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Experimental and theoretical research on bending behaviour of photovoltaic panels with a special boundary condition

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Abstract. Currently, the photovoltaic panels widely manufactured on market are composed of stiff front and back layers and the solar cells embedded in a soft polymeric interlayer. The wind and snow pressure are the usual loads to which working photovoltaic panels need to face, and it needs the panels keep undamaged under those pressure when they generate electricity. Therefore, an accurate and systematic research on bending behaviour of photovoltaic panels is important and necessary. In this paper classical lamination theory (CLT) considering soft interlayer is applied to build governing equations of the panel. A Rayleigh-Rita method is modified to solve the governing equations and calculate the static deformation and inter force of the photovoltaic panel. Different from many previous researches only analysing simply supported boundary condition for four edges, a special boundary condition which consists of two opposite edges simply supported and the others two free is studied in this paper. A closed form solution is derived out and used to do the numerical calculation. The corresponding bending experiments of photovoltaic panels are completed. Comparing the numerical results with experiment results, the accuracy of the analytical solutions are verified. The influence of boundary condition is shown by comparing the results with previous researches, and a guide for the photovoltaic panel installation is finally proposed based on those conclusions.

Keywords: photovoltaic panel; bending behaviour; classical lamination theory; Rayleigh-Rita method; special boundary condition; bending experiment

1. Introduction

According to the report from Ministry of Housing and Urban-Rural Department of P.R. China, building consumes 40% to 50% of the total energy in P.R. China each year, which is one of the main reasons for the aggravation of energy consumption. In order to solve it, building integrated photovoltaic (BIPV) has gained a great of attention and great advances in recent years. In BIPV, the photovoltaic (PV) module is designed and constructed with buildings at the same time, which makes it as one part of the building structure. Due to the requirements of lighting inside the building, the double glass PV module with better photopermeability are widely applied in the real structures. The photovoltaic panels studied in the present paper are just double glass PV module which consists of two glasses and an interlayer in where the cells are sealed by ethylene vinyl acetate (EVA) or polyvinyl butyral (PVB). Since the bending deformation under distributed force are both important to structural components and PV module [1], the bending behaviour of PV panels is studied carefully in the present paper to make sure that it has qualified stiffness and can work safety in BIPV. From 1990s, PV module designed to be integrated into building became commercially available and it promoted some relative research works [2]. One decade later, U.S. National Renewable Energy Laboratory (NREL)



promulgated a brief overview, in which the history of BIPV was summarized and some challenges about the BIPV future were stated [3]. Since it must satisfy the requirements of building component when the PV panel is installed as roof, wall or window in the BIPV building, the mechanical behaviour of it should be studied systematically. Naumenko and Eremeyev [4] believed that PV panel is the layered composite with relatively stiff skin layer and relatively soft core, and the layer-wise theory is suitable for it. They derived the differential equations based on layer-wise theory, but the equations are only solved for plate strip with simply supported boundary condition. Eisentrager etc. [5] adopted first order shear deformation theories (FSDT) to study the PV panel and laminated glass with weak shear stiffness. As to the theories and mechanic models for laminate composite, Vedrtnam and Pawar [6] made a review work on them and their introductions are mainly about the laminate glass plate which is extremely similar to PV panel. However, in many of works mentioned in that paper, the boundary conditions of the plates are all simply-supported for four edges.

The bending behaviour of PV panel is studied carefully in the present paper by both experimental and theoretical work. Different from many previous researches, a special boundary condition which is two opposite edges free and the other two edges simply-supported is considered. Hoff model which is one of the classical lamination theory (CLT) is adopted in this research. By the modified Rayleigh-Rita method, a closed form solution is derived out. The experiment is designed using water pressure to produce uniformly distributed force, so it is much more accurate than other research works using sand or brick. A frame is manufactured to simulate the special boundary conditions. Comparing the theoretical results with experimental results, the accuracy of the analytical solutions are verified. The theoretical model and solutions can be the fundamental works for the optimal design work in future.

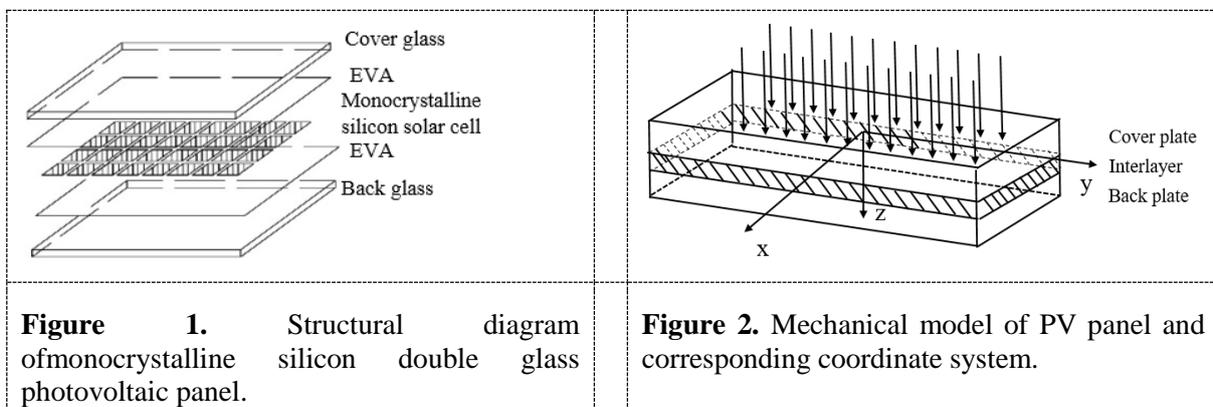
2. Structural analysis

2.1. Mechanical model and basic hypothesis

The basic components of PV panel are shown in figure 1, including cover glass, ethylene-vinylacetate (EVA), silicon solar cells and back glass. To simplify the problem and emphasize the main characters of the PV panel, a laminate plate model is applied and several hypotheses are made as follows.

- (1) The cover and backboard glasses are treated as top and bottom surfaces of the laminate plate, respectively. And both of them are simulated as isotropic plates with constant flexural rigidity.
- (2) The silicon solar cells layer is ignored and two EVA layers are merged as one layer which is defined as the interlayer of EVA.
- (3) The PV module is a soft core laminate plate and the stress of interlayer in x-y plan is ignored.
- (4) Only the anti-symmetrical deformation is studied in present paper, so $\sigma_z=0$, $\varepsilon_z=0$.

Based on those hypotheses, the mechanical model of PV panel under uniformly distributed force and the corresponding coordinate system are shown in figure 2.



2.2. Hoff model and governing equations

Hoff [7] modified Reissner theory and developed a Hoff model for laminated plate. In Hoff model, the flexural rigidities of surface plates are calculated but the interlayer is a relative soft layer. According to Hoff model, we could obtain the governing equations of PV panel under uniformly distributed force as

$$w = \omega - \frac{D}{C} \nabla^2 \omega \quad (1)$$

$$(D + 2D_f) \nabla^2 \nabla^2 \omega - \frac{2DD_f}{C} \nabla^2 \nabla^2 \nabla^2 \omega = q \quad (2)$$

$$\frac{1}{2} D (1 - \nu_f) \nabla^2 f - Cf = 0 \quad (3)$$

$$\text{with } D = \frac{E_f (h+t)^2 t}{2(1-\nu_f^2)}, \quad D_f = \frac{E_f t^3}{12(1-\nu_f^2)}, \quad C = G_c \frac{(h+t)^2}{h}$$

where E_f is the elastic modulus of the cover and the back glass plate, ν_f is the Poisson's ratio of the cover and the back glass plate, G_c is the shear modulus of EVA, t and h are the thickness of surface plate and EVA interlayer, respectively.

2.3. Special boundary condition

In previous reseachs, in order to simplify the problem, all four edges simply supported boudnary condition is mostly studied. In present paper, a special boudnary condition which is two opposite edges simply supported and the other two free is studied. The PV panel is simply supported at the edges $x=0$ and a , and free-free at the edges $y = \pm 0.5b$.

The boundary condition studied in present paper should satisfy the formulas as follows.

$$(M_x)_{x=0,a} = 0, (w)_{x=0,a} = 0, (\varphi_y)_{x=0,a} = 0, (M_x)_{x=0,a} = 0 \quad (4)$$

$$(M_y)_{y=\pm \frac{b}{2}} = 0, (M_{xy})_{y=\pm \frac{b}{2}} = 0, (M_{xy})_{y=\pm \frac{b}{2}} = 0, (Q_y)_{y=\pm \frac{b}{2}} = 0, (M_y)_{y=\pm \frac{b}{2}} = 0 \quad (5)$$

2.4. Modified Rayleigh-Rita method and closed-form solutions

A modified Rayleigh-Rita method is applied in present paper due to the special boundary condition. The deflection of PV panel under uniformly distributed force could be derived out as follows.

$$\begin{aligned} w &= \omega - \frac{D}{C} \nabla^2 \omega \\ &= \sum_{n=1}^{\infty} \left\{ \sum_{r=1}^6 e^{\lambda_{nr} y} \omega_{nr} + \frac{2q}{n\pi} [1 - \cos(n\pi)] \frac{1}{A_1 k_n^4 + A_2 k_n^6} \right\} \sin(k_n x) \\ &\quad - \frac{D}{C} \sum_{n=1}^{\infty} \left\{ \sum_{r=1}^6 [(-k_n^2) e^{\lambda_{nr} y} \omega_{nr} + \lambda_{nr}^2 e^{\lambda_{nr} y} \omega_{nr}] + (-k_n^2) \frac{2q}{n\pi} [1 - \cos(n\pi)] \frac{1}{A_1 k_n^4 + A_2 k_n^6} \right\} \sin(k_n x) \end{aligned} \quad (6)$$

2.5. Finite element analysis

To verify the results of Hoff model, a finite element analysis is performed by the use of ANSYS code. SHELL181 composite shell element is used for modeling. The rectangular shell structure is divided into five layers and they are cover glass, EVA, silicon battery sheet, EVA and back glass and the material of each layer is simulated as isotropic material. The mechanical properties of the model materials are shown in table 1.

Table 1. Material parameter values.

| Material | Parameter values | | |
|-----------------------------|----------------------------|---------------|---------------|
| | Modulus of elasticity /MPa | Poisson ratio | Thickness /mm |
| Reinforced glass | 7.2E+4 | 0.2 | 2 |
| Crystalline silicon battery | 1.44E+5 | 0.28 | 0.2 |
| EVA | 3.5E+1 | 0.3 | 0.8 |

3. Experimental analysis

Bending testing is performed for 8 specimens at room temperature and all of them are double glass photovoltaic modules (as shown in figure 3) which are provided by Suzhou Tenghui Photovoltaic Technology Co., Ltd. Five specimens are with size 1658×995×5 (unit: mm) and three specimens are with size 1658×995×7.4 (unit: mm). The cover and back glasses are 2mm for first group and 3.2mm for the second group, but the thickness of interlayer is same as 1mm.



Figure 3. Monocrystalline silicon double glass photovoltaic module.



Figure 4. The test frame for installing photovoltaic module.

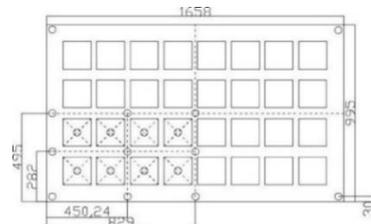


Figure 5. Arrangement diagram of strain measurement point (unit: mm).

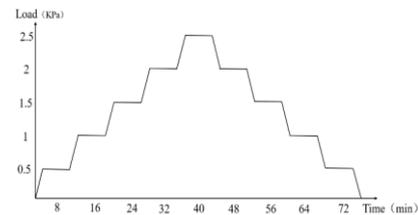


Figure 6. Test loading scheme for PV panels with 2mm glass.

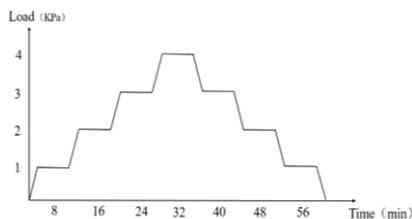


Figure 7. Test loading scheme for PV panels with 3.2mm glass.



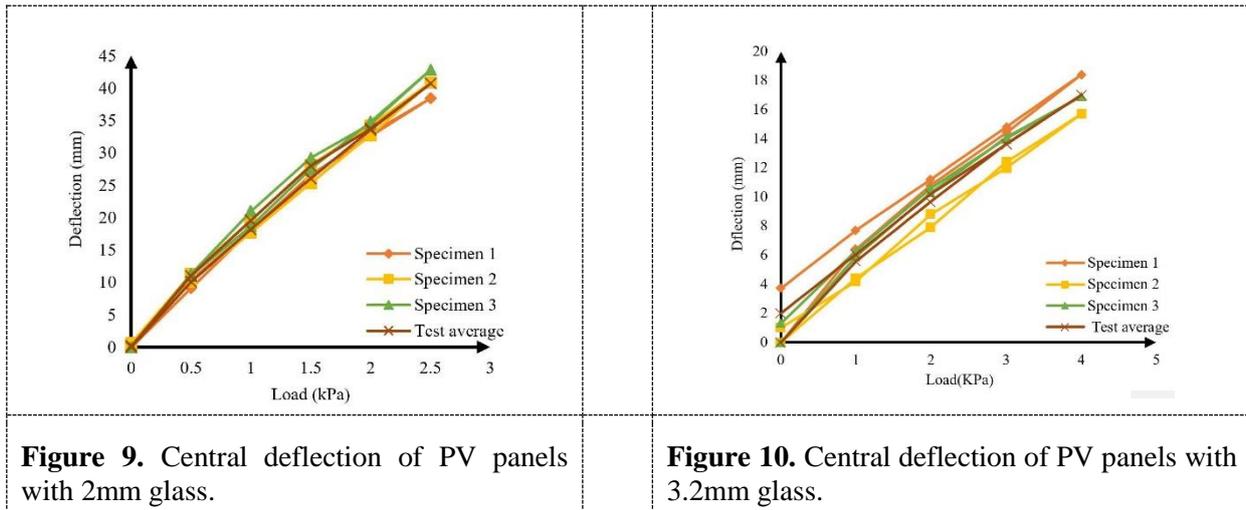
Figure 8. Test site.

The bending test was completed in National Photovoltaic Product Quality Supervision and Inspection Center at Chengdu, referring to the current quality inspection certification, IEC 61215[1]. The test frame (as shown in figure 4) can simulate the discussed special boundary condition. The strain measurement points are only set on a quarter part which is shown as figure 5. The PV panel strains are

collected by DH3816 static strain gauge, and the deflection at panel center is measured by a laser displacement meter installed under the panel. Different from previous experiments, water pressure is used to simulate the uniformly distributed force. The loading plan is different for two groups of PV panels since the bending behavior of them is different (as shown in figure 6 and figure 7).

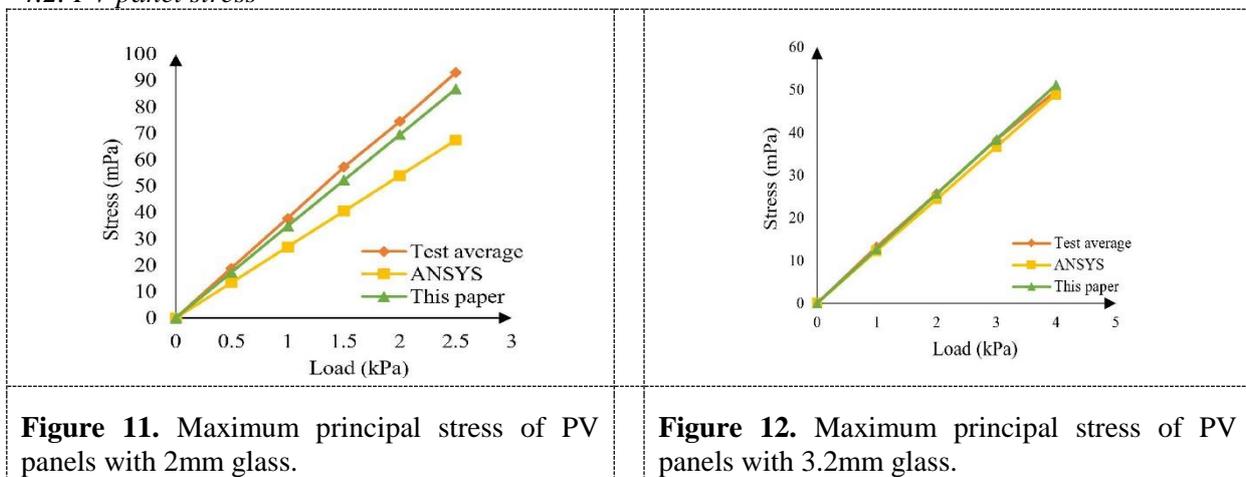
4. Verifications and discussions

4.1. PV panel deflection



From figure 9, the deflections calculated by both ANSYS and equation (6) are very close to the data measured in the test, so the accuracy of the proposed equations is proved. The deflections from ANSYS and equation (6) behave a linear elastic relationship, which is same as the test data. But equation (6) is better than ANSYS to predict the maximum deflection of PV panel. The figure 10 states clearly the linear elastic deformation of PV panel with 3.2mm glass too. And the proposed equations are more accurate. After the test, all the specimens were checked carefully and there was not nay cracks or breakages on the surface glass. It proves the safety of the PV panels, which just satisfy the requirements from the PV module certification, IEC 61215[1].

4.2. PV panel stress



In figure 11, the central stress calculated by proposed equations is much better than the ones from ANSYS. It is the same in figure 12 to the PV panels with 3.2mm glass. The accuracy of the proposed equations on the stress calculation is verified by those comparisons. From both figure 11 and figure 12, the central stresses calculated by equation (6) or ANSYS have a linear relationship to the water pressure, which is same as the deflection behaviour concluded in section 4.1. Comparing figure 11 with figure 12, with the increase of surface glass thickness, the central stress decreases clearly. The maximum stresses on the surface glass of PV panels are smaller than the limit stress of reinforced glass, so it is safe when they are used under those loads.

5. Conclusions and recommendations

The aim of this paper is to study the bending behaviour of the double glass PV panel with a special boundary condition, which is two opposite edge simply supported and the other two edges free. Both experimental and theoretical works are completed.

Based on the results we may conclude as follows:

- Hoff model is adopted in this research to describe the bending behaviour of PV panel. By using a modified Rayleigh-Rita method, a closed form solution is derived out.
- In experimental works, the special boundary condition is realized by a specific frame. The water is applied to provide uniformly distributed force instead of the sand or bricks.
- In both deflection and stress analysis, the calculation results obtained by ANSYS or proposed equation are very close to the experimental results.
- The deflection and stress calculated by proposed equation are more accurate than the ones simulated by ANSYS, so it can be used in the optimal design work of BIPV component.
- When the load is in a range of 2.4Kpa which is required by current certification of PV module, the PV panels behave a linear elastic deformation and there is not any damage.
- Both maximum deflection and maximum stress are located at the middle of PV panel, and it should be chosen as the key position and key point in future design work.
- With the increase of surface glass, the stress of PV panel decreases clearly. It is safer to choose thicker glass in the design work but the economy will be a problem.

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