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# Comparative Study on Static and Dynamic Analyses of an Ultra-thin Double-Glazing PV Module Based on FEM

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## Abstract

This paper presents a numerical simulation work on the mechanical behaviors of an ultra-thin double-glazing PV module under static and dynamic load conditions. Three different kinds of PV mounting configurations are investigated respectively to explore their influences on the static and dynamic performance of the studied module. For each kind of mounting configuration, static, modal and modal-based steady-state dynamic analyses are carried out by using the Finite Element Method, respectively. In the static analysis, two kinds of uniform pressure loading conditions with magnitudes of 2400 Pa and 5400 Pa, which are standing for the maximum wind load and snow load respectively according to the Standard of IEC 61215, are applied on the PV modules. After static analyses, modal analyses are performed to obtain the PV modules' natural frequencies and mode shapes. Based on the results of modal analyses, a steady-state dynamic analysis is conducted to determine the modules' dynamic responses to the harmonic excitations with an amplitude of 2400 Pa and frequencies ranging from 0 Hz to 100 Hz. The simulation results show that both the deformation and the stresses of three PV system are small in static analysis, but they are quite different in dynamic analysis. The dynamic displacement curves have obvious oscillations near the natural frequencies of PV modules and the amplitudes are large enough to damage the PV modules. The mounting configurations have a significant influence on both the static performance (strength and deformation) and dynamic performance (dynamic characteristics and responses). In conclusion, for this ultra-thin double-glazing PV module, it is not accurate and appropriate for evaluating the safety and stability of the PV module just through the existing static analysis in IEC 61215. The dynamic effects of the loading on PV module also need to be paid attention. Moreover, the mounting configurations should be designed to meet both the static and dynamic requirements.

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*Keywords*: BIPV; double-glass; photovoltaic; solar cell; green building; FEM

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## 1. Introduction

The PV module studied in this paper is an ultra-thin double-glazing module commonly used in practical building-integrated photovoltaic(BIPV) applications. Compared with the traditional components, an additional glass backside is used to replace the original polymeric backsheet for day lighting and strength, and the thicknesses of both the front and back glasses of the PV module are reduced from 3.2mm to 2.5mm. This PV module is frameless, and with a weight of just 24kg. A silicon edge sealing is applied to protect the module from mechanical shocks.

IEC 61215 provides mechanical load tests to ensure the qualification and safety of the PV module, which both the wind load and snow load are considered as static pressures. And the performance of PV module under static mechanical loads have been investigated by many literatures[1-3]. For the qualification of BIPV, the dynamic mechanical load should be under consideration as an additional test. Some literatures have been focusing on dynamic performance of PV modules[4,5]. However, both existing standards and literatures are most concentrating on the traditional PV modules with a toughened glass front panel and the influence of the mounting configurations on both the static and dynamic performance of the PV modules are not paid attention to.

Therefore, in this paper, a comprehensive safety evaluation including static and dynamic analyses, as well as the influence of mounting systems are investigated for an ultra-thin double-glass PV module to determine its qualification in BIPV application. Three kinds of configurations commonly used in practical application are considered in this paper. For each type of module mounting configuration, static, modal and mode-based steady-state dynamic analyses are conducted based on the Finite Element Method(FEM). The static performances of three PV systems are investigated by applying 2400 Pa and 5400 Pa uniform loads in accordance to IEC 61215 standard. Their dynamic performance are also studied via loading a dynamic load with an amplitude of 2400 Pa and frequencies ranging from 0 Hz to100 Hz. Lastly, the static and dynamic performance of different mounting configurations are compared and analyzed.

## 2. Methodology of FEM Modeling

### *2.1 Structure of the ultra-thin double-glazing PV module*

The PV laminate consists of 10×6 pieces of solar cells, and its dimensions are 1684×996mm. Solar cells adopted in the PV laminate are mono crystalline silicon wafer cells, each solar cell is dimensioned with 156×156mm. The layer structure of the PV module is shown in Fig.1. The thicknesses are 2.5mm, 400μm, 200μm, 400μm and 2.5mm, respectively.

### *2.2 FEM Model*

Fig.2 shows the model and finite element mesh employed to simulate the mechanical characteristics of the PV module. To reduce computational costs, one quarter of the plate dimensions H(Height)/2 ×W(Width)/2 with 6 layers of finite elements for each sheet of glass and 4 per sheet each EVA layer is used, except for modal analyses, which need a whole model. The solar cells are embedded in the EVA layers. Glass sheets and encapsulant interlayers are modeled using 8-node solid elements with incompatible modes to avoid locking in bending. The solar cells are modeled using 4-node shell elements with reduced integration. Table 1 presents the properties of the materials employed in the FEM model. Fig.3 shows three different mounting systems and their corresponding FEM models. In the first mounting system, the PV module is embedding into a support frame or structure with four edges fixed. In the second one, the PV module is always fixed by three clamps along each long edge. And in the third one, the four corners of the PV module are fixed by some grab split pieces.

In static analysis, 2400 Pa and 5400 Pa uniform loads were respectively loaded on the three PV systems in accordance to IEC 61215 standard. Modal analysis could examine the vibration characteristics (natural frequencies and mode shapes) of a structure, thus it is an essential procedure for designing a structure under dynamic loading conditions. It is also a basis for the subsequent dynamic analysis. The first fifty natural frequencies and modes extracted from modal analysis for each PV module are important parameters for designing a structure suffering dynamic loading conditions and determined by the both material properties (mass, damping, and stiffness) and boundary conditions. It is likewise a basis for the subsequent dynamic analysis.

After modal analysis, a modal-based steady-state dynamic analysis was conducted. A harmonic excitation with amplitude of 2400Pa, which is consistent with the maximum wind load in IEC 61215, and frequencies ranging from 0 Hz to 100 Hz was employed in the dynamic analysis.

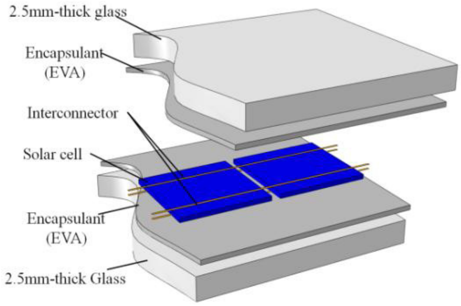


Fig. 1. Structural schematic diagram of the PV module

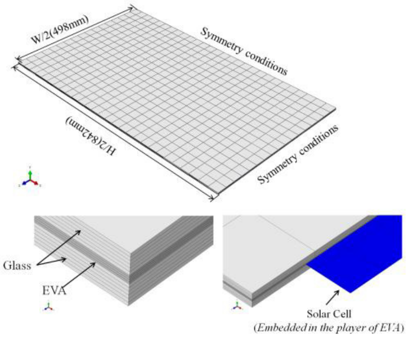


Fig. 2. Finite element meshes for PV module

Table 1. Materials' properties

| Materials | Young's modulus (GPa) | Poisson ratio | Mass Density (kg*m$^{-3}$) |
|---|---|---|---|
| Glass | 70 | 0.24 | 2500 |
| EVA | 0.0677 | 0.33 | 1030 |
| Si | 112.4 | 0.28 | 2329 |

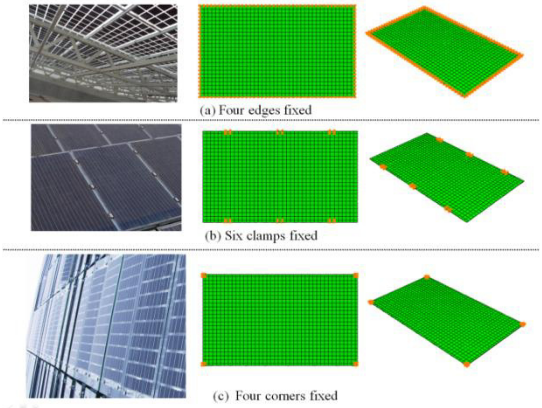

(a) Four edges fixed
(b) Six clamps fixed
(c) Four corners fixed

Fig. 3. Three mounting configurations and their corresponding FEM models

## 3. Results and Discussions

Fig.4 shows the static analysis results of the three PV modules under a uniform pressure loading of 5400 Pa. The maximum displacements and stresses are listed in Table 2. It is obviously found that the mounting configuration has a significant influence on the magnitudes and distribution of both the displacements and stresses. From the first to the third mounting configuration, the module stiffness decreased gradually, thus the deformation and stresses increased gradually, and the distribution characteristics were also changed. The maximum displacements concentrated in the center regions of the all PV modules, while the maximum stresses were occurring around the boundary regions. As the silicone sealant between the glass and boundary constraints was not considered in FEM, the stresses of the glass surface cannot be used as a criteria to determine its failure. The failure bending tensile stresses of silicon is about 200 MPa. Thus, the first and second mounting configurations could effectively support and protect the PV module while the third one is not recommended because the maximum stress (173.6 MPa) of the solar cell layer in this case was near to the limit value.

In structural dynamic problems, the response of a structure is usually dominated by a relatively small number of modes. Therefore, Table 3 just presents the first ten modes and the last one. And Fig.5 shows the first four modes. Obviously, different mounting configurations caused different vibration modes and frequencies because they changed the modules' boundary conditions.

The displacement curves of the middle point of back surfaces for three PV systems in dynamic analysis are shown in Fig.7, Fig.8 and Fig.9, respectively. For comparison, Fig.6 gives the displacements of the same point of three PV modules in static analysis under the same uniform pressure loading (2400 Pa). It can be seen that the dynamic displacement curves show obvious oscillations near some natural frequencies. That's because the corresponding modes of these frequencies have an obvious influence on the magnitude of the midpoint under loading condition along the Y-direction. For the first and second PV modules, the modes are the first and third ones; for the third PV module, the modes are the first and seventh ones.

The maximum absolute displacement of the three PV modules under static loading condition were 3.85 mm, 5.36 mm and 16.84 mm, respectively. While under dynamic loading condition they reached up to 26.417 mm, 34.408 mm and 414.382 mm, respectively. These deformations and stresses are large enough to cause cracks or fractures in the solar cell layer, even cause the damage or the failure of the entire PV module.

## 4. Conclusions

The ultra-thin double-glass PV module has a good performance under static loading conditions according to IEC 61215. Under the 5400 Pa uniform static load, the maximum deformation and stress of the PV system in four edges fixed manner were 6.392 mm and 61.18 MPa; and in six clamps fixed manner, they were 10.48 mm and 205.9 MPa respectively.

But under dynamic loading, both the displacements and stresses significantly increased, especially when the loading frequencies were near to some of natural frequencies. And the deformation were large enough to cause cracks or fractures in the solar cell layer, even the damage or failure for the whole PV module. For the ultra-thin PV modules, the manner of four corners being fixed was not recommended because its poor static and dynamic performance.

Due to the random characteristics of wind load, whose amplitude and frequencies vary with time, the dynamic performances of PV systems should be paid more attention on to ensure their safety and stability during the whole lifetime.

The mounting configurations have a significant influence on the static and dynamic performance of PV systems, so their design should be determined according to both the static and dynamic performance requirements. The design of the new PV modules and mounting configurations should avoid the resonance in their work stations and environment during the whole lifetime.

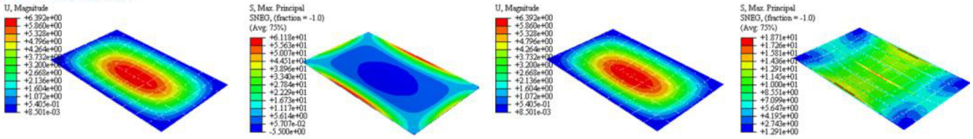
Table 2.The maximum displacements and stresses (Static,5400 Pa)

| Mounting configuration | displacement (mm) | | principal stress (MPa) | |
|---|---|---|---|---|
| | Whole module | Solar cell | Whole module | Solar cell |
| Four edges fixed | 6.392 | | 61.18 | 18.71 |
| Six clamps fixed | 10.48 | 9.931 | 205.9 | 63.95 |
| Four corners fixed | 22.78 | | 432.6 | 173.6 |

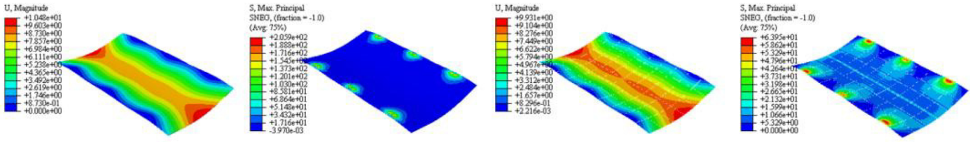
Table 3. Frequencies of PV system with three different mounting configurations (Hz)

| Mounting Configuration | Mode No. | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 50 |
| First system | 37.877 | 53.521 | 79.610 | 90.068 | 104.49 | 114.35 | 128.56 | 156.11 | 161.20 | 161.58 | 571.14 |
| Second system | 26.484 | 27.872 | 34.071 | 46.940 | 64.458 | 64.523 | 73.634 | 75.516 | 80.316 | 92.633 | 386.45 |
| Third system | 8.450 | 16.657 | 22.735 | 30.773 | 38.173 | 41.610 | 47.431 | 64.671 | 65.969 | 72.645 | 373.41 |

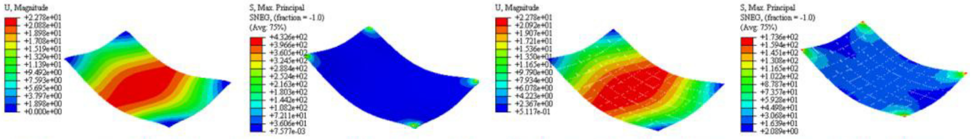
(a) Four edges fixed



(b) Six clamps fixed



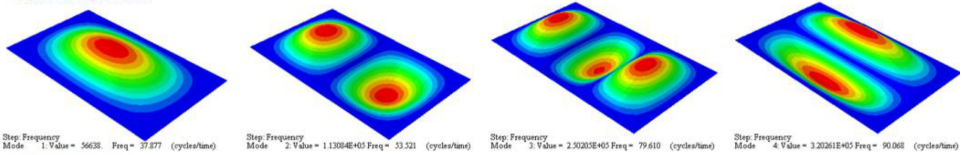
(c) Four corners fixed



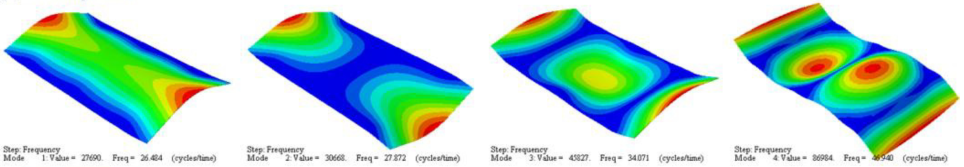
Displacements of the whole module Stresses of the whole module Displacements of solar cell layer Stresses of solar cell layer

Fig.4. The displacements and stresses of three PV systems (Static, 5400 Pa)

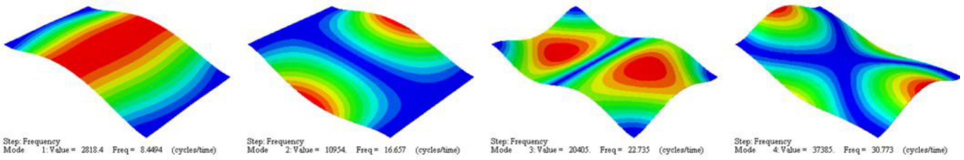
(a) Four edges fixed



(b) Six clamps fixed



(c) Four corners fixed



First mode Second mode Third mode Fourth mode

Fig.5 The first four modes of three PV systems

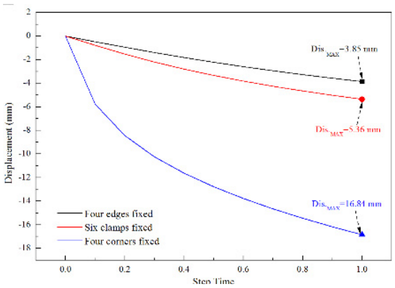


Fig. 6 The displacements of three system (static, 2400 Pa)

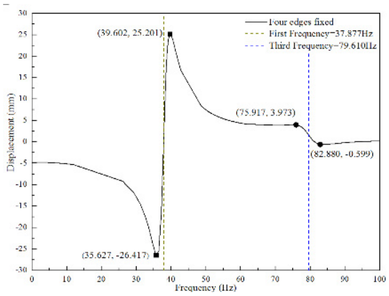


Fig. 7 The displacements of the first system (dynamic, 2400 Pa)

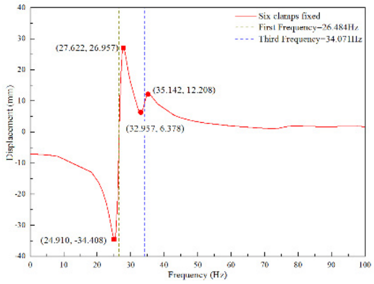


Fig. 8 The displacements of second system (dynamic, 2400 Pa)

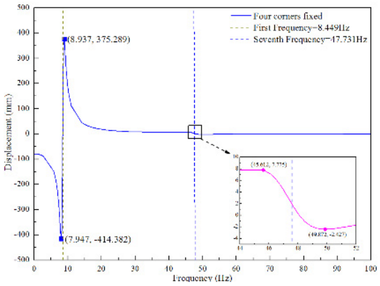


Fig. 9 The displacements of third system (dynamic, 2400 Pa)

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## Biography

Jinzhi DONG, PhD student from Civil Engineering of Tongji University. The major research interests lie in the seismic design, structure analysis, green building design, and solar energy application (BIPV).