Numerical analysis and Ultimate loading test of failure criteria for double-grazed PV modules

Chao Wang[1, a,] *, Zhenyang Feng[1, b], Yangdong Ni[2, c], Yubin Zhen[3, d]

[1] School of Mechanical Engineering, Changshu Institute of Technology, Changshu 215500, China

[2] System technology center, Canadian Solar Inc., Suzhou 215000, China

[3] Changshu R&D Institute of Technology, Dalian University of Technology, Changshu 215500, China

[a]cslgcw@cslg.edu.cn, [b]1842026970@qq.com, [c]yangdong.ni@canadiansolar.com, dzybwl@163.com

Keywords: double-glazed PV module, failure criteria, ultimate loadings, fixture contact

Abstract: The double-glazed photo-voltaic (PV) module has many advantages with comparing to traditional PV module in the solar industry. A PV module of a large area is going to bear large mechanical loadings from wind blowing and raining after installation. Therefore, the ultimate loading and failure criteria of the module are necessary to be investigated. In experiments, the loading was applied from the air cylinder squeezing machine. With experimental results by applying loadings on front or back sides, various finite element models were developed. The model with the EVA layer was conducted to be most accurate in predicting stress distribution and displacement. And a solid and shell combined model was further developed with considering clamping effect. Moreover, the stress predicted by the membrane element is more dependable. According to experimental and simulated results, the ultimate loading of the double-glazed PV module can be considered as +5400 Pa and -3200 Pa. And 60 MPa should be set at a critical point to a failure by developed FE model. With the established finite element model and ultimate loading tests, the failure criteria of double-glazed PV modules were well determined. Meanwhile, the method presented in this study could apply to design new products with various materials, dimensions of structure and fixture.

1. Introduction

In the solar energy industry, the reliability of mounting technology is particularly important to be investigated. To solve problems during outdoor use, the mounting technology of double-glazed method shows lots of advantages compared to the traditional single-glass method. Such as the problems of water vapor penetration, embrittlement, wrinkling is greatly improved. Nowadays, semi-tempered glass is safe enough to be used as a reliable structural material for bearing lager loadings [1]. The double glass component replaces the traditional backing plate with semi-tempered glass, which avoids the using of the aluminum alloy frame. This structure reduces the manufacturing cost and meets the production criteria for green manufacturing.

As photovoltaic (PV) modules with the large area have a risk of fracture due to wind blowing and raining in outdoor use. A trend of investigating failure criteria has been established to improve the structure reliability [2].

Only depend on loading test experiments could not determine the quality of the product itself and evaluate the failure point accurately. Besides, analyzing and optimizing the dimensions of structure and fixture need numerous experiments, which are a time-consuming work. The numerical simulation with finite element method is convenient and effective to avoid most of the experiments [3]. Early in 1976, Tsai et al. Study the stress field and deflection of a glass plate under wind blowing with numerical simulation [4]. They indicated that the performance capabilities of glass plates can be evaluated accurately when a combination of stress analysis and theory of probabilistic failure of brittle material is used. Failure analysis of tempered glass structure with pin-loaded joints or fixtures has been widely studied by applying FE modeling [5–8]. This study developed various finite element models with different features to establish a failure criterion of the double-glazed PV module. Firstly, with correct material properties and standard loading tests, the most accurate finite element model was developed. In this step, the model with the EVA materiel model was confirmed most effectively to predict stress distribution and displacement according to experimental results. With this obtained the finite element model and ultimate loading tests, the failure stress of double-glazed PV module was determined. Also, the membrane element was considered more suitable to predict stress distribution with a hypothesis of no shear deflection for this structure. To study fracture behavior under dynamic loading, LoadSpot is adopted by many researchers. It was developed to make the surface of module unobstructed during mechanical loading tests [9]. In this study, the ultimate loading tests were performed under air cylinder loading equipment, which simulated the loading in an outdoor situation.

Through the established finite element model and ultimate loading tests, the failure criteria of the double-glazed PV modules were well determined. Finally, the failure process of double-glazed PV module with fixtures is analyzed by experiments and numerical simulation. In which, contact, friction, stress, and deflection are involved. Meanwhile, the method presented in this study could apply to design new products with various materials, dimensions of structure and fixture.

2. Experimental procedure

2.1. Surface Strength Test of Semi-tempered glass

The surface strength of the semi-tempered glass is an important parameter in the ultimate loading tests of double-glazed PV module. Hence, it is necessary to be tested for helping to study the failure criteria. To obtain a reliable result, five pieces of semi-tempered glass were all tested by SSM-II surface stress tester. Moreover, five positions in each piece were chosen as test points and each point was tested over 2 times. The average surface stress intensity of five pieces was 70.44 MPa and the lowest stress intensity was 65.4 MPa. The 65.4 MPa was selected as the surface strength of semi-semi-tempered to ensure the result of the ultimate loading test could be reliable.

2.2. Displacement Test

The displacement test was conducted with air cylinders as shown in Figure 1. To confirm the accuracy of developed FE models, the displacements at 3 different loading conditions were investigated. The displacements at endpoint, midpoint of the short side, midpoint of the long side and centre point were measured under each loading condition. The measured results were listed in Table 1. Here, +2400 Pa means a loading of 2400 Pa applied at the front side and -2400 Pa means a loading of 2400 Pa applied at backside.

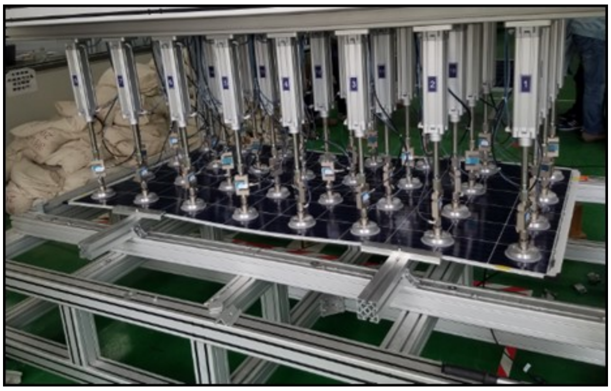

Fig. 1 Displacement test with air cylinder.

Table 1 Standard displacement test (mm)

Position	+2400 Pa	+5400 Pa	-2400 Pa
End point	7.22	10.19	11.58
Midpoint of short side	11.25	16.83	30.86
Midpoint of long side	11.5	15.74	18.37
Centre point	17	20.75	34

The displacement of the double-glazed PV module is slightly increased when the front loading increased from +2400 Pa to +5400 Pa. However, the displacement has a significant difference between front loading and back loading. For applying -2400 Pa at backside, the displacements of four points were all increased greatly. Inside, the displacement of centre point was increased from 17mm to 34mm. The reason could be summarized as the fixture structure lead to a different arm of force when applying loadings at the front side or backside. At last, the average displacement at +5400 Pa was adopted to validate the FE model.

2.3. Ultimate loading Test

The ultimate loading test was carried out to set up the failure criteria of double-glazed PV module. Failure criteria were consisting of failure loading and failure time in this study. The double-glazed PV module leads to failure with a large loading in a short failure time. Besides, to ensure the consistency of experimental results, the loading increase step size was 200 Pa and the fixture settings were the same.

With numerous ultimate loading tests, +5400 Pa and -3200 Pa were confirmed as the maximum loading of double-glazed PV module. The results of maximum displacement and failure time were listed in Table 2. Here, fixtures had a plastic deflection under -3200 Pa loading.

Table 2 Ultimate loading test

Loading	Max displacement	Failure time(min)
+5400	21	15
-3200	34	4

3. Numerical simulation

With built-in material and established material models, ABAQUS is an appropriate FEA package for simulating loadings which applied on double-glazed PV module. In this study, the ABAQUS was used to simulate displacement and stress distribution induced by loading at the front side or backside, and the results were compared with experimental measurements.

In the material modelling of glass, Zhang et al. found that Young's modulus for glass is relatively insensitive to strain rate, and it is suggested to use the static value [10]. Hence, 70GPa was adopted in this study.

Besides the parts of glass, the middle layer is the material of EVA. To et al. found resin material connect with glass is necessary to be analysed as it has a great influence on stress distribution [11]. In this study, the material of glass and EVA layer existed between two glasses were modelled as linear-elastic material, and the parameters are shown in Table 3. Besides, the shear module and compress module could be calculated as Eq. (1) and Eq. (2).

$$G_0 = E_0[2(1 + \upsilon_0)] \quad (1)$$

$$K_0 = E_0/[3(1 - 2V_0)] \quad (2)$$

Table 3 Material parameters for glass and EVA layer

Item	Density (Kg/m^3)	Young's modulus E (MPa)	Poisson's ration ν
Semi-tempered glass	2500	70000	0.22
EVA layer	1200	11	0.495

3.1. Modeling of clamping effect

The double-glazed PV module was installed by aluminium fixtures. The dimensions and positions of the fixture have a significant effect on the failure criteria of double-glazed PV module [12]. As well as the plastic deflection would even be caused under large loadings at experiments. Hence, the fixture with 250mm long and 60mm wide was modelled and set up a corresponding experimental situation. The modelling of the clamping effect was carried out by building corresponding elements and considering contact effects [13]. Shell elements were used to connect the fixture and glass. Panait has modelled the friction between aluminium and glass as a function of loading time as Eq. (3)[14]. As the loading was assumed as transient in this study, the friction factor in this study was set up as 0.2. The schematic of the fixture model is shown in Figure 2.

$$\mu = [1 + \frac{\beta}{\alpha}(1 - e^{-\alpha t}) + \frac{\gamma}{\delta}(1 - e^{-\delta t})]\mu_0 \quad (3)$$

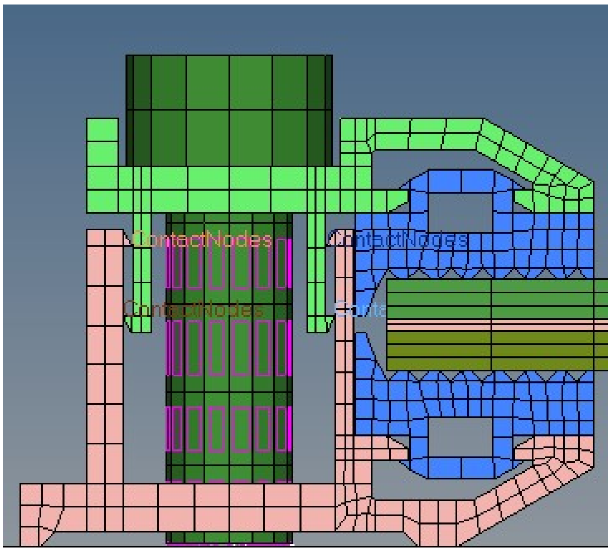

Fig.2 Side view of fixture model

3.2. Optimization of Finite Element Model

As mentioned above, the appropriate FE model among various FE models was validated with experimental measurements. With different element sizes, layer numbers, contact conditions and consideration of EVA layer, various FE models were developed. The calculated displacements under +5400 Pa from two represent FE models are listed in Table 4. Both two models have three layers of elements and make two glass was independent parts. But only model 2 considered the EVA layer between two parts. From Figure 3, the displacements of the midpoint of long side and centre point was well predicted by both two models. However, there existed a difference around 17~25% at endpoint. This was considered to be the leading way of the air cylinder was concentrated which made the displacement at the centre larger while the displacement at the edges smaller. Moreover, model 2 with the EVA layer is believed to be more accurate in predicting stress distribution than model 1.

As the model 2 with EVA layer was slightly better than model 1. It was recommended to be used to analyse stress distribution and displacement of the double-glazed PV module in the later study.

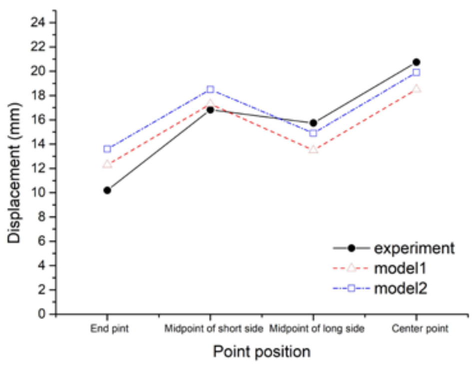

Fig.3 Displacement predicted by FE models

3.3. Modelling of Ultimate Loading

With results of ultimate loading tests, the failure stress was determined to some extent. At the same time, the failure stress induced by loading was sure to larger than the surface strength of semi-tempered glass. To further study the failure criteria of double-glazed PV module, the effects of loading on the displacement and stress distribution were analysed by numerical simulation. In this stage, solid element and membrane element were compared. The maximum stress and displacement obtained from the solid element and membrane element are shown in Table 4. Here, the predicted displacements were almost the same while the maximum stress predicted by the membrane element was larger than that of the solid element. As it was confirmed that the stress induced by +5400 Pa and -3200 Pa were an approach to the surface strength of semi-tempered glass. The stress predicted by the membrane element is more dependable.

Table 4 Simulation results of loading tests (mm)

Loading	Solid Element		Membrane Element	
	Stress	Displacement	Stress	Displacement
+5400	50.3	18.5	59	18.4
-2400	36.8	22.1	45.4	22.1
-3200	49.7	29.1	60.5	29

The maximum stress and displacement predicted by the FE models are shown in Table 5. When the loadings are applied from -3200 Pa to +5400 Pa, stress around 60 MPa were predicted by FE model. In ultimate loading tests, +5400 Pa and -3200 Pa were led to fracture as they made stress exceed surface strength of semi-tempered glass. While the surface strength of semi-tempered glass was determined as 65 MPa from experimental measurements. Hence, the model developed in this study could set the failure criteria at 60 MPa. Which means while calculated stress exceeds 60 MPa, the semi-tempered glass, as well as the double-glazed PV module, would lead to fracture. Meanwhile, the displacement under +5400 ~ +6000 Pa was further calculated to describe the failure criteria. The calculated stress and displacement were also shown in Table 5.

Table 5 stress and displacement under +5400 ~ 6000 Pa (mm)

Loading	Simulation		Experiment
	Stress	Displacement	displacement
-3400	64	30.7	35
-3200	60.5	29	33
-3000	56.8	27.3	31
-2800	52.9	25.6	27
-2600	49.3	23.8	26
-2400	45.4	22.1	26
+5400	59	18.4	19.1
+5600	60.88	18.7	21
+5800	62.7	19.1	23
+6000	64.6	19.4	23

The calculated Von-Mises stress distribution under +5400 Pa was shown in Figure 4. The maximum stress appeared at the contact plane between the module and fixture. And the maximum stress is around 59 MPa. The displacement calculated by the FE model was also shown in Figure 5. From this figure, it could be found out distinctly that the displacement at midpoint of the short side is larger than that at midpoint of the long side.

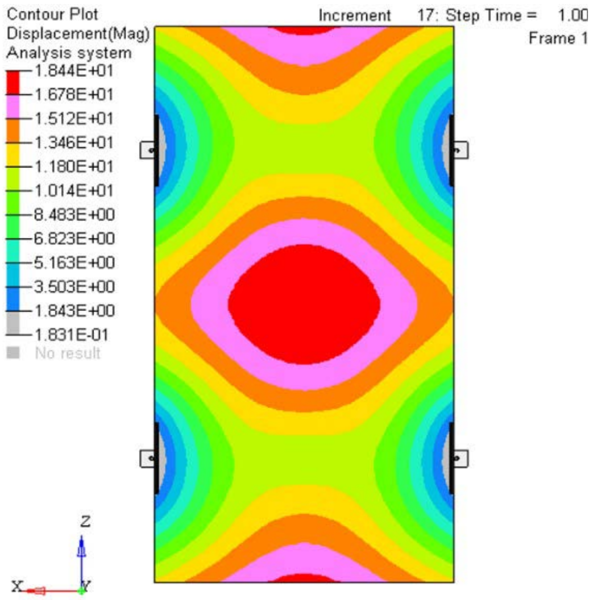

Fig.4 Stress distribution under +5400 Pa

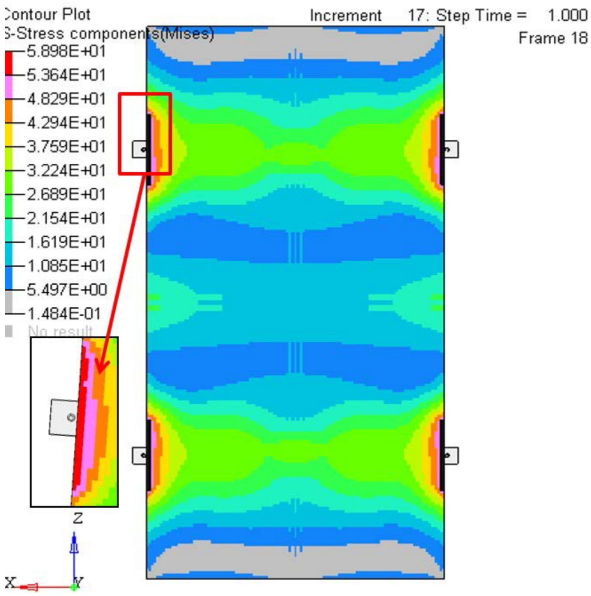

Fig.5 Displacement under +5400 Pa

4. Conclusions

In this study, the failure criteria of double-glazed PV module were determined by the finite element model and experimental investigation. Due to the loadings applied by the air cylinder is concentrated. The predict displacements at endpoints appeared an error from 17~25%. However, the displacements at other points and stress distribution were well predicted. A consistent conclusion was obtained by experimental results and numerical simulation, which could determine the failure stress of double-glazed PV module effectively. The finite element model developed in this study would contribute to optimize the design of double-glazed PV module and corresponding fixture.

(1) The ultimate loading of the double-glazed PV module can be considered as +5400 Pa and -3200 Pa, at which the double-glazed PV module would lead to a failure around 15 mins and 4 mins.

(2) Although the surface strength of semi-tempered glass was considered as 65 MPa by experimental measurements, the critical point of failure by the developed FE model was determined at 60 MPa.

(3) The material model of EVE layer was adopted in the developed FE model, which made the displacement and stress distribution well predicted.

(4) The stress distribution is suggested to be extracted from membrane element instead of the solid element. As the semi-tempered glass was assumed to fracture when the stress at surface exceeds the critical point.

Acknowledgments

This work was financially supported by Research start-up funds of Changshu Institute of Technology (KYZ2017040Z) and Jiangsu Key Laboratory of Recyling and Reuse Technology for Mechanical and Electronic Products (RRME201906).

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