hz and a second modal frequency of 5.21 Hz for the test-scale model. The close agreement between the experimentally identified dominant frequency and the first numerical mode indicates that the simplified finite-element representation is capable of reproducing the global dynamic behavior most relevant to preliminary design assessment. The difference between the test-based value and the first numerical frequency is approximately 0.5%, which is sufficiently small for engineering-level modal validation of a simplified support model. The experimental-numerical frequency comparison is summarized in Table 2.

The comparison suggests that the governing response mechanism is controlled primarily by global flexibility rather than by a highly localized deformation mode. This observation is important from a structural engineering standpoint. A support system may satisfy conventional static member checks, yet still display undesirable dynamic sensitivity if the lateral stiffness is insufficient. In canopy-type PV systems, such sensitivity can increase displacement demand, amplify internal-force response, and elevate risk at uplift-sensitive locations such as anchors, base connections, and panel-support interfaces.

The representative frequency-domain interpretation also indicates a weaker secondary response component near 5.2 Hz. This observation is consistent with the second numerical mode at 5.21 Hz, although the first mode remains the principal basis for experimental-numerical validation because it

governs the dominant transverse response. The presence of this higher component indicates that the structural system contains additional global vibration patterns beyond the principal mode. Even when the dominant frequency lies outside the most common range associated with very low-frequency excitation of rigid rooftop components, dynamic effects remain relevant for lightweight structures because serviceability, repeated excitation, and local connection durability may still govern their performance.

Source	Direction / mode	Frequency (Hz)	Comment
Shaking-table test	Dominant transverse response	4.17	Experimental principal response from FFT-based output-response identification
SAP2000 modal analysis	Mode 1	4.19	Closest numerical modal match for the test-scale model
SAP2000 modal analysis	Mode 2	5.21	Higher global mode

Table 3. Comparison between experimentally identified and numerically predicted modal frequencies.

6. Engineering Implications

The principal outcome of the study is not merely the numerical proximity between 4.17 Hz and 4.19 Hz. More importantly, the study shows that a simplified experiment-model pair can recover the dominant modal behavior of a rooftop canopy-type support system with useful engineering fidelity at the test scale. For engineering practice, this means that dynamic screening can be introduced without requiring a fully coupled aeroelastic model at the earliest design stage.

Three structural implications emerge from the results. First, dynamic assessment becomes especially important when the support system contains relatively slender columns, long unsupported framing segments, or elevated roof-edge exposure that may magnify lateral response. Second, stiffness-oriented refinement of the support layout can be an effective mitigation strategy because increasing global lateral stiffness reduces both displacement demand and sensitivity to directional excitation. Third, uplift-sensitive components should not be treated in isolation; their reliability depends partly on the global dynamic behavior of the frame to which they are attached.

These points do not replace code-based static verification. Rather, they indicate when static verification should be complemented by modal screening, refined numerical modeling, or further physical testing. For projects in typhoon-prone regions, the proposed framework offers a practical route for identifying potentially vulnerable configurations before they are finalized for detailed design and construction. The main engineering implications are summarized in Table 4.

Issue	Structural implication	Recommended engineering response
Low lateral stiffness	May increase displacement demand and internal-force amplification	Refine framing layout, increase stiffness, and check modal behavior early
Uplift-sensitive connections	Local vulnerability depends partly on global frame response	Assess anchors, base details, and module interfaces together with system dynamics
Slender or exposed support configuration	Higher risk of vibration-sensitive response under directional loading	Use dynamic screening before detailed design or physical wind study

Table 4. Engineering implications for rooftop canopy-type PV support design.

7. Limitations

Several limitations should be acknowledged to interpret the results correctly. First, the scaled specimen was intended primarily for vibration identification, and strict full mass similarity was not completely achieved. The experiment therefore supports relative modal assessment rather than exact prediction of full-scale response amplitudes or direct full-scale natural frequencies. Second, the shaking-table excitation did not reproduce the full pressure field, turbulence spectrum, or spatial variability of wind loading. The present study is consequently not a substitute for wind-tunnel testing or a full fluid-structure interaction model. Third, the available source records did not preserve a complete sensor-calibration sheet for every measurement channel; therefore, the manuscript reports the adopted response-processing procedure and repeatability logic, but does not claim a complete metrological uncertainty assessment for the acceleration system.

Fourth, the SAP2000 model was intentionally simplified so that it could be used as an engineering-level modal representation. It did not explicitly include every local attachment, module clamp, or secondary bracing condition that might influence local response. Fifth, the present manuscript focuses on global dynamic characteristics and structural vulnerability, not on long-term fatigue, detailed connection fracture, or progressive failure. These issues remain appropriate subjects for future study.

8. Conclusions

This study presented an experimental and numerical assessment of the modal characteristics and structural response vulnerability of a rooftop canopy-type photovoltaic support structure. On the basis of the biaxial shaking-table tests and SAP2000 modal analysis, the following conclusions can be drawn.

(1) The shaking-table program successfully identified the dominant vibration characteristics of the reduced-scale rooftop canopy-type PV support structure under directional excitation.

(2) The experimentally identified dominant frequency was approximately 4.17 Hz, whereas the first numerical modal frequency of the corresponding test-scale finite-element model was 4.19 Hz. This close

agreement indicates that the simplified finite-element model can adequately reproduce the global modal behavior most relevant to preliminary structural assessment.

(3) The dominant response of the system is governed primarily by global lateral flexibility. Insufficient stiffness may therefore amplify displacement demand and internal-force response, even in support systems that appear acceptable under routine static checks.

(4) For lightweight canopy-type PV support structures in typhoon-prone regions, code-based static wind design should be complemented by a preliminary dynamic check, particularly when the support layout is slender, elevated, or reliant on uplift-sensitive connections.

(5) The proposed framework is best regarded as a practical structural-dynamics-based screening tool for early-stage assessment and design refinement. Future work should incorporate direct aerodynamic loading, refined similitude conditions, improved local connection modeling, and wind-tunnel validation to quantify aeroelastic and durability-related behavior more rigorously.

List of abbreviations

ASCE: American Society of Civil Engineers; FEM: finite element method; FFT: fast Fourier transform; PV: photovoltaic; SAP2000: structural analysis program developed by Computers and Structures, Inc.; St: Strouhal number.

Declarations

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Data availability

The data supporting the findings of this study are derived from the experimental and numerical program described in the manuscript. Because the source project materials include project-specific drawings and internally generated analysis files, the dataset is not publicly deposited and is available from the corresponding author upon reasonable request.

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CRediT authorship contribution statement

Cheng-Wei Hung: Conceptualization, methodology, supervision, writing - review and editing. Chih-Hung Hsu: Investigation, data curation, formal analysis, visualization, writing - original draft. Pen-Chou Chen: Validation, interpretation of results, writing - review and editing.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT to improve language, organization, and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Figures

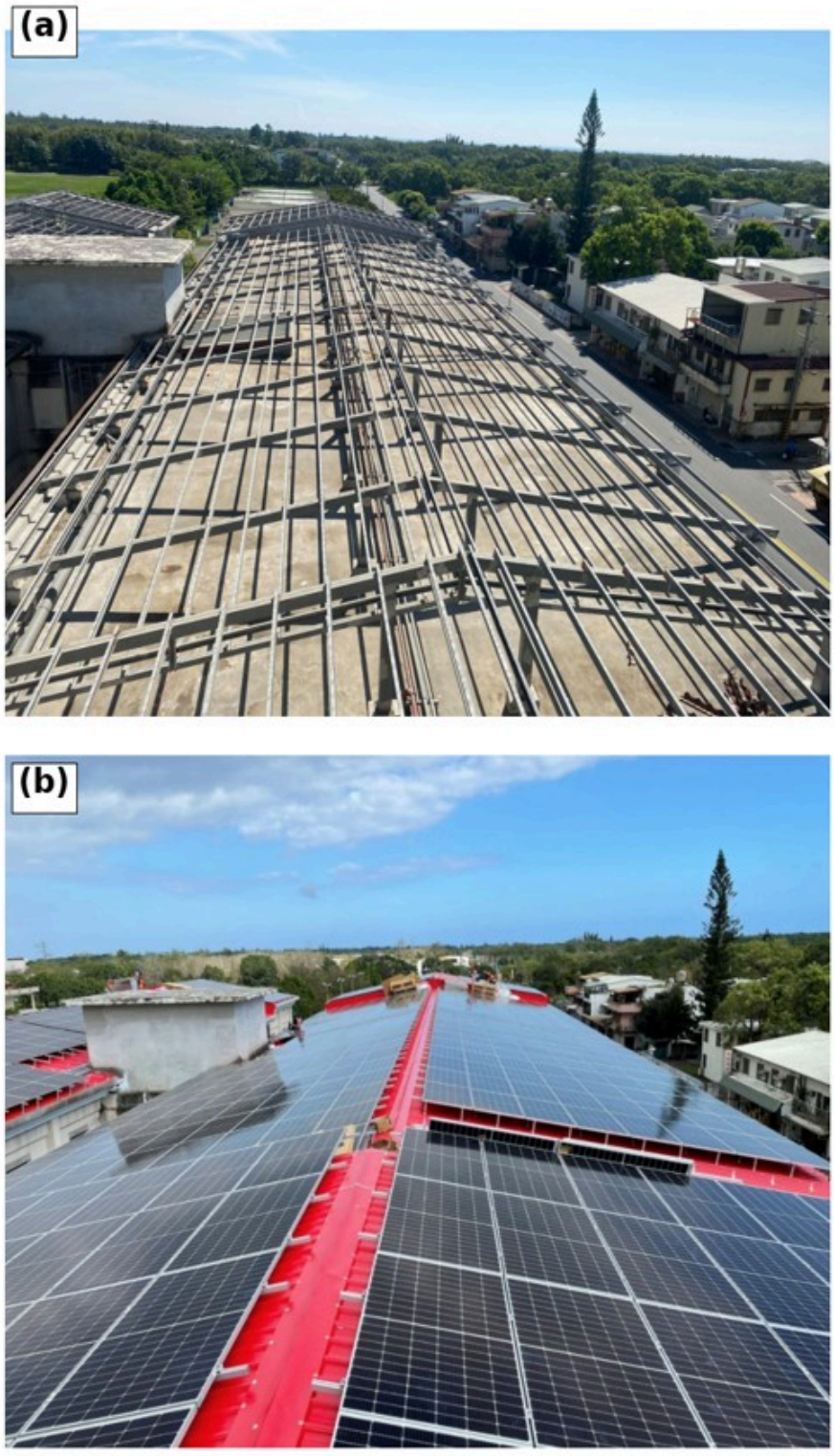


Figure 1

Rooftop canopy-type photovoltaic support installation conditions: (a) support frame before module installation and (b) completed rooftop PV installation.

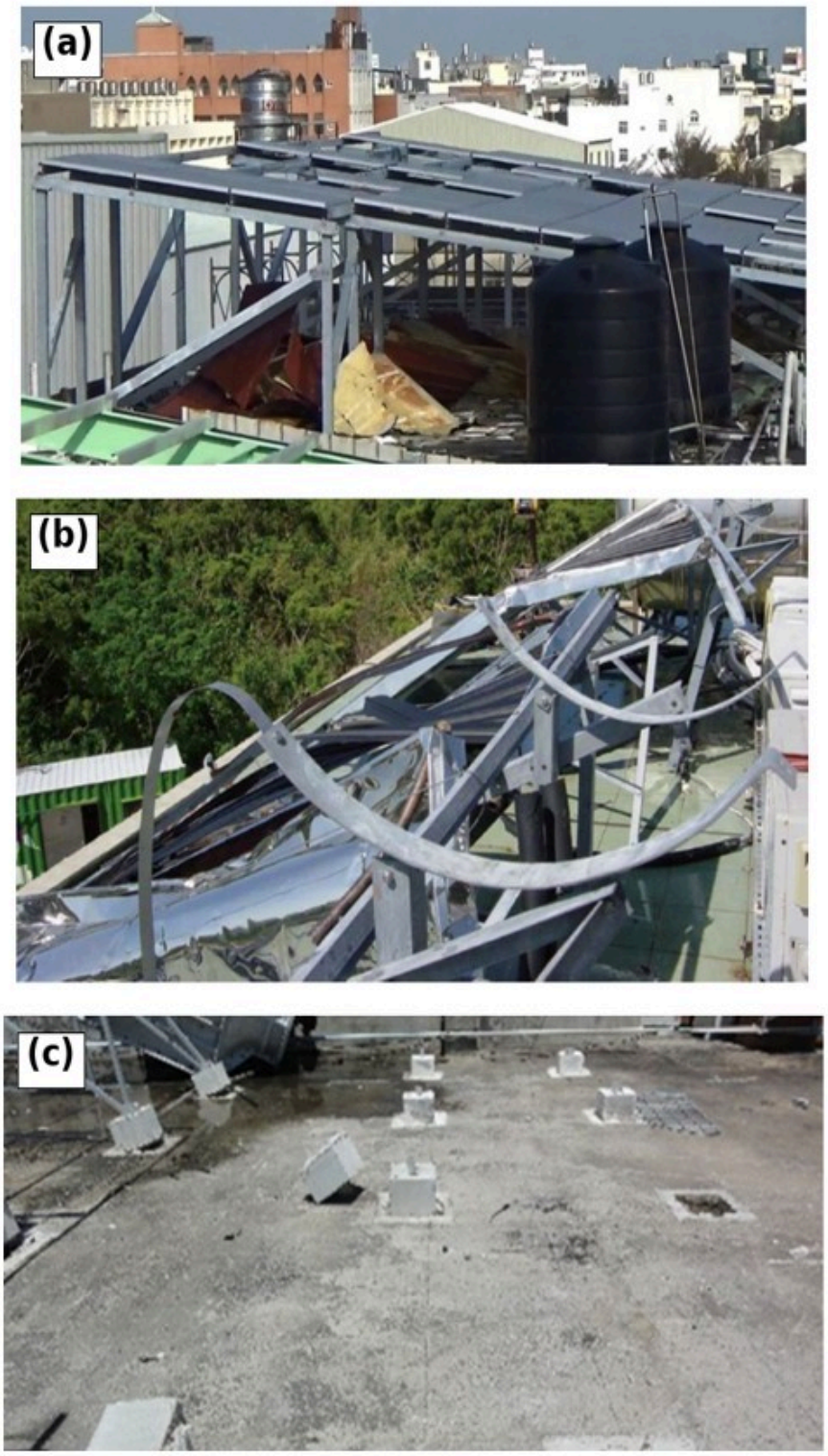


Figure 2

Representative support-frame and rooftop installation damage conditions from the source project: (a) damaged trellis-type PV frame, (b) damaged support members and module-bearing frame, and (c) base and anchor conditions after damage.

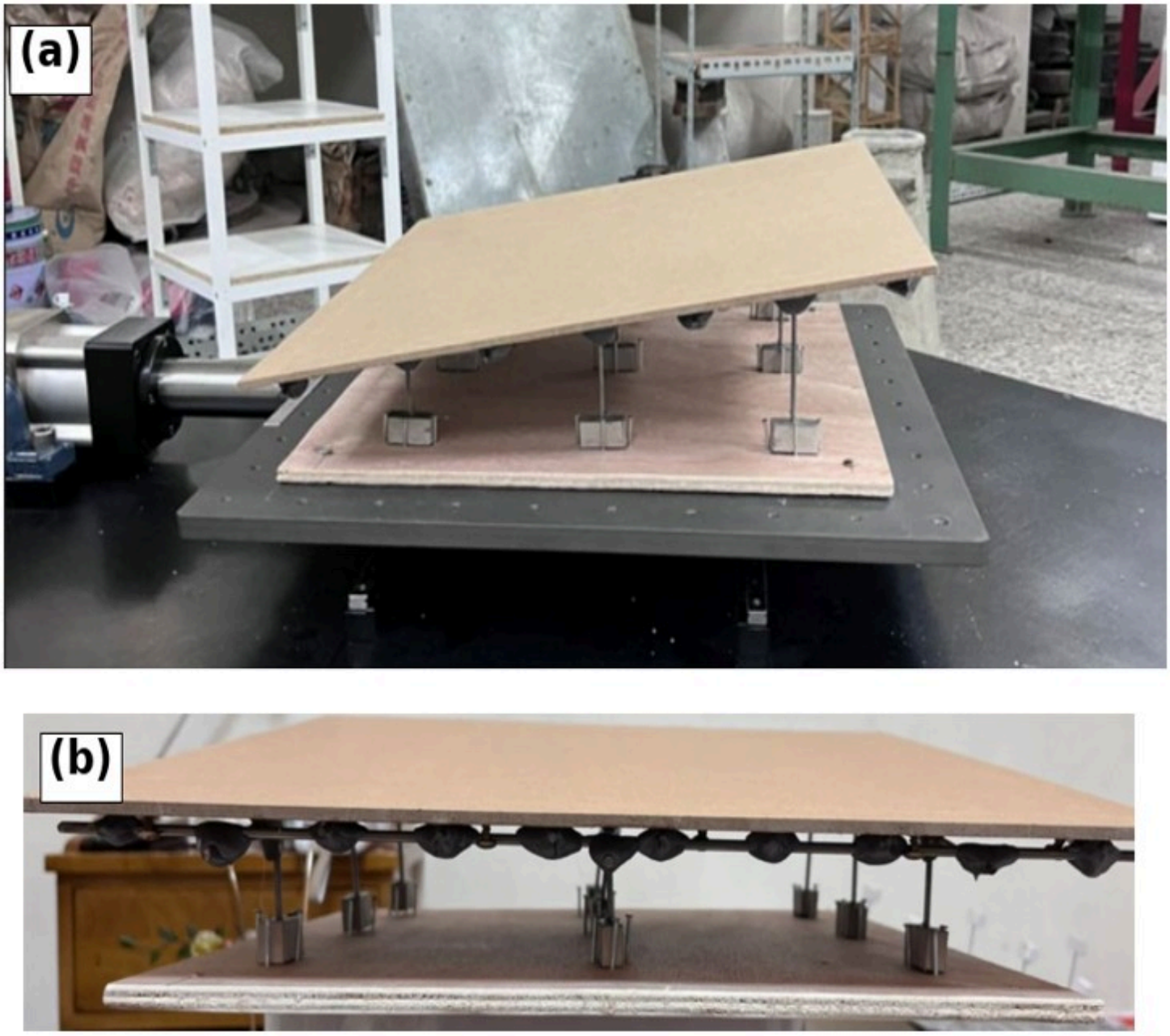


Figure 3

Reduced-scale specimen used in the shaking-table program: (a) specimen mounted on the RMAX biaxial shaking table and (b) side view of the reduced-scale support configuration.

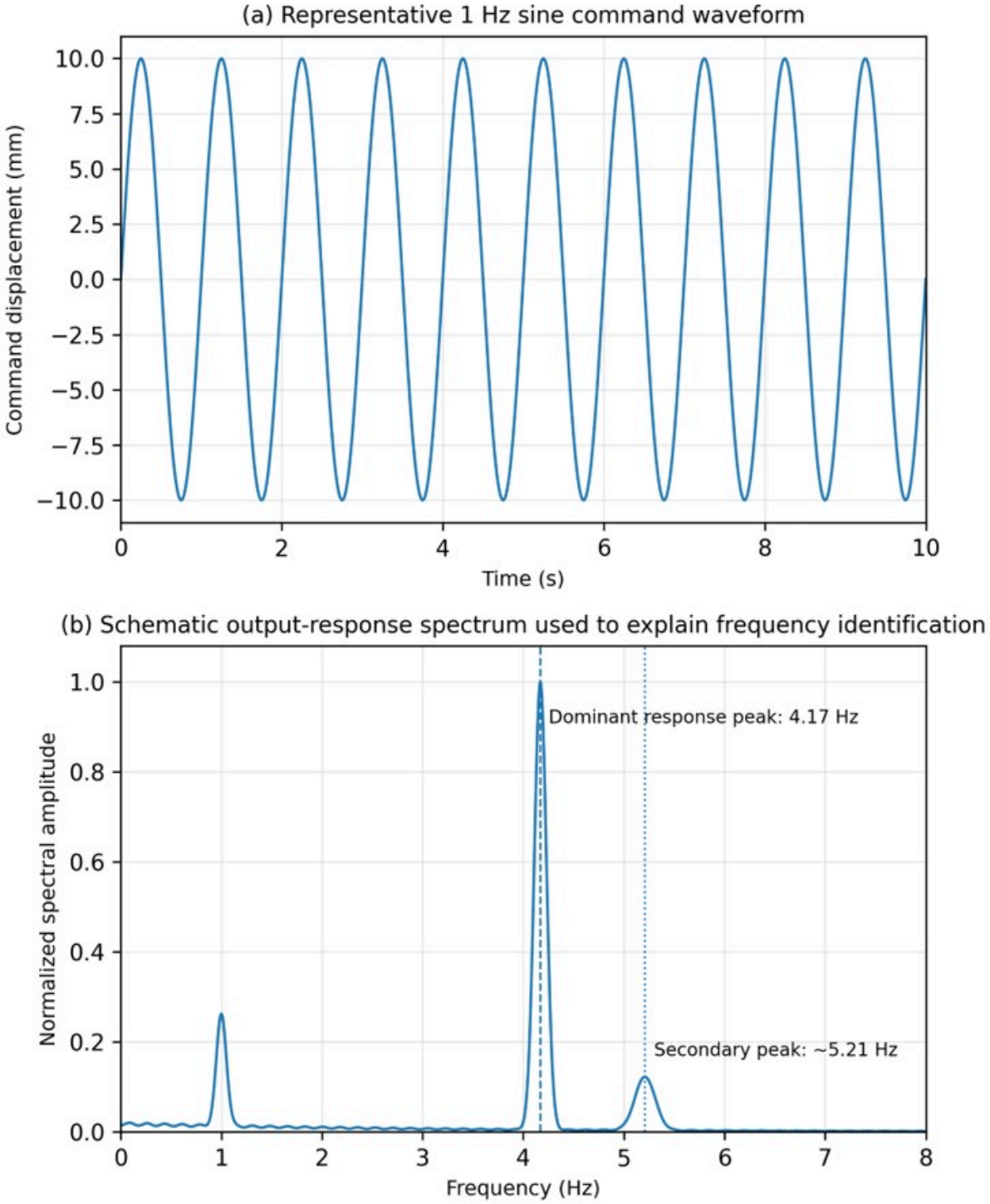


Figure 4

Schematic English illustration of the frequency-identification procedure: (a) 1 Hz command waveform and (b) normalized output-response spectrum used to explain the identification of the dominant structural peak at approximately 4.17 Hz and a secondary component near 5.21 Hz. Panel (b) is a schematic representation rather than a raw FFT record.

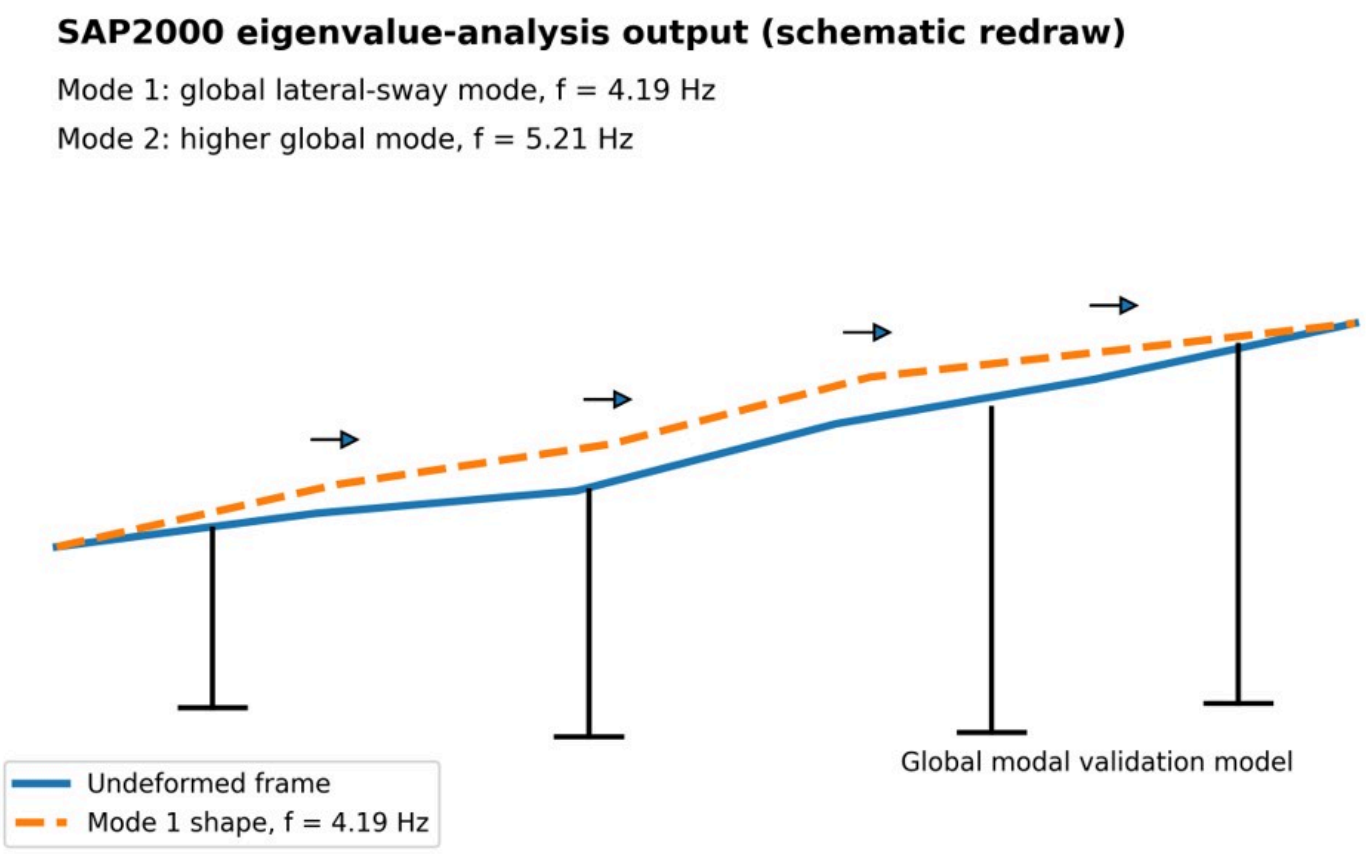


Figure 5

Simplified SAP2000 finite-element representation and schematic redraw of the representative eigenvalue-analysis modal output. The figure is a clean modal-output redraw used for publication clarity, not a static DEAD-load internal-force diagram.