A Review of Analysis of Structural Deformation of Solar Photovoltaic System under Wind-Wave Load.

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Abstract

Solar PV systems is a new type of energy that is being developed for use in ships in recent years. However, Solar photovoltaics are affected by many kinds of loads such as static loads and wind loads and it is important for designers to take into account the amount of stress (due to wind loads) experienced by the solar PV systems. In this paper, structural deformation of standalone, solar tracker, and module support of the photovoltaic system were analyzed under different wind-wave loads. Based on von Mises criterion, no structural failure (yielding/plastic deformation) is predicted to take place in all the solar PV systems reviewed in this paper under the given loading conditions.

1. Introduction

Renewable energy is becoming an increasingly important option for mitigating climate change and reducing pollution around the world. Due to its non-conventional, non-intrusive, and dependable nature, solar photovoltaic systems are becoming a widely used technology for power generation all over the world [1]. Despite their widespread use on land, PV systems still have a limited role in modern marine technology, serving mostly as providers for small sailing yacht batteries, buoys, and small lighthouses and this is expected to improve in the nearest future [2]. Solar energy is a novel type of energy that is being developed for use in ships. Solar photovoltaic (PV) modules are stretched across the hull deck in the shape of arrays, and solar energy is gathered to produce energy for the ship [3].

However, photovoltaic (PV) systems are commonly subjected to mechanical pressure loading within deployment conditions for both mainland and maritime applications. Many types of loads, such as static loads and wind loads, affect solar photovoltaic structures. Wind loads occur when high wind forces such as hurricanes or typhoons drift about the PV panel, whereas static loads occur when physical loads such as weight or force are applied to it [4]. Moreover, with several mechanical loading tests included into module qualification requirements [5] and cyclic deformation recognized as a source of component fatigue degradation [6], the importance of withstanding these pressure loading is well known. Despite the need to cut costs and materials, module deformation under load is still a desirable quantity to lower.

Due to the increasing demand for solar panels in mainland and maritime areas around the world, a significant amount of research has already been done to make them more cost effective, beaming, and efficient. However, it is also a challenge for construction engineers to equip them in such a way that they can withstand the susceptible wind loads [7]. In such mild or strong wind load conditions researchers all around the world are working to ensure not just the safety of the panels, but also the safety of the support structures. **Therefore, this paper explores/reviews the analysis of strength and structural deformation of standalone, solar tracker, and module support of photovoltaic system under wind-wave loads.**

2. von Mises Stress

The von Mises stress is an equivalent or effective stress at which yielding is predicted to occur in ductile materials. von Mises stress is given using principal axes in terms of the principal stresses σ1, σ2, and σ3 as [8] [9]:

$$\sigma' = \frac{1}{\sqrt{2}} \left[\left((\sigma 1 - \sigma 2)^2 + (\sigma 1 - \sigma 3)^2 + (\sigma 2 - \sigma 3)^2 \right) \right]^{\frac{1}{2}}$$

Nonetheless, there might be normal and shear stresses present at many sites in the material that are under either static or dynamic loads. Therefore, the state of stress can also be stated in terms of the normal stresses σx , σy , and σz , and the shear stresses τxy , τyz , and τzx , where the coordinate axes are non-principal axes. The von misses stress with respect to non-principal axes is given below [10]:

$$\sigma' = \frac{1}{\sqrt{2}} \left[\left((\sigma x - \sigma y)^2 + (\sigma y - \sigma z)^2 + (\sigma z - \sigma x)^2 \right) + 6\left((\tau xy)^2 - (\tau xy)^2 + (\tau xy)^2 \right) \right]^{\frac{1}{2}}$$

3. Stand-alone Solar PV System

Many parameters such as wind direction effect and drag and lift force coefficient have been investigated to show how much pressure is impacting on photovoltaic panels due to different wind direction and inclination angle. Also, the delamination approach of the internal package bonding of the layers of the panel which is mainly disturbed by the internal stress, strain, structural deformation and error management [11] [12]. These are essentially main factors in a PV panel for its sustainability in long run and all these effects are created because of the severe wind load. Therefore, this area of analysis becomes very imperative for the designers to understand how much damage is occurring and in which position the damage is mainly created to ensure long lasting capacity of the solar PV system.

In order to simulate the stress, strain and structural deformation phenomena occurring inside the stand-alone PV panel situated in roof top or ground plane due to severe wind loads, Suman et all [4] used the computational fluid dynamics (CFD) technique in ANSYS fluent platform. This was done by introducing 3D Reynolds averaged Navier Stokes algorithm through computational fluid dynamics (CFD) approach using the model of shear stress transport (SST) k-w turbulence. The stand-alone solar PV module was then immersed in the computational fluid domain. The dimensions of the Si material-based market available PV panel chosen is shown in Table 1 and Table 2 shows the mechanical properties of each layer of the PV module with thickness.

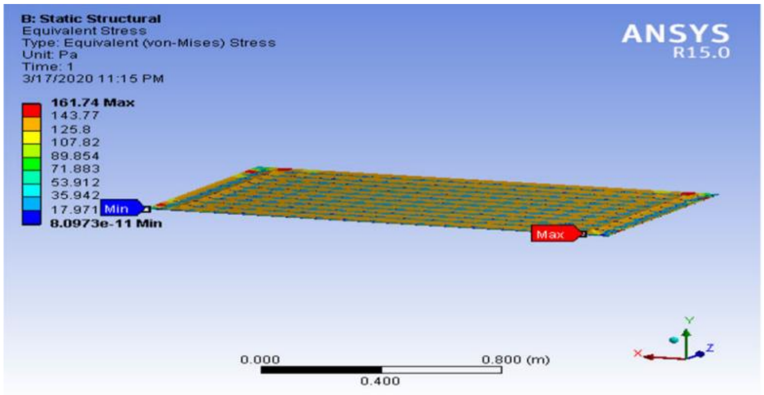
Table 1: Solar Panel Specifications

Parameter	Value
Length	65 inches
Width	39 inches
Depth	2 inches
Inclination angle	25°

Table 2: Mechanical properties of each layer of the PV module with thickness

Layers	Thickness	Young's modulus (GPa)	Poisson's ratio
Glass cover	0.003	70	0.22
PV cell (Si)	220×10^{-6}	180	0.275
EVA	400×10^{-6}	0.02	0.28
Rear contact	10×10^{-6}	108	0.25
PVF	1×10^{-4}	1.1	0.4

In their study, the wind speed was varied from a normal wind speed 10 km/h to severe wind speed or super cyclone 260 km/h to check that how the solar panel will behave when it is hit by such kind of severe wind load. To obtain a panoramic view of stress, strain and structural deformation of how these parameters are gradually increasing with their spectrum, Figs. 1, 2, 3 shows the steady increasing nature of these parameters at wind speeds of 10 km/h, 100 km/h and 260 km/h.



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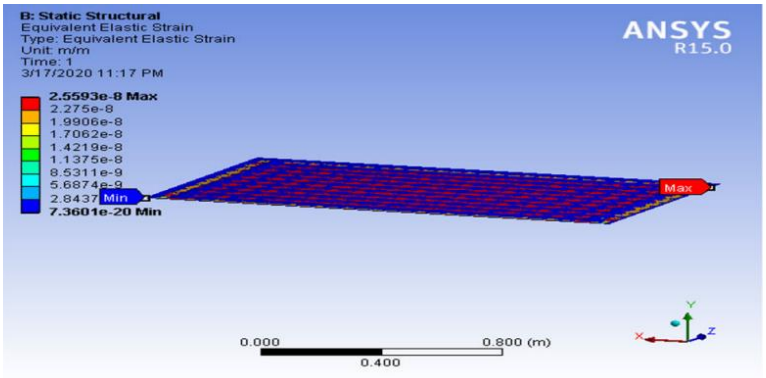

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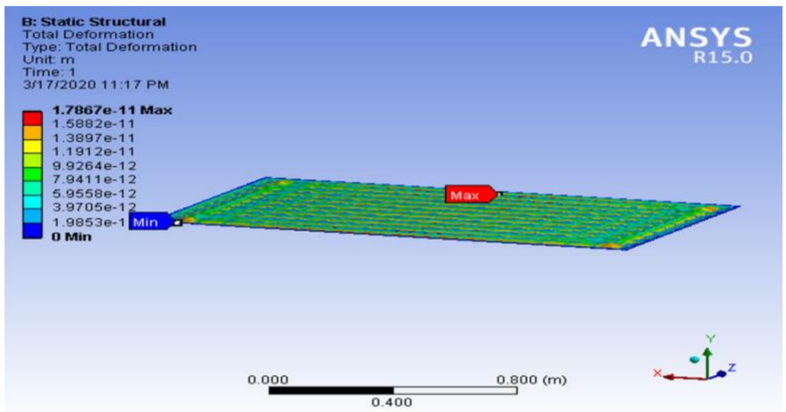

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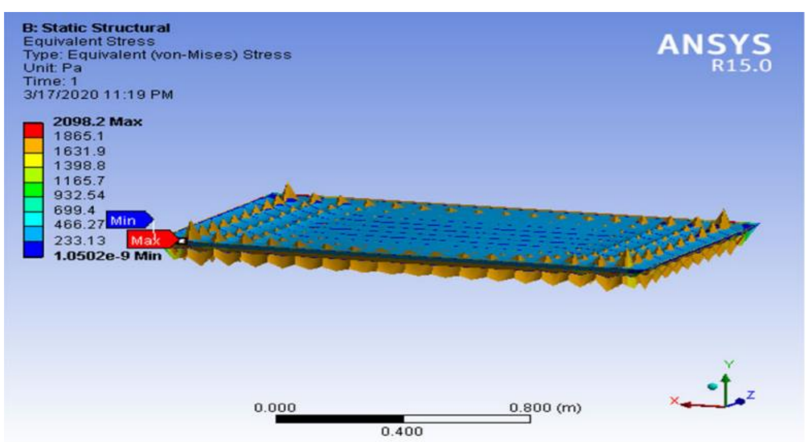
Figure 1: The spectrum of a) stress, b) strain and c) total deformation characteristics of the panel in 10 km/h wind load



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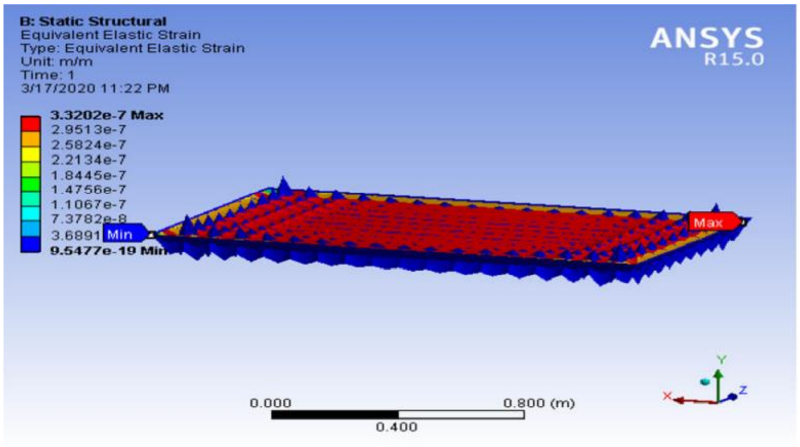

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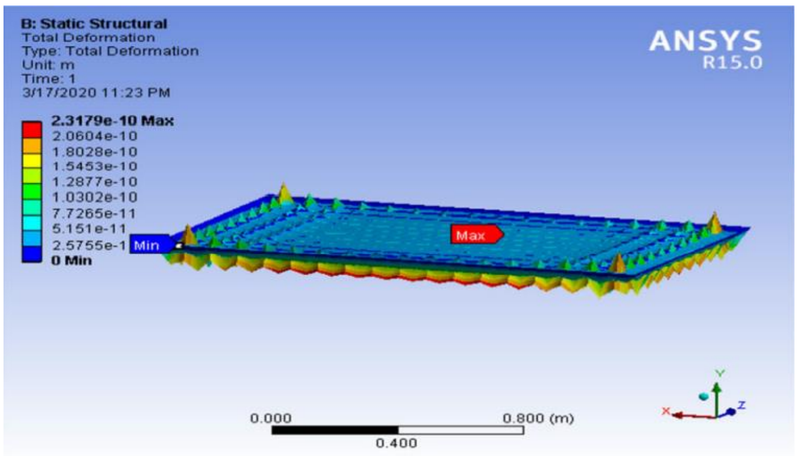

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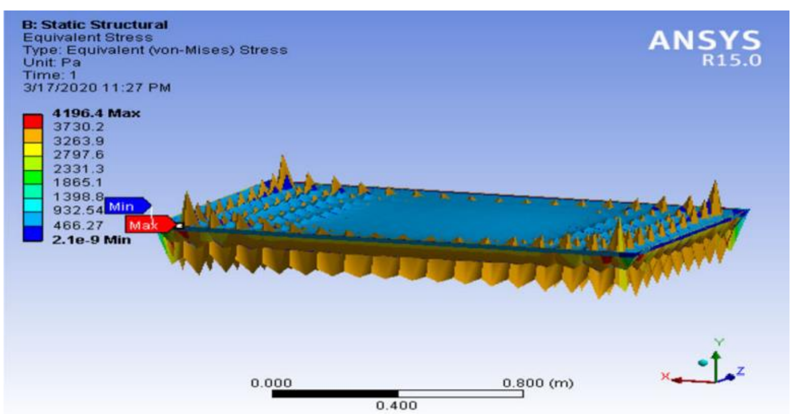
Figure 2: The spectrum of a) stress, b) strain and c) total deformation characteristics of the panel in 100km/h wind load



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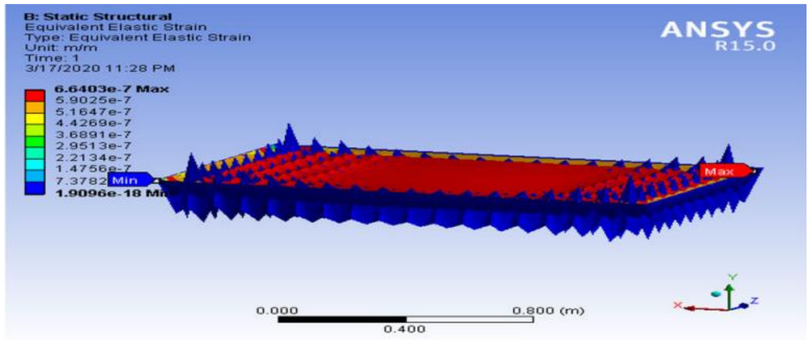

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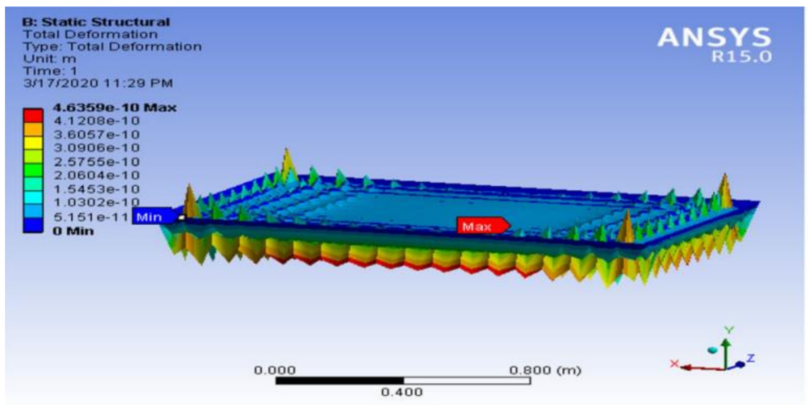

(c)

Figure 3: The spectrum of a) stress, b) strain and c) total deformation characteristics of the panel in 260km/h wind load

It can be seen from figure 1 above that when the wind load is 10 km/hr. (normal wind speed), the stress and strain generated inside the panel is 161.74 Pa is 2.55939 X 10–8 respectively and these values are negligible. Also, the spectrum shows that there is no change as such in total deformation. However, as the wind load was increased to 100 km/h as shown in figure 2, the stress and strain values increased to 1613.9 Pa and 2.553 9 10–7 and a clear sign of internal lamination breaking is visible.

Moreover, when the wind speed is increased to a speed of 260 km/h (super cyclone) as shown in figure 4, the internal stress and strain increased to 4196.4 Pa and 6.6403 9 10–7 and A huge amount of internal package breaking is visible. A common failure mode noticed in laminated panel is delamination where a material fractures into layers and this affects the lifetime of the solar photovoltaics. From the deformation nature and the strain characteristics, it was also observed that the pressure effects are maximum near to the leading edge on the top portion of the solar panel and gradually decreases towards to the trailing side of the panel. This shows that as the deformation increases the internal bonding of the atoms falls and it shows a stress characteristic which is caused due to the deformation of the atoms.

The effect of wind pressure on stress, strain and structural deformation is also shown in Figure 4 below.

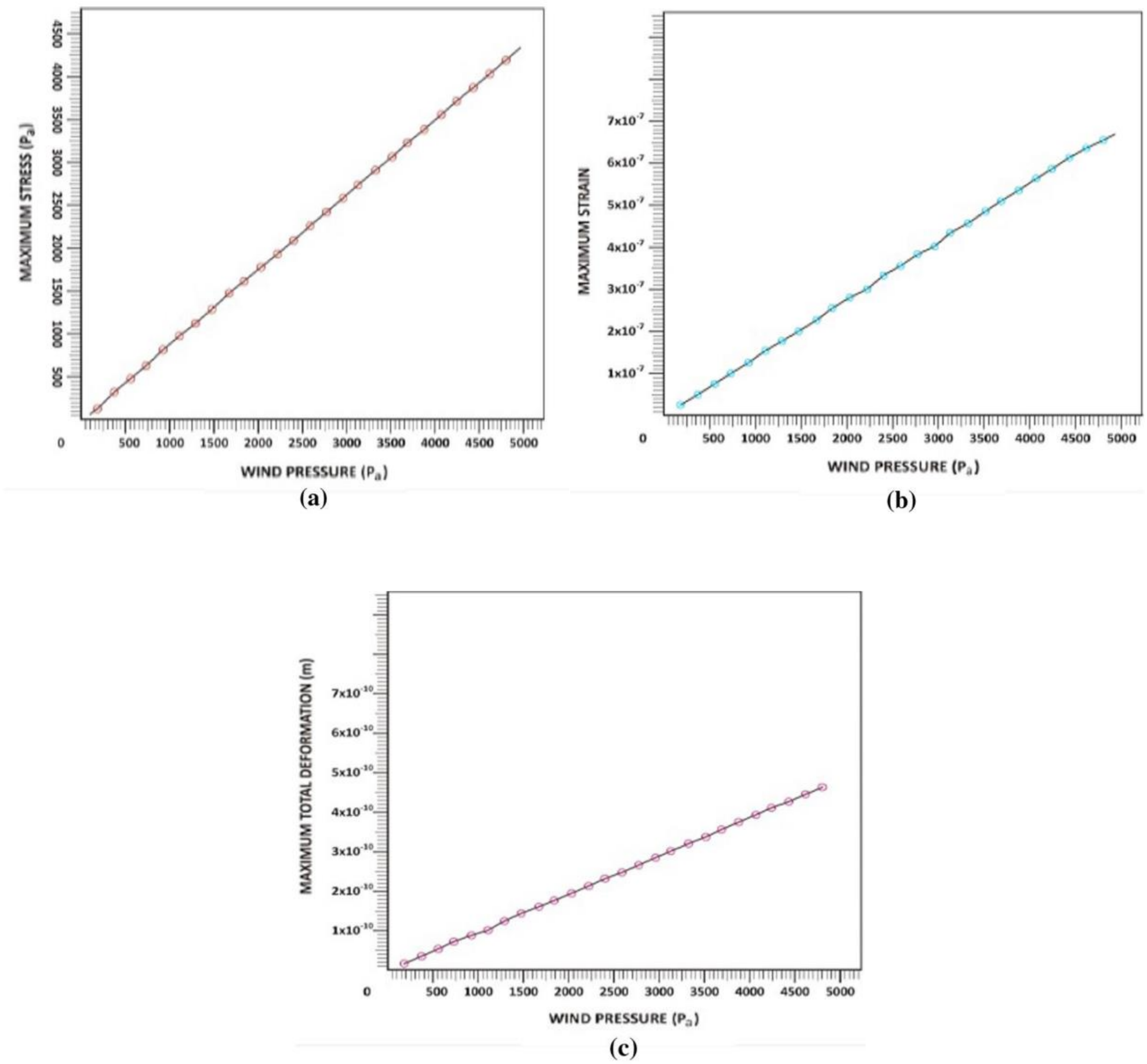

Figure 4: Wind load vs. a) maximum stress, b) maximum strain, c) maximum total deformation when the wind speed varying from 10 to 260 km/h

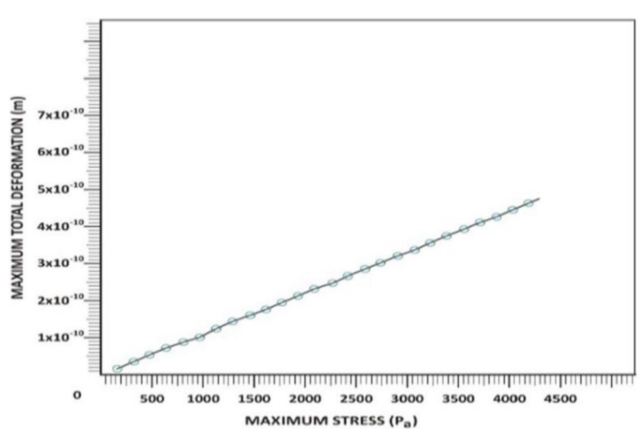

Figure 5: Overall view of maximum internal stress vs. maximum total deformation when the wind speed is varying from 10 to 260 km/h.

It can be seen that the as wind pressure increased, the stress, strain and structural deformation of the solar PV also increased gradually and due to this, the internal packaging is delaminated. As shown in Figure 5 (structural deformation vs stress), the structural deformation increased linearly as the stress build up increased inside a solar photovoltaic panel.

Overall, the amount of stress, strain and structural deformation experienced by solar PV system increases as the wind pressure/speed increases. This also that shows the amount of stress being generated inside the solar PV due to this wind loads causes structural damage and delamination. This shows that as the deformation increases the internal bonding of the atoms falls and it shows a stress characteristic which is caused due to the deformation of the atoms.

4. Solar Tracking PV System

A solar tracker is an important equipment in a photovoltaic system which enhance the annual power output by keeping the solar cell directed toward the sun and maintain power generation efficiency at a high level. A photovoltaic system with a solar tracker is particularly sensitive to wind loads because the drive mechanism supports the self-weight of modules and wind loads. Nonetheless, for a reliable operation of the solar PV system, not only is the solar tracker required to be able to withstand its own weight and external wind loads, it is also required to keep its deformation below a certain threshold.

In order to investigate the effects of self-weight and wind loads on the structural deformation of a reliable f a 2-kW PV sun tracking system, Chih-Kuang et all [13] used finite element analysis (FEA) in ANSYS to develop computer-aided engineering (CAE) technique. The solar PV tracking system investigated consist of a solar tracker attached to nine flat-panel PV modules with dimensions 1668 X 1000 X40 mm^3. Table 2 below shows the layer wise material properties of the photovoltaic panel.

Table 2: Material Properties of solar tracker used in the model

Material	Young's modulus (GPa)	Poisson's ratio	Yield stress (MPa)	Density (kg/m^3)
Solar glass	70	0.22	---	2500
A5052 aluminum alloy	70.3	0.33	193	2680
A6063-T6 aluminum alloy	68.9	0.33	214	2700
AISI 1053 steel	205	0.29	610	7850
AISI 4140 steel	205	0.29	415	7850
SUJ2 steel	205	0.29	2035	7850
SS400 steel	205	0.29	250	7750

In their study, the effect of gravity only, wind speed of 7m/s (25.2 km/h) and 12 m/s (43.2 km/h) on structural deformation of the PV system was investigated and for each wind speed, the elevation angle was varied from 10 to 75 degrees. However, the simulations were conducted in a linear elastic mode because the calculated von Mises equivalent stress was found to be less than the yield stress for each component of the PV system. Under gravity only condition, the highly stressed region in the solar tracker was found at the ball bearings and bushing.

The variation of maximum von Mises equivalent stress with elevation angle for the ball bearings and bushing are shown in Figure 6 below

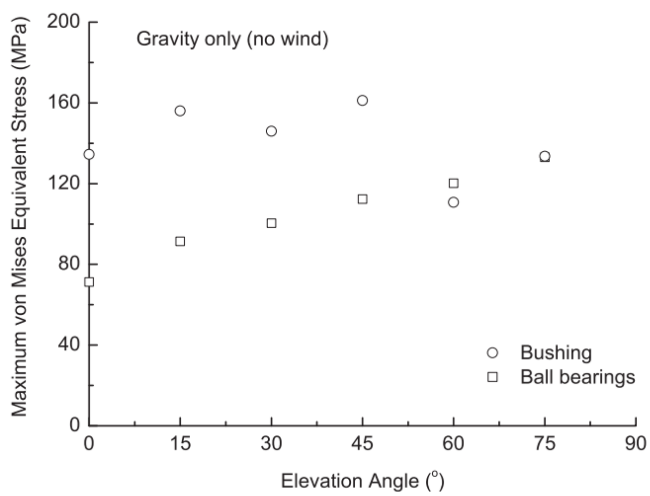

Figure 6: Maximum von Mises equivalent stresses in the bushing and ball bearings at various elevation angles under the effect of gravity.

It can be seen in figure 6 that as the elevation angle increases, the maximum von Mises equivalent stress in the ball bearing increases. Also, the maximum von Mises equivalent stress in the bushing is of 161.2MPa at elevation angles of 45 degrees and this figure is less than the yield stress of SS400 steel (250 MPa) as shown in Table 3. This shows that no structural failure (yielding/plastic deformation) is likely to occur for the solar PV system under gravity only during operation.

The variation of maximum von Mises equivalent stress with elevation angle for the ball bearings and bushing under a wind speed of 7 m/s and 12 m/s are shown in Figure 7 and 8 below.

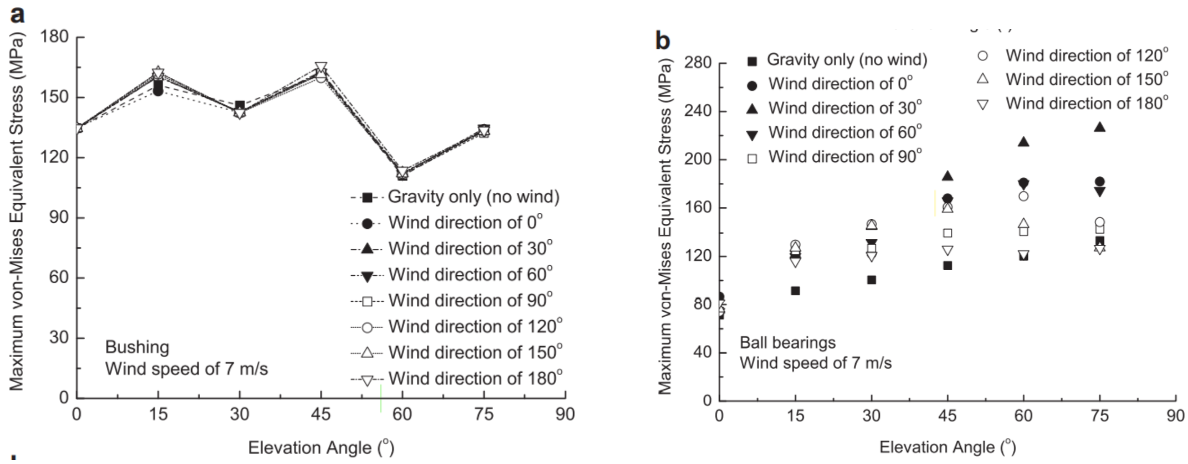

Figure 7: Maximum von Mises equivalent stresses in the (a) bushing and (b) ball bearings at various elevation angles under the effect of a wind speed of 7 m/s.

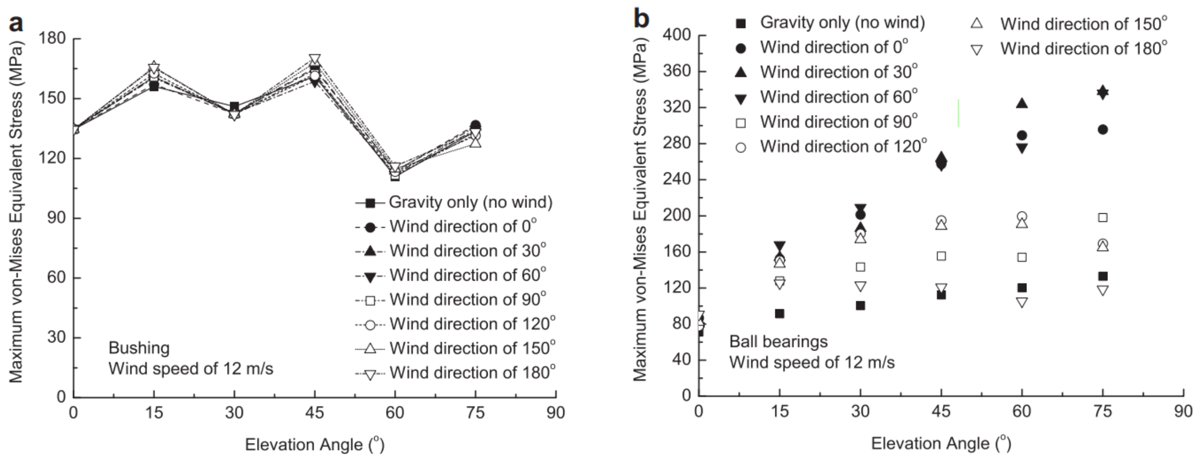

Figure 8: Maximum von Mises equivalent stresses in the (a) bushing and (b) ball bearings at various elevation angles under the effect of a wind speed of 12 m/s.

As the wind load was increased to 7m/s and 12m/s, and the absolute maximum von Mises equivalent stress takes place at ball bearings. Moreover, as seen in Figure 7 and 8 above, the wind loadings do not generate harmful effect on the bushing since the maximum von Mises equivalent stress in the bushing for gravity only (161.2 MPa) and wind speeds of 7 m/s (165.8 MPa) and 12 m/s (170.5 MPa) are all less than the yield stress of SS400 steel (250 MPa). Also, for a wind load increased to 7m/s and 12 m/s, the absolute maximum von Mises equivalent stress in the ball bearing is 226.3MPa and 338.1MPa respectively (both at elevation angle 75° and wind direction 30°) and this figure is less than the yield stress of SUJ2 steel (2035 MPa). This shows that no structural failure (yielding/plastic deformation) is likely to occur for the solar PV system under a wind load by a wind speed of 7m/s and 12m/s during operation.

Fig. 9 below shows a comparison of the maximum stress in the ball bearings under the effects of gravity alone and wind speeds of 7 m/s and 12 m/s in the wind direction of 30 degree.

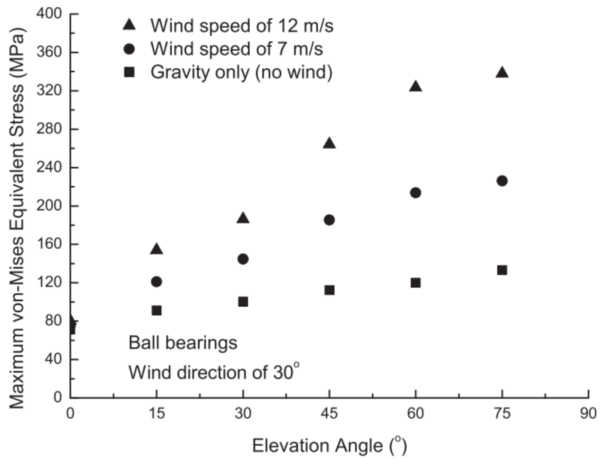

Figure 9: Comparison of the maximum stress in ball bearings under the effects of gravity alone and wind speeds of 7 m/s and 12 m/s with direction of 30°.

It can be seen that the maximum von Mises equivalent stress in the ball bearings increased rapidly for gravity only to wind speeds of 7m/s (25.2 km/h) and 12 m/s (43.2 km/h) from 133.7 MPa to 226.3 MPa and 338.1 MPa correspondingly as shown in figure 9. However, the absolute maximum von Mises equivalent stress for each of the wind loads is less than the yield stress of the material. Therefore, no structural failure is predicted for the given PV system subjected to these wind loads.

Overall, the amount of stress experienced by solar tracking PV system increases as the wind loading due to wind speed increases. Nonetheless, these stresses are lower than the yield stress of the materials used for the components. Based on von Mises criterion, no structural failure (yielding/plastic deformation) is predicted to take place in the 2-kW PV solar tracking PV system under the given loading conditions.

5. Solar Module Support

The module support structures of solar panels play a major role in a solar Photovoltaic system. Since the system would undergo common environmental loads and the wind load, it is also imperative to consider the effects of these loads on the module support to prevent destruction of module support [14]. In order to investigate the effect of wind loads on the structural deformation of a module support, Hong et al [15] used flow field analysis in ANSYS on the solar PV modules and supports which consist of solar panels (470mm X 680mm X 25mm) and brackets(steel) under several wind loads. The simulation was carried out using a PV inclination angle of 30° and wind direction of 90°. The wind speed considered were 32m/s (115.2 km/h), 42m/s (151.2 km/h) and 50m/s (180 km/h).

The von Mises equivalent stress of the PV support under 32m/s wind speed is shown in Figure 10 below from the structural static analysis. The largest von Mises stress (185MPa) is observed at the support junction in the bracket, where the thickness is shortest and the stresses of the PV module support are significantly lower than the yield stress of steel at other sections. Therefore, no structural failure (yielding/plastic deformation) is predicted to take place in the solar PV module support.

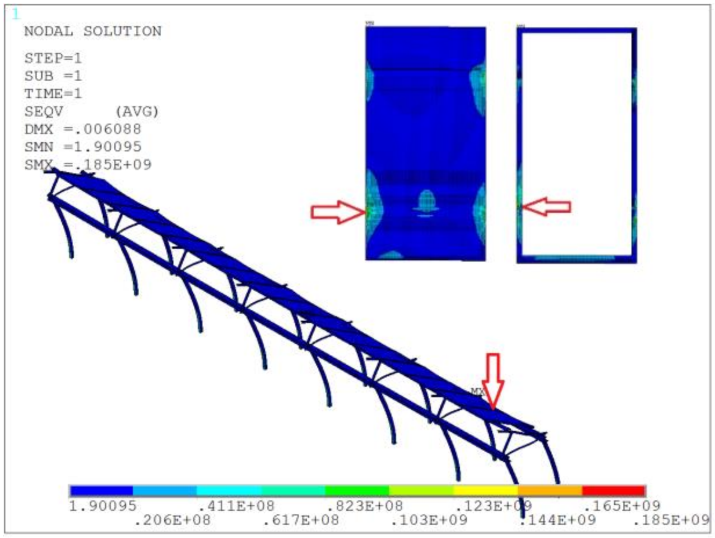

Fig 10: von Mises stress of PV module support (wind speed of 32m/s)

The von Mises equivalent stress of the PV support under 42m/s wind speed is shown in Figure 11 below from the structural static analysis The maximum von Mises stress (265MPa) is observed at the support junction in the bracket, where the thickness is shortest and the stresses of the PV module support are significantly lower than the yield stress of steel in other sections. Therefore, no structural failure (yielding/plastic deformation) is predicted to take place in the solar PV module support.

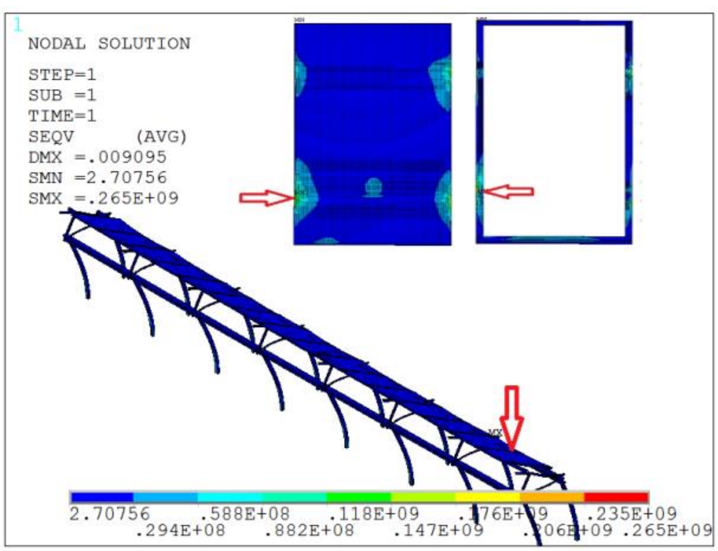

Fig 11: von Mises stress of PV module support (wind speed of 42m/s)

The von Mises equivalent stress of the PV support under 50m/s wind speed is shown in Figure 12 below. The maximum von Mises stress also occurs at the support junction in the bracket where the stress concentration occurs, and the stresses of the PV module support are significantly smaller than the yield stress of steel at other locations, as seen. Therefore, no structural failure (yielding/plastic deformation) is predicted to take place in the solar PV module support.

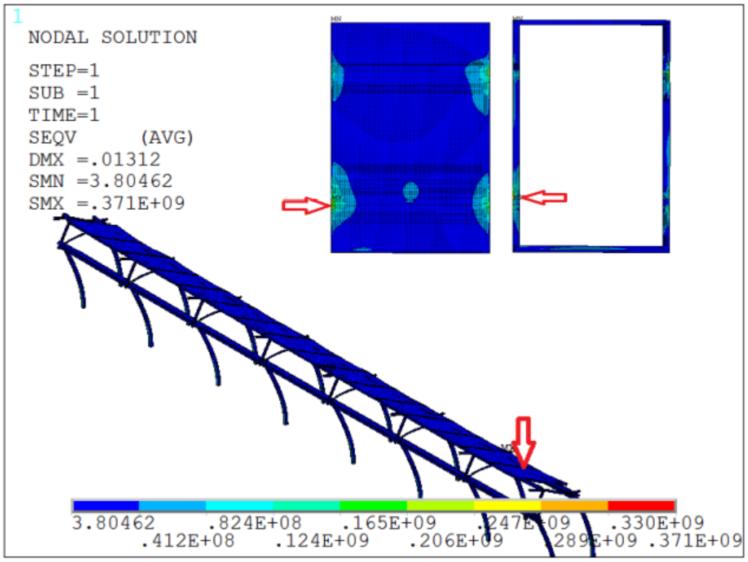

Fig 12: von Mises stress of PV module support (wind speed of 50m/s)

Overall, the amount of stress experienced by solar PV module support increases as the wind loading due to wind speed increases. Nonetheless, these stresses are lower than the yield stress of steel used. Based on von Mises criterion, no structural failure (yielding/plastic deformation) is predicted to take place in the solar PV module support under the given loading conditions.

6. Conclusion

As the wind pressure/speed increases, the amount of stress, strain and structural deformation increases in the solar PV and the internal bonding of the atoms falls gradually and due to this, the internal packaging is delaminated. Moreover, the amount of stress experienced by solar tracking system also increases as the wind loading due to wind speed increases. No structural failure (yielding/plastic deformation) is predicted to take place in the 2-kW PV solar tracking PV system considered based on von Mises criterion under the given loading conditions. Also, for a solar module support, the amount of stress experienced by solar PV module support increases as the wind loading due to wind speed increases. Nonetheless, if the stresses experienced by the support are lower than the yield stress of steel used, no structural failure (yielding/plastic deformation) is predicted to take place in the module support based on von Mises criterion under the given loading conditions. Therefore, it is important for designers to take into account the amount of stress (due to wind loads) experienced by the solar PV system, solar tracker and module support while choosing the best material for manufacturing and installation.

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