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Stress Analysis of Silicon Wafer-Based Photovoltaic Modules Under IEC 61215 Mechanical Load Test

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Abstract

Snow loading poses a significant problem to the integrity of photovoltaic (PV) modules. The weight of accumulated snow exerted on the PV modules can cause breakage of the glass cover and cells. The mechanical load test in IEC 61215 is designed to test the reliability of PV modules subjected to 2400 Pa, and subsequently to 5400 Pa of uniform load, in the revised standard. In this paper, finite element analysis is conducted to study the stresses in PV modules with non-tempered float glass, subjected to conditions in the mechanical load test. In this analysis, residual stresses that are induced during the module lamination process are taken into account in order to give an accurate representation of the existing stresses in the module. These residual stresses arise when the temperature of the PV laminate is lowered from the lamination temperature (typically 145 ºC) to room temperature, due to the differences in coefficient of thermal expansion (CTE) of the constituent PV laminate materials. The results show that in the glass cover of the PV module, the region around the point where the aluminium frame of the module is secured experiences a high tensile principal stress, which may cause the glass to fracture. The solar cells experience tensile stresses, but this is not crucial as the values do not approach the failure stress of the silicon cells.

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1. Introduction

Photovoltaic (PV) modules are expected to have a lifetime of at least 20 years in the field. To ensure this, the mechanical integrity of PV modules is of great importance. In countries which experience heavy and continuous snowfall, snow loading poses a significant problem to the integrity of PV modules. The weight of accumulated snow exerted on the PV modules can cause breakage of the glass cover and cells. Figure 1 shows the clearing of accumulated snow off PV modules [1].

Fig. 1. Clearing of accumulated snow off PV modules [1]

A PV module is made up of several layers of different materials bonded together. One of the most common is the glass/EVA/cell/EVA/backsheet laminate. During the lamination process, a high temperature is required to cure the ethylvinylacetate (EVA) which acts as the bonding material. The cells are embedded in the EVA, and the glass and backsheet layers are also adhered to the EVA. Due to the differences in the coefficients of thermal expansion (CTE) of the materials, warpage and deformation of the laminate occur and stresses are induced in the laminate as the temperature is brought down to room temperature. After the lamination process, the laminate is framed up, secured onto a support structure, and put into operation under the sun. For clarity, in this paper an unframed solar module is called a PV laminate and a framed one is called a PV module.

IEC 61215 consists of the examination of all the parameters which contribute to the ageing of PV modules and describes the range of qualification tests required for certification. In particular, the mechanical load test in IEC 61215 is appropriate for the qualification of the PV module subjected to snow loading. The standard (IEC 61215) specifies the mechanical load test to be performed on one module after damp heat exposure. Kajari-Schröder *et al.* [2] presented results from 27 modules that have been investigated with research purposes. No major visible damage and degradation of the maximum power output at standard test conditions (STC) is to be observed for a PV module to pass the test. In this paper, a uniform loading of 5400 Pa is applied to a PV module in the Finite Element Analysis (FEA) simulations to examine the stresses experienced by the PV module in the mechanical load test.

PV modules are exposed to heavy loads in their lifetime. During production, the soldering and lamination processes can lead to small cracks in the solar cells. These grow due to thermo mechanical loads as experienced in day and night as well as summer and winter cycles in the outdoors. The most consequential mechanical loads for PV modules after manufacturing result from transportation [3, 4] as well as from wind and snow loads [5-7]. Any of these mechanical loads may lead to cracks in wafer-based solar cells. To make it more challenging, the PV industry is moving to larger and thinner silicon wafers to reduce costs [8]. The thickness of the wafers has decreased from about 300 μm in 2003 to about 150 μm in 2010 [9]. As wafers get thinner, considerations have to be given to their mechanical strength as they are more sensitive to mechanical damages. Some studies have been conducted to analyze the stresses in wafers during the manufacturing cycle where the wafers are subjected to mechanical loads such as sawing, manual handling, liquid jets, transport systems and pick and place equipment [10]. Breakage analysis of Si wafers during handling and transport has also been done by a combination of wafer deformation measurements and finite element analysis [11]. Stress analysis of solar cells has also been taken to the PV pre-lamination process of soldering, to determine the residual stresses induced by this process [12, 13]. In relation to IEC 61215 tests, push and pull loads with 5400 Pa uniform distribution are applied on PV modules to determine the spatial distribution of cracks in PV modules. This also helps to assess how the crack orientation in solar cells affects the criticality of cracks. It could be shown that cracks parallel to the busbars have substantial impact on the power output of the PV modules [2, 14]. A solar module, with its different materials and mounting, is a complex system [15]. Different types of mounting systems will result in different stress situations within the PV module. In [16], four types of mounting systems: long edge and line support (LSL), long edge and two clips per edge (LSC), short edge and line support (SSL) and short edge and two clips per edge (SSC) are compared for mechanical load testing to determine which type of mounting system would results in less cell failure during mechanical load testing. The frame in the finite element model used in this paper should closely resemble the LSC mounting. It is secured at the quarter length of the frame along the long edge, however there is no mention in Dietrich's paper as to where the two clips are secured on the LSC frame. In addition, results of the LSC frame is not presented in Dietrich's paper, hence accurate comparison of results may be difficult. Crack formation and crack growth in encapsulated cells during mechanical load testing are also investigated in [17].

In this paper, the mechanical stresses of a PV module under a 5400 Pa uniform loading in accordance to IEC 61215 are studied using FEA. The stresses induced in the non-tempered float glass as well as in the silicon cells are investigated. The impact of snow loading on PV modules in practical cases can thus be studied.

2. Simulation model

The modelled PV laminate has the dimensions of an actual 12×6-cell laminate, measuring 1580 mm by 790 mm. The solar cells used are monocrystalline silicon wafer cells, each measuring 125 mm by 125 mm. Each solar cell is separated from its neighboring cells by a gap of 2 mm. The row of cells along the width is 21 mm from the frame while that along the length is 6 mm from the frame. The copper ribbons providing the series connection of the cells are not modeled, to reduce the complexity of the model. Details of simulations involving stringed cells with copper ribbons can be found in [15] and [18]. However, the bus-bar that links each column of cells at the top and bottom of the laminate is modelled as they may have an effect on the temperature distribution over the module exposed to the sun. The layers within the PV laminate consist of a top glass cover, solar cells and busbar, ethylvinylacetate (EVA) and Tedlar backsheet. Their thicknesses are 3.2 mm, 240 μm, 400 μm and 350 μm respectively. The solar cells and busbar are embedded in the EVA. Figure 2 shows the cross-section of the framed PV module and Table 1 gives the properties of the materials used.

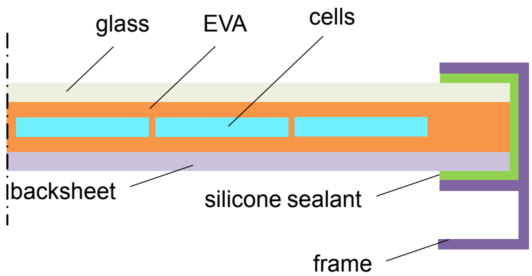

Fig. 2. Cross section of one half of the PV module

Table 1. Material properties

Material	Young's modulus/ GPa	Poisson ratio	CTE/ ppm
Glass	66	0.23	4.5
EVA	0.0677	0.33	90
Silicon	112.4	0.28	2.49
Backsheet	2.075	0.33	88
Aluminium	69	0.33	23.4
Silicone sealant	1	0.33	270

3. Simulation methodology

3.1. Lamination process

The model used in this step of the simulation is the PV laminate consisting of the glass sheet, EVA, cells and backsheet only. To cut down on computational cost and effort, symmetry of the laminate about the x and y axes is made use of, and thus, only a quarter model is required.

The laminate is placed such that the glass cover is on top and the backsheet layer is in contact with a surface such as a tabletop. Initial simulations have indicated that the edges of the laminate have approximately zero displacement from the tabletop, with only the centre of the laminate bowing upwards after the lamination process. Hence, a boundary condition of zero displacement is the z direction is applied to the edges of the laminate. Weight is taken into consideration by the application of gravity in the z-direction. During the actual lamination process, the assembled layers are pressed together in the laminator to remove any air that may be trapped in the layers. The temperature is then raised. At 120 °C, the EVA will start to soften. The temperature will be increased further to between 140 °C to 150 °C. At this higher temperature, the EVA will then be cured and the layers start to bond to one another [19]. At this higher temperature, called the lamination temperature, the laminate is at a stress-free state. Stresses will only be induced when the laminate subsequently cools down, due to the difference in CTE of the materials. For the purpose of this simulation, the lamination temperature is taken to be 145 °C. In the subsequent step of the simulation, the temperature of the laminate is brought down to a room temperature of 30 °C.

3.2. Mechanical loading

The laminate is then placed in an aluminum frame as shown in Fig. 2 and silicone is used to fill up the gap between the laminate and the frame at room temperature to form the PV module. When the PV module thus formed is then applied with a uniform loading, the residual stress in the laminate will redistribute, and stresses in the silicone sealant and aluminum frame to be induced. To perform the FEA of the stress distribution in the PV module subjected to mechanical loading, the initial stress distribution and deformation of the laminate obtained earlier from the FE simulation of the lamination process are first imported into the FE model. The silicone sealant and aluminium frame are then included in this model. As stipulated in IEC 61215, the mounting of the PV module structure is to be done as per the manufacturer's instructions. In the simulation model, a hole for fixing the PV module to a support structure is created at the quarter length of the frame and given the encastre boundary condition which constrains its displacement and rotation in all directions. A uniform distribution of 5400 Pa is then applied on the upper surface of the PV module.

4. Results and discussion

The stress distribution in the non-tempered glass cover of the PV module is shown in Fig. 3, where the units used in the scale is Pa. The region around the point where the aluminium frame of the module is secured experiences a high tensile principal stress, with the highest value at 207.6 MPa. This implies that failure due to fracture is bound to occur when a 5400 Pa uniform load is applied as the tensile strength of float glass ranges from only 24 MPa to 69 MPa [20].

The stress distribution in the cells of the glass cover is shown in Fig. 4. The cells near the centre of the modules experience tensile stresses, with the cell at the centre of the module experiencing the highest tensile stress of 106 MPa. The cells at the edges of the modules experience compressive stress, hence they are safe from fracture. The mechanical strength of a cell is dependent on the processing parameters and cell crystallinity. Four-point bending tests have been conducted on cell specimens of varying etching conditions during manufacturing, crystallinity, aluminium paste type and aluminium paste thickness [21]. From these studies, the bending tensile stresses at fracture in silicon are investigated and a range of values obtained. The failure bending tensile stress of silicon is about 200 MPa [21]. Stresses induced in the mechanical load test are lower than the maximum tensile stress of silicon, but as silicon is a brittle material that shows a large scattering of fracture stress, and practical experiments indicate the failure of silicon under the same situation, the simulated stress value may not be a foolproof indicator of reliability.

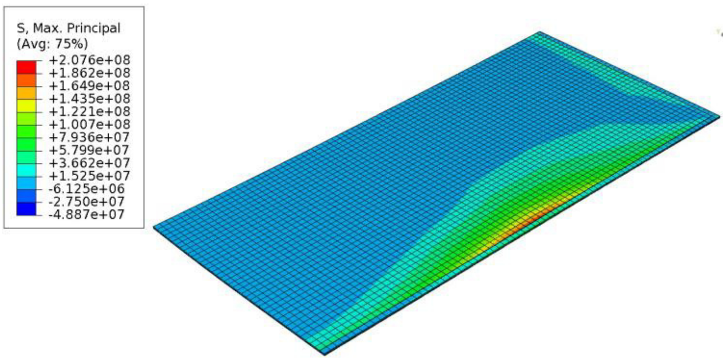

Fig. 3. Maximum principal stresses (Pa) in the non-tempered float glass cover

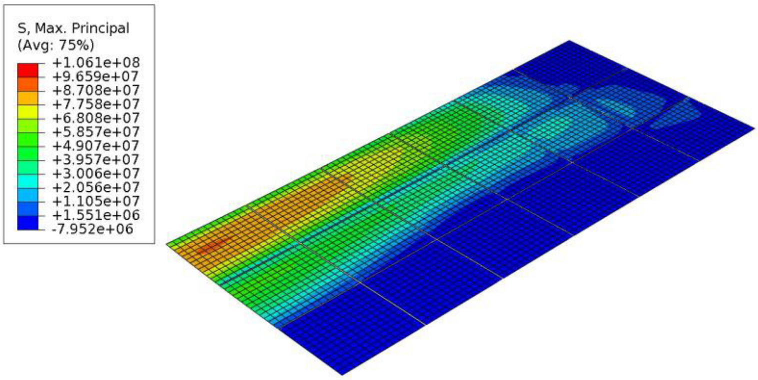

Fig. 4. Maximum principal stresses (Pa) in the cells of the PV module

5. Conclusions

A non-tempered glass PV module is successfully modelled with a finite element package and mechanical analysis was conducted for the situation when the modules were subjected to a 5400 Pa uniform load, as stipulated in the mechanical load test in IEC 61215. Failure due to fracture is bound to occur for the non-tempered glass as the tensile strength of non-tempered glass is way lower than the maximum principal stresses experienced by the glass cover in the simulation. The cells near the centre of the modules experience tensile stresses, with the cell at the centre of the module experiencing the highest tensile stress. The failure bending tensile stress of silicon is about 200 MPa. Stresses induced in the mechanical load test are lower than the maximum tensile stress of silicon, but as silicon is a brittle material that shows a large scattering of fracture stress, and practical experiments indicate the failure of silicon under the same situation, the simulated stress value may not be a foolproof indicator of reliability.

References

[1] Venetis K. Businesses in cold weather regions harnessing solar power to bring down utility costs. Green Vitals, 28 Feb 2011, <http://www.greenvitals.net/greenvitalsnet/2011/2/28/businesses-in-cold-weather-regions-harnessing-solar-power-to.html>

[2] Kajari-Schroder S, Kunze I, Eitner U, Kontges M. Spatial and orientational distribution of cracks in crystalline photovoltaic modules generated by mechanical load tests. *Solar Energy Materials and Solar Cells* 2011;95:3054-9.

[3] Reil F, Strohkendl K, Althaus J, Vaassen W. Mechanische Beanspruchungen fur PV-Module – Transportbelastungen, in: Sixth Workshop Photovoltaik - Modultechnik, TUV Rheinland, 2009.

[4] Pingel S, Zemen Y, Geipel T, Berghold J. Mechanical stability of solar cells within solar panels. *Proc. 24th European Photovoltaic Solar Energy Conf., Hamburg, Germany*; 2009, pp. 3459-3463.

[5] Potthoff T, Bode F, Kontges M. Bewertung der Zuverlassigkeit von PV- Modulen anhand von Elektrolumineszenzbildern, in: Fifth Workshop ‘‘Photo- voltaik-Modultechnik’’, TUV Rheinland, 2008.

[6] Kontges M, Kunze I, Kajari-Schroder S, Breitenmoser XP, Bjorneklett B. The risk of power loss in crystalline silicon based photovoltaic modules due to micro cracks. *Solar Energy Materials and Solar Cells* 2010;**95**:1131-7.

[7] Assmus M, Jack S, Weiss KA, Koehl M. Measurement and simulation of vibrations of PV-modules induced by dynamic mechanical loads. *Progress in Photovoltaics: Research and Applications* 2011;doi:10.1002/pip.1087.

[8] Dhere NG. Toward GW/year production of CIGS within the next decade. *Solar Energy Materials and Solar Cells* 2007;91: 1376-82.

[9] van Sark WGJH, Brandsen GW, Fleuster M, Hekkert MP. Analysis of the silicon market: will thin-film profit? *Energy Policy* 2007;35:3121-5.
[10] Wang PA. Industrial challenges for thin wafer manufacturing. Proc. 2006 IEEE *4th World Conference on Photovoltaic Energy Conversion*, *Piscataway*; 2006, p. 1179.
[11] Brun XF, Melkote SN. Analysis of stresses and breakage of crystalline silicon wafers during handling and transport. *Solar Energy Materials and Solar Cells* 2009;**93**:1238-47.
[12] Chen CH, Lin FM, Hu HT, Yeh FY. Residual stress and bow analysis for silicon solar cell induced by soldering. 2009, http://140.116.36.16/paper/c38.pdf.
[13] Gabor AM, Ralli M, Montminy S, Alegria L, Bordonaro C, Woods J, Felton L. Soldering induced damage to thin solar cells and detection of cracked cells in modules. *Proc. 21st European Photovoltaic Solar Energy Conference and Exhibition*, *Dresden, Germany*; 2006, p. 2042.
[14] Kajari-Schroder S, Kunze I, Kontges M. Criticality of cracks in PV modules. Energy Procedia 2012;27: 658-63.
[15] Dietrich S, Pander M, Sander M, Schulze SH, Ebert M. Mechanical and thermo-mechanical assessment of encapsulated solar cells by finite-element simulation. *Proc. of the SPIE – The International Society for Optical Engineering*, 2010, Vol. 7773, p. 77730F.
[16] Dietrich S, Sander M, Pander M, Ebert M. Interdependency of mechanical failure rate of encapsulated solar cells and module design parameters. *Proc. of the SPIE—The International Society for Optical Engineering*, 2012, vol. 8472, 2012, pp. 84720P-1-84720P-10.
[17] Sander M, Dietrich S, Pander M, Ebert M, Bagdahn J. Systematic investigation of cracks in encapsulated solar cells after mechanical loading. *Solar Energy Materials and Solar Cells* 2013;**111**:82-9.
[18] Meier R, Kramer F, Wiese S. Thermo-mechanical behaviour of copper ribbon materials. *Proc. 24th European Photovoltaic Solar Energy Conference*, *Hamburg, Germany;* 2009, p. 3413.
[19] Czanderna AW, Pern FJ. Encapsulation of PV modules using ethylene vinyl acetate copolymer as a pottant: a critical review. *Solar Energy Materials and Solar Cells* 1996; **43**:101.
[20] Axinte E. Glasses as engineering materials: a review. *Materials and Design* 2011; **32(4)**: 1717-32.
[21] Popovich VA, Yunus A, Janssen M, Richardson IM, Bennett IJ. Effect of silicon solar cell processing parameters and crystallinity on mechanical strength. *Solar Energy Materials and Solar Cells* 2011; **95**: 97-100.