

Finite Element Modelling and On-Site Measurements for Roof Mounted Photovoltaic Solar Panels under High Wind Load

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ABSTRACT

The application of dynamic wind load on photovoltaic (PV) solar systems mounted on flat roofs influenced their structural behavior significantly. It is implied that when the PV solar system is exposed to extreme weather characteristics such as low temperatures, these might influence the load distribution along each layer of the solar panel, which is composed by multiple layers of different materials. Therefore, the high record of weather characteristics as one scenario in addition to the field experiment were designed to describe parametric structural behavior of PV solar system help to increase the precision of study.

According to the mentioned procedures different parameters of weather characteristics measured with instrumentation at the site of PV panel installation at the University of Ottawa where the low temperature equal to -24.3°C and wind speed of 11.8 m/s recorded. The mechanical and thermal properties of full-scale specimen and load application that computed based on weather record for every two minutes of January and February from northern side of specimen, introduced to FEM software SAP 2000. Moreover, the support structure and connection used to assemble real specimen considered in modeling with respect to average temperature equal to -7°C that caused to simulate 36 different cases to compare with simultaneous experiment designed to measured strain within same period.

The second investigation involved instrumenting a full-scale PV solar panel specimen with 13 half-bridge strain gauges on both surfaces of the PV solar panel, which were used to measure strain values in longitudinal and transversal directions of solar panel and also on the top and bottom edges of the same panel. According to an equivalent uniform Young's modulus

numerically determined for the five layers of the PV solar panel, and with respect to the Hook's law, the stresses were found to be equal to 50 Mpa for strain gauges at the mid area of PV solar panel,. This value was used to calibrate boundary conditions of the FE model namely the Fix-Equal and the Pin-Equal conditions along the edges of the solar panel and along the mounting frame.

Dedication

I would like to express my gratitude to all those who helped me during the writing of this thesis.

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CHAPTER 1: INTRODUCTION

Significant increase of photovoltaic (PV) solar industry forces engineers to develop evaluation guidelines for wind load on solar arrays and structural analysis approaches. Therefore, this topic is considered within subsections and provisions of some design codes, such as one published by American Society of Civil Engineers [1] as cladding and components with which need to be met ASCE7-10 [1]. Moreover, a document prepared by Structural Engineers Association of California (SEAOC) [2], [3] specifically looks at wind loads on photovoltaic arrays on flat roof low-rise buildings. However, there are some specific cases such as extreme weather condition that need to be considered in the study of load distribution on PV solar panels, which leads to different procedures and methodologies.

Analytical investigations and wind tunnel tests are recommended for more accurate estimation with respect to various parameters, which are able to affect the load distribution along the structural members constituting the PV solar panels systems. The wind tunnel tests relies on testing scaled specimens under pressured induced by wind flow modeled based on topography of location and geometry of model considered [4]. However, the analytical procedure takes advantages of powerful software products to model the wind effect on the PV panels by employing numerical methods of computational fluid dynamics (CFD) and finite element analysis (FEA). In addition, it needs to be considered that many assumptions should be introduced to each model for achieving results that are more accurate. Numerical and experimental procedures are already in place, however because each type of PV solar panels arrangement and installation might be different, results from the real installation sites should

be considered. Therefore, field measurements on PV solar panels would provide the best estimation for wind loads and structural behavior of the PV panel. However, these are very limited in the literature, mostly due to the inaccessible surface of the panel, which needs to be exposed to the sunlight and cannot be covered by instruments and also due to the lack of granting access to the installation sites by the PV solar panels system owners.

Generally, the dynamic analytical procedure is based on time-history analysis that considers the main behavior of wind loading function versus a time interval and is carried out by employing structural software available. For application on PV solar panels, Schellenberg, [5] performed a nonlinear FE analysis to study the wind dynamic load on the PV solar panels arrays with respect to the effects of damping and initial conditions, to provide structural response more accurately. The force value of the function diagram computed with respect to numerical method or value obtained from the pressure tap employed in the wind tunnel experiment, where the net pressure computed from wind load in a wind tunnel test. Full-scale testing models and scaled models are two other methods used in experiment (wind tunnel test) where the wind velocity is used to compute the wind load within various times. [4]

1.1. Wind characteristics and PV system specifications

As it was mentioned previously, a number of factors are affecting the wind load distribution along a PV solar system. Some are related to weather and wind characteristics and other depend on the type of installation method, geometry and mechanical and thermal properties of different parts of the PV systems exposed to wind. Moreover, the dynamic load application of wind flow on different members with respect to direction of stream, wind speed and temperature variation are able to influence the stress-strain distributions on the PV panel.

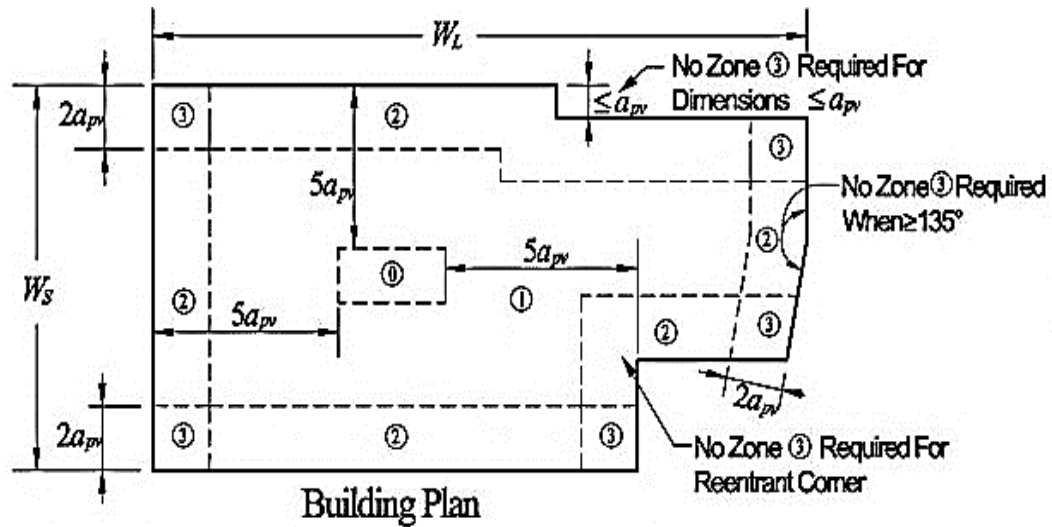


Figure 1-1 Three Zones to install solar PV system depend on wind speed and directions [6]

Each solar panel consists of various materials with wide different coefficient of thermal expansion and Young's modulus that can be affected by the low or high temperatures. The amount of distributed strain along solar panel affected by temperature reduction that adds more fragility to system leads to higher stress along solar panel due to variation of materials used to build solar panel and support frame materials.

Finally, the total area exposed to wind load considered with respect to the sheltered area of the elements located behind other members, and the type of connections between different elements. All these parameters and their variations are able to be simulated when using the analytical investigation procedure for each the respective case of study, which used to compute stress-strain within each member. However, some parameters such as the exact mechanical and thermal properties of each structural member under different temperatures are not possible

to be replicated in the various experimental procedures, based on the modeled PV solar panels specimens.

1.2. Problem statement

The influence of wind load on photovoltaic solar systems must take into consideration a number of parameters, such as airflow characteristics, type of installation and mechanical and thermal properties of each structural member used. In the following chapters, a parametric study concentrating on these characteristics along with the investigating procedures will be presented. In addition, it will be described how some of these investigation procedures reach to reasonable accurate results, however others fail to provide precise response for all the analyzed cases. This occurs usually due to a different number of factors, which could affect the structural behavior of the PV solar panel specimen under wind loads. For instance, due to boundary layers and dimension limitations of the standard wind tunnels, installation of full-scale PV system specimen is almost impossible. Thus, engineers and researchers focused on employing scaled model specimen that are usually made from plastic or plywood. Therefore, this procedure cannot be used for studying the load distribution along the thickness of solar wafer of the PV panel that means that the inhomogeneity of PV system plus the mechanical and thermal properties of the panel is neglected.

In the other case, the investigations involving the equivalent static or dynamic wind load applied at the surface of solar panel, although these use the advantages of simulating a real specimen with exact mechanical and thermal characteristic taken into consideration, all parameters of wind characteristic as mentioned in section 1.1 are neglected. Usually, these

types of experiments considered to study and model stress-strain distribution, ultimate deformation or crack extension along the thickness of the specimen within different layers.

Finally, the last type of studies focused on modeling and simulation of both airflow and specimen with capable numerical method and software products. Weather characteristics and specimen properties defined for different FEM and CFD software to simulate the behavior of PV solar panel. The accuracy of this type of study depends on how specimen and the air stream modeled.

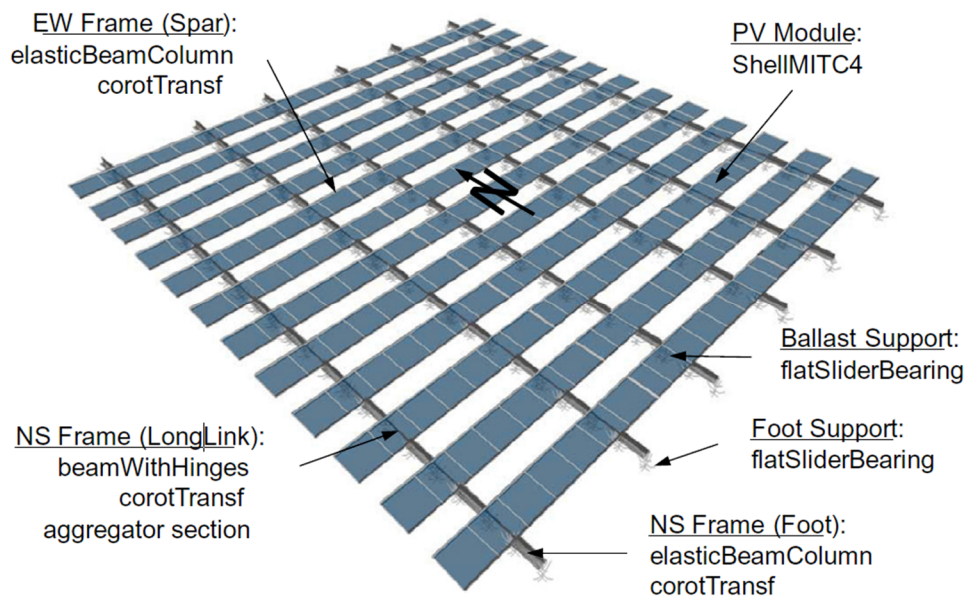


Figure 1-2 Analytical procedure , FEM Modeling [4]

1.3. Research Objectives

With respect to significant increase in demand of solar energy, most of the companies prefer to mount PV solar systems on flat roof of low, medium and high-rise buildings. This type of installation needs to consider the problems mentioned in section 1.2. Moreover, the

extreme weather characteristics of the winter season in the Ottawa region introduced a new case of study.

According to the problem mentioned above, the current research aimed at achieving the following goals:

- Ø Instrumenting a site location to install a PV system and measure the weather characteristics of the winter season, such as wind velocity and temperature variation to compute the dynamic and static wind load applied on PV solar panels.
- Ø Develop the FEM of the PV solar system, using a commercial software and to apply the load and temperature computed based on the site measurements to the PV solar panel model and on any surface of support structure exposed to the wind stream. Moreover, study on structure of standard solar panel and some type members used to install PV solar system was conducted.
- Ø Compare the data gained from FEM PV solar panel model to the stress values measured by sensors installed on the full-scale PV panel at the site, for a specific period.

1.4. Significance of Study

As mentioned in section 1.1 many of the parameters which need to be employed in a simulation of wind loading on PV solar system must be accurately simulated and should not be neglected as in most of the studies performed in the past. Moreover, with respect to section 1.2, many studies conducted their investigation based solely on FE analysis or only on wind tunnel experiments, without much information about the wind loading at a real PV solar panels

site and structural response of a functioning PV solar panels system, especially in extreme weather conditions. Therefore, field measurements for roof mounted PV solar panels under high wind loads are considered in the present research and the measurements outcomes are compared with the values obtained from finite element model of the PV solar panel system. To do this, as accurate as possible it is decided to mount strain gauge sensors on both surfaces of the PV solar panel; however, most of the sensors on the upper surface were lost due to the high snow accumulation. Moreover, in the FE model, the effect of temperature variation ranging between -40°C to $+40^{\circ}\text{C}$ was investigated and a sensitivity analysis was conducted to determine the panel mesh dimensions effect and the influence of the layers of different materials composing the solar wafer of the PV solar panel was carried out.

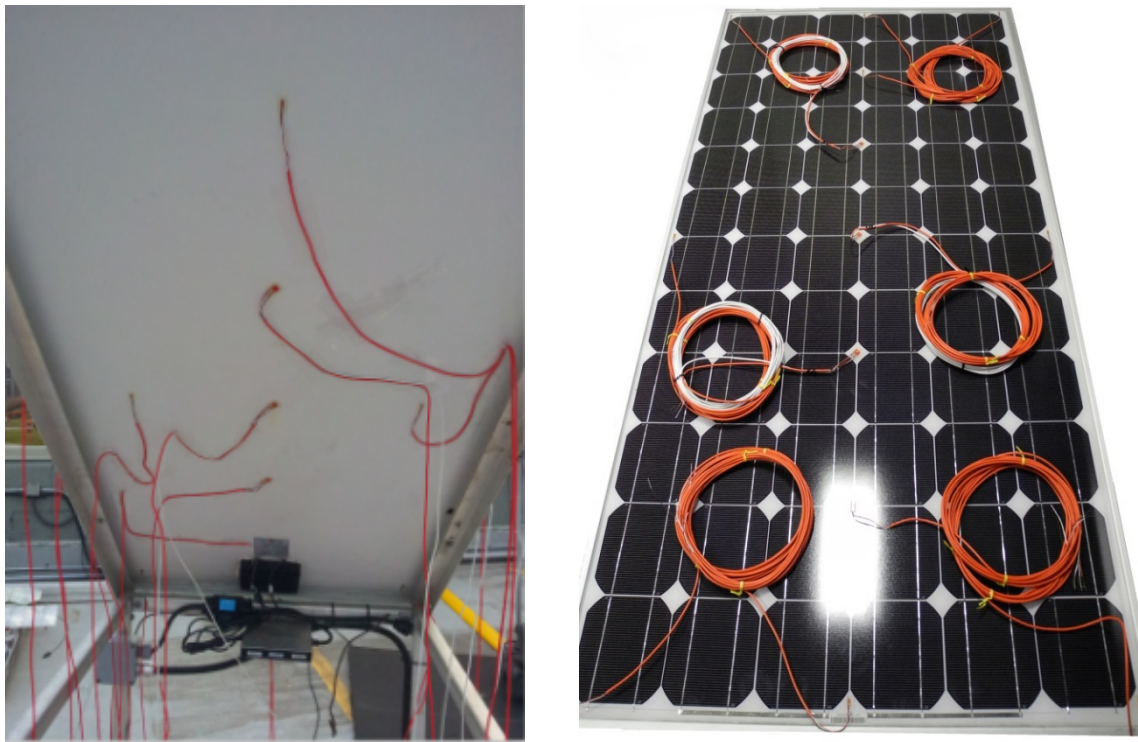


Figure 1-3 Installation of sensors on front and back face of solar panel for more accurate result

1.5. Research Methodology

To perform an accurate structural investigation on PV solar panel system, first it is required to collect sufficient information from different design codes and documents reporting various evaluation procedures and calculation methods of the studied structures. Most recent experimental and numerical research conducted for PV solar panels is also carefully detailed and interpreted. Moreover, the behavior of airflow plus mechanical and thermal properties of the solar wafer specimen as a multilayer system, and the finite element method needs to be reviewed. These topics will be presented in chapter 2 as part of the literature review.

Chapter 3 concentrates on the numerical modeling and the simulation of the PV multilayer solar panel with respect to mechanical and thermal parameters, which have effect on load distribution. Moreover, other parameters, such as effect of five different temperatures governing the winter season in the Ottawa region, and thickness reduction plus mesh sensitivity considered in static linear analysis under three different uniform loads scenarios are presented.

To extend the accuracy of the study, weather data recorded within January and February 2014 for every minute is applied to the FEM model prepared based on real PV solar specimen mounted on rooftop of Mann Parking building of the University of Ottawa. The FEM model draws for different types of joint and connection with respect to boundary conditions to be calibrated with the data obtained from the specimen instrumented with a number of 13 strain gauges that collect data for time lag of two minutes. Various conditions and assumptions are explained in chapter 4 as field measurement and PV solar system modeling.

Chapter 5 presents the govern functions of the static and dynamic wind loading applied to each member of PV solar system, plus the simulation results with respect to three Linear elastic, Linear Modal (Eigen vectors) and Direct-integration Time-History Analysis. Finally, the outcomes of the simulation are compared with the data measured by strain gauges installed at particular points on the surface of the PV panel.

CHAPTER 2: LITERATURE REVIEW

For decades, scientists have been working on different types of clean and promising energies that are convertible to today's usual usage for daily life and industry. Different type of technologies helped to convert sun light energy as one of most accessible types of resources of electricity. Usually, the advantages of PV solar panels are taken to produce electricity by exposure to sun light directly.

Commonly, light intensity and large contact area of inclined PV solar structures mounted on the flat rooftop of building and tilted orientation of the structure are causes for vulnerability of PV solar system to the wind load. Due to significant number of complexity of wind behavior, most of conducted studies concentrate on stability of PV solar panels systems especially for the roof-mounted cases where distributed wind loads are transferred from frames to roof thus causing significant uplift load. This load is applied is transferred from the PV solar panels to the roofing system and needs to be considered in the design of the building. Moreover, the dead weight of the PV solar system is another parameter that needs to be considered in load computation. Therefore, different members and the weight of their behavior under wind load can be easily determined. However, the influence of weather characteristics and wind load components with respect to the location of the installed PV solar panel need to be studied accurately.

In addition, there are few design codes and documents prepared based on different procedures of investigation for determining the behavior of each structural member or of the

entire PV solar system under particular wind loads following the type of installation and these will be described in the following sections.

2.1. PV Solar System Structures: Methods of installation

The significant effect on load distribution and how a PV solar system is installed on flat rooftop determined a classification of the solar systems following mainly three ways of installing a solar array. Unattached (ballast-only) PV solar panel systems resist to wind and seismic forces by their high weight and friction whereas loads are fully transferred to structural frame for both upward and downward forces in Fully Framed system. Meanwhile, a more moderate type of installation, specified by SEAOC PV1 [3], is the Attached roof-bearing PV panel systems. “Attached roof-bearing systems are fastened to the roof structure at one or more attachment points, but they also rest on the roof at specific support points that may or may not occur at the same locations as the attachment points. The load path for upward forces is different from that for downward forces. These systems may include additional weights (ballast) as well” SEAOC PV1 (February 2012) [3].

2.1.1. Balance of System (BOS)

To transfer the applied wind load to roofing system or foundation, a number of structural members must work together. Typically, photovoltaic (PV) systems consist of two main parts, solar panels and Balance of System (BOS) equipment. The latter includes factory assembled

foundations or support structures and electrical system while the PV solar panel consists of different layers of material which can convert solar energy to electricity.

However with respect to orientation and height of the PV solar system, the pressure of applied wind load would change, therefore the procedure of load distribution along structural BOS members will not be the same. When airflow is reaching to the solar array, distributed loads transfers from spar members, which keep the PV solar panel into the sheet-metal frame. The metal frame is bolted to the members called longitudinal links, which are used to add more stiffness and form a continuous structure. These types of bolted connections use to allow the support structure to adjust to variations of roof slope. Finally, load distributed along the longitudinal links are transferred to the roof and to the deck based on design and weight of solar array [5].

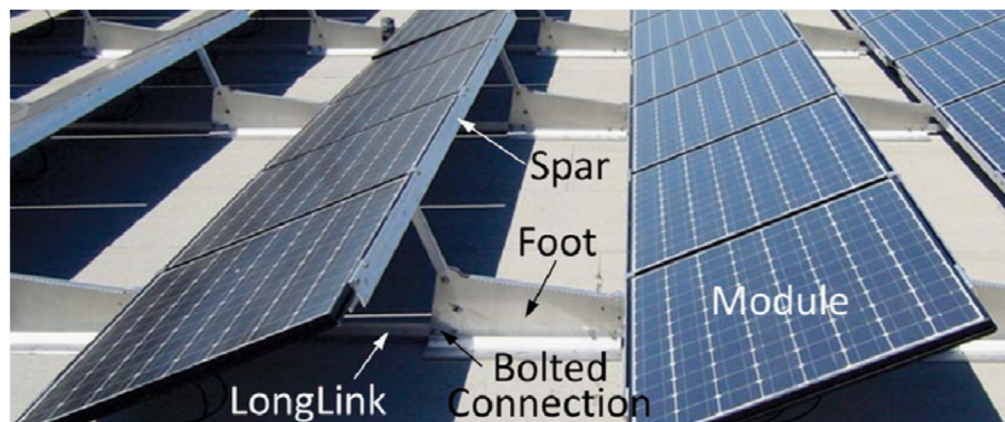


Figure 2-1 Balance of System members and the way load transfer from solar panel to foundation [5]

2.1.2. PV Solar Panel

Next structural member is the PV solar panel, which plays an important role in the behavior of the wind load on PV solar array and in the load distribution along all frame members. Large surface to apply wind load, light weight, long length of connection along perimeter and inhomogeneity of sandwich due to different layers of material caused significant effect in the whole system due to any change occurred in the condition of the PV solar panel.

A major number of standard solar panels contain 5 layers of materials with different thickness, mechanical and thermal properties (Fig. 2-2) [7]. Many studies conducted with respect to the properties and behavior of each layer and their influence on the load distribution along the three directions x, y and z of the PV solar wafer. However, the peculiar behavior of two layers of Ethylene Vinyl Acetate (EVA) and Silicon caused many studies to verify and test the mechanical and thermal properties of each material [8],[9],[10],[11].

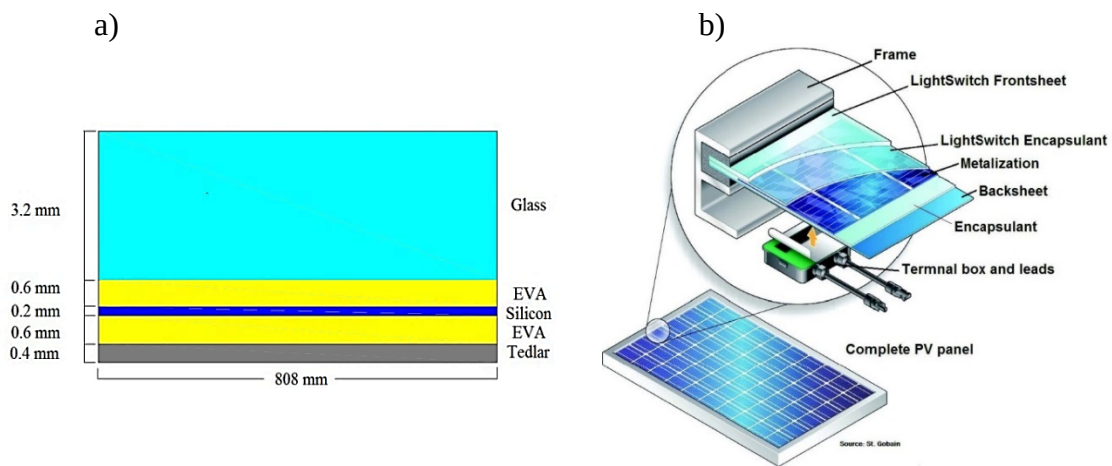


Figure 2-2 Different layers of solar panel a) dimensions b) layout with respect to support frame[7]

Modulus of elasticity of silicon layer was investigated by Pérez [8] because that silicon is not an elastically isotropic material. It is noted that a cubic crystal has three elastic values with respect to each three dominant directions; however, the thermal properties are isotropic. Therefore according to the compliance S and C stiffness Hopcroft, [9] and Pérez, [8] both took advantages of fourth rank tensor to describe Hook's law with respect to a respective direction. After simplification the two following equation matrixes were considered for compliance and stiffness as Young modulus by Hopcroft, [9] and Pérez, [8].

$$\sigma = C\varepsilon \quad (2-1)$$

$$\varepsilon = S\sigma \quad (2-2)$$

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{12} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{12} & 0 & 0 & 0 \\ c_{12} & c_{12} & c_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{44} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} \quad (2-3)$$

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{12} & 0 & 0 & 0 \\ s_{12} & s_{11} & s_{12} & 0 & 0 & 0 \\ s_{12} & s_{12} & s_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{44} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \quad (2-4)$$

However according to the equations 2-1 to 2-4 Hopcroft, [9] recommended to take Young's Modulus 169 Gpa with respect to x or y directions and 130 Gpa with respect to the inclined direction at 45° off x-y plane. The value of 163Gpa is recommended by Fraunhofer Center for Silicon, Germany [10] as well, for all directions of cubic crystal material.

Another type of studies conducted regarding the behavior of EVA and Silicon layers at different temperatures involve a series of dynamic and static experiments between -30° to 85° Celsius performed at Fraunhofer Center for Sustainable Energy Systems and Dow Corning

Midland Plant [11] to study the behavior of 160 μm and 200 μm thickness EVA and silicon encapsulates (adhesive materials) with respect to the cracks development criteria. Surprisingly, two opposite behaviors were recorded within different temperatures. As it is clear from the figures 2-3 and 2-4 [11], by decreasing the temperature from ambient temperature to -30°C , with respect to a constant load value, the stiffness of EVA increased significantly, which caused the cracks development to expand. On the opposite way, by increasing the temperature to 85°C the flexibility of the mentioned EVA layer grown rapidly and no crack formation was recorded within the experiment. In contrast, it was that the Silicon layer, at the same conditions of experiment behaved independently. No cracks shown in different cases of applied load with respect to the different all range of temperature.

Regards to other type of data collection at the same study, storage modulus recorded (figure 2-5, [11]) within -50° to 100°C clarifies that the EVA layer influence within the specified range of temperatures. On the contrary, the storage modulus of silicon layer remains constant without significant change within different temperatures. As another parameter, the development of shear modulus was studied by recording the large amplitude of temperature variation between -40° to 160°C , at Fraunhofer Center for Silicon [10]. The remarkable decrease in the value of shear modulus between -40° to 0°C from 23 μpa to 1.5 μpa shown in figure 2-6 [10] confirmed the significant influence of temperature variation on the behavior EVA layer.

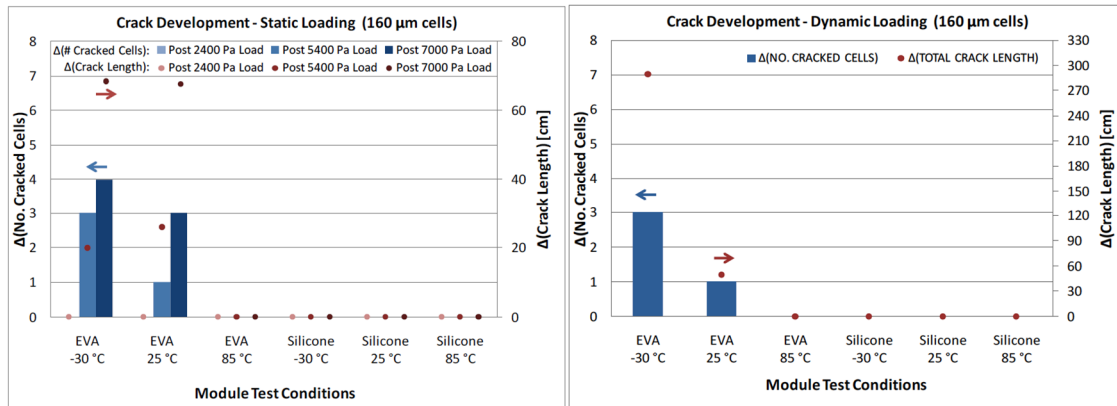


Figure 2-3 Behavior of EVA and Silicon layers with respect to static and dynamic loading on 160 μm layer within -30° to 85° Celsius [11]

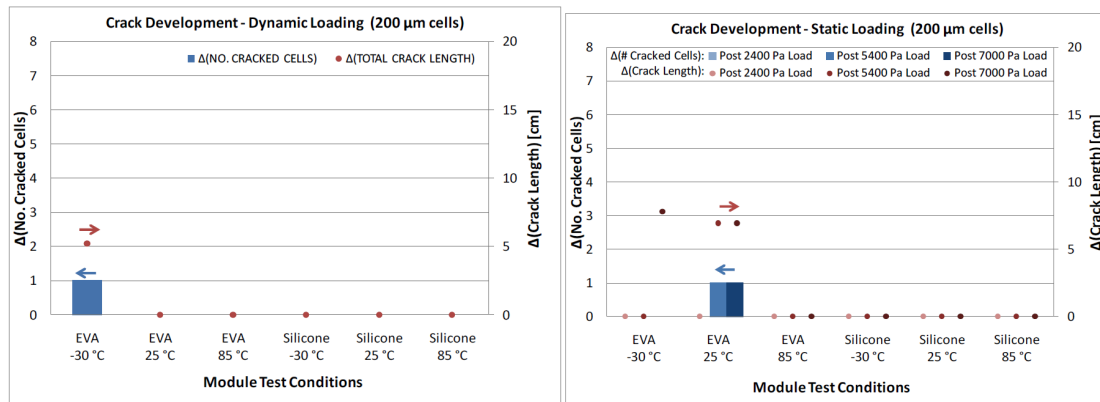


Figure 2-4 Behavior of EVA and Silicon layers with respect to static and dynamic loading on 200 μm layer within -30° to 85° Celsius [11]

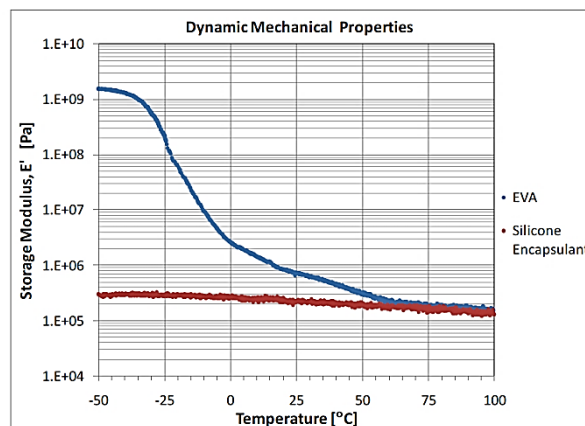


Figure 2-5 Amplitude of Storage modulus variation of EVA and Silicon layers with respect to the -30° to 85° Celsius temperature application [11]

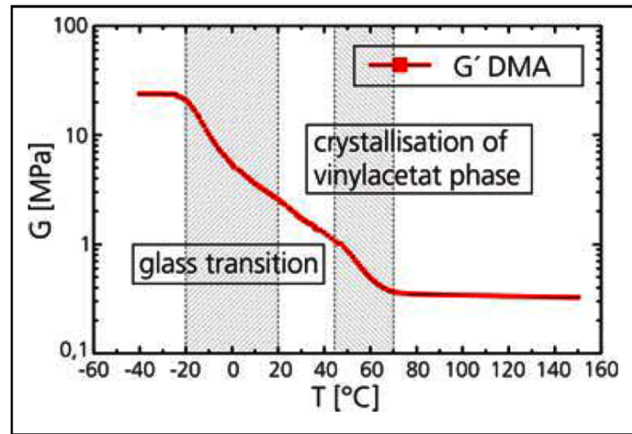


Figure 2-6 Variation of Storage modulus variation of EVA layers regard to the -40° to 160° Celsius temperature application [10]

2.2. Wind Flow Characteristics on Roofs

As mentioned in the previous sections wind flow and weather characteristics influence the behavior of PV solar system outstandingly. The air stream creation caused by the difference between high and low air pressures leads to air acceleration from high to low pressure. This procedure create a variable dynamic load acting on the any surfaces element stands in front depend on height, shape and total area of element normal to the air flow. The complex behavior of the air stream particularly in the case of a vast number of changing intensity leads to a hysteretic behaviors of the structure, causing a remarkable number of studies carried out for understanding the wind load characteristic facing the PV solar system mounted on flat roofs. Some of these will be described below.

The wind load approaching the low-rise buildings from one side is forcing the stream to flow up in the vertical direction and to reach to the roof edge and re-direct along the entire surface of the top roof. According to the figure 2-7 [2] the air stream reaching the roof's leading

edge does not flow smoothly over the roof. The layers diverted at the corner or edge region would try to re-attach to the top side of roof causing a break of some layers at the leading edge and creating a zone where an air swirling (separation bubble) beneath it is formed, called flow separation zone [2]. However, the wind tends to re-attach on the surface of rooftop as soon as possible. Therefore, for wide enough low-rise buildings this trend forms another area on the roof calls reattachment area [2]. At this zone, separated air stream comes down and attaches again to the roof surface and wind flow is almost parallel to the roof surface beyond that point. With the recommendation of Structural Engineers Association of California (SEAOC) reattachment zone is considered to be located on the roof surface at about twice the distance of the building height, from the roof edge. [2]

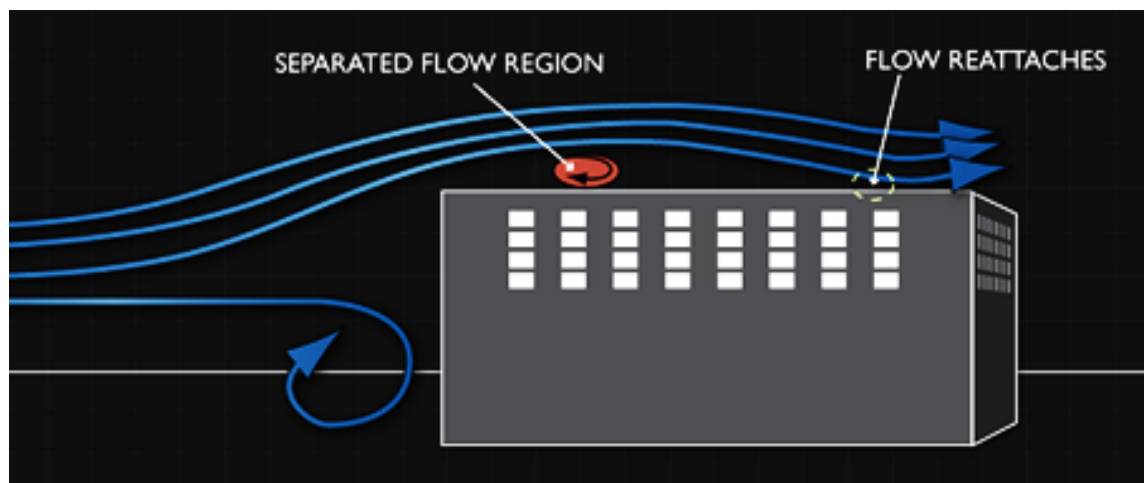


Figure 2-7 Wind behaviour regard to three separation, reattachment and leading side regions [2]

As it is shown in figure 2-7 [2], some layers of flow swirl are formed in the horizontal direction beneath the above stream at the flow separation zone. The movement of air stream

toward the upper side of the roof edge regard creates a blockage of flow by the windward wall of low-rise building, causing the creation of wall stream that limits the passage of the horizontal air streams and makes a shelter area before reattachment zone with consideration to swirling stream at the edge of the building. This wind behavior yields to the absence of any significant positive pressure action with respect to the vertical gravity direction [12]. Moreover, the swirled stream forms a vortex at the edge of building near the parapet that applies strong uplift force to the PV solar panel installed around edge side [13]. However, lack of positive pressure can cause some changes in the wind speed. In this regard, Radu [12] note that “The mean speed above the roof surface reduced to 60% of the value measured at a point far upstream of the building while the roof level the turbulence intensity is about twenty times greater”. This would be worse where the wind flow approaches the corner side of the building where a Delta-Wing vortex appears [13]. The worst peak uplift pressure measured exactly beneath the separated flow zone according to the diagonal stream [14]. Figure 2-8 shows the edge side vortex and the respective wind flow.

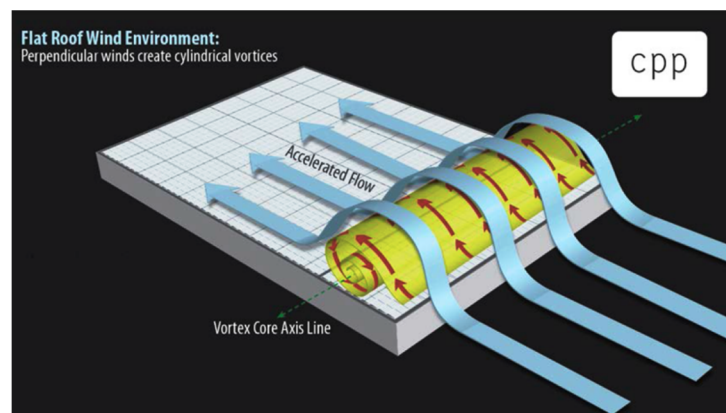


Figure 2-8 Vortex creation at the edge side of building and accelerated air flow [14]

Absolutely, the wind behavior causing the Delta-Wing vortices (figure 2-9 [2]) are almost the same with what happened in the simple swirling stream with a few differences. In

the case of cornering wind flow, two conical vortices originate from the corner side and radiate toward the middle the roof with higher wind speeds than the approaching (initial) flow and significantly increasing the uplift pressure [14]. Therefore, vertical component of wind loads applied to the PV solar systems would be much greater in the corner zones rather than the middle of the roof. Moreover, due to the vulnerability to the speed and direction, of the PV solar panels mounted on the roof, the question of how and where PV solar systems should be placed at the roof top needs to be considered. [2]

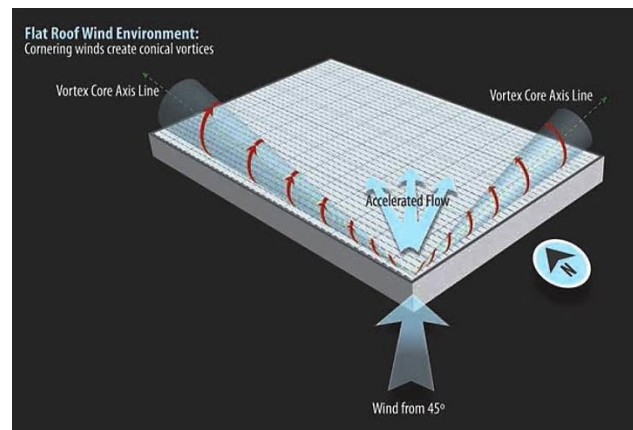


Figure 2-9 Delta-Wing vortices; accelerated wind flow with higher intensity of uplift pressure [2]

According to the different angles of wind flow reaching the edge side of low-rise building, three regions of wind load intensity are specified. Figure 2-10 prepared by SEAOC [2] details these regions to three edges, corner and interior zones represented with yellow, red and white respectively. According to the case whether the computation of the wind load is performed for the roof or for the PV solar panel installed on the roof, the width of edge region (wind flow separations zone) would be different. This value could be equal to 0.4 or twice the building height depending on the amount of wind load on roof using standard components and

cladding or using PV solar photovoltaic panels considered, respectively [2]. To make the definition of these regions more clear SEAOC [2] illustrates these regions as “The interior zone is set back from the building edges approximately two building heights. Beyond this point, the airflow is increasingly beyond the flow reattachment so that the flow travels parallel to the roof surface. The edge zones are those areas within two building heights of the building edge and airflow is characterized by flow separation and vortex formation. The corner zones are located in the building corners within two building heights and the air flow is characterized by the most severe effects of the corner vortices.”

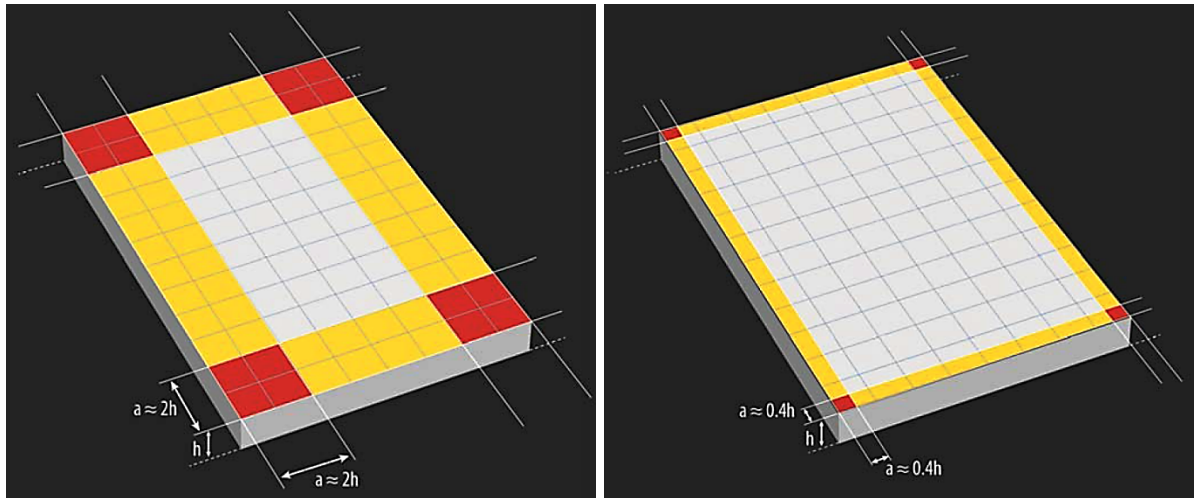


Figure 2-10 Wind load regions according to roof using standard components and cladding or using solar photovoltaic panel [2]

2.3. Codes and design requirements

Few numbers of codes and documents study the photovoltaic systems in provisions and sections, some of them prepare the recommendations based on their geometric configuration of the solar system and the estimation procedure of wind load distribution to main structure.

For instance, American Society of Civil Engineers (ASCE) studies on the behavior of PV solar system as cladding and components with particular conditions [1]. However, the documents prepared by Structural Engineers Association of California (SEAOC), investigates PV Solar system independent [2].

Usually, codes and design guidelines introduce different methodologies to study the behavior of structures or structural elements under induced wind load. Three main procedures namely, simplified, analytical and experimental procedures are recommended by the two mentioned codes ASCE 7-10 [1] and SEAOC report [2]. Usually, the first procedure is based on static load computation. However, two analytical and experimental procedures cover non-linear dynamic loading by modeling the structural behaviors with numerical methodologies or taking the advantage of scaled PV panel specimens or real PV solar panels and weather conditions.

2.3.1. Simplified procedure (Equivalent static loads)

Typically, in design procedure such as that recommended by the Structural Engineers Association of California (SEAOC), the applied wind loads computation procedure take advantages of equivalent static loads [5]. According to ASCE 7-10 [1] simplified procedure used to determine design wind pressures without any experimental test is based on previous tests of particular types of components and cladding [4].

According to the ASCE 7-10 [1], PV solar arrays need to be mounted parallel to the slope roof surface at a distance between 3 to 6 inches above the roof surface to the bottom of the PV frame. Moreover, the building's height must be less than 60 feet high (for low-rise

buildings) and building should meet the rigidity defined in section 6.2 of the code, which mentions that the fundamental frequency of buildings and structures should be more than 1 Hz. This limitation was developed as a worst-case scenario for low-rise buildings. Moreover, the height of the PV mounting structures is typically less than 10 feet with fundamental frequency higher than one requirement, defined above. With respect to this case, the ASCE 7-10 [1] support setting the 1 Hz limitation for PV solar systems. Other array's configurations or building-integrated PV is not addressed particularly in the load recommendations covered by the codes. [15]

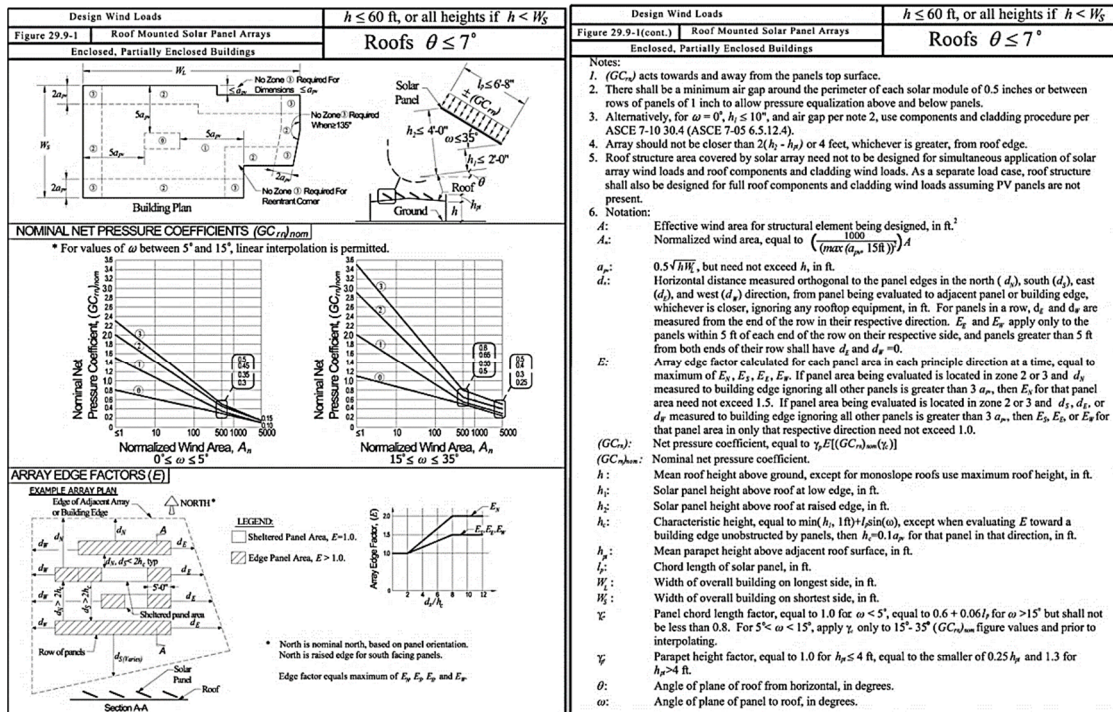


Figure 2-11 The procedure design wind load computation describes at figure 29.9-1 of Structural Engineers Association of California (SEAOC) PV2 August 2012 [2]

In contrast, the Structural Engineers Association of California (SEAOC) presents some documents based on the Design Basis Earthquake in ASCE 7-10 and resists the lateral seismic

force specified in ASCE 7-10, with some fundamental differences [1]. On the contrary to ASCE PV solar system studied independently prepares the permission for zero degree roof slope based on three types of installation mentioned in section 2.1. Moreover, the maximum permitted height of center of mass of the solar array could be 36 inches and the height of the PV solar array could change in regard to the length chord and the angle of the PV solar panel to roof [3], [2]. Figure 2-11 shows the figure describes the procedure of the design wind load computation prepared by SEAOC PV2 [2].

2.3.2. Analytical Procedure

The analytical procedure takes advantage of the powerful software products to model the wind load and PV specimen with respect to CFD (Computational fluid dynamics) and FEA (finite element analysis) numerical methods. Although there are many limitations and requirements needed to be met for more accurate results, in this procedure for each specific case, the efficiency and economic advantage of such study, convinced most of PV solar project owners to use this procedure. ASCE 7-10 provides some requirements and limitations in section 6-5 of Chapter 6 [1] to take advantage of such analytical procedure.

One accurate method to compute the behavior of structures under dynamic load induced by wind stream is the response -history analysis. Schellenberg, [5] notes in his study that “Response-history analysis is a mean for investigating the effects of structural dynamics on the behavior of solar arrays and the appropriateness of equivalent static analysis procedures.” In addition, he [5] adds, “advances in structural analysis capabilities allow the potential for dynamic response-history analysis to provide more accurate structural simulations and to

improve static load design practices.” These confirm by Goda [16] that “Structural responses due to wind loading are generally limited to those of linear elastic systems. However, on rare occasions, inelastic behavior of structural systems due to intense wind events could result in dramatic destructive consequences”.

To compute the dynamic response of the structure due to induced wind load, three important measures need to be considered that govern the behavior of a structure: length, force and time. Other parameter need to be considered is linearity or non-linearity of a member that is introducing the hysteretic behavior of structure whether nonlinear response-history analysis is considered. Moreover, the hysteretic behavior of structure plus structural damping of the components and the type of structure support influences the energy dissipation that needs to be considered in study in order to achieve more accurate results [5].

One way to take advantage of the analytical procedure is by using the Finite Element Method (FEM) which is one of the most capable numerical method based on introduced respective to compute displacement and numbers of other parameters. This method works with the ability of dividing a member to tons of elements with particular dimension that called Mesh. More accurate result will be expected by better mesh size (mesh sensitivity) as it noted by Thohura and Islam [17] “When generating a finite element mesh, one can expect more accurate results with more refined mesh (smaller size but larger number of elements within a confined area).”

The procedure accuracy of FEM computation stands on which shape of mesh considered. Salajegheh [18] noted that according to the mesh type, in general triangular or quadrilateral shapes are recommended for two-dimensional studies and tetrahedron or brick shapes find better use for three-dimensional systems considered, depending also on the terms extracted

from Pascal's triangle or pyramid to make equation for each node and compute displacement for each node. For the mentioned case, the equations generated with consideration of geometry, constraints, mechanical properties, and loads, which applied to matrix for each element, would be based on the principle of minimum total potential energy.

According to the external energy, matrix of stiffness $[k]$ produced with respect to force $(\mathbf{F})$ and displacement (δ) and the internal energy (strain-energy density) that is equal to $\frac{1}{2}\sigma\epsilon$ [18]. The importance of matrix preparation Logan [19] noted “Matrix methods are a necessary tool used in the finite element method for purposes of simplifying the formulation of the element stiffness equations”; these matrix methods need to be considered for all nodes depending on the mesh size. It would be clear that by decreasing the mesh size number of nodes, the number of equations increase significantly leading to more time consumption simulation. Therefore, the importance of accuracy needs to consider the mesh size, besides the time consumption where Thohura and. Islam [17] mentioned that “However as the model gets larger (In FEA, larger model does not mean larger geometry, but rather the complexity due to the number of elements used), the computer will spend more time to generate the results of the analysis. It is often very important to minimize the computing time without a significant loss in the accuracy of the solution.”

2.3.3. Experiment procedure

Nowadays a major number of engineers prefer to choose analytical modeling and simulations, based on the scaled experiments performed in the wind tunnel or for real wind load because of accurate results they provide. Although experimental test accuracy is

significant with other studies, the amount of money spent for such tests would not help convincing project owners to choose this way for detailed investigations. However, to take advantages of accuracy of these procedure different characteristics of case study plus geometry and the topography of the specimen at the given location should be accurately modeled and tested in a boundary layer wind tunnel [4].

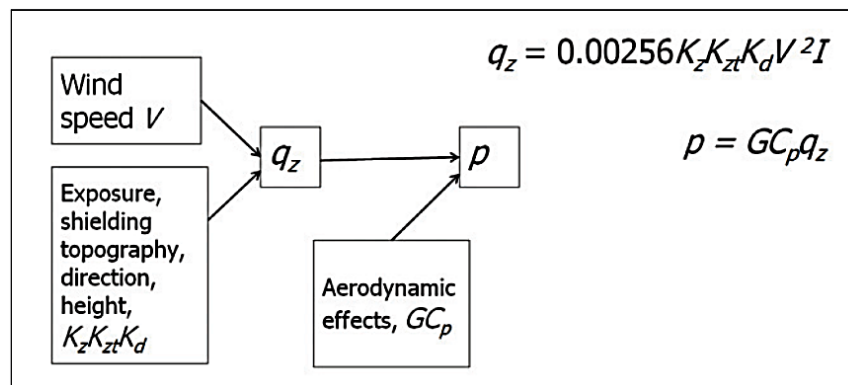


Figure 2-12 According to ASCE 7 different parameters need to introduce to system computation of mean wind force [4]

For computation of wind load over a PV solar system, three possible test types exist: the aero-elastic flyaway models, the Force-balance static models and pressure tapped models each using different instrumentation to identify the dynamic behavior of the models, the static forces acting on the model and the pressure at the surface of the tested model.

Kopp [4] mentioned in their “Fly-away testing of aero-elastic models is not only a well-established methodology for testing but also one that is intuitively easy to explain. In this type of test, the solar array model is placed on the model building in the tunnel and the wind speed is increased until the array moves. While this method of testing is intuitive and straightforward, there are a variety of challenges inherent in the process”. Moreover, according to the second

type of modeling they [4] noted that using the array models with strain gauges and load cells attached at connection points would successfully replace the standard aero elastic fly-away models, however placing the instrumentation would remain a challenge. Besides, some explanations added in regards to the pressure tapped models which it is mentioned that that the net forces on the surface of the array models can be obtained by opening tiny holes on the surface of the model and connecting them to hollow plastic tubes, through which the wind speed would be measured and the associated pressure can be calculated. [4]

There is another type of experiment, which has the advantages of real specimen induced open-air wind load considered. For this case, usually PV solar system instrumented with strain gauges to measure the value of deflection within particular period is used. Totally, the value of measured strain is considerably small and strain is often expressed as microstrain ($\mu\epsilon$), which is equal to $\epsilon \times 10^{-6}$ [20]. When a bar strained at uniaxial force direction a parameter known as Poisson strain causes to allow the bar to elongate in the direction of applied load. These phenomena provide the Poisson's ratio which is defined as the negative ratio of the strain in the transverse direction (perpendicular to the force) to the strain in the axial direction (parallel to the force), or $\nu = -\epsilon_T/\epsilon$. [20]

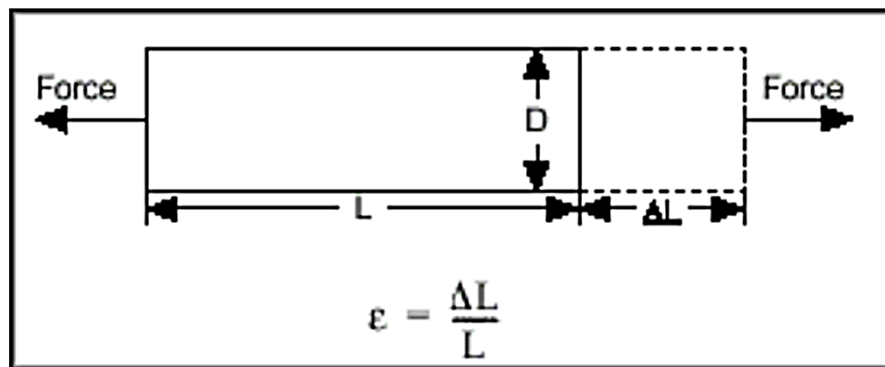


Figure 2-13 Uniaxial strain along force applied direction [20]

A strain gauge uses the concept of electrical resistance that varies in direct proportion to the amount of strain placed on it. Usually, the metallic strain gauge are the most common gauges and consists of very fine wire metallic foil arranged in a grid pattern. The pattern maximizes the amount of metallic wire or foil subject to strain in the parallel direction (active grid length). The cross sectional area of the grid is minimized to reduce the effect of shear strain and Poisson strain. [20]

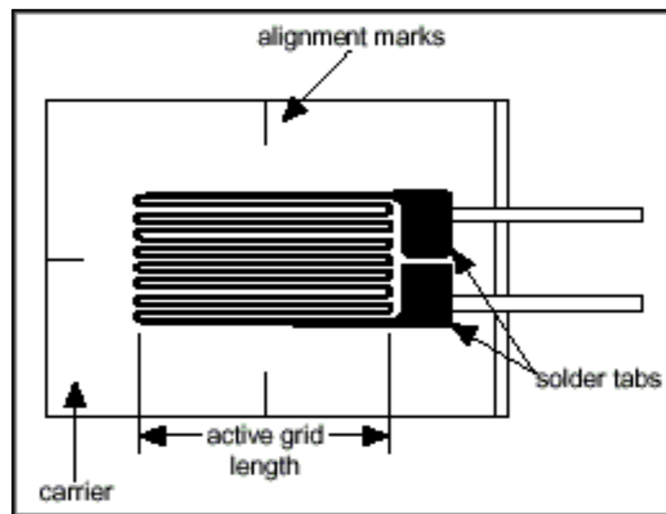


Figure 2-14 Uniaxial strain along force applied direction [20]

CHAPTER 3: Parametric Study, PV Panel modeling

Each PV solar panel consists various materials with very different coefficient of thermal expansion (CTE) and Young's Modulus, which can cause different thermal stresses within the same PV solar panel. Moreover, the properties of the encapsulated panel exhibit a strong dependence on temperature that leads to a change in mechanical properties of the material used for different layers of the solar panel. Furthermore, the external loads transferred to the inner solar cells are considerably affected by the temperature variation. The load transfers to the successive layers constituting the solar panel that can lead to some mechanical failures mostly caused by displacement along the thickness of solar panel [21].

It is clear that the amount displacement, or to be more clear, the strain compensation depends on shear stiffness and thickness of sandwich (successive layers of the solar panel). By reducing the thickness wafer, higher deformation and more stress can distribute along the thickness of solar panel that can cause cracking and deboning. The amount of distributed stress along solar is affected not only by the thickness, but also by the temperature reduction. This reduction usually adds more fragility that cause higher stress along solar panel. Finally, inhomogeneity of multi-layers PV solar panel needs to be considered in study of stress distribution. Different mechanical properties of each layer applied to non - adhesive behavior of the sandwich can stress up to 20 % regarding to Dietrich and Pander [10].

There are not known material properties specifications for the PV solar panel installed on the roof of Mann parking building, therefore two standard types of layered structures [10] were studied, applied directly to our PV solar panel model. Moreover considering that the field measurements took place in the winter season, the variation of thickness and temperature are

studied in the current research to find maximum displacement of the solar panel based on the mechanical properties of each layer. For this case 1.580 m×0.808 m×0.005 m (H×W×D) PV solar panel, as per the dimensions of the PV solar panel installed on the roof of the Mann parking building, is considered. As detailed in chapter 2, the PV solar panel is fabricated as a sandwich containing up to 5 layers of different materials, such as glass, silicon cells, tedlar and the Ethylene Vinyl Acetate (EVA) connected together by the aid of the adhesive layers. Table 3.1 shows the mechanical properties of each layer that used for various computations performed in the current investigation. The mechanical properties for each layer were chosen as per the extensive studies [10]. Moreover, the thickness and the distance between centerline of each layer and the whole solar panel used in the sandwich are defined for both 5-layers and 3-layers panels in Table 3.2. As it will be presented in the section below, the values considered as mechanical characteristics of Ethylene Vinyl Acetate (EVA) will be neglected in the material that will focus on studying the behavior of the 3-layers PV solar panel with height of 3.8 mm. Two schematic section 5-layers and 3-layers solar panel are shown in Figures 3.1. The height used in these section views is exaggerated to clarify the thickness of each layer.

Therefore, by the aid of numerical and FEM methods presented in next sections, the behavior of photovoltaic solar panel with respect to the following parameters was studied:

- 1- Temperature variation from -40° C to +40° C
- 2- Reduction of thickness of solar panel from 5 mm to 3.8 mm
- 3- Different size of the mesh used in the FE modelling

Table 3-1 Mechanical properties of different materials used in multi-layer PV solar panel

Materials	Glass	Eva	Silicon	Tadler
Coefficients & Modulus				
Mass per unit volum	2510	940	2329	3950
Modulus of Elasticity (Pa)	7.31E+10	3.48E+06	1.63E+11	2.10E+09
Poission's ratio	0.22	0.4	0.223	0.35
Coefficient of Thermal Expansion (1/K or 1/C)	8.70E-06	2.25E-04	2.57E-06	6.71E-05
Shear Modulus (Pa)	2.996E+10	1.24E+06	6.66E+10	7.62E+09

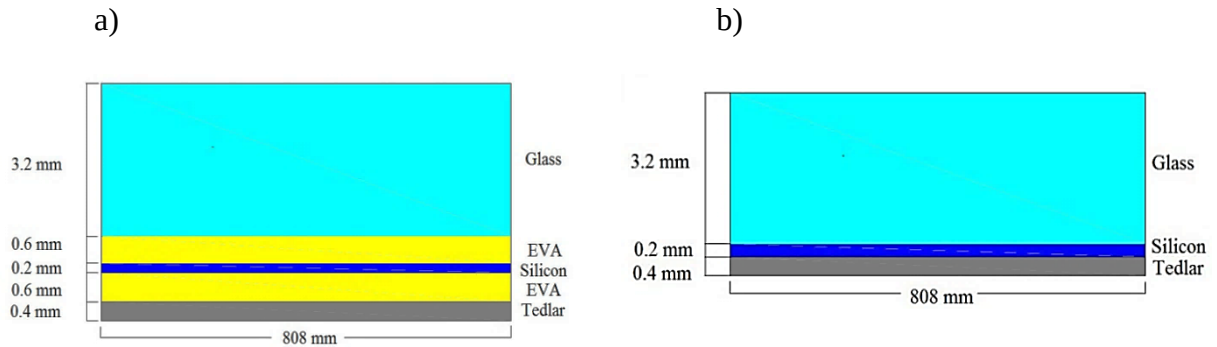


Figure 3-1 Schematic section views 1 of a) 5-layers b) 3-layers solar panel

Table 3-2 Thickness and distance between centerline of each layer and whole solar panel for a) 5-layers solar panel b) 3-layers solar panel (These values recommended directly for this document by Fraunhofer Center for Silicon Photovoltaics CSP)

5-layers standard solar panel			3-layers solar panel		
Layers	Thickness (mm)	Distance from center line (mm)	Layers	Thickness (mm)	Distance from center line (mm)
Glass	3.2	0.9	Glass	3.2	0.3
EVA	0.6	-1	Silicon	0.2	-1.4
Silicon	0.2	-1.4	Tedlar	0.4	-1.7
EVA	0.6	-1.8			
Tedlar	0.4	-2.3			

3.1 Thickness and Temperature effect on the multi-layer PV solar panel

3.1.1 Variation of Young's modulus within -40° C to +40° C

According to the consideration of cube with unity of each dimension with respect to x, y and z axes. If the mentioned membered enforced to elongate in all directions, therefore ϵ_x ϵ_y ϵ_z are the strains about the x, y and z directions and ν is the Poisson ratio. As it is clear, the strains are very small that caused to smaller value of their products that will be even smaller and may be omitted, therefore [22];

$$\nu = (1+\epsilon_x) (1+\epsilon_y) (1+\epsilon_z) \quad (3.1)$$

$$\nu = 1+ \epsilon_x + \epsilon_y + \epsilon_z \quad (3.2)$$

If this change in volume is denoted by e [22] then:

$$e = \nu - 1 = 1+ \epsilon_x + \epsilon_y + \epsilon_z - 1 \text{ or } e = \epsilon_x + \epsilon_y + \epsilon_z \quad (3.3)$$

Regard to bulk modulus for isotropic materials that are under constant pressure and change the one cubic unit of volume [22]:

$$k = \frac{E}{3(1-2\nu)} \quad (3.4)$$

$$e = \frac{p}{k} \quad (3.5)$$

Referring to bulk modulus equation $1-2\nu > 0$, yields to $0 < \nu < \frac{1}{2}$. This means that for an ideal material, stretched in one direction without any lateral contraction, $\nu = 0$. Another case,

of an ideal material with $\nu = \frac{1}{2}$ and bulk modulus equal to infinity, would be perfectly incompressible ($e = 0$). [22]

The following assumptions were considered before proceeding to the estimation of the temperature effect on the Young modulus:

- 1- Poisson's Ratio of EVA's which is equal to 0.4¹ (close to perfectly incompressible material [22])
- 2- Static linear behavior consideration in this study (Nonlinearity of silicon layer mentioned in Hopcroft's study[7])
- 3- Significant value of modulus elasticity of Silicon rather EVA in the encapsulant[10]
- 4- Uncertainty of material properties due to a variety of suppliers and confidential data which is measured only by industry partners and it is not published (lack of enough references)
- 5- The mechanical and thermal properties of EVA layer were significantly influenced by the temperature, when compared with the other layers. Therefore, the only material investigated in this study is the EVA

Regards to a constant poisson's ratio and variation of shear modulus within - 40° C to +40° C modulus elasticity could be computed considering the following equation for various temperatures [22]:

$$G = \frac{E}{2(1 + \nu)} \longrightarrow E = 2G(1 + \nu) \quad (3-6)$$

Some experiments were performed by Fraunhofer Center for Silicon-Photovoltaics [10] for the layered PV panel subjected to temperatures between -40° C and 40° C and the Shear modulus G was determined for different conditions (Fig. 3.2) it could be noticed that under

–20°C and above +60°C the Shear modulus is almost constant, however between the -20 and 60 C a linear decrement of the bulk modulus was reported [10].

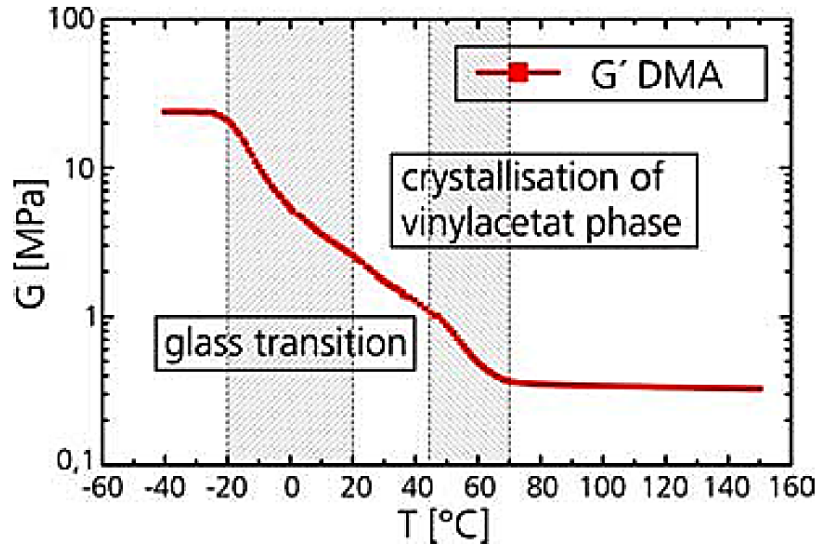


Figure 3-2 Characteristic development of shear modulus over temperature for an EVA [10]

Therefore based on the data presented in figure 3.2 five readings were chosen, as presented in Table 3.3 and these values were implemented in the FE model built for the PV solar panel.

Table 3-3 Young's modulus of EVA material within various temperatures

	1	2	3	4	5
Temperature	-40	-20	0	20	40
Shear Modulus (μpa)	23	20	1.5	1.25	1.05
Poisson's Ratio	0.4	0.4	0.4	0.4	0.4
Modulus of Elasticity (μpa) $E=2G(1+ \nu)$	64.4	56	4.2	3.5	2.94

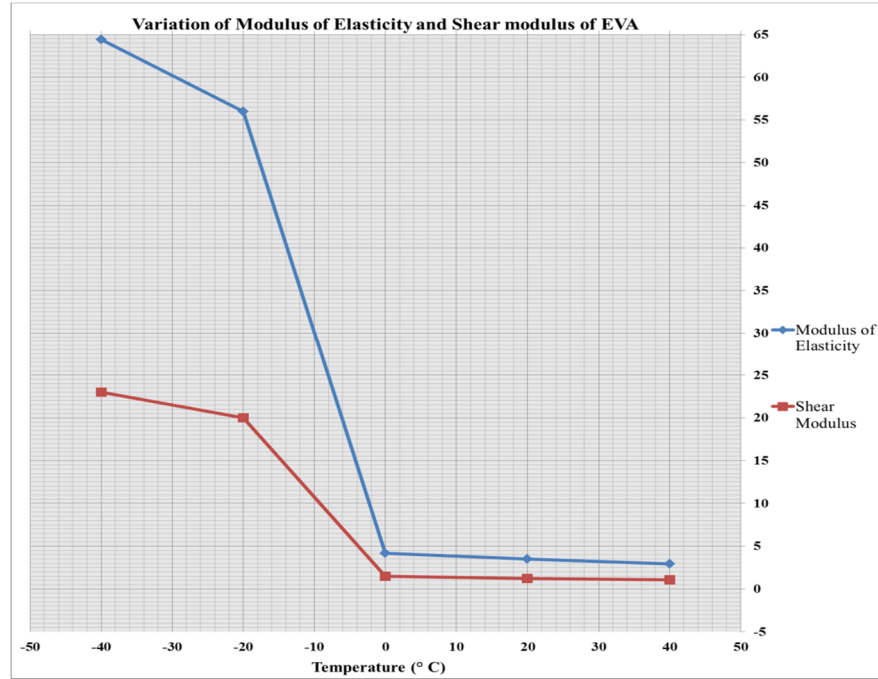


Figure 3-3 Characteristic development of shear and Young’s modulus of EVA layers between - 40° C to +40° C

The EVA adhesive layer alone was reported [10] to have a slightly different evolution especially from 0° C, therefore the material properties as detailed in Table 3.3 and figure 3.3 were employed in the simulation.

3.1.2 Equivalent Young’s modulus for Five-layer solar panel

Due to the lack of enough references regarding the behavior of each layer forming the PV solar panel but based on study carried out by Fraunhofer Center for Silicon Photovoltaics CSP in Germany [10], it was concluded that the EVA layers behavior is completely different

for different temperature. Thus, the total Young's modulus of solar panel in -40°C , -20°C , 0°C , $+20^{\circ}\text{C}$ and $+40^{\circ}\text{C}$ must be individually computed.

Linear and isotropic behavior of each layers is considered in following steps as main assumption. Another assumption is related to the effect of increasing or decreasing temperature and the associated temperature transfer between the layers which is actually ignored, due to low effect of temperature variation within mentioned amplitude on 4 other layers rather significant changes in Young's modulus of EVA especially in temperatures below zero. All the glass materials used in solar panel should meet IEC 61215 protocol to 1,000 hours of damp heat exposure and 10 cycles of humidity-freeze testing [9].

To compute the equivalent Young's modulus of the PV solar panel to replace instead of all the layers, with one single material of equivalent properties, it needs to convert all layers to EVA then change converted area to main section area of the PV solar panel. For this computation each two adjacent materials were considered as follows.

Firstly, silicon layer was changed to glass by increasing the area. To do this a ratio of the two Young's modulus was computed and was multiplied to the area of the silicon layer to be convert to glass. The new area of converted layer was add to the glass to change to tedlar (aluminum) layer. The same procedure was employed for the next step between glass and tedlar, with the fraction value of the Young's modulus of glass over tedlar multiplied to the computed area of glass from the previous step. Next step was considered between tedlar and EVA. The same procedure as in step one was applied with a consideration to the area computed in this step is the one for one layer of EVA and section area of another layer added up to reach to total area needed to have same strength as multilayer solar panel have.

Finally, in order to complete the properties of the layered panel, introducing a replacement material instead of the new EVA section in order to reduce the total section area, which will represent the real dimension of the PV solar panel. To complete this, the concept mentioned above needs to be considered again but with different unknown parameters to be solved. Another expression of above procedure is the Young's modulus of each material which is multiplied to section area and is constant. Consequently, when one Young's modulus or section area change, another parameter needs to decrease or increase to balance the mechanical properties of the layer. For the above case, the Young's modulus of the PV solar panel that is converted to EVA material needs to increase in order to reduce the computed section area to follow the exact geometry of the sandwich.

As mentioned above, all the steps are considered for five different temperatures to study on effect of these variations on Young's modulus of solar panel with the temperature as one important factor of strength and reliability of the PV solar panel structure under static loading. This material converting procedure was proposed and successfully applied by Tahooni, [23]. In the following section, the steps of the material converting procedure described for ambient temperature with the results for the mathematical procedure and attached table are presented for 5-layers and 3-layers panels and the case most suitable for modeling the PV solar panel installed on the Mann packing building is chosen. All the following procedure mentioned by Tahooni, [23]

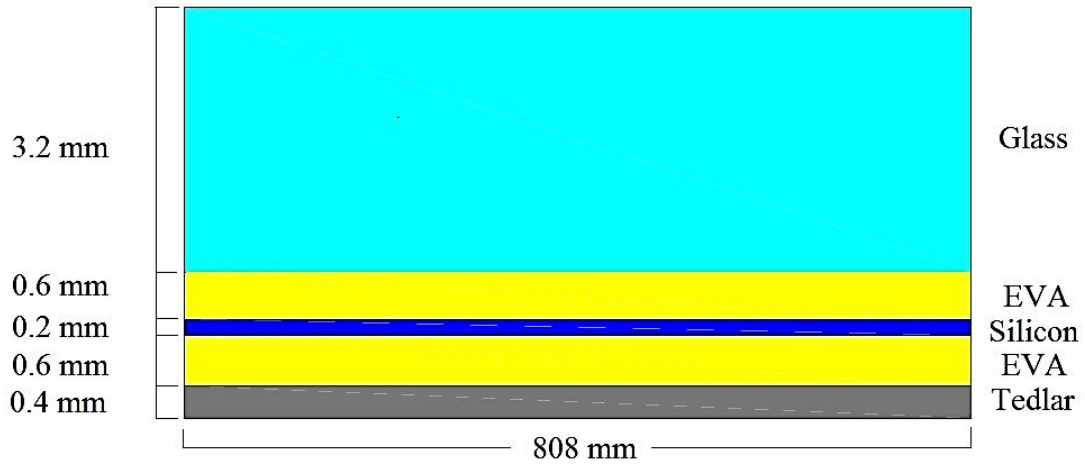


Figure 3-4 Schematic section views of 5-layers solar panel

1. Convert Silicon to Glass:

Factor of Young's modulus:

$$n = \frac{E_{Si}}{E_{Gl}} = \frac{163 \times 10^9}{73.1 \times 10^9} = 2.23 \quad (3.7)$$

Converted area of Silicon layer:

$$A_{Gl \text{ converted}} = (n)A_{Si} = 2.23 \times 1.616 \times 10^{-4} = 3.6 \times 10^{-4} \text{m}^2 \quad (3.8)$$

Total area of Glass:

$$A_{Gl \text{ total}} = A_{Gl} + A_{Gl \text{ converted}} = (25.85 + 3.6) \times 10^{-4} = 29.46 \times 10^{-4} \text{m}^2 \quad (3.9)$$

2. Convert Glass to Tedlar (Aluminum):

Factor of Young's modulus:

$$n = \frac{E_{GL}}{E_{Tad}} = \frac{73.1 \times 10^9}{2.1 \times 10^9} = 34.81$$

Converted area of Glass layer:

$$A_{Ted \text{ converted}} = (n)A_{Gl} = 34.81 \times 29.46 \times 10^{-4} = 0.10255 \text{m}^2$$

Total area of Tedlar (Aluminum):

$$\begin{aligned} A_{\text{Ted total}} &= A_{\text{Ted}} + A_{\text{Tadconverted}} = \\ &3.23 \times 10^{-4} + 0.10255 = 0.1028 \text{ m}^2 \end{aligned}$$

3. Convert Tedlar (Aluminum) to EVA:

Factor of Young's modulus:

$$n = \frac{E_{\text{Ted}}}{E_{\text{EVA}}} = \frac{2.1 \times 10^9}{3.48 \times 10^6} = 603.488$$

Converted area of Tedlar (Aluminum) layer:

$$A_{\text{EVAconverted}} = (n)A_{\text{Ted}} = 603.488 \times 0.1028 = 62.0766 \text{ m}^2$$

Total area of EVA:

$$\begin{aligned} A_{\text{EVA total}} &= A_{\text{EVA}} + A_{\text{EVAconverted}} = \\ &4.85 \times 10^{-4} + 62.0766 = 62.0771 \text{ m}^2 \end{aligned}$$

The value obtained above related to one converted layer of EVA that needs to be added to another EVA's Area due to the existence of layers of EVA:

$$A_{\text{EVA total}} = 4.85 \times 10^{-4} + 62.0771 = 62.078 \text{ m}^2$$

4. The total section area of the layers needs to be replaced with the solar panel section that is equal to 62.078 m^2 , if EVA material has Young's modulus of $3.48 \mu\text{pa}$. However, the unknown to be computed through this replacement procedure is the Young's modulus of the converted material (named α) which is replacing the EVA with the same strength but with 5-layers section area of the solar panel:

$$A_{\text{EVA total}} \times E_{\text{EVA}} = A_{\text{Solar Panel}} \times E_{\alpha} \quad (3.10)$$

$$62.078 \text{ m}^2 \times 3.48 \times 10^6 = 0.00404 \times E_{\alpha}$$

$$E_{\alpha} = 53.47 \times 10^9 \text{ pa}$$

All these conversion steps and determination of the equivalent areas and Young's modulus were repeated for other temperatures and the results are summarized in the following tables:

Table 3-4 Young's modulus of solar panel as uniform material at - 40° C

Material	Height(m)	Length(m)	Area(m ²)	E (pa)				
Glass	3.20E-03	8.08E-01	2.59E-03	7.31E+10				
Eva (-40 °C)	6.00E-04	8.08E-01	4.85E-04	6.44E+07				
Silicon	2.00E-04	8.08E-01	1.62E-04	1.63E+11				
Eva (-40 °C)	6.00E-04	8.08E-01	4.85E-04	6.44E+07				
Tadler(AL)	4.00E-04	8.08E-01	3.23E-04	2.10E+09				
SUM	5.00E-03	8.08E-01	4.04E-03					

Sil-Gla	Material	Height	Length	Area	E	n Sil-Gla	Aconverted= (n) * A	Total Area=A+Aconverted (Glass)
	Glass	3.20E-03	0.808	0.00258560	7.31E+10	2.230	0.00036034	0.00294594
	Silicon	2.0E-04	0.808	0.00016160	1.63E+11			

Gla-Tad	Material	Height	Length	Area	E	n Gla-Tad	Aconverted= (N) * A	Total Area=A+Aconverted (Tadler)
	Tedlar	4.0E-04	0.808	0.00032320	2.10E+09	34.810	0.10254674	0.10286994
	Glass			0.00294594	7.31E+10			

Tad-EVA	Material	Height	Length	Area	E	n Tad-EVA	Aconverted= (n) * A	Total Area=A+Aconverted (EVA)
	Eva	6.0E-04	0.808	0.00048480	6.44E+07	32.609	3.35445466	3.35493946
	Tedlar			0.10286994	2.10E+09			

Converted Area of all layers to Eva based on modulus of elasticity equal to 64.4 μpa								3.355
Based on total area equal to 3.355 m ² modulus of elasticity would be 64.4 μpa now what would be modulus of elasticity fo area equal to 0.00404m ² AE=(AE)'								5.349E+10

Table 3-5 Young's modulus of solar panel as uniform material at - 20° C

Material	Height(m)	Length(m)	Area(m ²)	E (pa)				
Glass	3.20E-03	8.08E-01	2.59E-03	7.31E+10				
Eva (-20 °C)	6.00E-04	8.08E-01	4.85E-04	5.60E+07				
Silicon	2.00E-04	8.08E-01	1.62E-04	1.63E+11				
Eva (-20 °C)	6.00E-04	8.08E-01	4.85E-04	5.60E+07				
Tadler(AL)	4.00E-04	8.08E-01	3.23E-04	2.10E+09				
SUM	5.00E-03	8.08E-01	4.04E-03					

Sil-Gla	Material	Height	Length	Area	E	n Sil-Gla	Aconverted= (n) * A	Total Area=A+Aconverted (Glass)
	Glass	3.20E-03	0.808	0.00258560	7.31E+10	2.230	0.00036034	0.00294594
	Silicon	2.0E-04	0.808	0.00016160	1.63E+11			

Gla-Tad	Material	Height	Length	Area	E	n Gla-Tad	Aconverted= (N) * A	Total Area=A+Aconverted (Tadler)
	Tedlar	4.0E-04	0.808	0.00032320	2.10E+09	34.810	0.10254674	0.10286994
	Glass			0.00294594	7.31E+10			

Tad-EVA	Material	Height	Length	Area	E	n Tad-EVA	Aconverted= (n) * A	Total Area=A+Aconverted (EVA)
	Eva	6.0E-04	0.808	0.00048480	5.60E+07	37.500	3.85762286	3.85810766
	Tedlar			0.10286994	2.10E+09			

Converted Area all layers to Eva based on modulus of elasticity equal to 56 μpa								3.859
Based on total area equal to 3.859 m ² modulus of elasticity would be 56 μpa now what would be modulus of elasticity fo area equal to 0.00404m ² AE=(AE)'								5.349E+10

Table 3-6 Young's modulus of solar panel as uniform material at 0° C

Material	Height(m)	Length(m)	Area(m ²)	E (pa)				
Glass	3.20E-03	8.08E-01	2.59E-03	7.31E+10				
Eva (0 °C)	6.00E-04	8.08E-01	4.85E-04	4.20E+06				
Silicon	2.00E-04	8.08E-01	1.62E-04	1.63E+11				
Eva (0 °C)	6.00E-04	8.08E-01	4.85E-04	4.20E+06				
Tadler(AL)	4.00E-04	8.08E-01	3.23E-04	2.10E+09				
SUM	5.00E-03	8.08E-01	4.04E-03					
Sil-Gla	Material	Height	Length	Area	E	n Sil-Gla	Aconverted= (n) * A	Total Area=A+Aconverted (Glass)
	Glass	3.20E-03	0.808	0.00258560	7.31E+10	2.230	0.00036034	0.00294594
	Silicon	2.0E-04	0.808	0.00016160	1.63E+11			
Gla-Tad	Material	Height	Length	Area	E	n Gla-Tad	Aconverted= (N) * A	Total Area=A+Aconverted (Tadler)
	Tedlar	4.0E-04	0.808	0.00032320	2.10E+09	34.810	0.103	0.10286994
	Glass			0.00294594	7.31E+10			
Tad-EVA	Material	Height	Length	Area	E	n Tad-EVA	Aconverted= (n) * A	Total Area=A+Aconverted (EVA)
	Eva	6.0E-04	0.808	0.00048480	4.20E+06	500.000	51.435	51.43545623
	Tedlar			0.10286994	2.10E+09			
Converted Area all layers to Eva based on modulus of elasticity equal to 4.2 µpa								51.436
Based on total area equal to 51.436 m ² modulus of elasticity would be 4.2 µpa now what would be modulus of elasticity fo area equal to 0.00404m ² AE=(AE)'								5.347E+10

Table 3-7 Young's modulus of solar panel as uniform material at +20° C

Material	Height(m)	Length(m)	Area(m ²)	E (pa)				
Glass	3.20E-03	8.08E-01	2.59E-03	7.31E+10				
Eva (40 °C)	6.00E-04	8.08E-01	4.85E-04	2.94E+06				
Silicon	2.00E-04	8.08E-01	1.62E-04	1.63E+11				
Eva (40 °C)	6.00E-04	8.08E-01	4.85E-04	2.94E+06				
Tadler(AL)	4.00E-04	8.08E-01	3.23E-04	2.10E+09				
SUM	5.00E-03	8.08E-01	4.04E-03					
Sil-Gla	Material	Height	Length	Area	E	n Sil-Gla	Aconverted= (n) * A	Total Area=A+Aconverted (Glass)
	Glass	3.20E-03	0.808	0.00258560	7.31E+10	2.230	0.00036034	0.00294594
	Silicon	2.0E-04	0.808	0.00016160	1.63E+11			
Gla-Tad	Material	Height	Length	Area	E	n Gla-Tad	Aconverted= (N) * A	Total Area=A+Aconverted (Tadler)
	Tedlar	4.0E-04	0.808	0.00032320	2.10E+09	34.810	0.103	0.10286994
	Glass			0.00294594	7.31E+10			
Tad-EVA	Material	Height	Length	Area	E	n Tad-EVA	Aconverted= (n) * A	Total Area=A+Aconverted (EVA)
	Eva	6.0E-04	0.808	0.00048480	2.94E+06	714.286	73.479	73.47901541
	Tedlar			0.10286994	2.10E+09			
Converted Area all layers to Eva based on modulus of elasticity equal to 56 µpa								73.480
Based on total area equal to 73.48 m ² modulus of elasticity would be 2.94 µpa now what would be modulus of elasticity fo area equal to 0.00404m ² AE=(AE)'								5.347E+10

Table 3-8 Young's modulus of solar panel as uniform material at +40° C

Material	Height(m)	Length(m)	Area(m ²)	E (pa)				
Glass	3.20E-03	8.08E-01	2.59E-03	7.31E+10				
Eva (40 °C)	6.00E-04	8.08E-01	4.85E-04	2.94E+06				
Silicon	2.00E-04	8.08E-01	1.62E-04	1.63E+11				
Eva (40 °C)	6.00E-04	8.08E-01	4.85E-04	2.94E+06				
Tadler(AL)	4.00E-04	8.08E-01	3.23E-04	2.10E+09				
SUM	5.00E-03	8.08E-01	4.04E-03					
Sil-Gla	Material	Height	Length	Area	E	n Sil-Gla	Aconverted= (n) * A	Total Area=A+Aconverted (Glass)
	Glass	3.20E-03	0.808	0.00258560	7.31E+10	2.230	0.00036034	0.00294594
	Silicon	2.0E-04	0.808	0.00016160	1.63E+11			
Gla-Tad	Material	Height	Length	Area	E	n Gla-Tad	Aconverted= (N) * A	Total Area=A+Aconverted (Tadler)
	Tedlar	4.0E-04	0.808	0.00032320	2.10E+09	34.810	0.103	0.10286994
	Glass			0.00294594	7.31E+10			
Tad-EVA	Material	Height	Length	Area	E	n Tad-EVA	Aconverted= (n) * A	Total Area=A+Aconverted (EVA)
	Eva	6.0E-04	0.808	0.00048480	2.94E+06	714.286	73.479	73.47901541
	Tedlar			0.10286994	2.10E+09			
Converted Area all layers to Eva based on modulus of elasticity equal to 56 µpa								73.480
Based on total area equal to 73.48 m ² modulus of elasticity would be 2.94 µpa now what would be modulus of elasticity fo area equal to 0.00404m ² AE=(AE)'								5.347E+10

As expected, was noticed that in order to keep a constant value of the equivalent Young's modulus for the 5-layers solar panel, the area of each layer was re-adjusted, through the conversion procedure detailed above and documented by Tahooni, [23]. For lower temperatures, below 0° C, the equivalent Young's modulus was $E_{\alpha} = 53.49 \times 10^9 \text{ Pa}$ while for higher temperatures the Young's modulus was $E_{\alpha} = 53.47 \times 10^9 \text{ Pa}$.

3.1.3 Young's modulus of Three-Layers solar panel without EVA

One important case of this study is the investigation of the PV solar panel deflection in regard to the reduced thickness of the solar panel, through analytical procedure. Due to the low value of Young's modulus of EVA, this material was omitted from the layers of the modeled PV solar panel. The same procedure as the one used in the section 3.13 for computing the

uniform Young's modulus of the 5- layers solar panel was also considered in the case of the 3-layers solar panel. In comparison with 5-layer solar panel, the uniform Young's modulus of model without EVA layers increased significantly with respect to the reduced section area, as it will be shown below.

The increasing value of the Young's modulus with respect to the thickness reduction of this model, leads to complex behavior of the sandwich real PV panel specimen under wind load. Regarding to Beer and Johnston, [22] all materials with same Young's modulus have same stiffness or ability to resist a deformation within the linear range. However, they could have large variation in yield strength, ultimate strength and ductility.

On the other hand reduction of cell thickness leads to higher deformation and stress [10]. Consequently, the 3-layers solar panel is modeled within linear range and compared with the 5- layers model to figure out the dominant effect of absence of EVA, under same type and value of loading, the increased ability to resist a deformation with large value of Young's modulus or the decrease in the same ability due to thickness reduction. To complete this, the maximum deflection computed by finite element software for both multi-layers systems compared with each other for 3 different mesh sizes was also investigated at the end of this chapter.

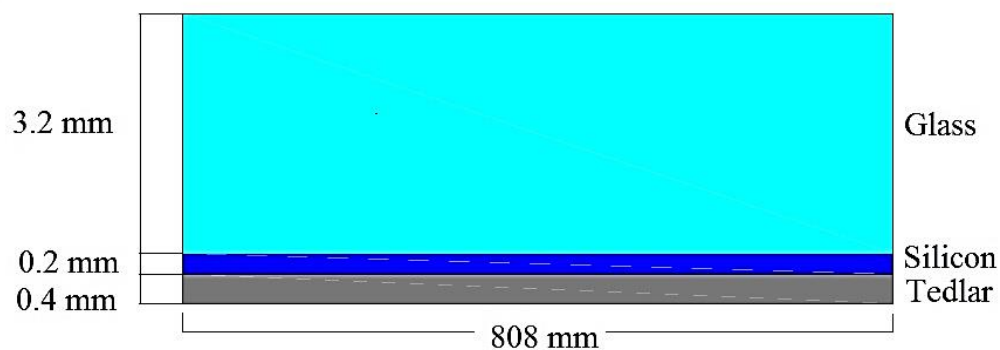


Figure 3-5 Schematic section views of 3-layers solar panel

Table 3-9 Young's modulus of 3-layers solar panel as uniform material

Material	Height(m)	Length(m)	Area(m ²)	E (pa)				
Glass	3.20E-03	8.08E-01	2.59E-03	7.31E+10				
Silicon	2.00E-04	8.08E-01	1.62E-04	1.63E+11				
Tadler(AL)	4.00E-04	8.08E-01	3.23E-04	2.10E+09				
SUM	3.80E-03	8.08E-01	3.07E-03					

Sil-Gla	Material	Height	Length	Area	E	n Sil-Gla	Aconverted= (n) * A	Total Area=A+Aconverted (Glass)
	Glass	3.20E-03	0.808	0.00258560	7.31E+10	2.230	3.60339261E-04	0.00294594
	Silicon	2.0E-04	0.808	0.00016160	1.63E+11			

Gla-Tad	Material	Height	Length	Area	E	n Gla-Tad	Aconverted= (n) * A	Total Area=A+Aconverted (Tadler)
	Tedlar	4.0E-04	0.808	0.00032320	2.10E+09	34.810	0.10255	0.10286994
	Glass			0.00294594	7.31E+10			

Converted Area all layers to Tadler based on modulus of elasticity equal to 2.1 Gpa								0.103
Based on total area equal to 0.103 m² modulus of elasticity would be 2.1 Gpa now what would be modulus of elasticity fo area equal to 0.00404m² AE=(AE)'								7.036E+10

For the 3-layers compacted together, in the absence of the adhesive EVA material was noticed that the total area of solar panel's section decreased, however Young's modulus increase significantly.

3.2 Finite Element Modeling:

After the comparison between the mechanical properties of the two types of PV solar panels with 3-layers and 5-layers arrangement respectively, these need to be analyzed under the effect of static and dynamic forces, to verify their structural integrity. Thus, the finite element software CSI-SAP 2000 used to model various cases and to determine the maximum deflection, the moments and the stress distribution. To achieve this, an accurate model of the PV panel, with all materials properties and geometry of the layers need to be introduced in the software. This chapter concentrated on modeling the layered PV solar panel, while the mounting frame and connections will be explained in detail in chapters 4 and 5.

3.2.1 Modelling of the Solar Panel as Multi-layer Shell Element:

To model the multi-layer PV solar panel material properties defined through the software would be challenging especially for the silicon layer, as an anisotropic material; hence based on the recommendations of Fraunhofer Center for Silicon Photovoltaics CSP research center, Germany [10] who were contacted for exchange of information, an assumption was made regarding the specific material properties considered for silicon uniformly applied in all directions. In addition, isotropic material properties and density for Glass, EVA, Silicon and Tedlar (Aluminum) layers applied to the software with respect to the International System of Units (SI).

The geometrical dimensions of the PV solar panel installed on the roof of the Mann parking building are 1.580 m×0.808 m×0.005 m (height ×width ×thickness) (Fig.3.6 a) and b) as presented in the specifications provided by the manufacturer (Morgan Solar Ltd.). The multilayers structure of the PV panel are described as a first layer of glass, protecting a second layer of poly-crystalline-EVA cells and protected on the back with a resistant aluminum material; this arrangement is very similar to the 5-layers configuration documented above. The FE model of the PV solar panel was created in accordance with the manufacturer geometric details (Fig. 3.6), with the exception of the thickness, which was dictated by the temperature and Young modulus characteristics discussed above. The boundary conditions and connection with the truss frame on which the panel was mounted, will be discussed in Chapter 4.

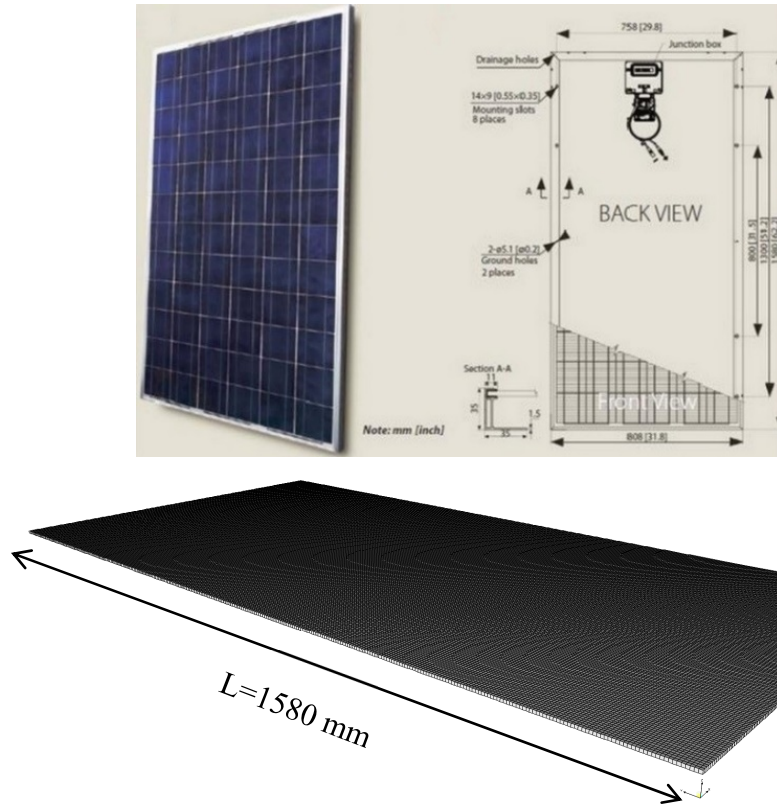


Figure 3-6 Geometric details of the PV solar panel besides the Finite element model

Non-linear shell multi-layered option for area elements were considered when defining and arranging different layers of solar panel one above another. The behavior of layered member described by CSi Analysis Reference as” Membrane deformation within each layer uses a strain-projection method (Hughes, 2000). In-plane displacements are quadratic. Unlike for the homogeneous shell, the “drilling” degrees of freedom are not used, and they should not be loaded. These rotations normal to the plane of the element are only loosely tied to the rigid-body rotation of the element to prevent instability. For bending, a Mindlin / Reissner formulation is used which always includes transverse shear deformations. Out-of-plane displacements are quadratic and are consistent with the in-plane displacements” [37]. To define this section area, three types of section area are available in the software: Stress or Strain Plane

Area, Asolid Area and finally Multilayer Non-linear shell element. Due to the numbers of layers of different materials required in the model, the latter option was chosen. Therefore, the thickness and the distance between the centerline of each layer and the solar panel, as determined in table3-2 were modeled so that it will represent each of the layers of the PV panel.

Next parameters defined were the material angle and material component behavior of each layer that were considered equal to zero for Non-linear and linear behavior with respect to the x, y, z directions. These parameters were considered for both 5-layers and 3-layers thickness reduced models. The interaction between the layers is automatically considered by the software based on the linearity or non-linearity defined for each material (linear behavior considered). Final parameters that need to be checked were related to the validation of the layers thickness and geometric overlap. The total thickness calculated must be equal to 5 mm for 5-layers solar panel and 3.8 mm for 3-layers one. Moreover, the summation of overlaps and gap between layers should be equal to null or some negligible value that do not affect the modeling assumptions. These three parameters are important checkpoints to assure the accuracy of shell element behavior as a specific layer in the encapsulated PV solar panel. The geometry, thickness and other parameters used for 5-layers and 3-layers element are shown in figure 3.1, Tables 3.1, and 3.2.

3.2.2 Mesh Sensitivity:

The accuracy of the result got from finite element analysis depends completely on the boundary conditions and shape of each segment and mesh size. Thohura and Islam, [17] noted

that the more refined mesh (smaller size but larger number of elements) yield to more accurate results. Nevertheless, with larger model, more computing time is required to generate the results of the finite element analysis. In FEA, the complexity due to the number of elements means larger model not the larger geometry[17]. Thus, 5 mm, 10 mm and 50 mm meshes were considered to find appropriate size while minimized the computing time without a significant loss in the accuracy of the solution .These three mesh sizes were applied to x, y, and z directions of the solar PV panel modeled with shell elements as shown in figures 3.7 (a,b,c). In order to determine the effect of this mesh sensitivity on the results, the definition of a standard testing loading must be introduced.

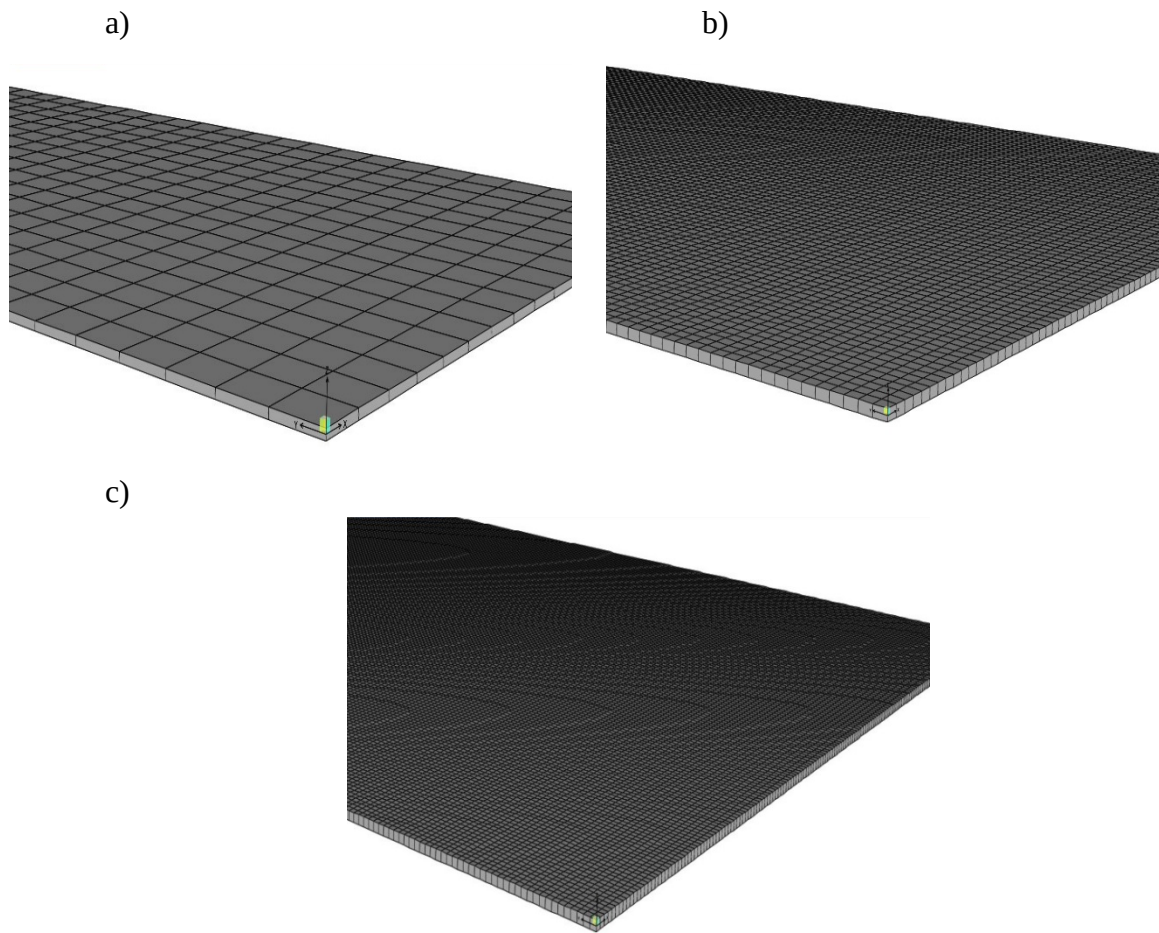


Figure 3-7 Three Mesh sizes for the PV solar panel of a)50 mm b)10 and c)5 mm

3.2.3 Load and Temperature applied to the FE model of PV solar panel:

To study the structural behavior of the PV solar panel as a layered structure, assigning the type of supports and a uniform static load on the shell element is required, to compute the maximum values of displacement, stress, moment etc. Moreover, a fixed support was applied to every of the four corners of the modeled PV solar panel. Then 400N, 600N and maximum 700N of uniform load in z direction (vertical or uplift direction) applied to the 5 mm five layers solar panel. Furthermore, another case was introduced without any external load to study the behavior of solar panel with respect to the other parameters. It must be noted that for this step of the analysis, the PV solar panel is considered without any surrounding frame. Moreover, due to the main objective of the current study that is to investigate on the wind load effect on fully framed PV panels attached to flat roofs, generally the uniform load employed was applied in this along the z uplift direction.

On the other hand, various temperatures assigned to different models. The default temperature of the FEM software is equal to zero degrees Celsius, which it changed initially to the ambient temperature based on the mechanical properties of each material that defined previously. For the next analysis steps, 5 steps of temperatures from -40°C and $+40^{\circ}\text{C}$ were applied to each element and along with the loading step mechanical properties of each element were changed accordingly. The only case that the temperature load has not been applied to system was ambient temperature where the study and natural temperature of material properties both were equal to 20°C .

According to the three mesh sizes, of 50 mm, 10 mm and 5 mm, as presented in Figure 3-7, several loadings were analyzed of 0 N, 400 N, 600 N and 700N for the 5-layer PV solar

panel model. Totally, 60 different cases were studied in the FEM software SAP 2000 to determine the maximum displacement with respect to the 5 step of temperature mentioned before. This number reduced to nine for 3-layer solar panel for which the temperature effect was neglected due to absence of EVA layer, to study the effect of thickness reduction. Results from a limited number of cases are presented in section 3.3.

3.3 Load application and results:

With respect to the linear method considered in section 3.1.1, to determine the effect of temperature and the variation of the Young's modulus of the EVA layer, table 3.3 and figure 3.3 show the significant effect of temperature variation on the value of Young's modulus as a factor of stiffness. According to the assumption made the effect of temperature variation on the adjacent layers neglected. Therefore, a series of computation cases, corresponding to the cases presented in section 3.1.2 plus the uniform values mentioned in tables 3.4 to 3.8 showing that the Young's modulus of the sandwich does not vary significantly from -40°C to 40°C and it is around 53.47 Mpa.

According to the low effect of temperature on the stiffness of the solar wafer, the thickness reduction was another case to study which was considered with respect to elimination of the EVA layers, that yields to an obvious increase in the value of Young's modulus, to almost around 70.36 Mpa. Due to the high difference in the Young modulus between the two types of layered panels investigated, it seems that the 3-layers specimen could

register lower deflection than the 5-layers model. Therefore, the higher value of Young modulus leads to less deflection under the load applied logically.

As it was detailed in the previous sections, different parameters and different loadings were considered when determining the maximum value of deflections, in brief, according to both multi-layer cases; each three different mesh sizes for five temperatures under uniform applied uplift load were simulated and compared. Another simulation considered according to study the temperature variation effect under zero load application. The uniform load applied to bottom surface of the horizontal solar plate, which should be in the elastic behavior range, far from cracking limits shown in specimen in Fig. 3.8. [21]. Sander [21] experimentally and numerically studied the development of cracks in the encapsulated solar cells and recommend the figure 3.8 (a) with respect to experimental simulation procedure for bending type of loading. They specified that the cracks appear on the cell where the load registered around 800N at ambient temperature, as shown in figure 3.7(b), where the displacement was around 45 mm. Therefore, it is intended to study the structural behavior of the panel in the elastic range where no crack seen in the panel. Thus, three values of uplift load (400N, 600N and 700N) were applied on 3 and 5 layers model. This assumption was made mainly because no cracking was recorded on the PV panel installed on the roof of the Mann parking building and the main objective of the current research is to calibrate the FE model with the experimental measurements obtained from the instrumented PV panel, and not to analyses the yielding behavior for the layered plate of the solar panel itself.

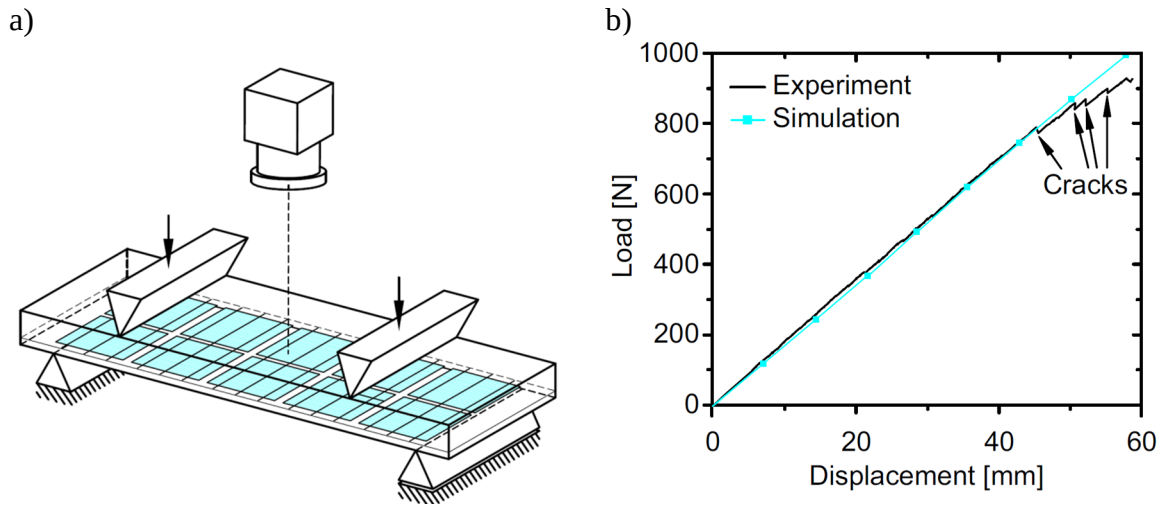


Figure 3-8 (a,b) Experiment run and curve prepared by M. Sandera and his colleagues [21] with respect to study on the cracks development in solar panel

The displacement distribution along the PV solar panel, for different meshes, temperatures and loadings, are presented in Figs. 3.9 to 3.31 and, the maximum values of the displacements are shown in tables 3.10 to 3.14. However, the maximum displacements shown in these tables are close to each other, with consideration of 5 mm mesh size the displacement value showed as the most accurate value for all cases. Therefore, due to the reason that thickness of specimen for 5-layers wafer was chosen to be equal to the same value, it was aimed to concentrate on accuracy. Thus, the 5 mm mesh size was considered to study the structural behavior of solar panel. The displacement of the PV solar panel model registered lower values than the displacement reported by Sandera [21], because the boundary conditions and the loading scenarios are different in the current research.

The max value of displacement computed for 3-layers PV solar panel at ambient temperature (20° C) where 400N, 600N and 700N were applied, are equal to 3.64mm, 9.10mm and 11.20 mm respectively (Figs.3-9 to 3-11 and Table 3.10). The same conditions considered

for 5-layers PV solar panel led to displacements of 2.66 mm, 5.60mm and 7 mm (Figs. 3-12 to 3-3-16. And Table3-11) for the load steps mentioned above which clearly shows that the thickness reduction has direct influence on increasing the maximum displacement and the probability of cracks occurring in the model even if the elimination of EVA layers leads to higher value of Young's modulus.

Another criterion a PV solar panel faces when it is mounted in Ottawa region, is the wide range of temperature from -40°C to 40°C which can affect differently based on high wind load applied to surface of PV solar panel. Therefore, 5 temperatures -40°C , -20°C , 0°C , 20°C and 40°C were modeled for 5-layers PV solar panels with respect to specified value of uplift uniform load plus one final case with zero external load application. From Figures 3-12 to 3-31, it can be noticed that the displacement distribution is not uniform, especially for negative temperatures. Maybe, this behavior comes from the shrinkage of the internal energy, the thermal and the mechanical properties of each layer at -40°C does not allow to the entire specimen to curve in the same direction as the applied load, even when the 700N load is applied uniformly to the bottom side of the model. The displacement compensation effect of temperature for 400N continues up to the case where the temperature reaches 0°C (Fig3-12 to 3-14.). For 20°C and 40°C , the effect of heating and a better transfer at the molecular level of each material helps the model to curve uniformly in the direction of applied load (Figs3-15 and 3-16).

Another common point between all analyzed models is the shape of the displacement distribution along the surface of the PV solar panel. In colder cases where negative temperature is achieved, the largest value of displacement is registered at the center point of the panel and

decays linearly towards the edges and supports, forming an elliptical shape. However, this shape changes to lines perpendicular to the smaller side of PV solar panel model for ambient temperatures of 20° C, but would recover the elliptical distribution for very high temperatures of 40° C (Figs 3-12 to 3-26).

For the final case, the behavior of the PV solar panel with respect to the variation of temperature without any application of external load was studied. Figures 3-27 to 3-31 provided show how the weight of solar panel plus the five steps of temperature could affect the deflection of the solar panel. As it is clear from figures 3-27 to 3-31 that by increasing the temperature from -40° C to +40° C the deflection decreased from around -13 mm to -1.10 respectively, which shows how the variation of temperature could influence the behavior of solar panel significantly.

Consequently, based on the assumption made and based on the results gained from numerical procedure to find equivalent Young's modulus, the stiffness of solar panel increased significantly by decreasing the thickness where the temperature variation changes the behavior of structure slightly. However according to the FEM simulation procedure, both mentioned parameters have considerable influence on deformation of solar panel. With respect to the 5 mm high quality the mesh size, it is shown in tables 3-11 to 3-14 that minus values of temperature especially -40°C plus the weight of solar panel caused to see negative value of displacement. Henceforth, by increasing the temperatures the value of displacement tends to increase along the Z direction.

3.3.1 3-layers solar panel:

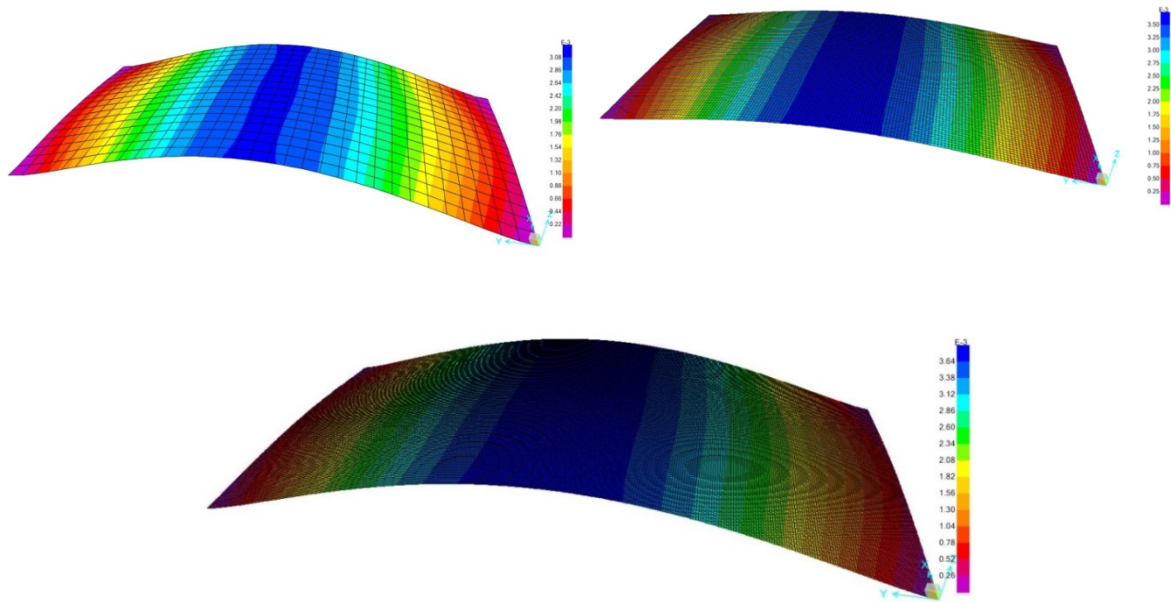


Figure 3-9 Displacement distribution of 3-layers solar panel under 400N load at ambient temperature-50 , 10 & 5 mm mesh applied to model from top respectively

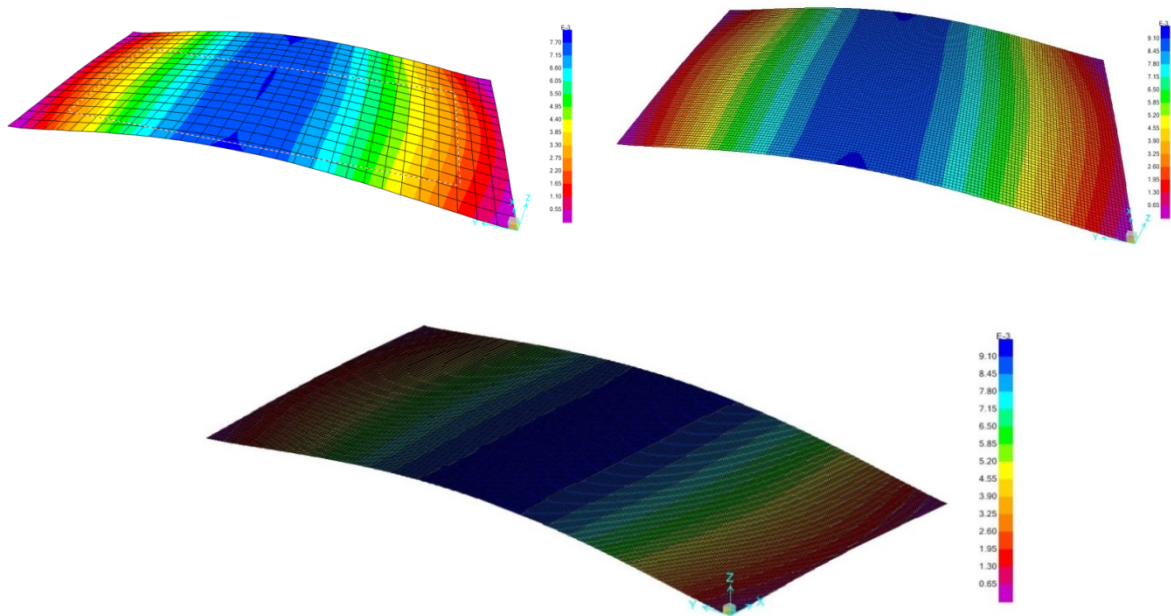


Figure 3-10 Displacement distribution of 3-layers solar panel under 600N load at ambient temperature-50 , 10 & 5 mm mesh applied to model from top respectively

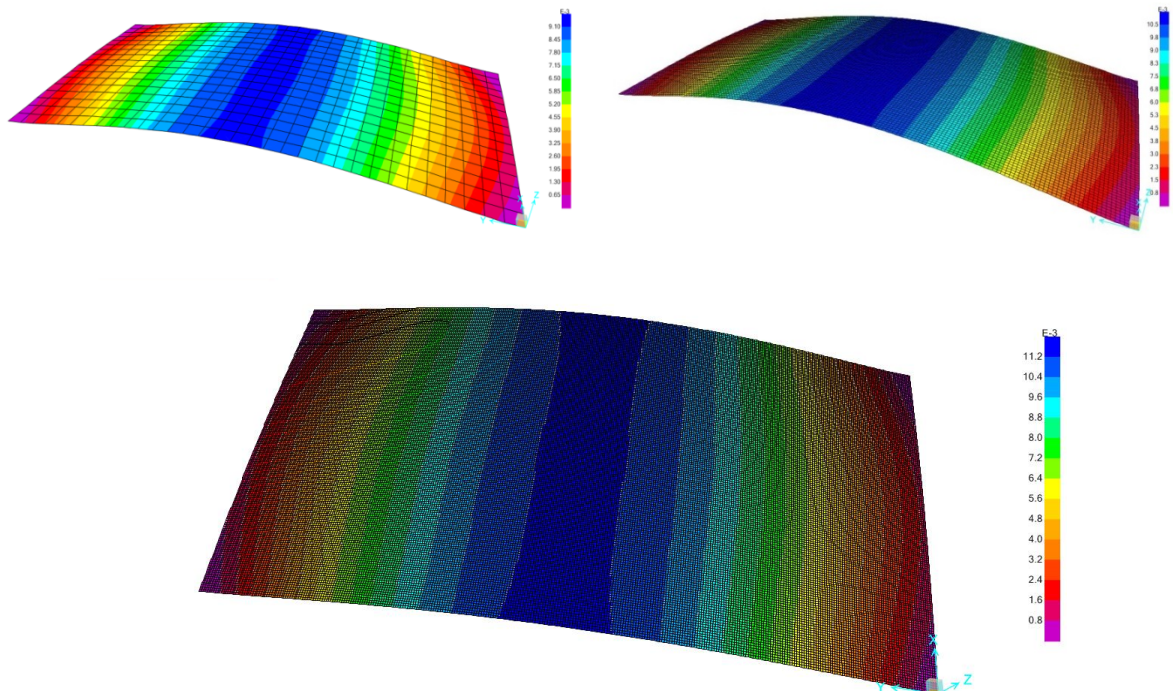


Figure 3-11 Displacement distribution of 3-layers solar panel under 700N load at ambient temperature-50 , 10 & 5 mm mesh applied to model from top respectively

Table 3-10 Maximum displacement of thickness decreased solar panel at ambient temperature–SAP 2000

Max. Displacement of 3-layers solar panel (mm) at 20°C			
Applied load \ Mesh Size	Mesh Size (5 mm)	Mesh Size (10 mm)	Mesh Size (50 mm)
400 N	3.64	3.50	3.08
600 N	9.10	9.10	7.70
700 N	11.20	10.50	9.10

3.3.2 5-layers solar panel under 400N uplift load:

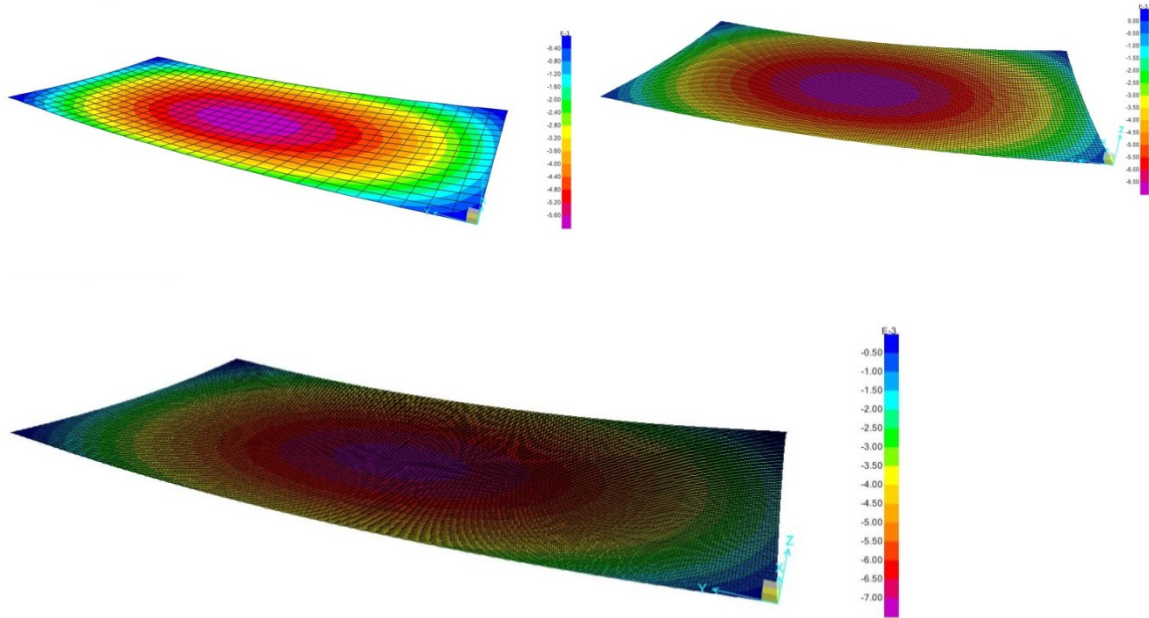


Figure 3-12 Displacement distribution of 5-layers solar panel under 400N load at -40°C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

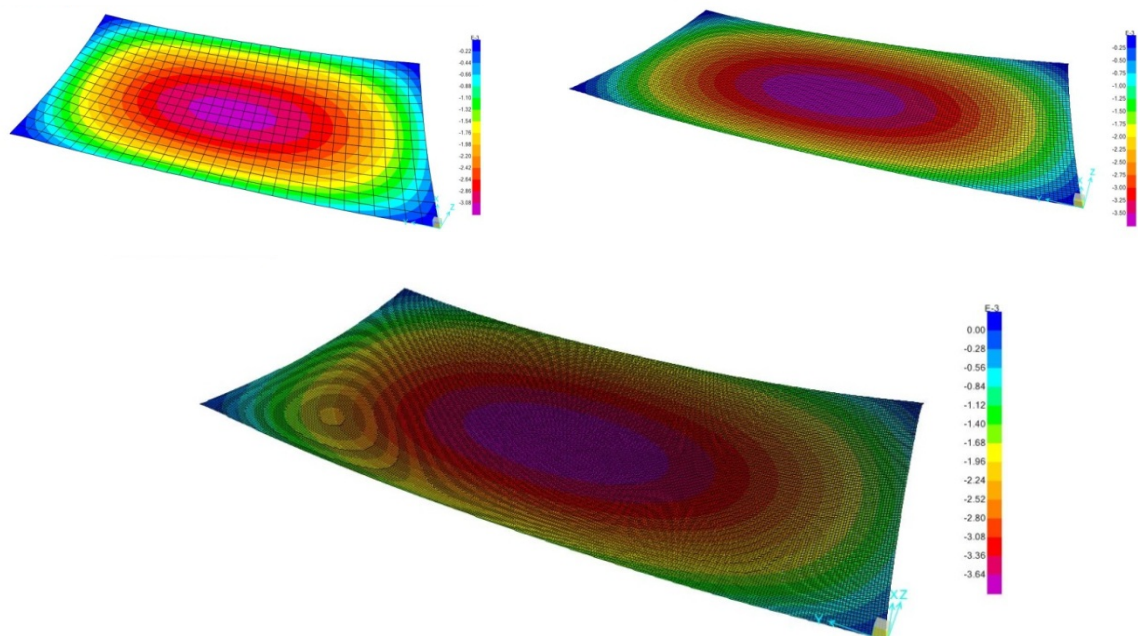


Figure 3-13 Displacement distribution of 5-layers solar panel under 400N load at -20°C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

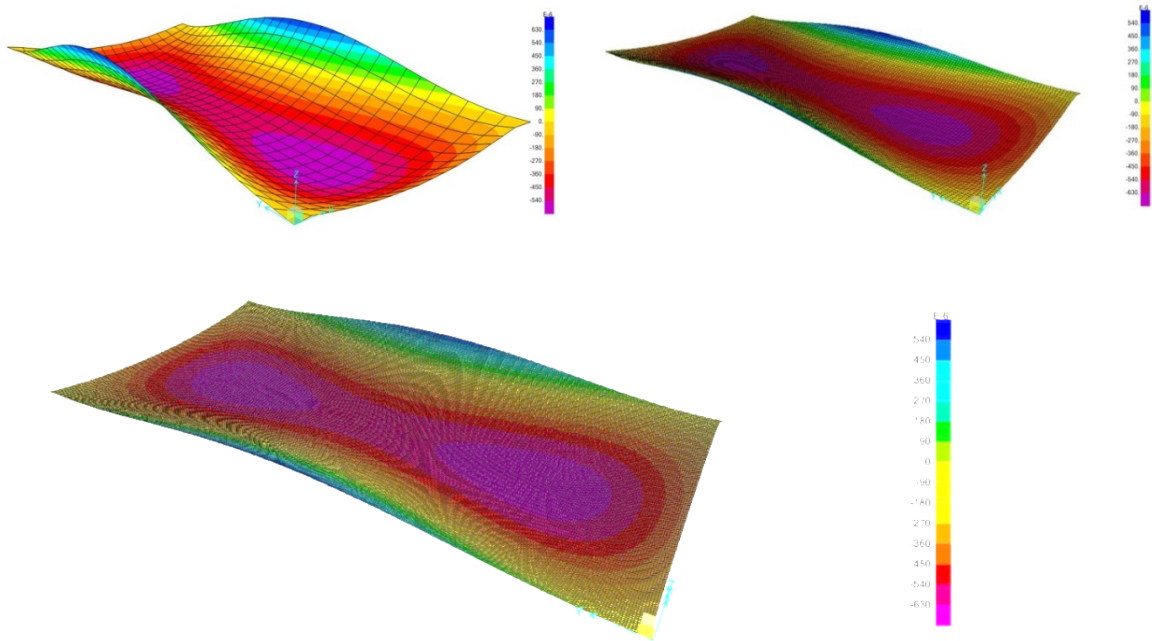


Figure 3-14 Displacement distribution of 5-layers solar panel under 400N load at 0° C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

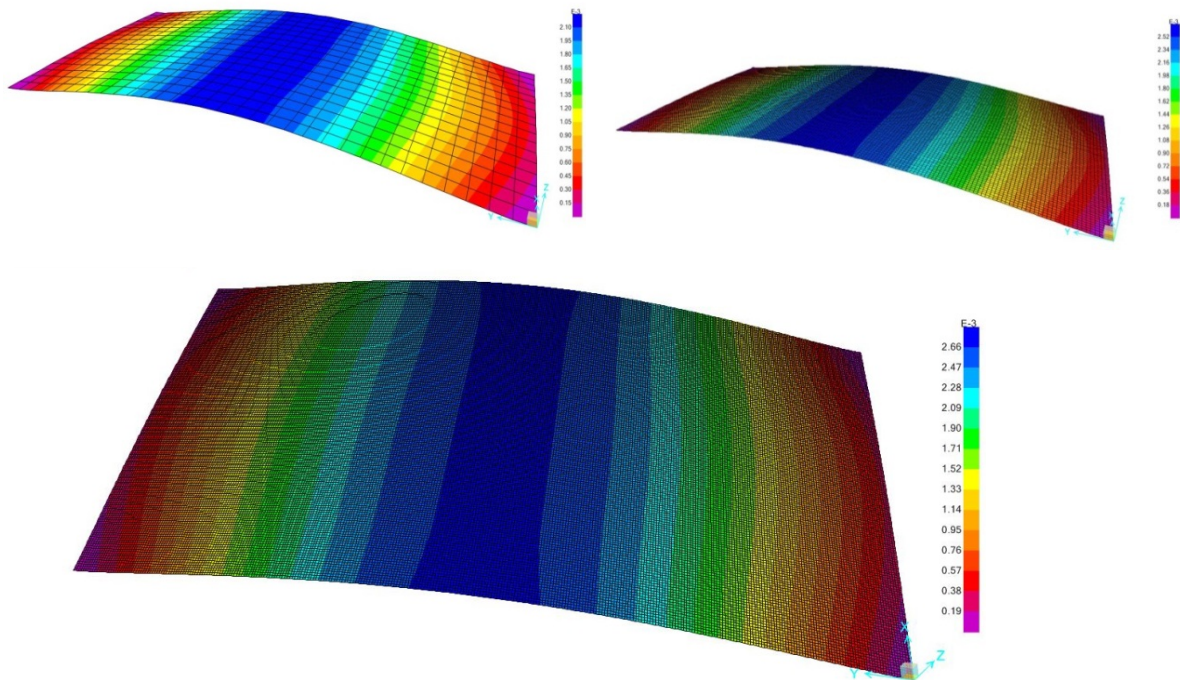


Figure 3-15 Displacement distribution of 5-layers solar panel under 400N load at 20° C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

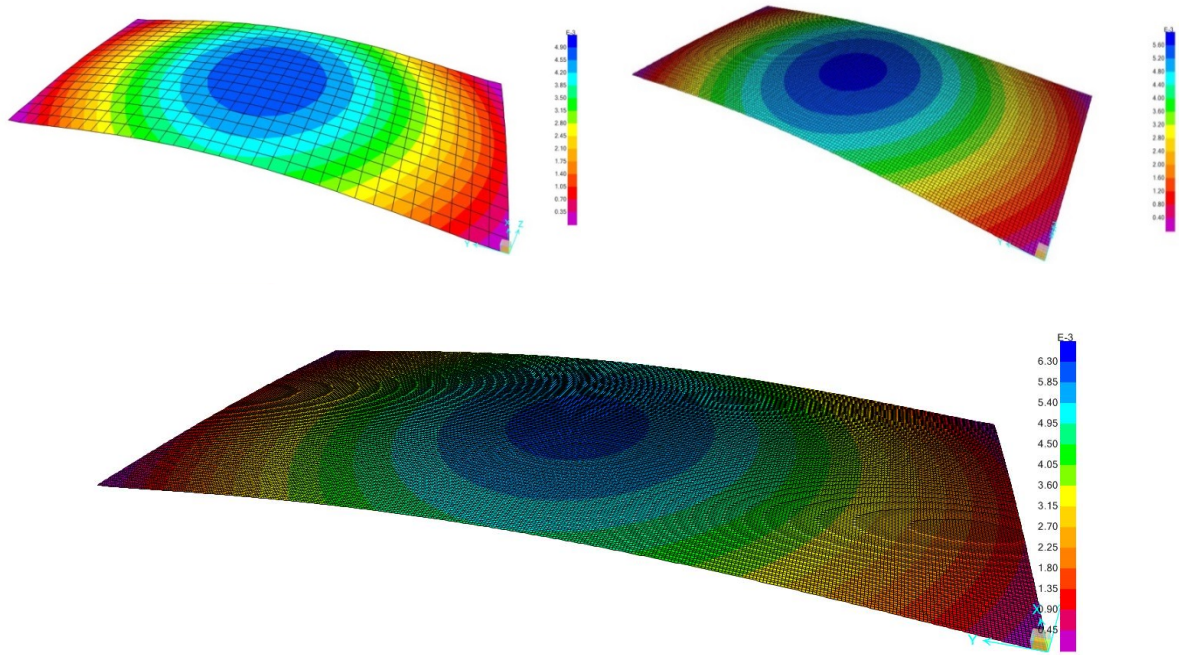


Figure 3-16 Displacement distribution of 5-layers solar panel under 400N load at 40° C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

Table 3-11 Maximum displacement of solar panel at under 400N uniform load – SAP 2000

Max. Displacement of 5-layers solar panel (mm) under 400N uniform uplift load					
Temperature Mesh Size	-40°C	-20°C	0°C	20°C	40°C
5 mm	-7.00	-3.64	-0.63	2.66	6.30
10 mm	-6.50	-3.5	-0.63	2.52	5.60
50 mm	-5.60	-3.08	+0.63	2.10	4.90

3.3.3 5-layers solar panel under 600N uplift load:

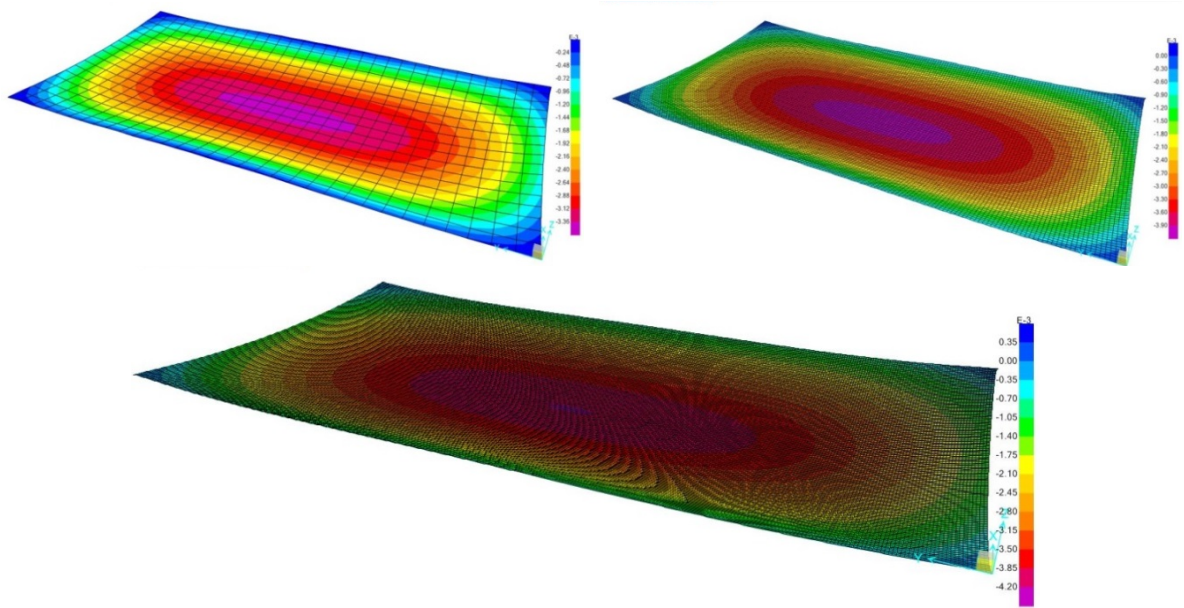


Figure 3-17 Displacement distribution of 5-layers solar panel under 600N load at -40°C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

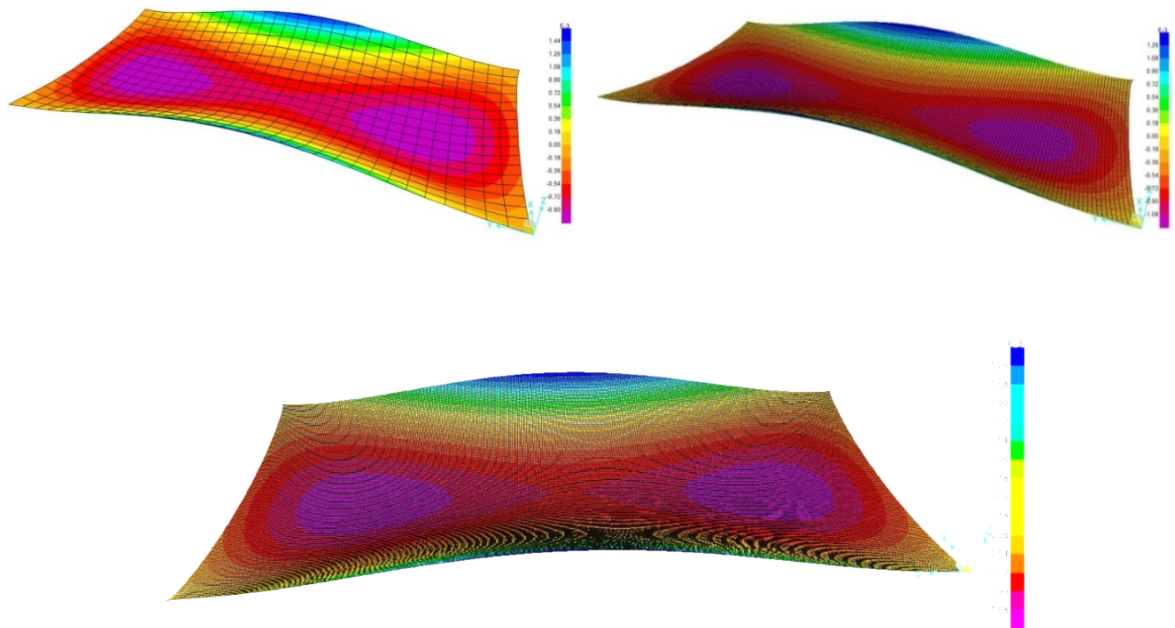


Figure 3-18 Displacement distribution of 5-layers solar panel under 600N load at -20°C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

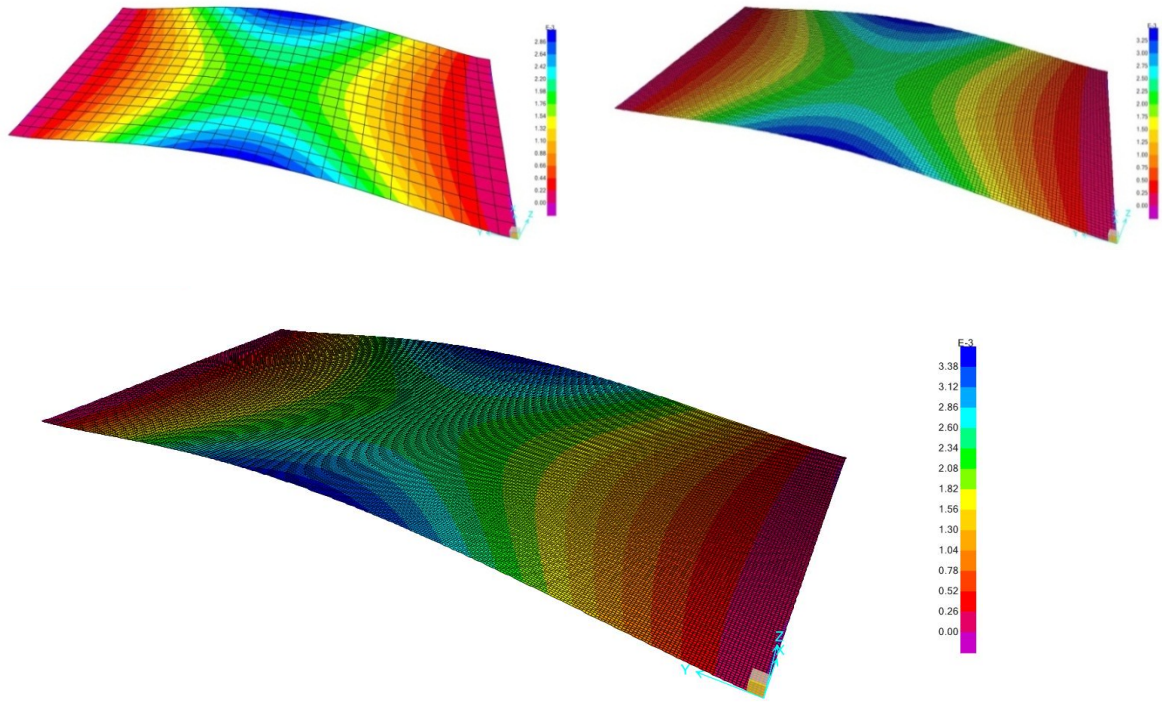


Figure 3-19 Displacement distribution of 5-layers solar panel under 600N load at 0° C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

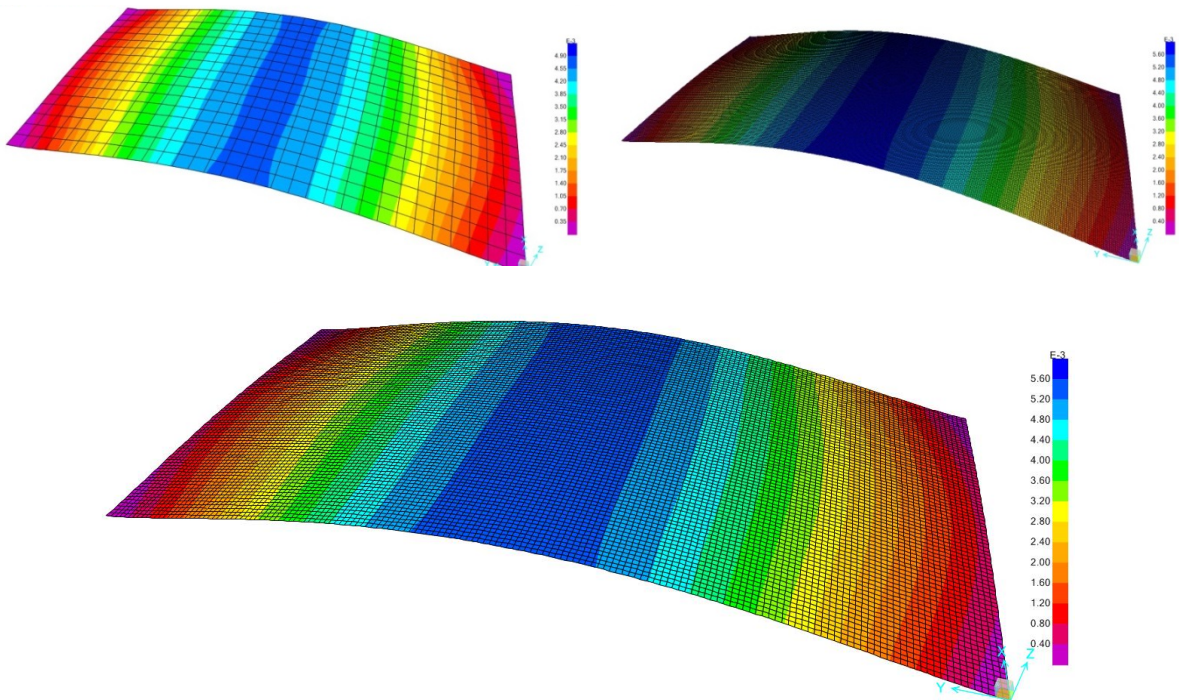


Figure 3-20 Displacement distribution of 5-layers solar panel under 600N load at 20° C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

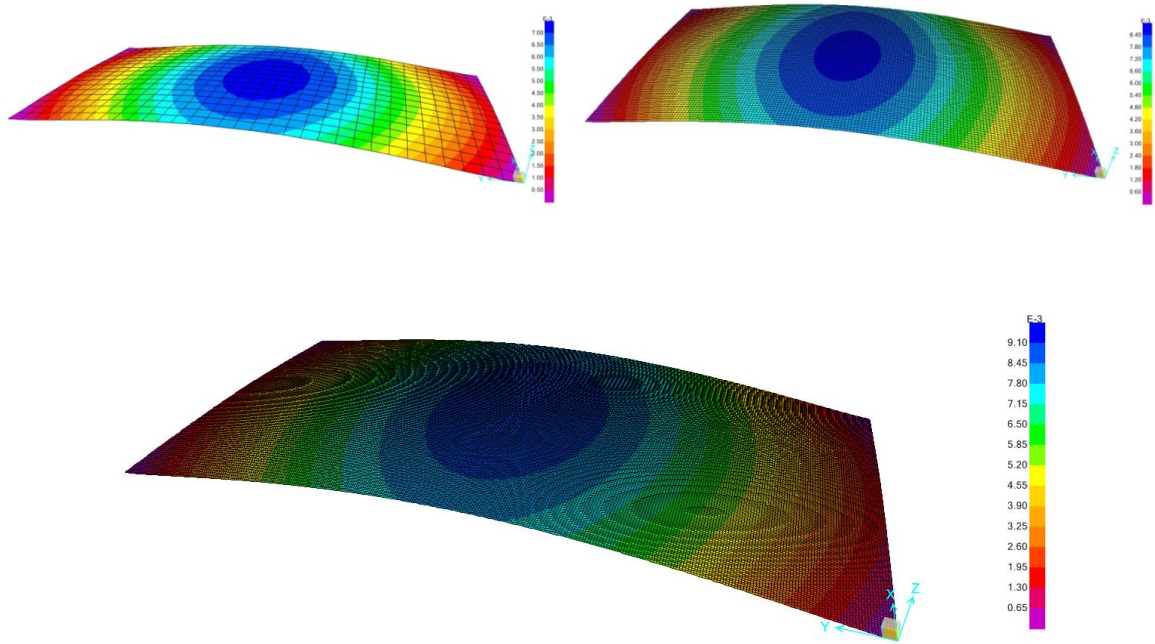


Figure 3-21 Displacement distribution of 5-layers solar panel under 600N load at 40° C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

Table 3-12 Maximum displacement of solar panel at under 600N uniform load – SAP 2000

Max. Displacement of 5-layers solar panel (mm) under 600N uniform uplift load					
Temperature Mesh Size	-40°C	-20°C	0°C	20°C	40°C
5 mm	-4.20	1.26	3.35	5.60	9.10
10 mm	-3.90	1.26	3.25	5.60	8.40
50 mm	-3.36	1.44	2.86	4.90	7.00

3.3.4 5-layers solar panel under 700N uplift load:

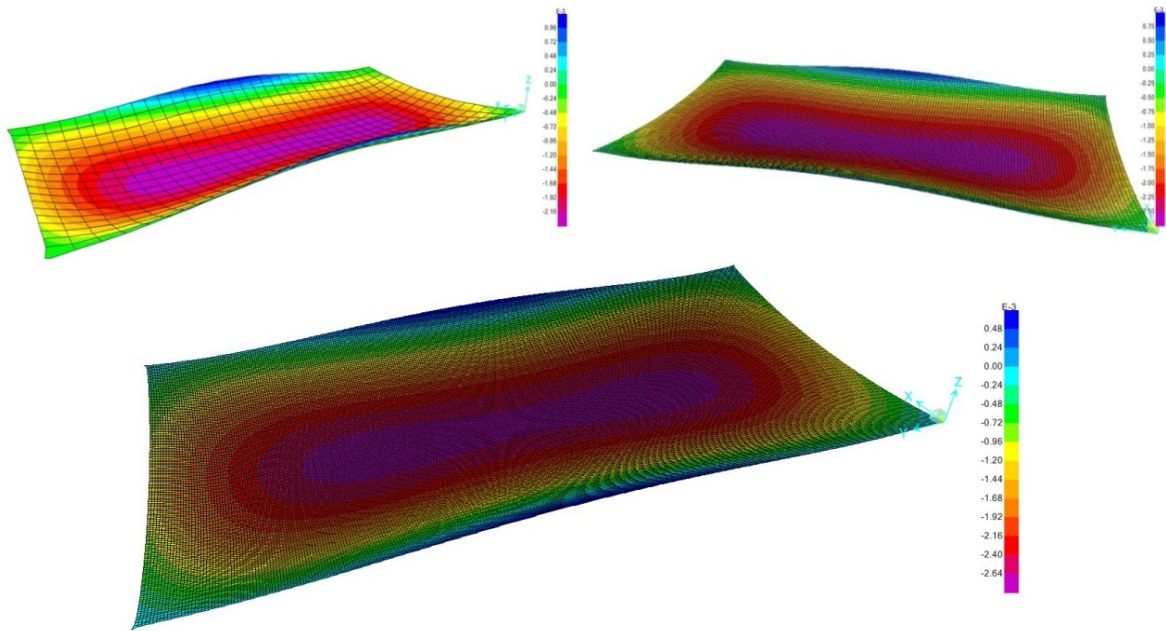


Figure 3-22 Displacement distribution of 5-layers solar panel under 700N load at -40°C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

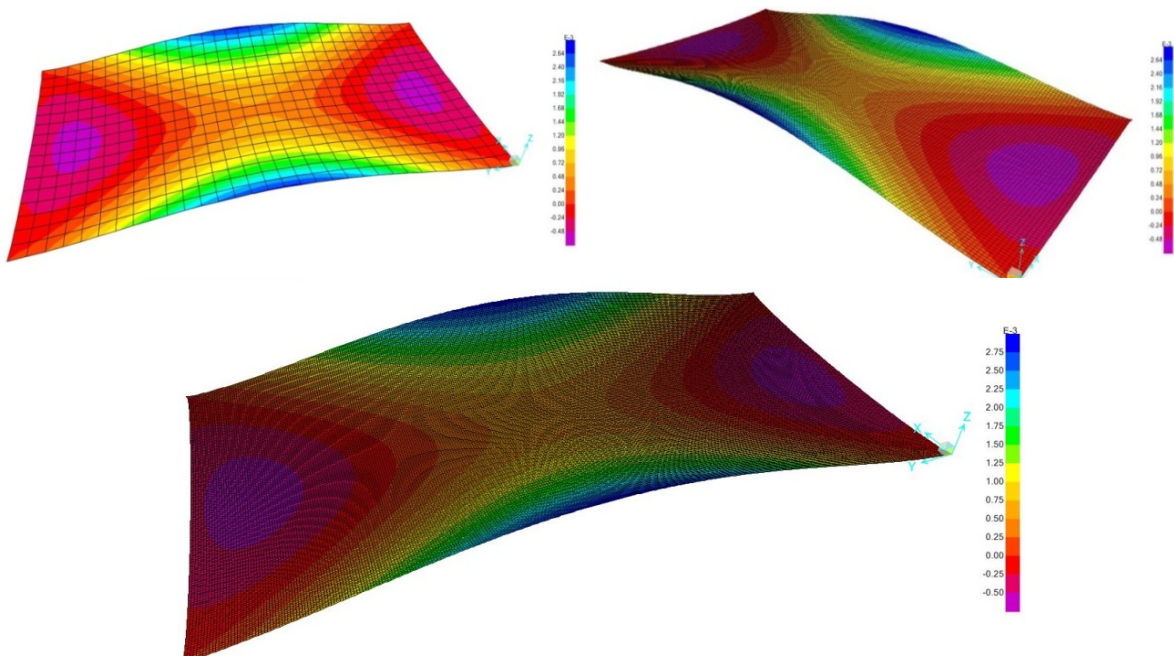


Figure 3-23 Displacement distribution of 5-layers solar panel under 700N load at -20°C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

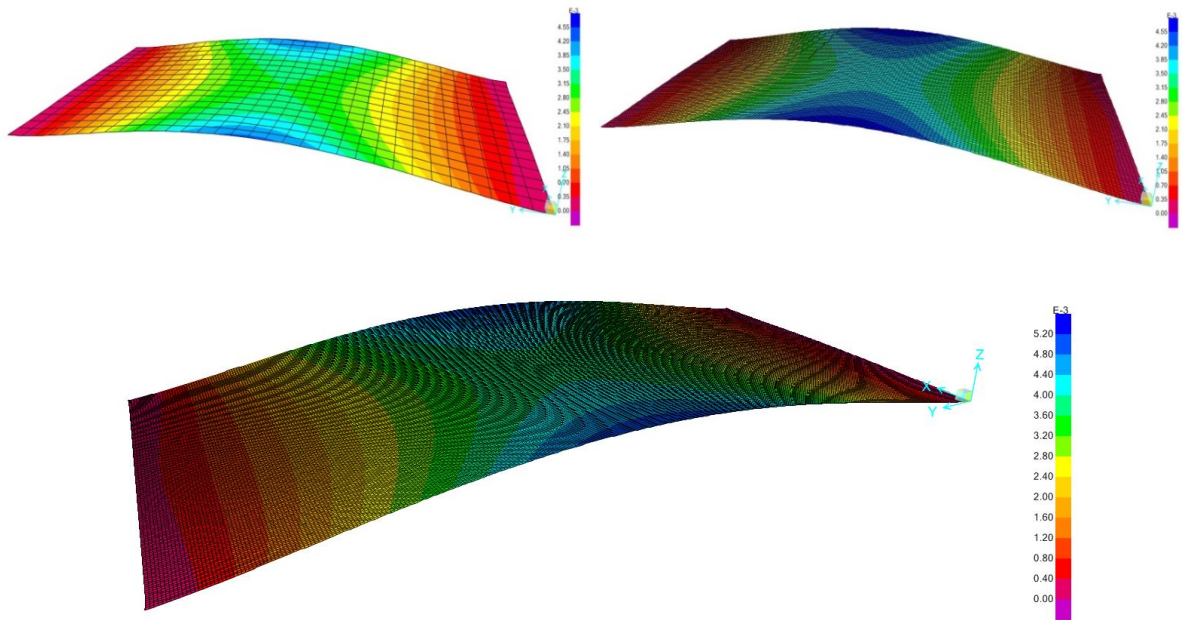


Figure 3-24 Displacement distribution of 5-layers solar panel under 700N load at 0° C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

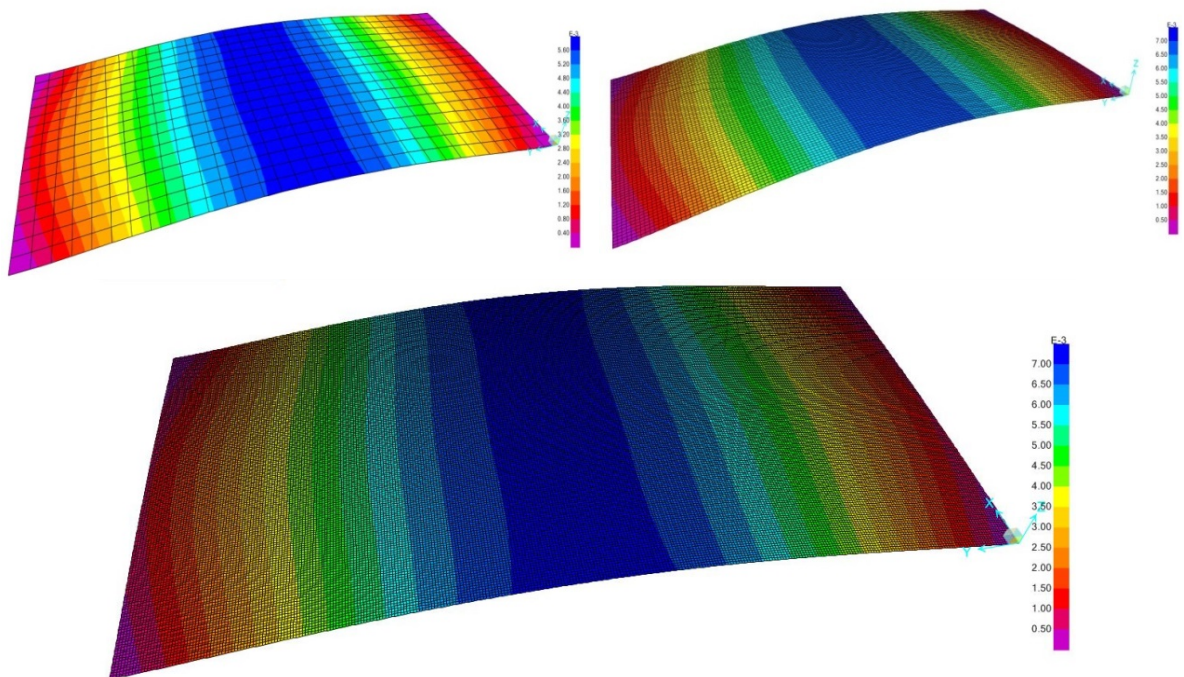


Figure 3-25 Displacement distribution of 5-layers solar panel under 700N load at 20° C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

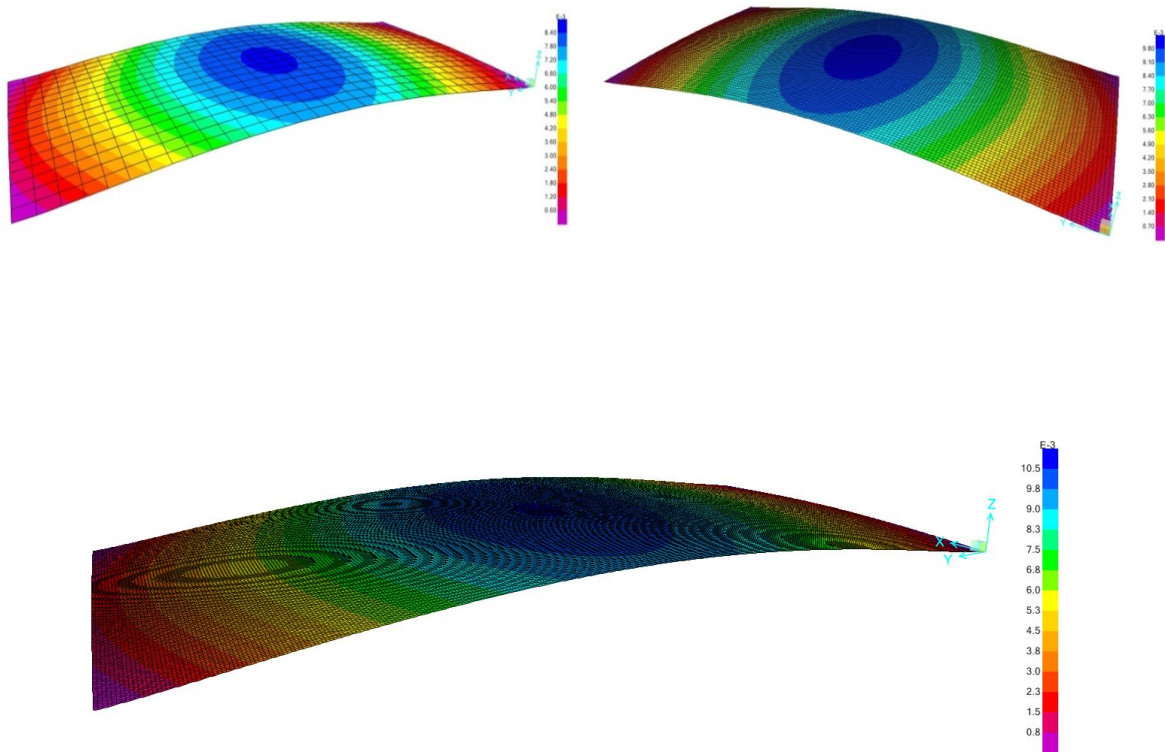


Figure 3-26 Displacement distribution of 5-layers solar panel under 700N load at 40° C temperature-50 , 10 & 5 mm mesh applied to model from top respectively

Table 3-13 Maximum displacement of solar panel at under 700N uniform load – SAP 2000

Max. Displacement of 5-layers solar panel (mm) under 700N uniform uplift load					
Temperature Mesh Size	-40°C	-20°C	0°C	20°C	40°C
5 mm	-2.64	2.75	5.20	7.00	10.50
10 mm	-2.50	2.64	4.55	7.00	9.80
50 mm	-2.16	2.64	4.55	5.60	8.40

3.3.5 5-layers solar panel and temperature variation effect:

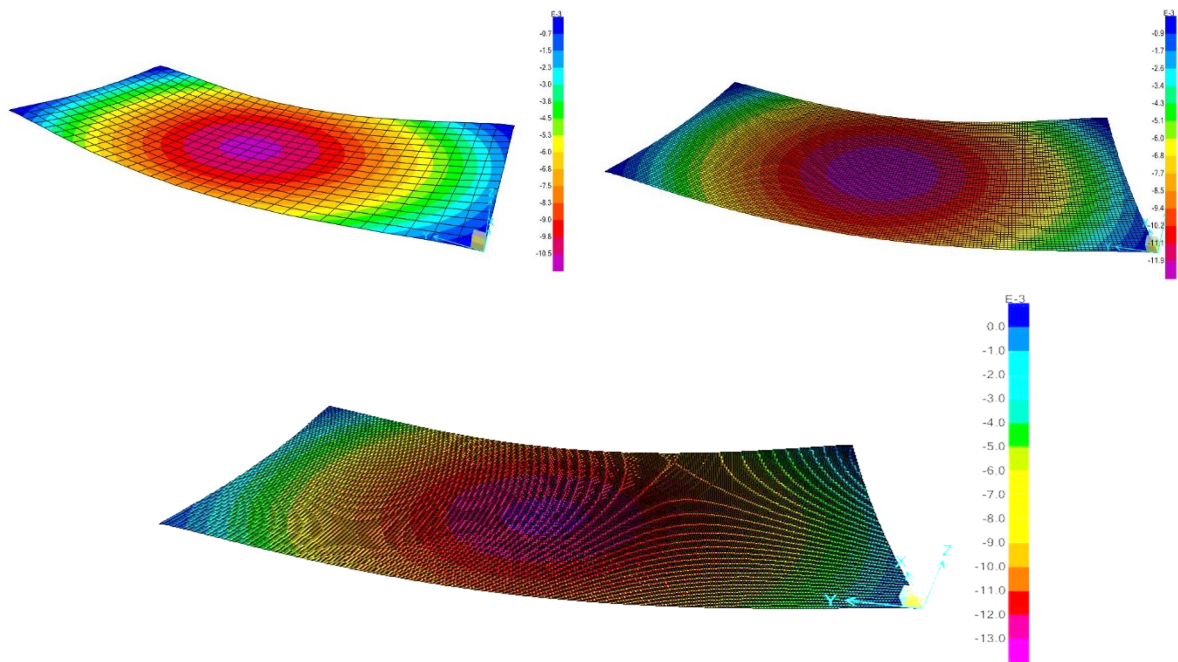


Figure 3-27 Displacement distribution of 5-layers solar panel at -40°C temperature -50 ,
10 & 5 mm mesh applied to model from top respectively

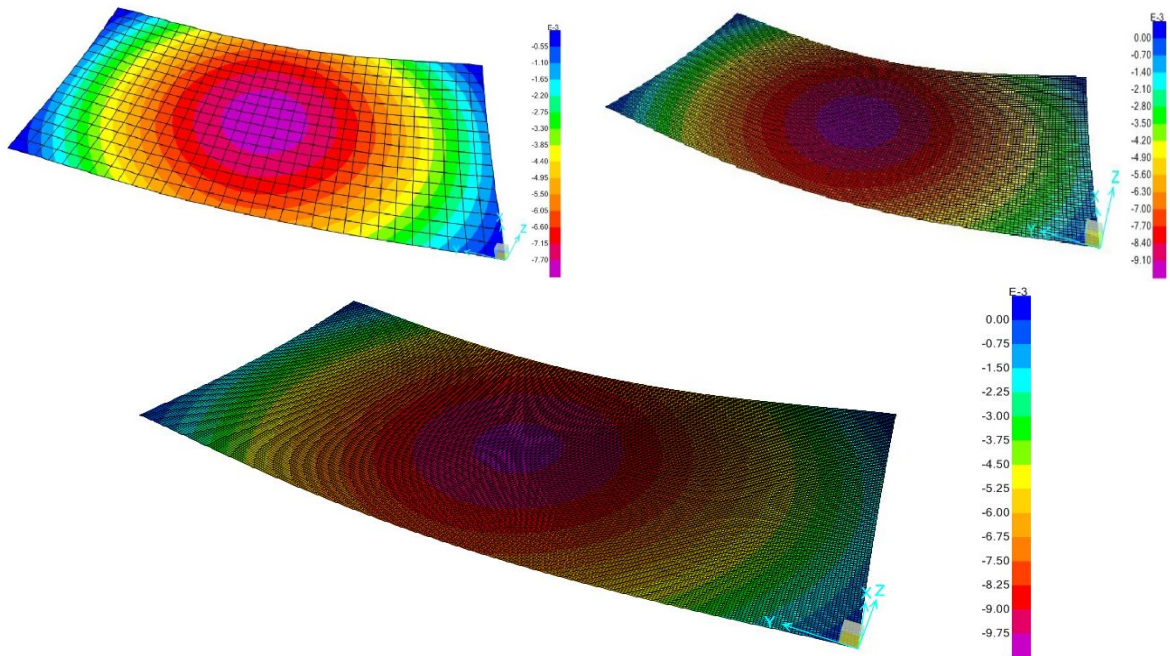


Figure 3-28 Displacement distribution of 5-layers solar panel at -20°C temperature -50 ,
10 & 5 mm mesh applied to model from top respectively

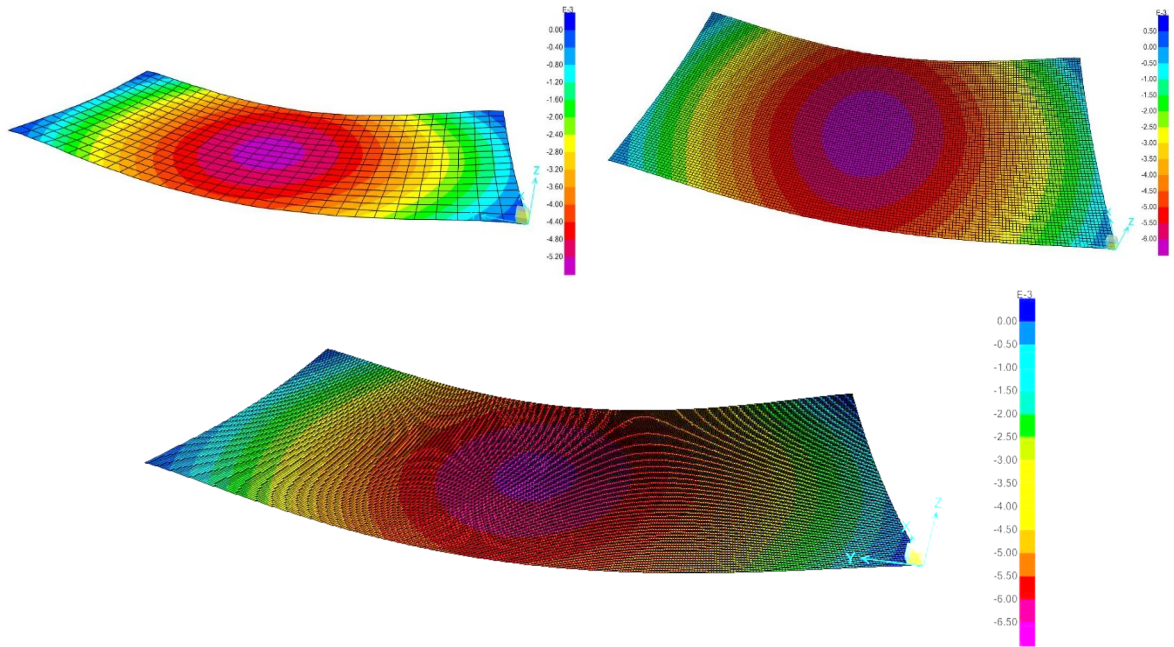


Figure 3-29 Displacement distribution of 5-layers solar panel at 0° C temperature –50 ,
10 & 5 mm mesh applied to model from top respectively

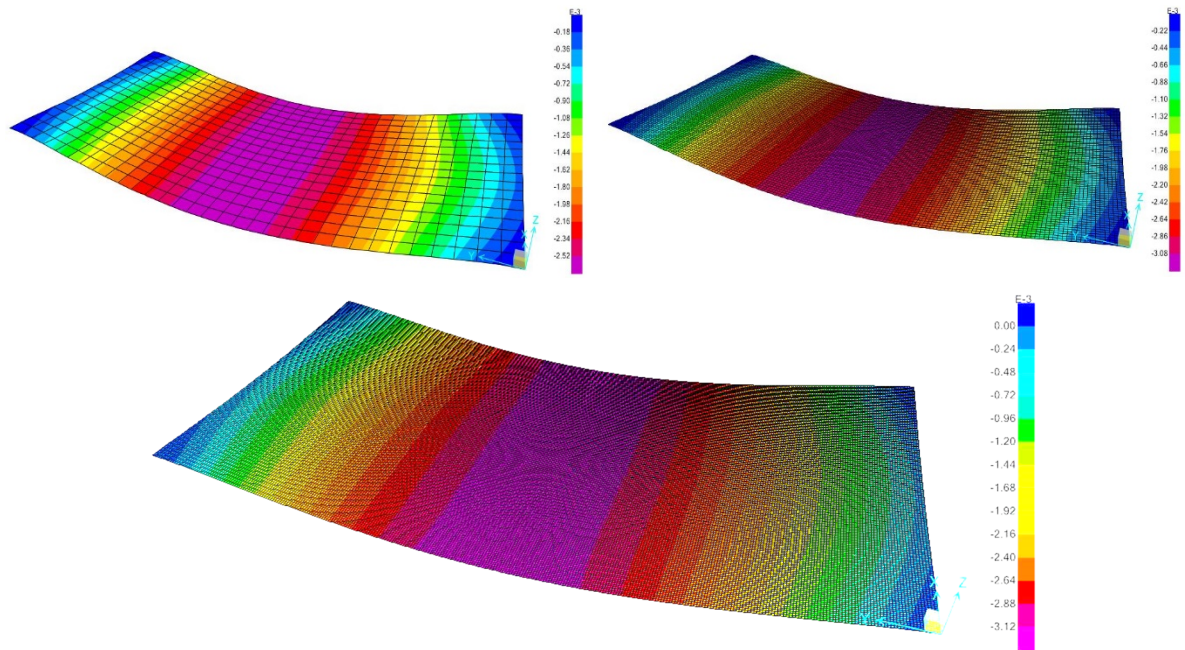


Figure 3-30 Displacement distribution of 5-layers solar panel at +20° C temperature –50
, 10 & 5 mm mesh applied to model from top respectively

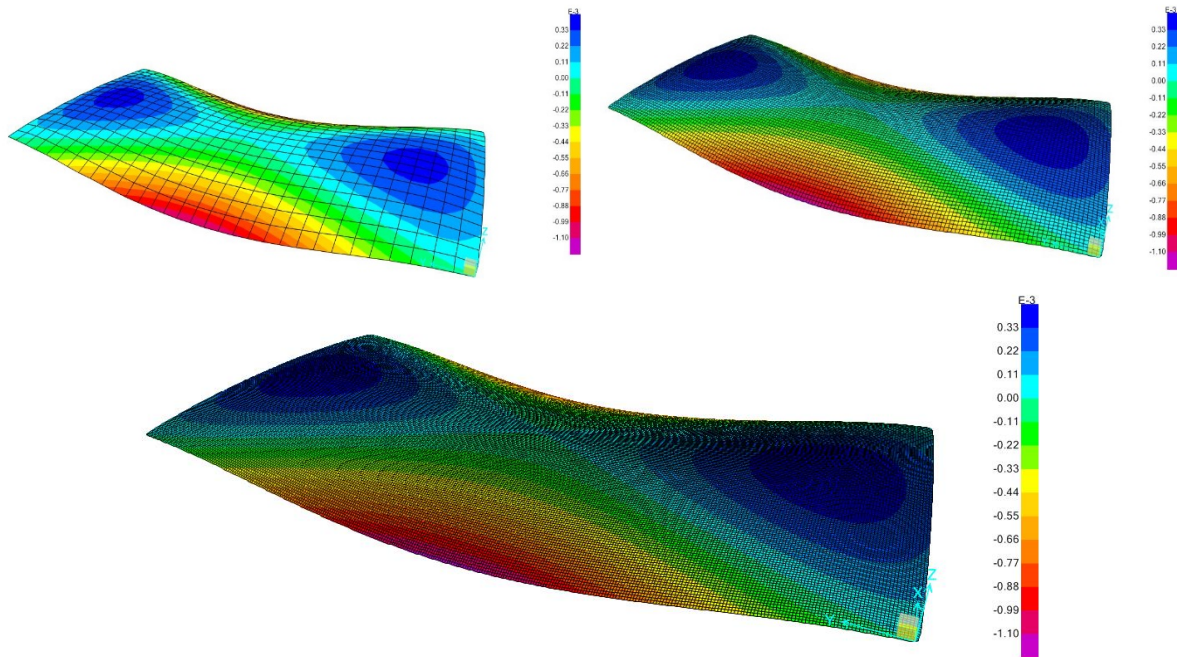


Figure 3-31 Displacement distribution of 5-layers solar panel at +40° C temperature – 50 , 10 & 5 mm mesh applied to model from top respectively

Table 3-14 Maximum displacement of solar panel at under 700N uniform load – SAP 2000

Max. Displacement of 5-layers solar panel (mm) under 0 N uniform uplift load					
Temperature Mesh Size	-40°C	-20°C	0°C	20°C	40°C
5 mm	-13.00	-9.75	-6.50	-3.12	-1.10
10 mm	-11.90	-9.10	-6.00	-3.08	-1.10
50 mm	-10.50	-7.70	-5.20	-2.52	-1.10

Chapter 4: PV Solar System Modeling and Field

Measurement

To study the behavior of all members of PV solar system under wind load, a full scale specimen installed open air conditions that provides ability to measure weather characteristics accurately. The complex evolution of the dynamic wind load on any surface, is affected by a vast number of factors. Each PV solar panel, due to inclined installation, different supporting system and wind speed characteristic, has to be investigated.

As it mentioned in chapter two, photovoltaic (PV) solar panel systems consist of two main parts: Balance of System (BOS) and the PV solar panel. In chapter 3, the material of each layer, the geometry and the behaviour of the PV solar panel without any surrounding frame under specific load studied. One important point was the direction of applied load on solar panel which was only in lift direction. However, with respect to tilted specimen mounted on roof top the wind load could apply in different directions depending on the geometry and the weather characteristic. Another parameter which influenced this study is the dominant temperature application which governed in the Ottawa region when the measurements took place, within the period of research on the PV panel specimen to simulate the behaviour of the FE model. Thus, one 5-layer solar panel and the supporting structures of the PV solar system was considered under wind flow according to average temperature, e.g. The PV solar

fully frame system installed on the flat roof top of Mann Parking building of the University of Ottawa.

After instrumenting the PV solar panel, another important study was performed for determining the weather characteristic and the parameters that the behaviour of wind load on solar panel could be influenced by. At the site where the PV panel was mounted, the wind direction or the so called angle of attack was another important Issue which has significant effect on intensity of wind loading on the PV system. Therefore a weather station at site location collected data such as humidity, temperature, air pressure and other parameters and the collected data was used to compute the wind load on the PV panel specimen and to determine the displacement and other parameters of wind induced force for the investigated PV system with FEM SAP 2000 software.

4.1. Weather Data

As mentioned a weather station at the site of experiment measured specific data for one minute intervals between January and February 2014. Temperature, percentage of relative humidity, wind speed, air Pressure and wind direction data were collected in SI units. Unfortunately, some data was missing due to unexpected repairing and interruptions during the collection procedure. For instance, on January mechanical Issues caused to miss recording data from 1st to 4th January and from 21st to 29th January and before that, on February 4th some records showed incorrect values. Therefore, to ensure the continuity of the data for the period of data collection, all measurements recorded between Jan 21st to Feb 4th neglected. Thus, the

temperature, humidity, wind direction and wind speed magnitude were studied for the remaining time interval.

For temperature parameter the maximum registered values of 6.3°C and 5.74°C were recorded on Jan 13th and Feb 22nd respectively (Figs. 4.1 a and b). The minimum recorded temperatures were -23.18°C and -24.33°C on Feb 12th and Jan 21st respectively. The minimum and maximum values of the recorded temperature used for selecting the appropriate mechanical properties of the 5-layers PV solar panel presented in chapter 3 and for performing the validation of the FEM model. The scattering of periodic temperature for both months are shown in figures 4.1 a) and b); an average temperature of about -7°C was estimated for the period of collecting data.

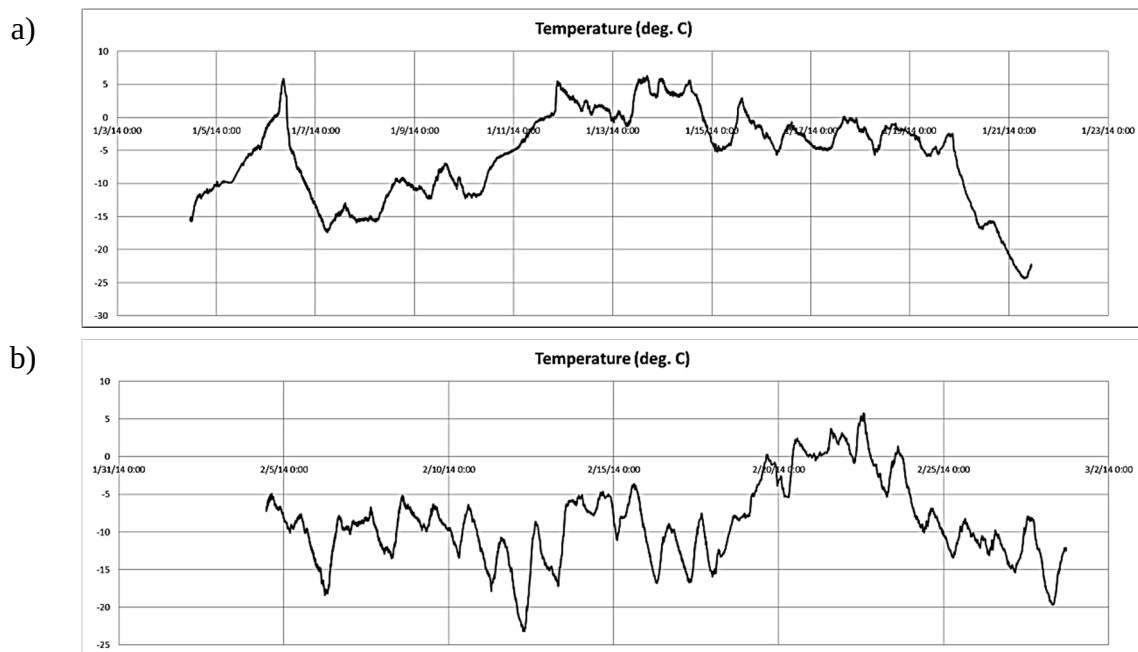


Figure 4-1 Magnitude of recorded periodic temperature ($^{\circ}\text{C}$) for a) Jan 2014 b) Feb 2014

Humidity and air pressure are two other parameters recorded within the Jan-Feb 2014 period of time. Significant values of relative humidity equal to 100% were recorded on January 6th and 11th, however the value reduced to 98.63% on February 21st. On the other hand, the minimum humidity percentages of 50.45% and 35.02% were recorded on Jan t 16th and Feb 22nd. The daily variation of relative humidity for both January 2014 and February 2014 are represented in figures 4-2 a) and b).

The maximum registered air pressures were recorded on February 12th and Jan 09th and had very close values of 102.79 kPa and 102.98 kPa respectively. The minimum air pressures were on February 14th and January 11th and were equal to 98.6 kPa and 97.77 kPa respectively. The air pressure fluctuation for the January- February 2014 period are shown in figures 4-3 a) and b) respectively.

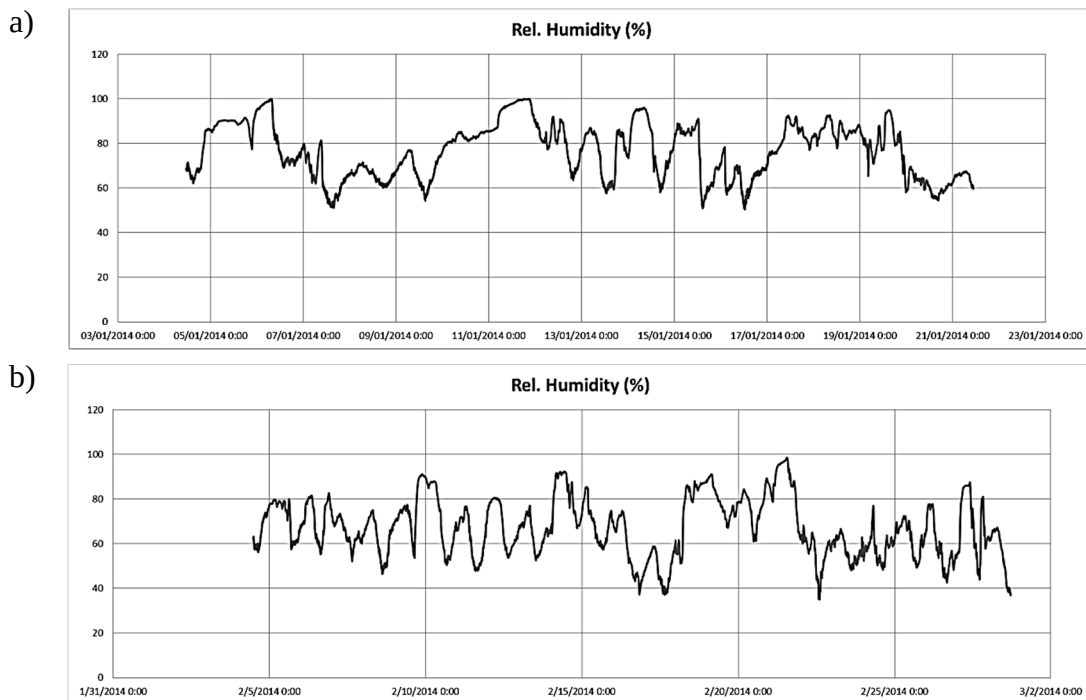


Figure 4-2 Amplitude of a variable periodic relative humidity (%) for a) Jan 2014 b) Feb 2014

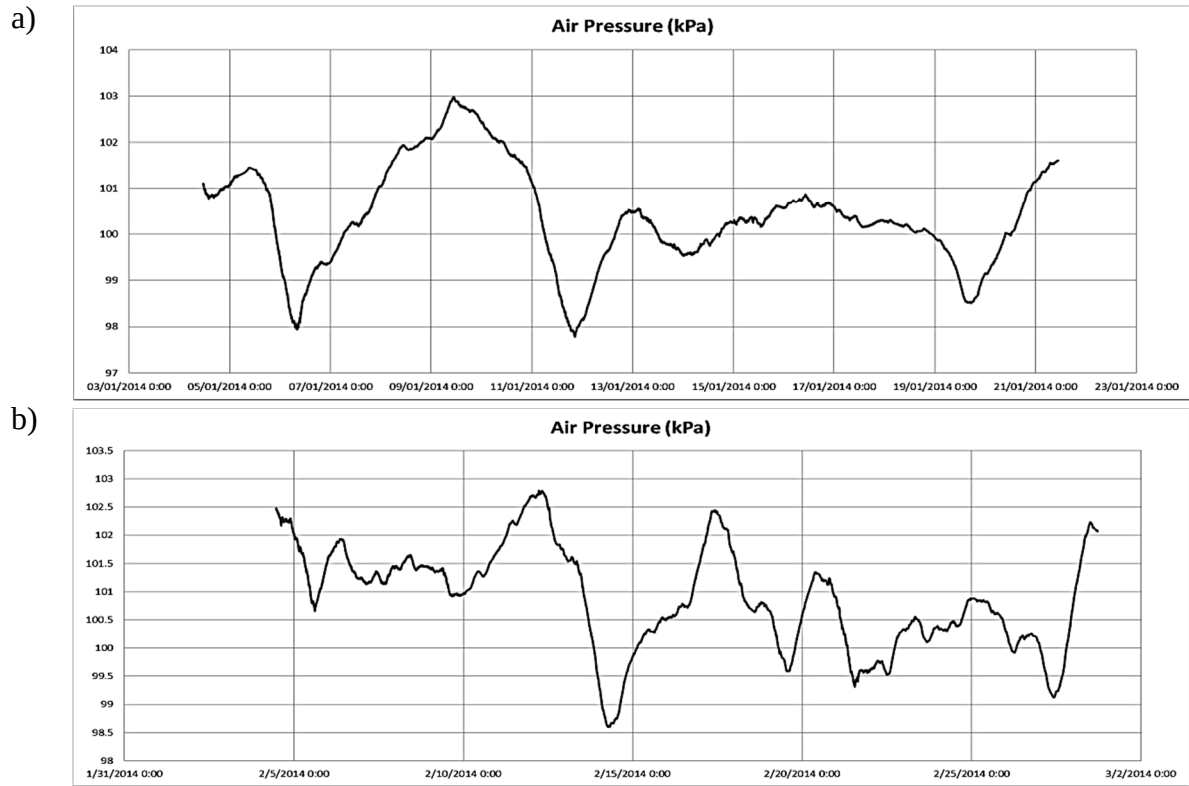


Figure 4-3 Amplitude of a variable periodic air-pressure (kPa) for a) Jan 2014, b) Feb 2014

Finally, for the wind speed intensity, the maximum registered values were 11.78 m/s and 9.95 m/s and were recorded on Jan 6th and Feb 22nd respectively. The minimum wind speeds were on Feb at 8th and 9th equal to 0.23 m/s and the same value was recorded on Jan 10th. It needs to be note that the negative values of the wind speed were considered as positive values but for a different wind direction, hence the data shown in figures 4-4 and 4-5 doesn't contain values below zero. Therefore, three different graphs in regard to the average, the maximum and the minimum wind speeds recorded for each time step are captured in the fluctuating curves for January and February 2014 in figures 4-4 and 4-5. Also because the

critical response of the PV solar panel was of interest, the focus was mainly on the maximum wind speed recorded values.

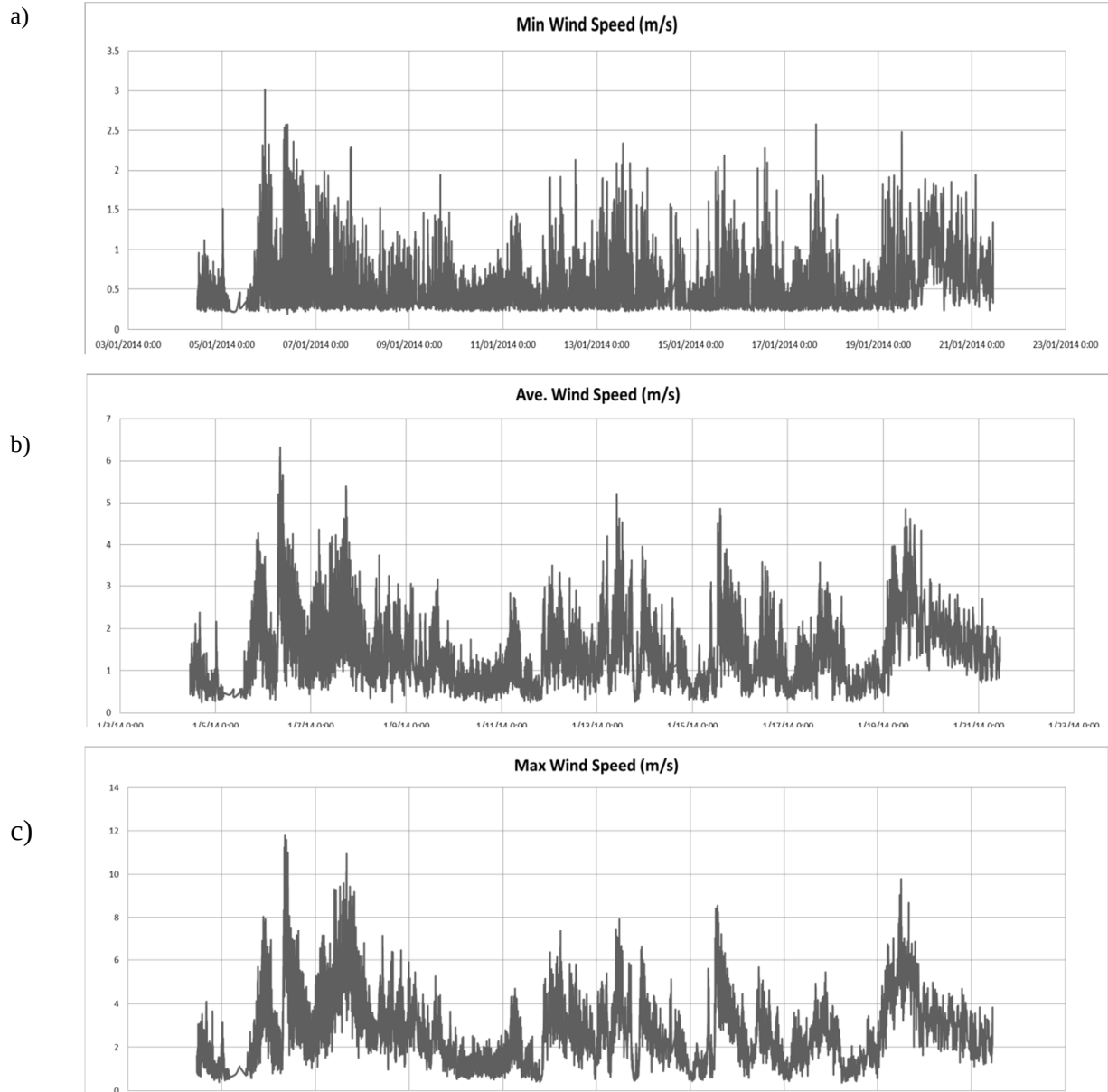


Figure 4-4 Amplitude of variable (m/s) for a) Minimum b) Average c) Maximum values of wind speed intensity for January 2014

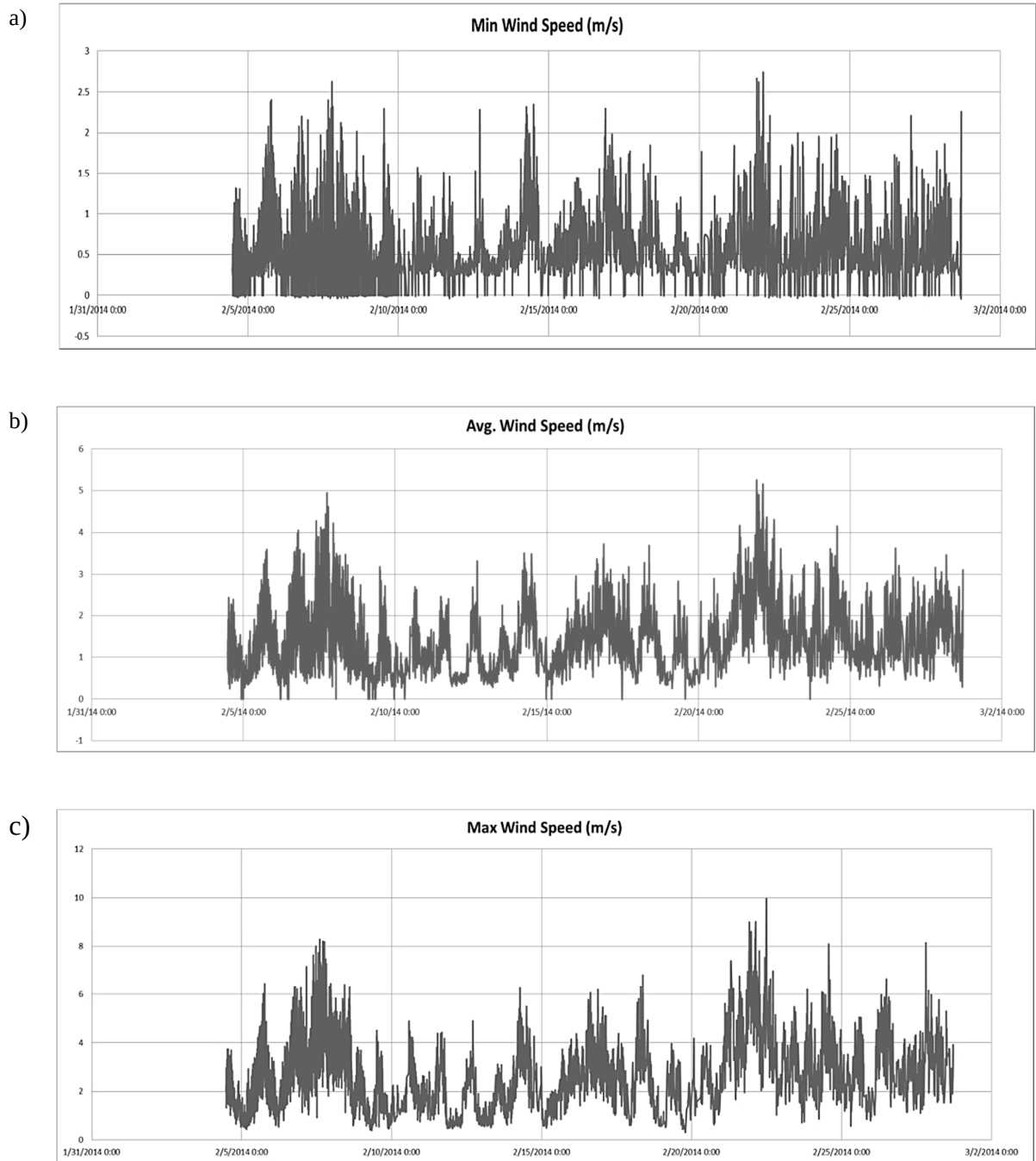


Figure 4-5 Amplitude of variable (m/s) for a) Minimum b) Average c) Maximum values of wind speed intensities for February 2014

4.2. Wind load:

According to section 4.1 all collected data needs to be applied on the PV system to compute the wind load within particular time and the resistance of the panel at a given temperature. Usually, a high number of variations should be considered to compute wind load on any surface facing the wind, depending on the geometry of the element and the weather characteristics that are measured. Firstly, the geometry of the support structure and the PV solar panel surrounding the frame are dimensioned and tabled to compute nominal areas based on the main concept of wind load that applied to any surface which encounters. Then in regards to the wind speed measurements the wind load is computed for each part of the structure.

4.2.1 Geometry of Frame Structure:

According to the PV panel specimen mounted on site, 5-layer solar panel framed installed on the roof top of Mann Parking of the University of Ottawa and 2 types of frame sections were used to install the support structure and the solar panel surrounding frame. One was a box frame $0.04\text{ m} \times 0.04\text{ m} \times 0.003\text{ m}$ (H×W×t) and the other one was a custom style aluminum section which was made to keep the of the PV solar panel within the dimension of $1.580\text{ m} \times 0.808\text{ m} \times 0.005\text{ m}$ (H×W×D) as shown in figure 4-6. The profile of the tubular aluminum section used for this frame (fig. 4-6) was used as per the recommendations of the PV solar panels manufacturers.

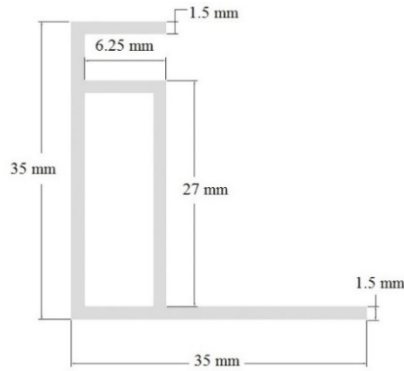


Figure 4-6 Custom Style made [24] frame of solar panel

The bottom flange of the surrounding frame is screwed to the box frame (support structure) in 3 points at equal distances from each other and from the corner which means a total of 12 screws corresponding to 12 connecting points used for the FEM model as described below. Five different lengths of box frame 0.53, 0.808, 1.00, 1.22 and 1.58 m were used for the support structure which was fully fixed to the roof system. Moreover, all frames are jointed together with special type of screws which tighten enough to control rotation and translations. The layout dimensions of the frames used to assemble the support structure are shown in figure 4-7.

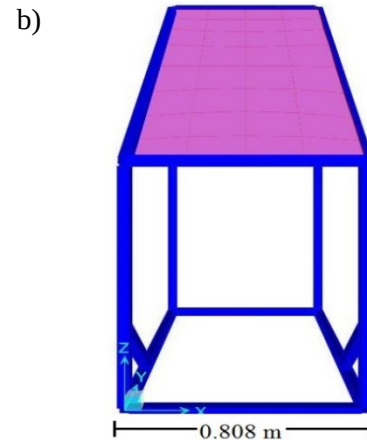
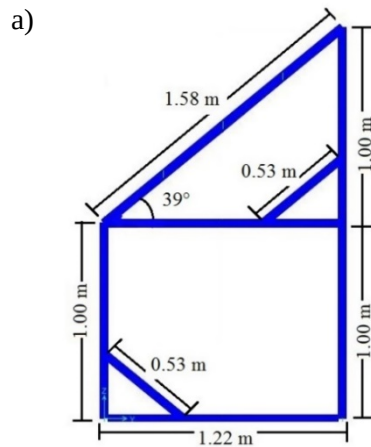


Figure 4-7 Support frame of the PV solar system modeled a) x-z section and b) 3-dimensional view

4.2.2 Air Density:

One important parameter need to apply lift and drag forces formula is air density value which needs to be computed accurately. The air density is dependent on the temperature, humidity and the open air stream pressure directly, where could be various at any location. In general the value for the air density above the sea level is approximately 1.2 kg/m^3 , however this is not the exact value considered for the Ottawa in January and February.

Table 4-1 Measured weather data with period of one minute, the University of Ottawa

Timestamp	Temperature (° C)	Rel. Humidity (%)	Air Pressure (kPa)
1/4/2014 11:41	-15.13	68.08	101.02
1/4/2014 11:42	-15.19	68.23	101.01
1/4/2014 11:43	-15.34	68.30	101.01
1/4/2014 11:44	-15.47	68.93	101.01
1/4/2014 11:45	-15.64	69.18	101.01
1/4/2014 11:46	-15.63	69.75	101.00
1/4/2014 11:47	-15.72	70.31	101.00
1/4/2014 11:48	-15.72	70.53	101.00
1/4/2014 11:49	-15.73	70.66	101.00

The dry air density is the mass of the molecules of air in a certain volume, which is modified with considerations of temperature, pressure and humidity. According to the Ideal Gas Law for dry air:

$$\rho_d = \left(\frac{p}{T * R_d} \right) \quad (4.1)$$

Where:

ρ_d = Dry air density, kg/m^3

P = Absolute pressure, Pascal

T = Temperature, °K (273.15+° C)

R_d = Specific gas constant for dry air which is equal to 287.04 J/ (kg °K)

The above formula is considered for dry air, however the large value of humidity needs to be applied to compute moist air density. Neglecting the small errors due to non-ideal gas compressibility and vapour pressure measurements not made over liquid water, W. H. Brutsaert and D. Reidel [25] considered the moist air density as:

$$\rho_{\text{humid air}} = \left(\frac{p}{R_d * T} \right) * \left(1 - \frac{0.378 e}{p} \right) \quad (4.2)$$

Where:

$\rho_{\text{humid air}}$ = Density of humid Air, kg/m³

P = Absolute pressure, P = P_d + P_v, Pascal

R_d = Specific gas constant for dry air which is equal to 287.04 J/ (kg °K)

e = pressure of water vapor (partial pressure), Pascal

T = Air temperature, °K

The partial pressure of water vapour is applied in equation 4.2, to compute the air density in regards to the relative humidity which given by [26], [27]:

$$RH = \frac{e}{e_s} \quad (4.3)$$

$$e = 6.11 * 10^{\left(\frac{7.5 * T_d}{237.7 + T_d} \right)} \quad (4.4)$$

$$e_s = 6.11 * 10^{\left(\frac{7.5 * T}{237.7 + T} \right)} \quad (4.5)$$

Where:

RH = Relative humidity, Percent

e_s = saturated vapour pressure (partial pressure), Pascal

T = Air temperature, ° C

T_d = Dewpoint temperature, ° C

In the following steps the mathematical procedure is described for determining the air density at -17.5° C, relative humidity equal to 84.36% and measured absolute pressure equal to 101370 Pascal:

1. Compute saturated vapour pressure:

$$e_s = 6.11 * 10^{\left(\frac{7.5 * T}{237.7 + T}\right)} = 6.11 * 10^{\left(\frac{7.5 * (-17.5)}{237.7 + (-17.5)}\right)} = 1.55 \text{ Pa}$$

2. Compute partial pressure of water vapour according to the relative humidity percentage:

$$RH = \frac{e}{e_s} \rightarrow 84.36 \% = \frac{e}{1.55} \rightarrow e = \frac{84.36 * 1.55}{100} = 1.306 \text{ Pa}$$

3. Compute Density of humid air:

$$\rho_{\text{humid air}} = \left(\frac{p}{R_d * T} \right) * \left(1 - \frac{0.378 e}{p} \right)$$

$$\rho_{\text{humid air}} = \left(\frac{101370}{287.04 * (273.15 - 17.5)} \right) * \left(1 - \frac{0.378 * 1.306}{101370} \right)$$

$$\rho_{\text{humid air}} \approx 1.381 \text{ kg/m}^3$$

The table 4.2 shows the density of humid air within different temperatures, time segment, humidity and the recorded air pressure.

Table 4-2 Various humid air densities within different Temperatures and time

Timestamp	T (°C)	RH(%)	Air P(kPa)	GR (W/m2)	R_d	e_s	e	ρ Humid Air
1/4/2014 11:41	-15.13	68.08	101.02	0.00	287.04	1.89	1.29	1.36
1/4/2014 11:42	-15.19	68.23	101.01	0.00	287.04	1.88	1.28	1.36
1/4/2014 11:43	-15.34	68.30	101.01	0.00	287.04	1.86	1.27	1.36
1/4/2014 11:44	-15.47	68.93	101.01	0.00	287.04	1.84	1.27	1.37
1/4/2014 11:45	-15.64	69.18	101.01	0.00	287.04	1.81	1.25	1.37
1/4/2014 11:46	-15.63	69.75	101.00	0.00	287.04	1.81	1.26	1.37
1/4/2014 11:47	-15.72	70.31	101.00	0.00	287.04	1.80	1.26	1.37
1/4/2014 11:48	-15.72	70.53	101.00	0.00	287.04	1.80	1.27	1.37
1/4/2014 11:49	-15.73	70.66	101.00	0.00	287.04	1.80	1.27	1.37

4.2.3 Drag and Lift Wind forces:

The force acting on a surface standing in front of the airflow is equal to a dynamic pressure, q , which is equal to one-half the square of the airflow velocity times the density of air. According to Anderson [28] the definition as an equation forms by:

$$q = \frac{1}{2} \rho V^2 \quad (4.6)$$

Where:

$$\rho = \text{Air Density, kg/m}^3$$

$$V = \text{Airflow velocity, m/s}$$

To apply the dynamic pressure on solar panel it needs to define the drag and lift forces in along wind direction and uplift direction beforehand. The drag and lift forces applied to surface positioned normal or perpendicular to air flow depend on the shape, air flow characteristics (direction, humidity, speed and other considerations) and the inclination angle of object in regard to the wind flow. These factors applied to the main equation and the drag and lift forces [29] given by:

$$F_D = \frac{1}{2} C_D \rho A_D V^2 \quad (4.7)$$

$$F_L = \frac{1}{2} C_L \rho A_L V^2 \quad (4.8)$$

Where:

$$C_D = \text{Drag coefficient}$$

$$C_L = \text{Drag coefficient}$$

A_D = Projected area on the along wind direction, m²

A_L = Projected area on the uplift direction, m²

F_D = Drag force, N

F_L = Lift force, N

The drag or lift forces application on solar panel need to be considered along the respective direction which involves modifications for area and drag and lift coefficients. The face dimension of modeled solar panel was equal to 1.58 m×1.00 m which was inclined with an angle of 39° from roof surface. Two views of solar panel installation are shown at figure 4-7 above.

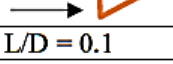
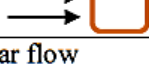
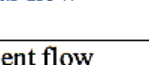
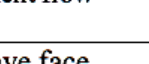
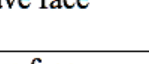
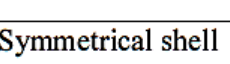
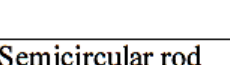
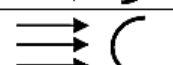
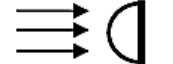
4.2.2.1. Drag and Lift coefficients:

The drag coefficient and lift coefficients (C_D , C_L) are two non-dimensional parameters that take into account with respect to the angle of airflow reaching to the surface and shape of the specimen. The significant change in value of coefficients depends on the shape of the specimen exposed to wind. Therefore, numerous researches were performed to study these coefficients for each shape in respect to the attack angle. However, most of the studies focused on coefficients or forces with respect to angles up to 30 degrees. Therefore, the drag and lift coefficient for angle 39° need to be figured for BOS and Structure of PV solar system. An assumption was made before computation that frame structure surrounding solar panel considers symmetric shape same as support structure but with different dimension which is equal to 0.035 m×0.035 m×0.0015 m (H×W×t).

According to Sadraey [30] the effect of varying the shape of the object would influence the drag coefficient and the values for standard sections are shown in table 4-3. The values recommended in this table were used to determine the drag coefficients for all the frames sections used to install PV solar panel and to calculate the wind-induced load. To do this the aspect ratio of each frame section was applied as per the table. Moreover, Steggel [31] studied the flow around rectangular cylinders with respect to aspect ratios ranging from 0.25 to 1.0 and angles of wind attack between 0° to 90° . Figure 4-8 considered by Steggel [31] shows the amplitude of a variable coefficient of lift and drag with the values determined by C.W. Knisely, [32] for both coefficient. Some wind tunnel experiments performed by Knisely [32] on rectangular cylinders with aspect ratio ranging from 0.25 to 1.0 and for angles of attack from 0° to 90° . In the other case Sohankar [33] for both coefficients from 1.0 to 4.0 as aspect ratio and with angles of attack from 0° to 90° are shown in figure 4-9. These are almost similar to values exhibit in Knisely's figure with aspect ratio equal to one.

Table 4-3 The effect of two and three dimensional shape on drag coefficient [30]

No	Body	Laminar/turbulent	Status	C_D
1	Cube	$Re > 10,000$		1.05
2	Thin circular disk	$Re > 10,000$		1.1
3	Cone ($\theta = 30^\circ$)	$Re > 10,000$		0.5
4	Sphere	Laminar $Re \leq 2 \times 10^5$		0.5
		Turbulent $Re \geq 2 \times 10^6$		0.2
5	Ellipsoid	Laminar $Re \leq 2 \times 10^5$		0.3-0.5
		Turbulent $Re \geq 2 \times 10^6$		0.1-0.2
6	Hemisphere	$Re > 10,000$	Concave face	0.4
		$Re > 10,000$	Flat face	1.2
7	Rectangular plate	$Re > 10,000$	Normal to the flow	1.1 - 1.3
8	Vertical cylinder	$Re \leq 2 \times 10^5$	$L/D = 1$	0.6
			$L/D = \infty$	1.2
9	Horizontal cylinder	$Re > 10,000$	$L/D = 0.5$	1.1
			$L/D = 8$	1
10	Parachute	Laminar flow		1.3

No	Body	Status	Shape	C_D
1	Square rod	Sharp corner		2.2
		Round corner		1.2
2	Circular rod	Laminar flow		1.2
		Turbulent flow		0.3
3	Equilateral triangular rod	Sharp edge face		1.5
		Flat face		2
4	Rectangular rod	Sharp corner		$L/D = 0.1$ 1.9
				$L/D = 0.5$ 2.5
				$L/D = 3$ 1.3
		Round front edge		$L/D = 0.5$ 1.2
				$L/D = 1$ 0.9
				$L/D = 4$ 0.7
5	Elliptical rod	Laminar flow		$L/D = 2$ 0.6
				$L/D = 8$ 0.25
		Turbulent flow		$L/D = 2$ 0.2
				$L/D = 8$ 0.1
6	Symmetrical shell	Concave face		2.3
		Convex face		1.2
7	Semicircular rod	Concave face		1.2
		Flat face		1.7

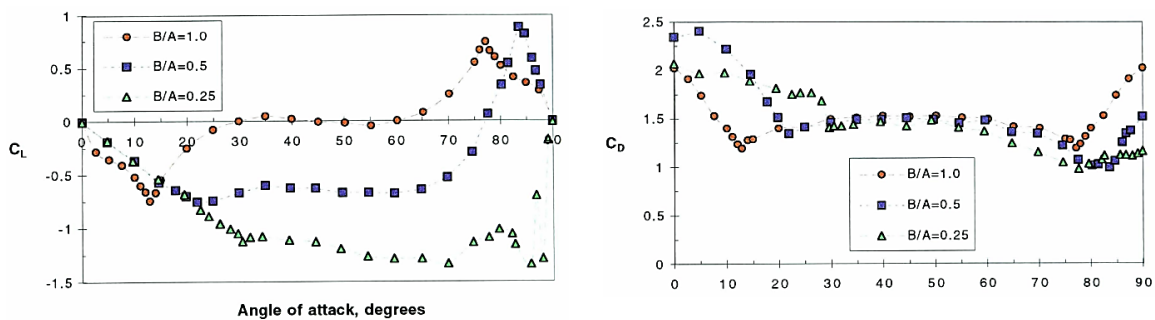


Figure 4-8 Amplitude of a variable coefficient of lift and drift-computed by C.W. Knisely, (1990)[32] with respect to Steggel (1998) [31]

a)

b)

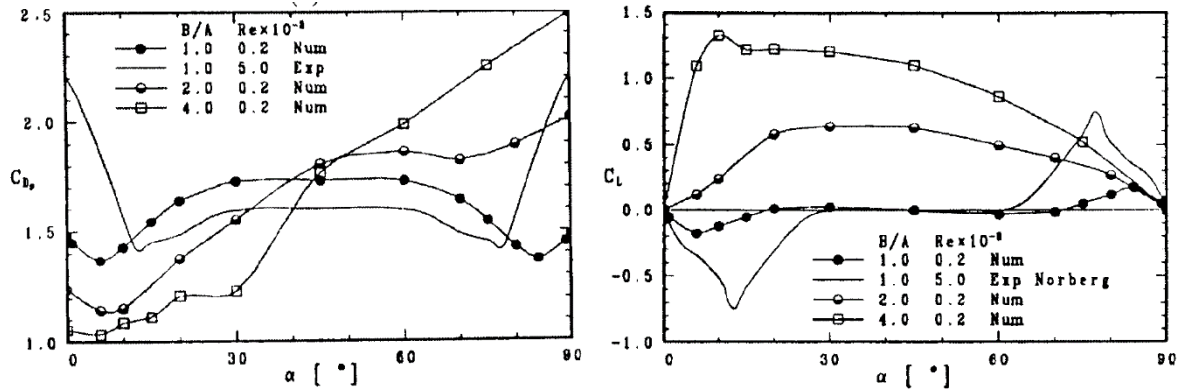


Figure 4-9 Amplitude of a variable coefficient of lift and drag-computed by Sohankar (1996) [33] with respect to Steggel (1998) [31]

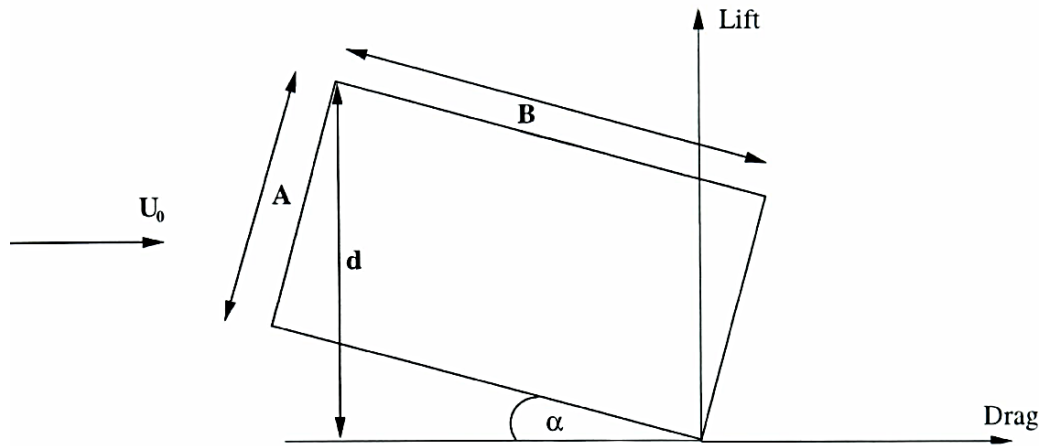


Figure 4-10 Generalized geometry of wind induced rectangular cylinder considered by Steggel [31]

On the other hand Takahashi [34] studied a flat, thin plate similar to a wing, which using a micro-electro-mechanical systems sensor to measure the drag and lift coefficients. He ran an experiment to study the effect of angle of attack within the range of 0° to 90° . The schematic setup and procedure of directivity and measurement are shown in figure 4-11. According to the figure 4-12 drag and lift coefficient values were perfectly calibrated for a wide range of angles.

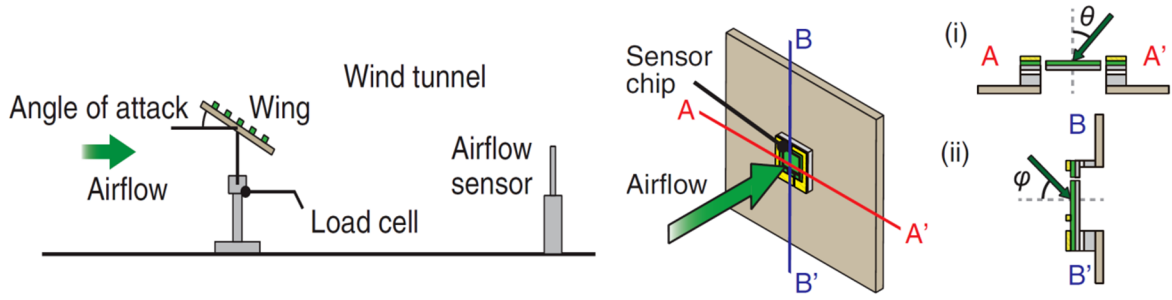


Figure 4-11 Schematic setup and procedure of directivity and measurement [34]

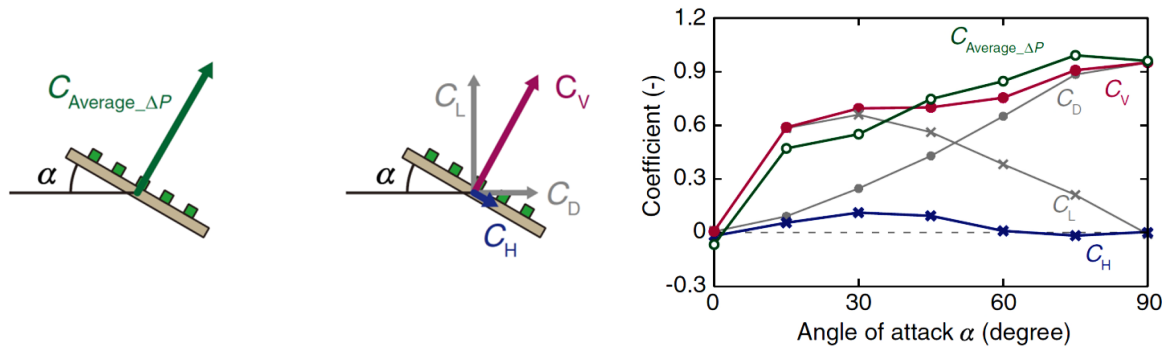


Figure 4-12 Drag and lift coefficient for a thin flat plate [34]

Consequently, considering the PV solar panel installed on the roof of the Mann Parking building, which is inclined with $\alpha = 39^\circ$ the drag and lift coefficients were interpolated from the Figure 4-12; for the inclined frame members the assumption was made earlier in this section that the coefficient of drag and lift are based on table 4.3. However, it seems that due to the location where the frame was installed, exactly above the support structure drag force only was acting on some of the frame members. On the other hand frame member number 4 which used as braced element needs to bear drag and lift forces distributed along the members, due to the dynamic characteristic of wind load. Nevertheless, due to the length considered for this member a simplification assumption was made to ignore wind load on this member for certain wind direction, when the frame number 4 is in the sheltered area provided by number 1, therefore is shielded.

The values of drag and lift coefficient based on previous tables and figures presented in this section, were used as per table 4-4 and per figure 4-13 for most of the members of the frame and the PV solar panel. The most significant values were noticed for the lift coefficient C_L where the 39° and 0° angles of attack are considered. Surprisingly many of the C_L values were 0 for small angles of attack, as it can be seen in the table 4-4 below. However, all these values experimentally found by C.W. Knisely, (1990) [32] were validated by Sohankar (1996) [33].

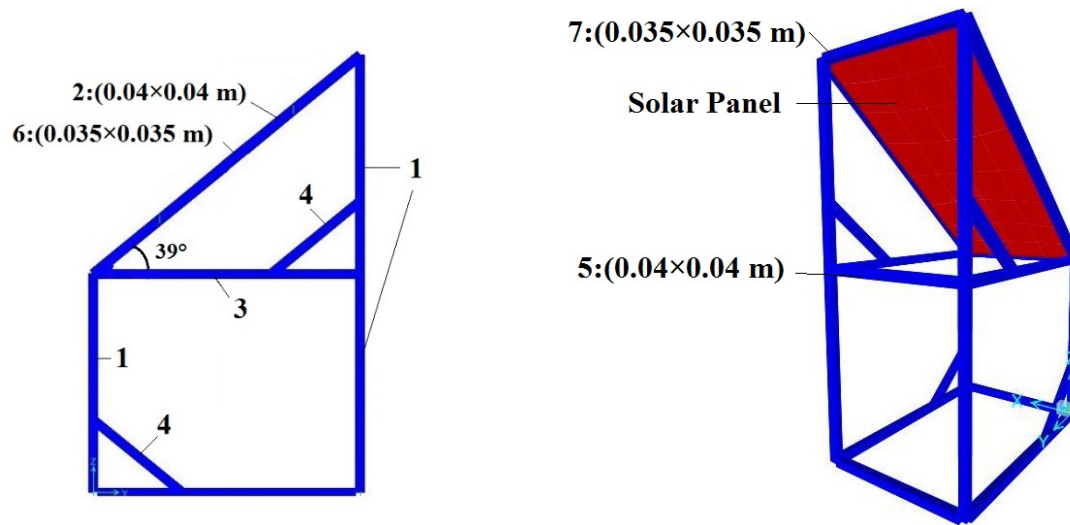


Figure 4-13 Different members considered for C_L & C_D coefficient

Table 4-4 The Lift and drag coefficients of different members with respect to angle of attack

Member Number	Member type	Area induced Lift & Drag Force (m^2)	Angle of attack	Lift Coefficient (C_L)	Drag Coefficient (C_D)
1	Box (0.04x0.04 m)	1.00×0.04	0° Vertical Direction	0	0.6
2	Box (0.04x0.04 m)	1.58×0.04	39°	0	1.5
3	Box (0.04x0.04 m)	1.22×0.04	0° Horizontal Direction	0	2.2
4	Box (0.04x0.04 m)	0.53×0.04	39°	0	1.5
5	Box (0.04x0.04 m)	0.808×0.04	0° Horizontal Direction	0	2.2
6	Box (0.035x0.035 m)	1.58×0.035	39°	0	1.5
7	Box (0.035x0.035 m)	0.808×0.035	0° Horizontal Direction	0	2.2
Solar Panel	Multilayer	1.58×0.808	39°	0.6	0.4

4.2.2.2. Force computation:

As it was mentioned previously the wind load applied to the PV solar panel are applied along two directions, drag force which is along wind direction and lift force which is in the uplift wind direction. The value of load in each direction changed due to wind speed or the wind attack angle that was applied to equation with respect to drag or lift coefficient and the respective projected area. Both coefficients determined in section 4.2.2.1, however used the projected area for each direction normal to wind flow. Figure 4-14 shows the geometry of 2D x-z plane section cut to compute A_D and A_L with respect to airflow direction. According to the values determined in the previous step and the projected area for each direction, drag and lift forces were computed based on maximum wind speed for all frames and PV panel during specific filtered time which was collected from weather station. Moreover, with respect to the area computed facing the wind direction, the end offset values for connection of structure and frames to solar panel, needs to be considered. However due to small size of the members used for installation, this criteria eliminated drag and lift force computation.

$$A_{solar\ panel} = 1.58 \times 0.808\ m^2$$

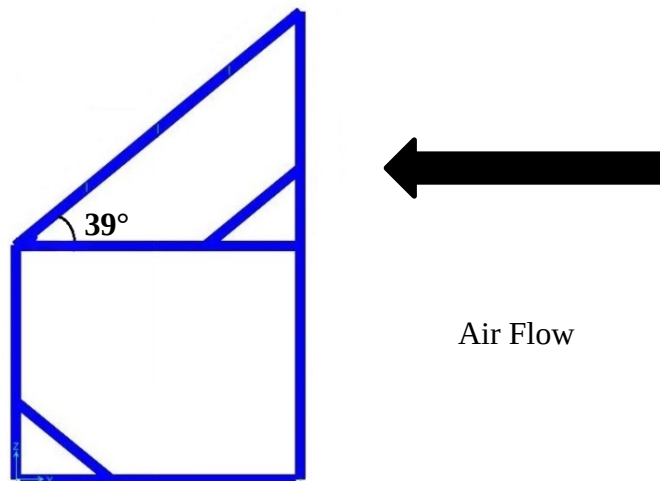


Figure 4-14 2D X-Z view of solar panel and attached frame

1- Compute projected area for drag and lift for PV solar panel:

$$A_D = (1.58 \times 0.808) \times \sin 39^\circ = 0.803 \text{ m}^2$$

$$A_L = (1.58 \times 0.808) \times \cos 39^\circ = 0.992 \text{ m}^2$$

2- Compute parametric drag and lift pressure based on density and maximum wind speed for PV Solar panel:

$$F_D = \frac{1}{2} C_D \rho A_D V_{max}^2 = \frac{1}{2} \times 0.4 \times 0.803 \rho V_{max}^2 = 0.16 \rho V_{max}^2$$

$$F_L = \frac{1}{2} C_L \rho A_L V_{max}^2 = \frac{1}{2} \times 0.6 \times 0.992 \rho V_{max}^2 = 0.297 \rho V_{max}^2$$

Density and maximum wind speed for each time lag applied to two parametric values for drag and lift force equations. As it mentioned in first part of this chapter two other minimum and average wind speed data collected by site instrumentations. However, the maximum values of wind speed needs to be considered to compute the most intense value of pressure leading to larger displacement on surface facing the wind flow. Table 4-5 shows the forces F_D and F_L for within 9 minutes of January 2014. The maximum drag and lift force applied on the PV solar wafer computed in January 2014, were equal to 27.25N and 50.6 N respectively. Furthermore, 20.34 N and 37.76 N were the values for the mentioned forces in Feb 2014. Figures 4-15 and 4-16 show the variation of drag and lift loads scattering along the selected period of time between January and February.

Table 4-5 Drag and Lift force computation for each time lag on solar panel

Timestamp	T (° C)	RH(%)	Air P(kPa)	R _d	e _s	e	ρ Humid Air	Max. Wind Speed (m/s)	F _D	F _L
1/4/2014 11:41	-15.13	68.08	101.02	287.04	1.89	1.29	1.36	1.42	0.44	0.82
1/4/2014 11:42	-15.19	68.23	101.01	287.04	1.88	1.28	1.36	1.25	0.34	0.63
1/4/2014 11:43	-15.34	68.30	101.01	287.04	1.86	1.27	1.36	1.67	0.61	1.13
1/4/2014 11:44	-15.47	68.93	101.01	287.04	1.84	1.27	1.37	1.69	0.62	1.16
1/4/2014 11:45	-15.64	69.18	101.01	287.04	1.81	1.25	1.37	1.95	0.83	1.54
1/4/2014 11:46	-15.63	69.75	101.00	287.04	1.81	1.26	1.37	1.23	0.33	0.61
1/4/2014 11:47	-15.72	70.31	101.00	287.04	1.80	1.26	1.37	1.25	0.34	0.64
1/4/2014 11:48	-15.72	70.53	101.00	287.04	1.80	1.27	1.37	0.74	0.12	0.22
1/4/2014 11:49	-15.73	70.66	101.00	287.04	1.80	1.27	1.37	1.09	0.26	0.48

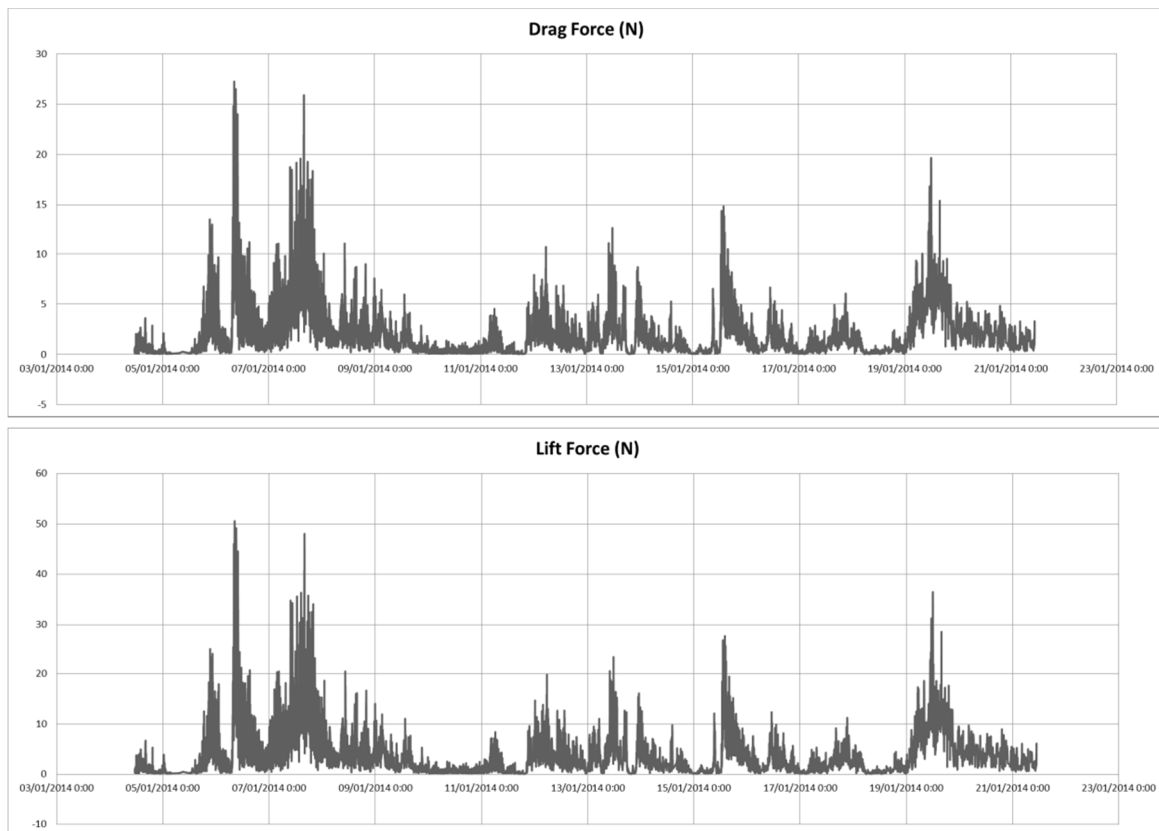


Figure 4-15 Scattering of Drag and Lift Load along solar panel within the selected data on January

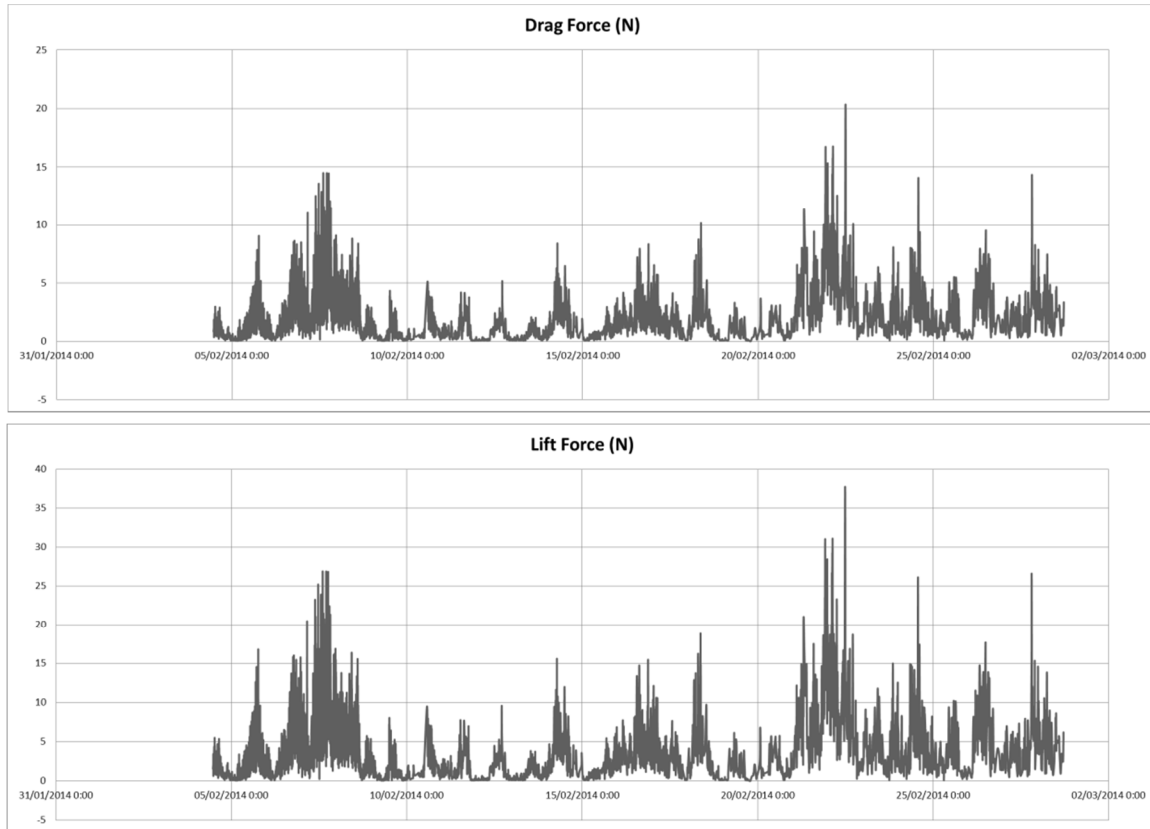


Figure 4-16 Variation of drag and lift forces for the PV solar panel within the selected data on February 2014

After computation of horizontal and vertical components of wind load applied to solar panel wafer, the same procedure need to apply to all frames with respect to value considered in table 4-4 and equations (4.7) and (4.8). It is clear that lift force for all frames equal to zero so the drag force computed for different frames number with respect same value of weather data collected from weather anemometer and other instruments.

1- Compute Drag's Area for all frames with respect to Angle of attack:

$$A_{D1} = (1.00 \times 0.04) = 0.04 \, m^2$$

$$A_{D2} = (1.58 \times 0.04) \times \sin 39^\circ = 0.0397 \, m^2$$

$$A_{D3} = 0 \text{ m}^2$$

$$A_{D4} = 0 \text{ m}^2$$

$$A_{D5} = (0.808 \times 0.04) = 0.0323 \text{ m}^2$$

$$A_{D6} = 0$$

$$A_{D7} = (0.808 \times 0.035) = 0.0282 \text{ m}^2$$

It needs to be mention that the value of area determined for member number 3, 4 and 6 are based on wind flows acting on the back side of specimen and the sheltered area prepared by member number 1 and 2 was considered. However, the direction of wind attack could not always be as considered above so any change in direction, changes the wind load on specimen with respect to surface wind flow normal. To compute wind load for this case a vast number of other factors such as angles of installation, new projected area and dynamic behaviour of wind stream where it reaches to the surface should be considered.

- 2- Compute parametric drag and pressure based on density and maximum wind speed for all frames:

$$F_{D1} = \frac{1}{2} C_{D1} \rho A_{D1} V_{max}^2 = \frac{1}{2} \times 0.6 \times 0.04 \rho V_{max}^2 = 0.012 \rho V_{max}^2$$

$$F_{D2} = \frac{1}{2} C_{D2} \rho A_{D2} V_{max}^2 = \frac{1}{2} \times 1.5 \times 0.0397 \rho V_{max}^2 = 0.0297 \rho V_{max}^2$$

$$F_{D3} = \frac{1}{2} C_{D3} \rho A_{D3} V_{max}^2 = \frac{1}{2} \times 2.2 \times 0 \rho V_{max}^2 = 0$$

$$F_{D4} = \frac{1}{2} C_{D4} \rho A_{D4} V_{max}^2 = \frac{1}{2} \times 1.5 \times 0.0133 \rho V_{max}^2 = 0.01 \rho V_{max}^2$$

$$F_{D5} = \frac{1}{2} C_{D5} \rho A_{D5} V_{max}^2 = \frac{1}{2} \times 2.2 \times 0.0323 \rho V_{max}^2 = 0.0355 \rho V_{max}^2$$

$$F_{D6} = \frac{1}{2} C_{D6} \rho A_{D6} V_{max}^2 = \frac{1}{2} \times 1.5 \times 0.0348 \rho V_{max}^2 = 0$$

$$F_{D7} = \frac{1}{2} C_{D7} \rho A_{D7} V_{max}^2 = \frac{1}{2} \times 2.2 \times 0.0282 \rho V_{max}^2 = 0.031 \rho V_{max}^2$$

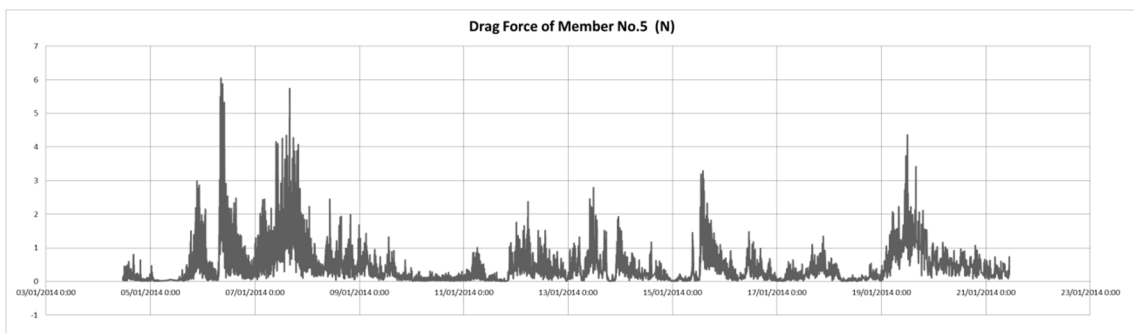
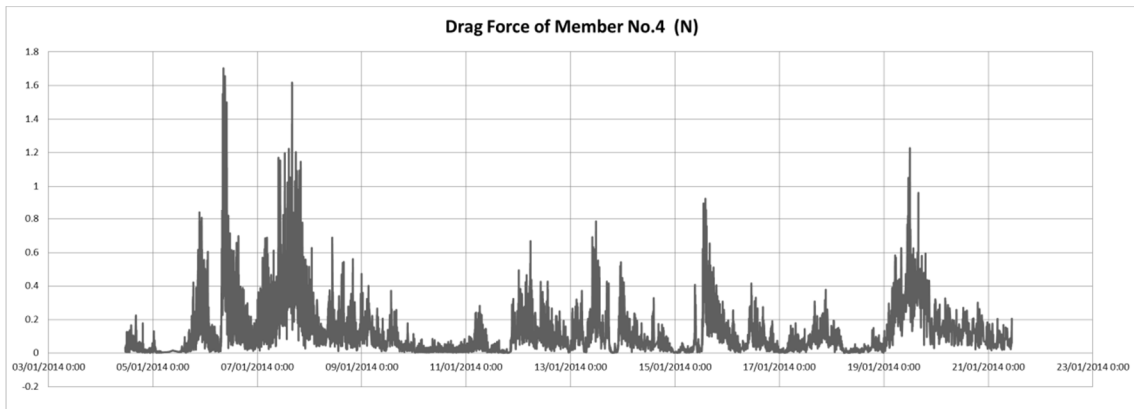
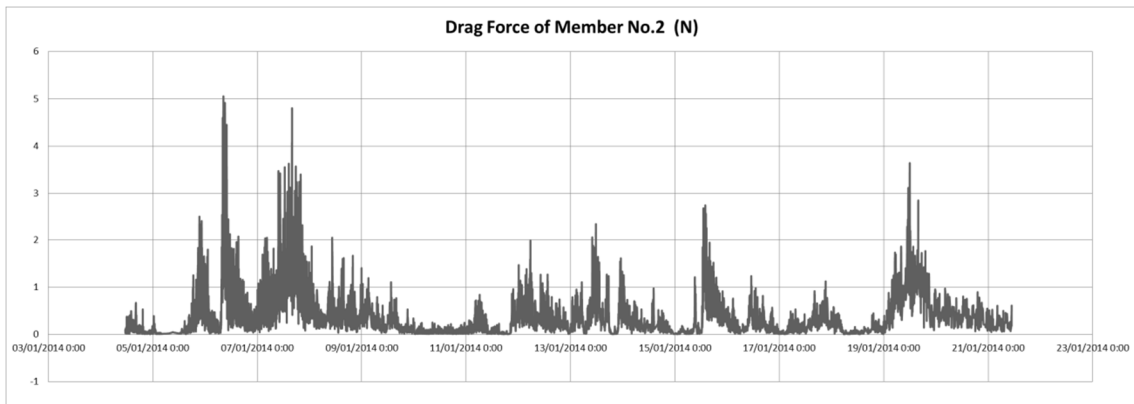
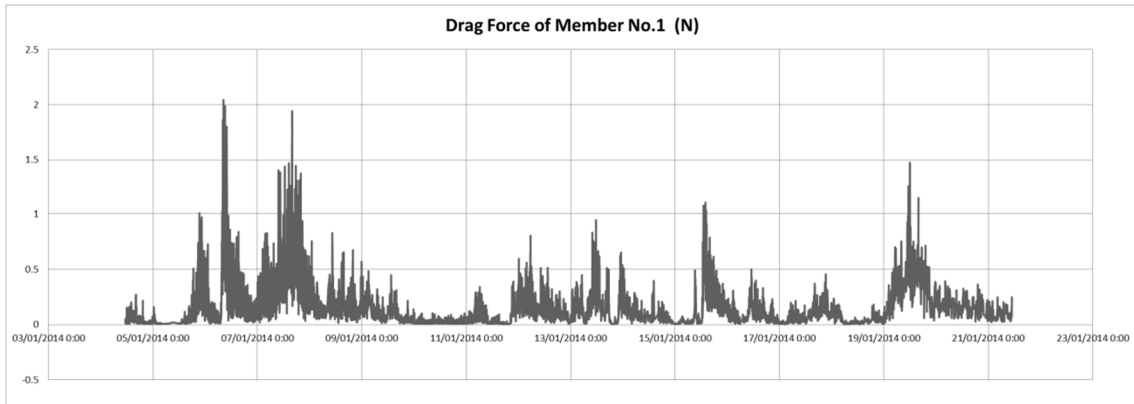
Table 4-6 shows the values of F_D for different members within 9 minutes of January 2014. The maximum drag load on different frames induced wind load computed for Jan was equal to 6.045 N where applied to member number 5. The value of 4.513N applied to same element as most intense value of drag force in Feb. Table 4-7 clears the maximum values of drag force distributed during the period of data collection and figures 4-17 and 4-18 clear the drag load scattering along the selected period of time between January and February 2014.

Table 4-6 Drag and Lift force computation for each time lag on different members

Timestamp	T (° C)	$\rho_{\text{Humid Air}}$	Max. Wind Speed (m/s)	F _{D1}	F _{D2}	F _{D3}	F _{D4}	F _{D5}	F _{D6}	F _{D7}
1/4/2014 11:41	-15.13	1.36	1.42	0.03	0.08	0.00	0.03	0.10	0.00	0.09
1/4/2014 11:42	-15.19	1.36	1.25	0.03	0.06	0.00	0.02	0.08	0.00	0.07
1/4/2014 11:43	-15.34	1.36	1.67	0.05	0.11	0.00	0.04	0.14	0.00	0.12
1/4/2014 11:44	-15.47	1.37	1.69	0.05	0.12	0.00	0.04	0.14	0.00	0.12
1/4/2014 11:45	-15.64	1.37	1.95	0.06	0.15	0.00	0.05	0.18	0.00	0.16
1/4/2014 11:46	-15.63	1.37	1.23	0.02	0.06	0.00	0.02	0.07	0.00	0.06
1/4/2014 11:47	-15.72	1.37	1.25	0.03	0.06	0.00	0.02	0.08	0.00	0.07
1/4/2014 11:48	-15.72	1.37	0.74	0.01	0.02	0.00	0.01	0.03	0.00	0.02
1/4/2014 11:49	-15.73	1.37	1.09	0.02	0.05	0.00	0.02	0.06	0.00	0.05

Table 4-7 The maximum Drag and Lift force computed for each month of investigation for different members

Member number	1	2	3	4	5	6	7
Month of study							
Drag force on January (N)	2.044	5.058	0.000	1.703	6.046	0.000	5.280
Drag force on February (N)	1.526	3.776	0.000	1.272	4.514	0.000	3.942



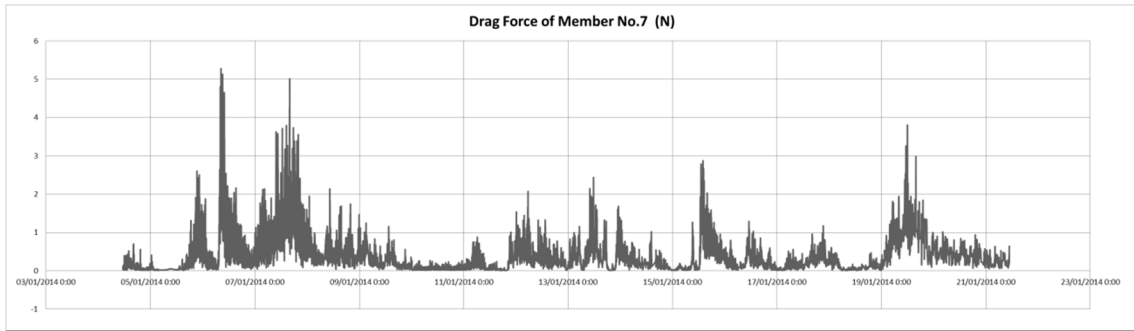
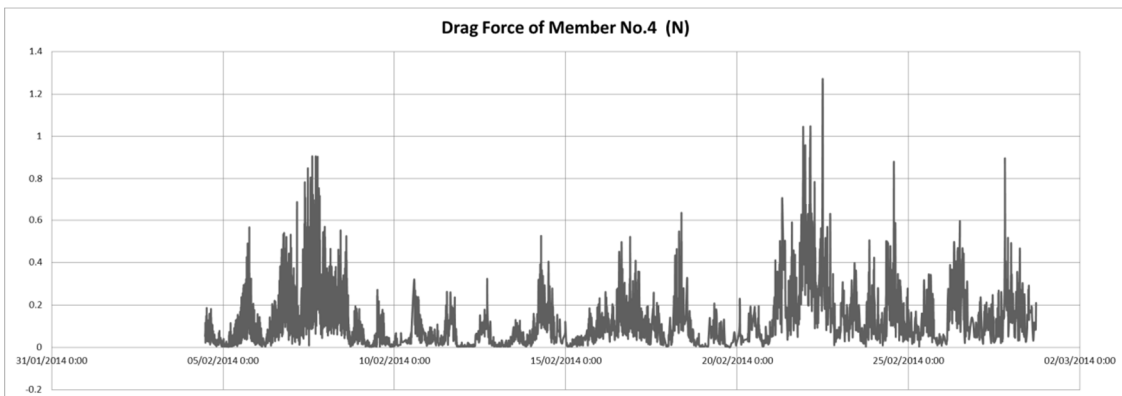
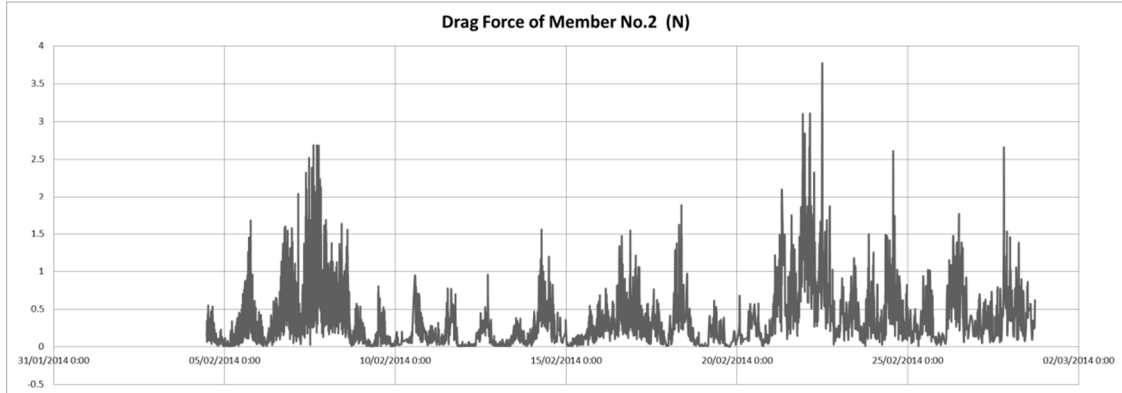
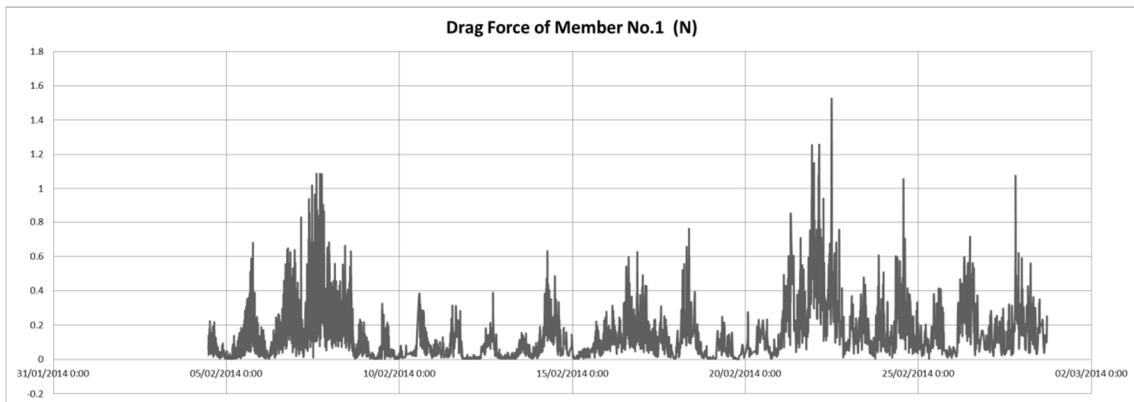


Figure 4-17 Scattering of Drag Load along 5 members within the selected data on January



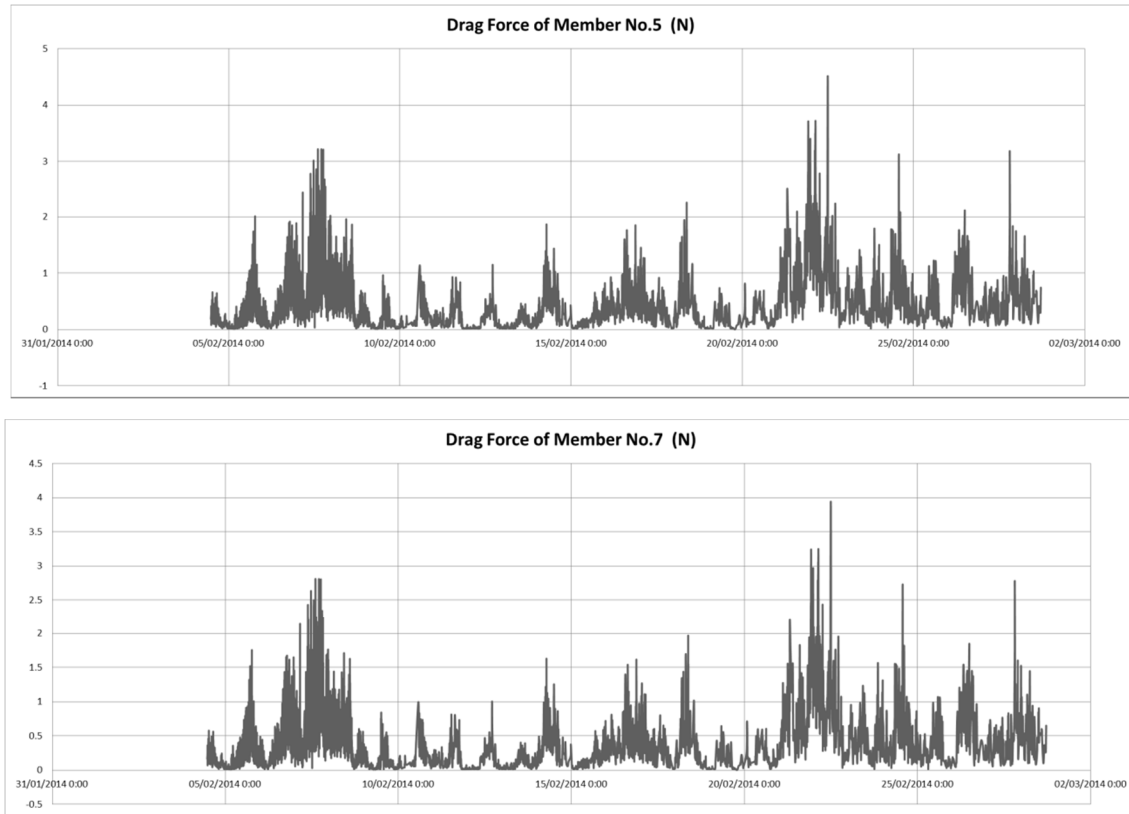


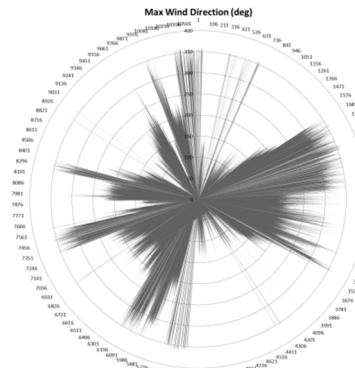
Figure 4-18 Scattering of Drag Load along 5members within the selected data on February

4.2.4 Wind direction:

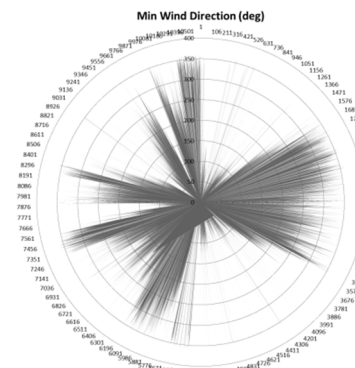
Drag and lift loading at each time interval could be computed and applied in various directions. As it is noted above, the wind load is variable dynamic load acting on the any surfaces element stands in front depend on direction, shape and wind speed. In previous sections shape of surface and velocity accounted to compute pressure on system. Another parameter affecting the total pressure acting on PV panel surface is the direction of the wind that needs to be considered in load application due to dynamic characteristic of wind load.

To determine the wind direction applied to the system of installation, this parameter measured same as the other weather data for every 1 minute in January and February 2014 at the roof of the Mann Parking of the University of Ottawa. Wind direction collected data classified in three values minimum, average and maximum for directions between 0° to 360° . Zero or 360° is considered as north direction, 180° should be south direction and according to clockwise convention 90° went for east and in opposite side 270° goes for west directions. In northern hemisphere most of PV solar panels due the location of sun, are facing to south, so the system is completely vulnerable the wind speed direction from north. Regarding to data collected, two dominant wind directions were recorded , between 340° and 350° and other one between 190° and 220° .The former direction means that the wind speed approached the PV panel from the north and the latter almost equivalent to opposite direction, south. Maximum, minimum and average wind directions are shown in Figure 4-19 (a, b, c) and 4-20 (a, b, c) for January and February 2014.

a)



b)



c)

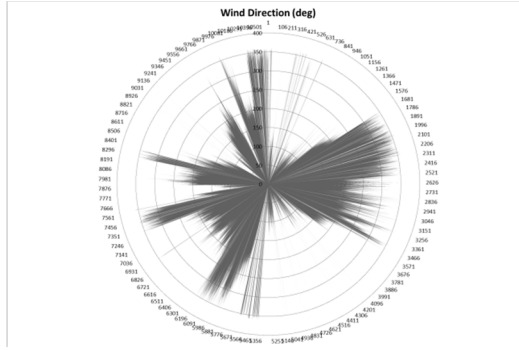
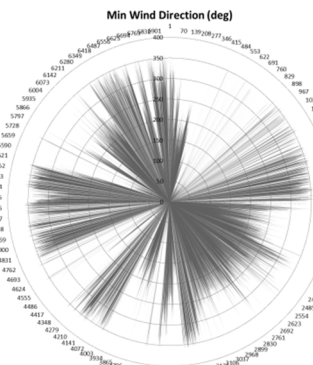
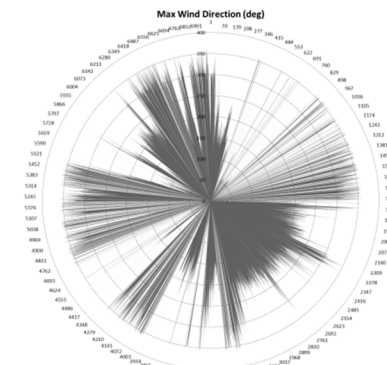


Figure 4-19 a) Maximum, b) Minimum and c) Average wind direction for Jan 2014

a)



b)



c)

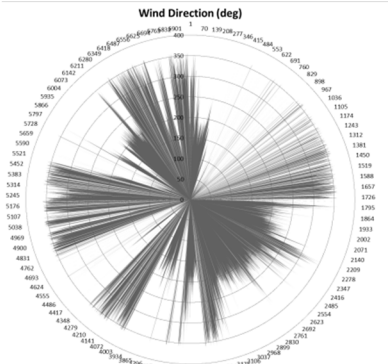


Figure 4-20

a) Maximum, b) Minimum and c) Average wind direction for Feb 2014

4.3. Finite Element Modeling:

As it mentioned early in this chapter the behaviour of PV solar system induced wind load is function of wind speed acting on each element separately. The drag and lift loads computed depend on wind attack angle for primary wind load based on surface dimension of each member plus weather collected data such as wind speed and humid air density. Moreover, two main directions of wind attack figured out to compute the most critical condition PV system faced. To analyze all above cases it needs to define and assign the geometry and wind load characteristic to FEM software similarly to the analysis performed in chapter 3.

The procedure of FEM computation at the first step focused on discretization and mesh shape preparation depends on two or three dimensional analysis. The former consideration divided to Triangular or Quadrilateral shapes and the latter to Tetrahedron or Brick shapes depends on terms extracted from Pascal's triangle or pyramid to make equation for each node and compute displacement for each node. These procedure held by forming a shape function with consideration of displacement and stiffness matrices for each node. The principle of minimum total potential energy considered for external and internal load to form stiffness matrix $[k]$ which the external energy is product of force ($\mathbf{F}$) and displacement ($\boldsymbol{\delta}$) and the internal energy (strain-energy density) one is equal to $\frac{1}{2}\sigma\epsilon$ [18]. The total number of terms which need to be considered in the equation depends on the total number of nodes (edge or middle), degrees of freedom and also total load applied to each element. The figure 4-21 a,b,c,d shows number of terms considered in two dimensional and three dimensional mesh shapes [18].

To do the accurate modeling, advantages of a PV solar system that contains a solar panel plus aluminum support structure mounted on flat roof of the Mann Parking of the University of Ottawa taken to measure exact geometry and mechanical properties. Moreover, according to the FEM software SAP-2000 used, Brick considered as mesh shape which manually sized depend of mesh sensitivity.

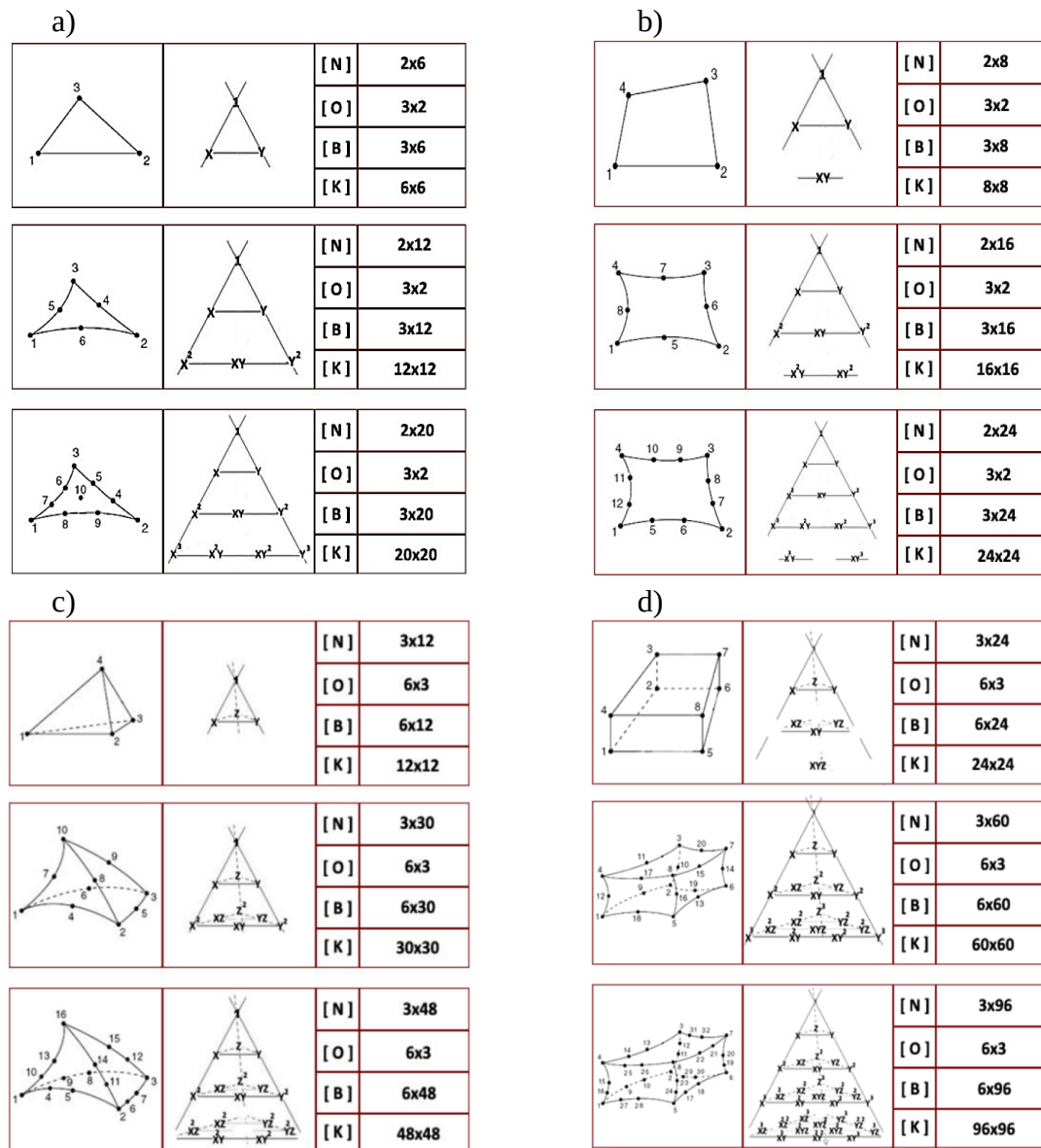


Figure 4-21 Number of terms need to be considered in a) Triangular b) Quadrilateral c) Tetrahedron d) Brick mesh shapes for stiffness matrix [18]

4.3.1. Frame Section Modelling:

The mechanical properties and geometry of each element and joint introduced to FEM software to study on displacement and load distribution around PV solar system induced wind load. Both types of PV frames considered in section 4.3.1.1 are modelled based on commands prepared by the software.

According to modeling of the Aluminum Box frame 4 cm×4 cm×0.3 cm (H×W×t), a shortcut command used to define section's dimension and material. As it shown in figure 4-22(a) dimensions and material set to form a section with the mechanical properties of the section mentioned in part (b).

In the other hand, definition of Custom Style Aluminum section in the software needs another way to obey. Advantages of command of Section Designer were taken to model the section same as what defined in figure 4-6. Due to small size of all frame section used to install solar panel an assumption made to eliminate the top plate of frame section as shown in figure 4-23 thus this is considered a time consuming job of the modeling and solar wafer application in distance less than 2mm in the exact place.

The mechanical properties and the elastic stress distributions along both members were studied with respect to the unit force (Ton, m) and moment (M_x & M_y) application ($P=1$, $M_x=1$ & $M_y=1$) for both cases (mechanical properties and elastic stress distribution) determined in figures 4-23 and 4-24. It is clear that the mentioned parameter has significant effect on mechanical properties, load distribution and more important the stiffness of (moment of inertia) along the frame. Therefore, to save time and mechanical behavior of frame section, the solar panel and surrounding custom style frame section was applied to the same gridline

instead of previous assumption. It must be noted that two types 3 layers and 5 layers of PV solar panels were modeled in chapter 3, therefore in this section modeling of frames is considered.

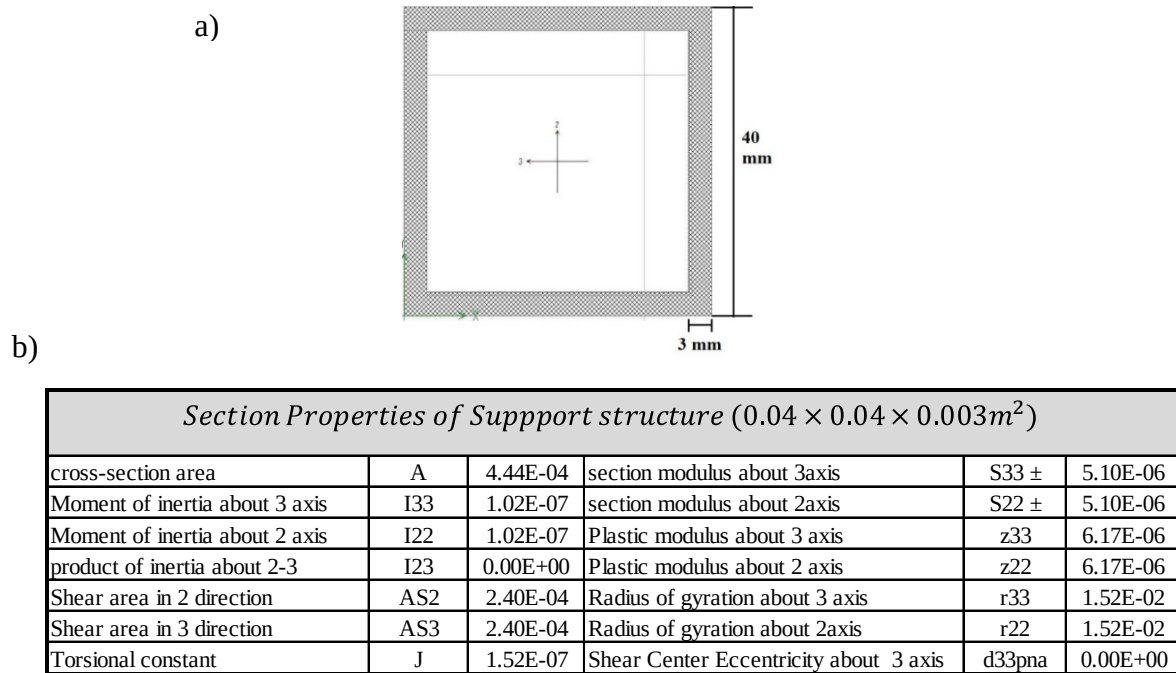
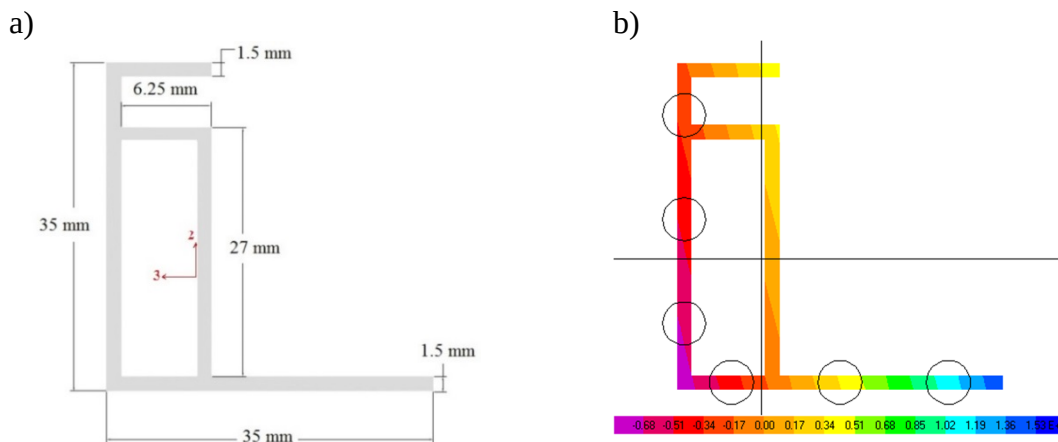


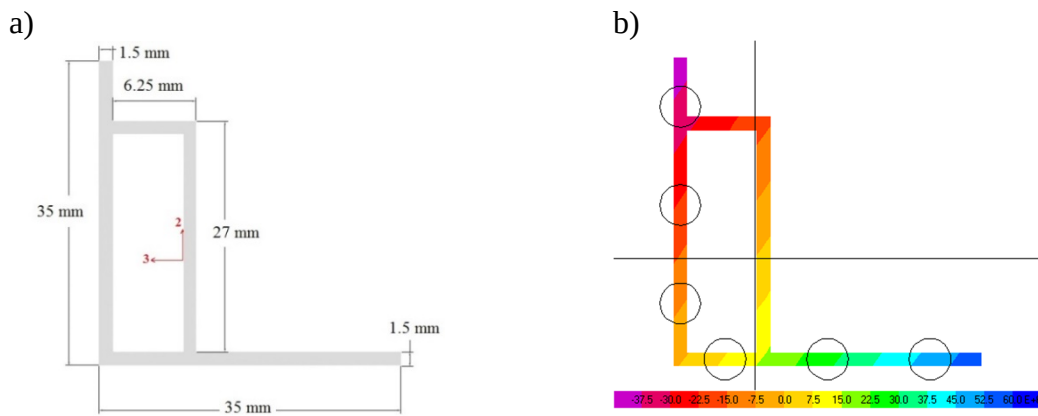
Figure 4-22 Aluminum Box Frame section a)view and b) Mechanical properties



c)

Custom Style Frame Section					
cross-section area	A	1.69E-04	section modulus about 2axis	S22 (+face)	1.45E-06
Moment of inertia about 3 axis	I33	2.53E-08	section modulus about 2axis	S22 (-face)	5.03E-07
Moment of inertia about 2 axis	I22	1.31E-08	Plastic modulus about 3 axis	z33	1.86E-06
product of inertia about 2-3	I23	8.99E-09	Plastic modulus about 2 axis	z22	1.12E-06
Shear area in 2 direction	AS2	9.47E-05	Radius of gyration about 3 axis	r33	1.20E-02
Shear area in 3 direction	AS3	6.78E-05	Radius of gyration about 2axis	r22	8.79E-03
Torsional constant	J	1.29E-10	Shear Center Eccentricity about 3 axis	d33pna	-1.84E-03
section modulus about 3axis	S33 (+face)	1.21E-06	Shear Center Eccentricity about 2 axis	d22pna	3.71E-04
section modulus about 3axis	S33 (-face)	1.81E-06			

Figure 4-23 Case I - Aluminum Custom style Frame section a)Plane View and b)Stress View c) Mechanical properties



c)

Custom Style Frame Section					
cross-section area	A	1.55E-04	section modulus about 2axis	S22 (+face)	1.39E-06
Moment of inertia about 3 axis	I33	1.90E-08	section modulus about 2axis	S22 (-face)	4.99E-07
Moment of inertia about 2 axis	I22	1.29E-08	Plastic modulus about 3 axis	z33	1.53E-06
product of inertia about 2-3	I23	8.13E-09	Plastic modulus about 2 axis	z22	1.07E-06
Shear area in 2 direction	AS2	8.83E-05	Radius of gyration about 3 axis	r33	1.11E-02
Shear area in 3 direction	AS3	6.19E-05	Radius of gyration about 2axis	r22	9.11E-03
Torsional constant	J	1.18E-10	Shear Center Eccentricity about 3 axis	d33pna	-2.35E-03
section modulus about 3axis	S33 (+face)	8.32E-07	Shear Center Eccentricity about 2 axis	d22pna	-2.77E-04
section modulus about 3axis	S33 (-face)	1.56E-06			

Figure 4-24 Case II - Aluminum Custom style Frame section a)Plane View and b)Stress View c) Mechanical properties

4.3.2. Joints and boundary conditions (Mesh sensitivity):

The analysis of behavior of any structure, joints and connecting points considered as high importance parts of study due to the degree of freedom described depends on type of

connection. Angle of linked member to joint, section types and many other parameters could affect the displacement of any supports which need to be study in any case.

Twelve Number of screws used to install the PV Box frame as support structure and to connect custom made solar frame to support box frame. Therefore, screws and type of connections in all joints depend on different factors applied to FEM software. This means some holes need to be modeled to screw members together that made the system unbalanced and had significant effect on displacement as first result of computation. The main computational function of FEM software stands on fine discretization and quality of mesh considered to model to compute the most accurate value results from load distribution along member. According to study of S. Thohura and Md. Shahidul Islam on the quality of mesh elements and respective influence on stress distribution on a plate with holes meshed with quadrilateral element [17], by increasing number of nodes which means reducing the mesh size with consideration of making Aspect Ratio (A ratio of Length over height of mesh in any surface) sufficiently close to ideal value equal to one, the accuracy of outlook report got from analysis increase significantly. However, reaching to this value of aspect ratio needs hours to spend and it is not possible in most of the time.

According making a hole in a member with respect to the quadrilateral mesh shape, the quality of discretization plays important role. Round shape of modeled element asked for smaller and smaller side of mesh in one direction, however the other remains constant that means stay far from ideal Aspect Ratio and less accurate results. Therefore, to increase the accuracy of analysis more time need to spend to make different size of quadrilateral mesh depends on distance from circular shape. Usually, to do this procedure vast number of divisions needs to introduce to FEM software around each hole with different mesh size. Figure 4-25

(a,b,c,) exhibit different cases considered by S. Thohura and Md. Shahidul Islam[17] to study on their respective results.

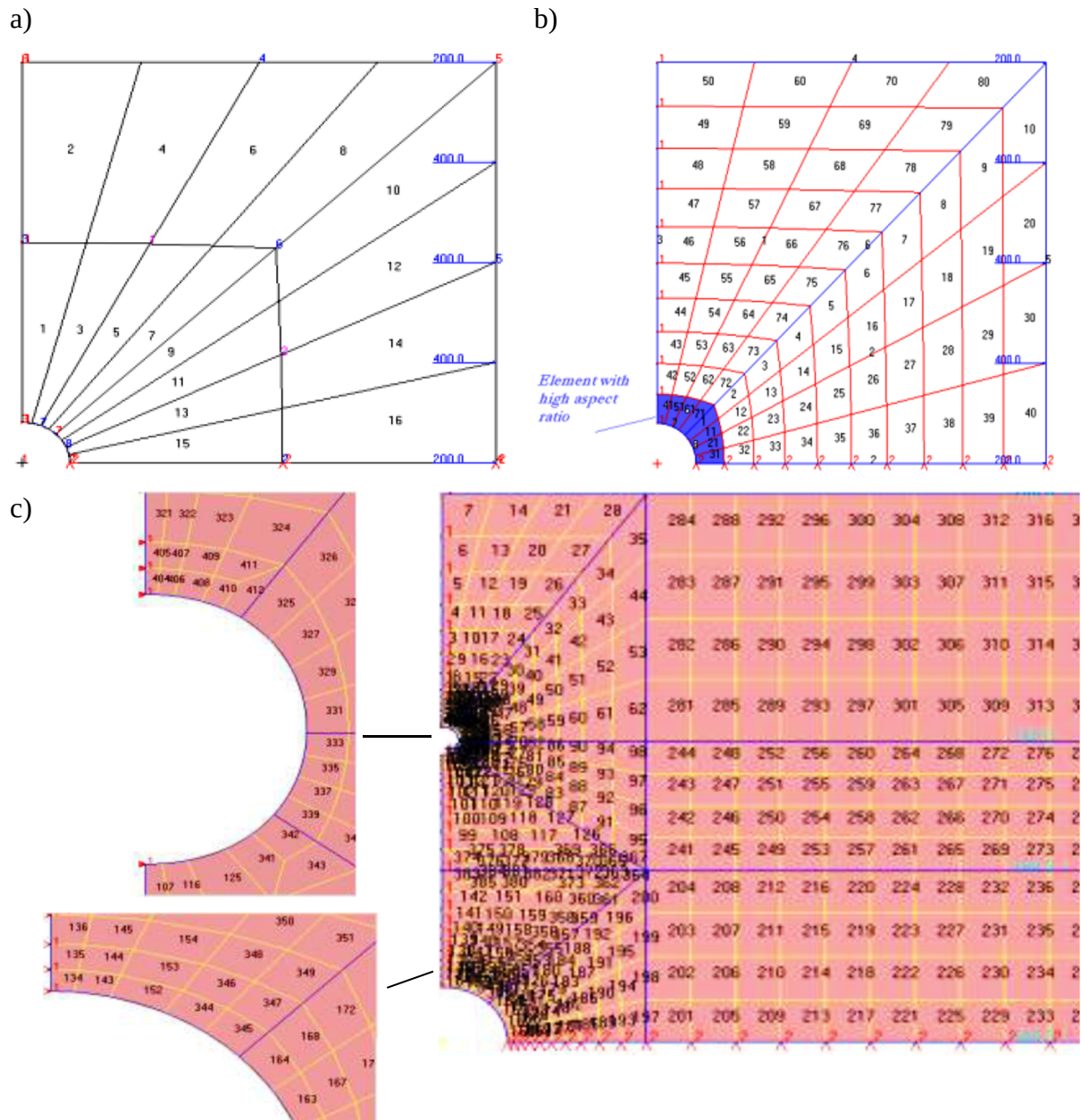


Figure 4-25 Three different considered to reach to high quality Mesh with respect to Aspect Ratio [17]

According to the difficulties mentioned and due to small size of Box and Custom made section leads to pretty small size of holes in joint of support structure and surrounding frame, besides the time need to spend to simulate model in SAP 2000 due to limitation of software to produce different type and size of mesh along a member, alternative types of connections considered (screws and holes eliminated) to model based on interaction and ability of software to simulate behavior each joint under distributed load. Note that to compensate the impact of hole elimination and stiffness reduction caused by this assumption, all pinned connection modeled without spring application and default software primary conditions consider.

1. Box Frames connect together to form support structure that due to the advantages of Spring and Overlap Toothed Lock Washer taken to tighten the screws and control rotations, two types of fix (continuous) and pinned connection considered to study on this connection. Figure 4-26 shows a model of this connection.

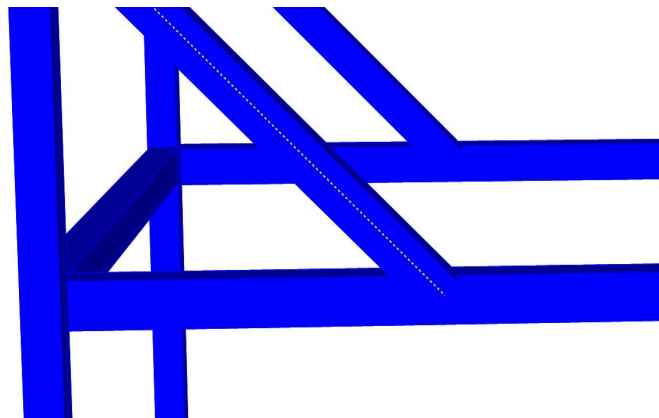


Figure 4-26 Two different Box Frames connection considered to model support structure

2. To connect the support structure to surrounding frame of solar panel a grid line with 2 mm distance above the tilted side of support structure defined to apply PV panel and alternative way to model screws. Both frames divided to four relatively equal parts at each side to introduce 3 screws at middle nodes which means 12 nodes prepared for each frame to connect to another. Therefore, three different commands of FEM software Link Two Joints, Equal and Rod constrains considered to model screws behavior. Figure 4-27 shows divisions and connections between two frames. It needs to mention that all other nodes shown in the figure are regular type of nodes which only shown as extrude view FEM software.

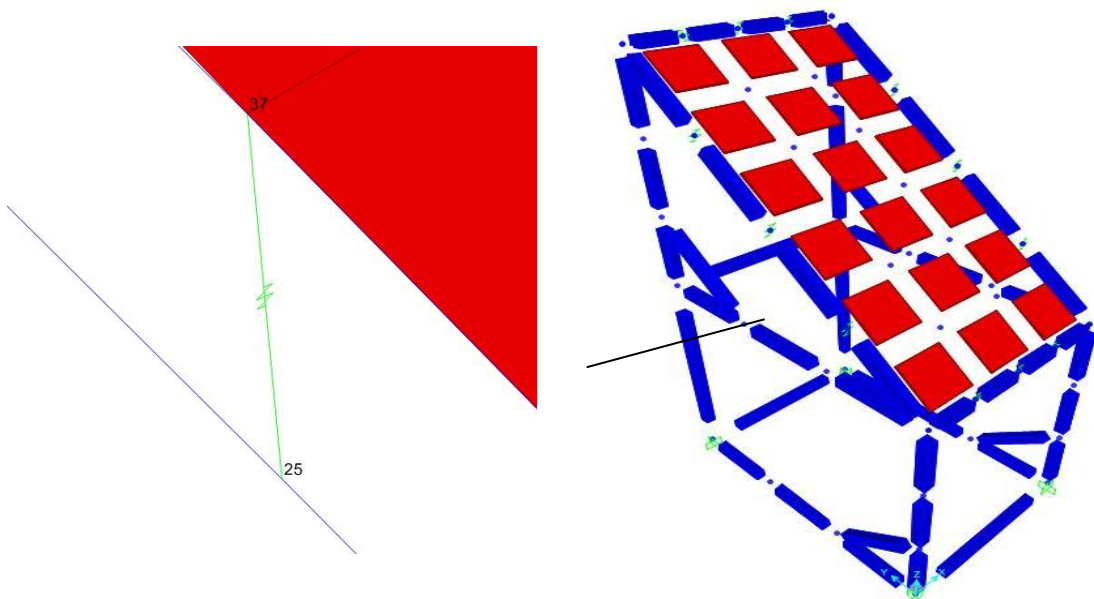


Figure 4-27 Modeling the connection between Support Structure and Solar panel frame

2.1. Link two joints:

In most of the cases, this type of connection used to model non-linear behavior of the elements, such as dampers and nonlinear springs that is able to show their behavior especially in non-linear time history analysis. However, linear behavior predicted too to define fix, free or spring joints to control the transverse (U) and Rotation (R) about to three x,y,z directions. To model Pin connection caused by screwing two frames, U_x and U_y considered as fix joints.

2.2. Joint Constraint/Equal:

Usually, advantages of this type of connection are taken to model hinges or expansion joints. With respect to this type of modelling two nodes fix together completely, where each node represent as each end of a screw. Therefore small length of screw in modeled the transition and rotation of both node consider fix about each other.

2.3. Joint Constraint/Rod:

This connection considered that two joints connect together with the main concept of automatic solid rod preparation, which is only transverse to the direction of longitudinal axis. Usually the strength of most screws is more than members connected together, therefore due to very small distance considered between two frames yield to large amount of fixity in all directions. In this type of joint the distance between any elements along longitudinal axis remains constant.

4.4. Experiment Setup and instrumentation

A 15.5kg poly-crystalline PV solar panel installed to withstand high wind-pressure, snow loads, and extreme temperature variations. The solar panels system installed at the Mann Parking of the University of Ottawa, where due to parapet height and better absorption of sun light it the raised from the ground with a height of 1m. However, such installation is slightly different than the standard installation used for commercial and residential buildings.

To increase the accuracy of investigation as main aim of study, the specimen instrumented with 13 strain gauges were placed in the center cross line of solar panel. They layout at equal distance of about 26.8 cm starting from both ends in along the shorter side of specimen plus the middle line. The only change in installation occurs that the same layout considered for the mid-line where a cross line seen. Three unidirectional strain gauges installed at middle of specimen perpendicular to the mentioned direction. Except these 3 half bridge strain gauges two more quarter bridge strain gauges installed along the mentioned direction .The same layout considered for the back side of solar panel where both strain gauges at each point of top and bottom surface connected together to increase the accuracy of measurement. With respect to mentioned installation the uniaxial strain gauges were converted to half bridge which influenced on exactness of values measured, significantly. Figure 3 in chapter of introduction shows the layout of installation. Unfortunately, three strain gauges at the top side of inclined system for both upper and bottom surface of solar panel due extreme weather condition were lost. Therefore, 20 strain gauges (26 sensors) remain compute the strains values for each point where installed. The final layout of strain gauges is shown in figure 4-28.

Finally, all 20 strain gauges wired to a multiplexer as a terminal with one output channel that wired to measurement instrument called data logger to measure strains with numerical procedure from electrical resistance.

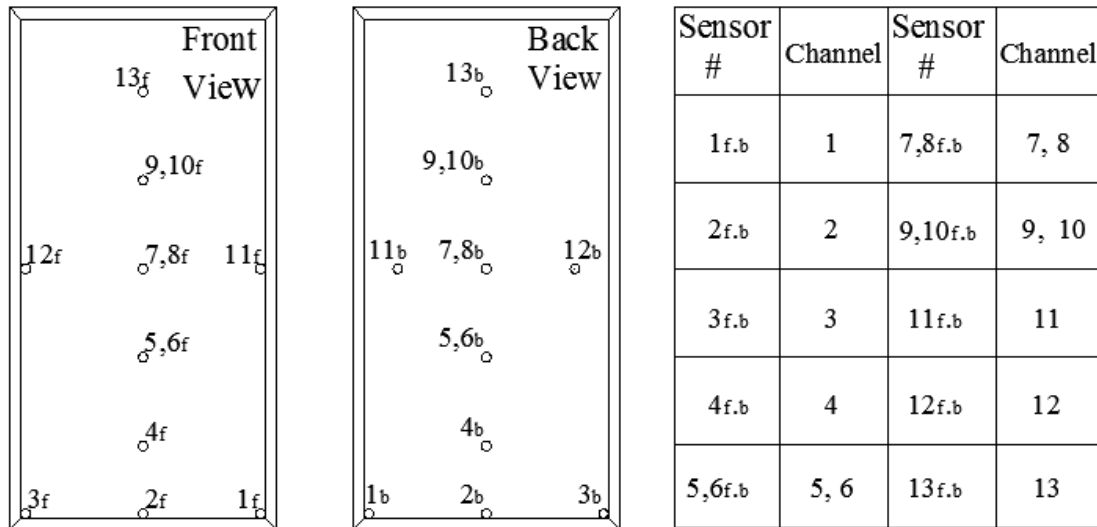


Figure 4-28 The layout of strain gauges after missing three sensors at the top side of the panel

4.4.1 Strain Gauges

The advantages of water proof, pre-wired 120Ω WFLA-3-11 Quarter Bridge (uniaxial type) and WFCA-3-11 half bridge (biaxial 2-element cross stacked type) strain gauges were taken to measure the value of strain due to load application. The change in strain of a structural element can be converted to the change in electrical resistance of the strain gauge. However, this change in resistance is very small. In order to measure the change in resistance of strain

gauges this should be converted to the change in voltage signal, then the signal is amplified, and finally the strain values will be recorded by the datalogger.

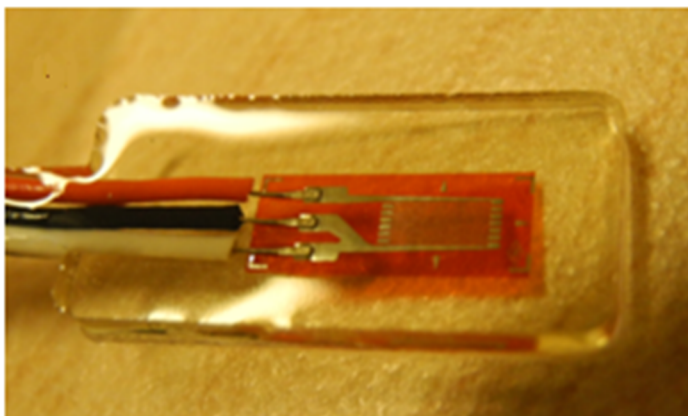


Figure 4-29 The quarter strain gauges

4.4.2 The AM16/32B Multiplexer

As it mentioned to read data total of 20 strain gauges (26 sensors) remained, so 13 input channels were required to connect all wires. However, the CR1000 had only 1 available input channel, the rest being used for the sunlight energy collection measurements. Hence the AM16/32B Relay Multiplexer installed to wire in all the strain gauges with one output channel to link to the Data logger. The device multiplexes 16 groups of four lines (a total of 64 lines) through four common (COM) terminals. Alternatively, a manual switch setting allows the AM16/32B to multiplex 32 groups of two lines (also on a total of 64 lines) through two COM terminals. In this project, the model is 2×32, and the COM ODD is used to connect to the 2 channel of datalogger.

In order to connect all wires to the multiplexer, two quarter-bridge strain gauges which installed at the same position but in front and back surface of solar panel were connected

together. This run by connecting the high signal wire (red wires) of the two sensors and connecting the low signal wires (black wires) and the ground (transparent cover wire) to the multiplexer, in order to form a half strain bridge. The white color wire was jumped with the black wire from fabrication; hence using just one of them for connecting to the multiplexer, would suffice. The same procedure considered with two biaxial strain gauges to make full bridge strain gauge. Figure 4-30 (b) shows how strain gauges connect to a AM16/32B Relay Multiplexer.

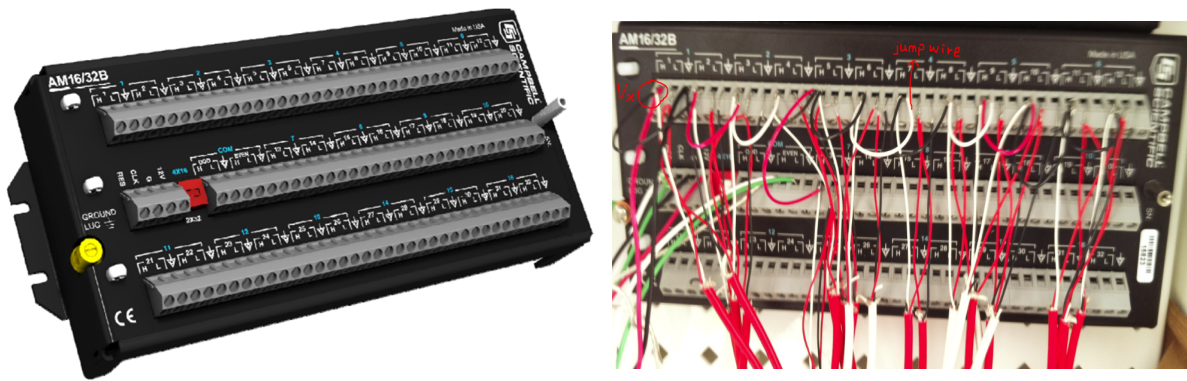


Figure 4-30 The AM16/32B Relay Multiplexer a)input panel [35] b) wired with strain quarter bridge gauges

4.4.3 CR1000 Measurement and Control Datalogger

The CR1000 datalogger divides to two main parts; one a measurement and control module and second wiring panel where uses an external keyboard/display and AC power supply. The Low consumption of energy and a battery which recharged AC power produced by a solar panel prepare this ability for data logger to operate for long period of time. The datalogger was programed to read the 26 strain sensors connected to the multiplexer, with a

time lag of 2 minutes each, so that the data incoming from the 32 channels of the multiplexer can be performed only through the reading of 1 input channels on the datalogger.

Totally, the accuracy of measurement is increased by a stop in operation when the primary power drops below 9.6V. It was noted by Campbell Scientific, INC that the CR1000 operates from a power supply with voltage ranging from 9.6 to 16 Vdc, and is internally protected against accidental polarity reversal [36]. In addition, the temperature compatibility of measurement noticed by the company where the standard operating is between -25° to $+50^{\circ}$ C and abled to extend to the range of -55° to $+85^{\circ}$ C.



Figure 4-31 The CR1000 Measurement and Control Datalogger [36]

Chapter 5: Data calibration; FEM simulation and

Experiment data

The complex dynamic behavior of wind load is function of various parameters such as site condition, temperature, wind speed, geometry of structure and many of other factors. This could be more complicated with respect to the lightweight and large contact area of PV solar structure. Simultaneously, this could be extreme where an inclined solar system installed in northern hemisphere faced to northern wind flown from behind.

According to description of wind flow characteristic where it meets the edge side of building , with respect to the parapet and building height the reattachment point located about twice of the building height where separated wind flow comes down and beyond this point wind flows almost parallel to the roof surface. The site of specimen mounted on roof top of Mann Parking located far from the northern edge of the building, which prepares particular condition of wind flow characteristic that it is not behave exactly same as what behind reattachment zone . However, due to difficulty of study for such case, the angular components of wind flow neglected and assumed that wind flown parallel to the roof surface. Therefore, extreme nominal drag and lift components of wind force attacked from backside of PV solar system simultaneously. Although this flow type could apply the most powerful drag force to the specimen, the lift force could be more complex and powerful where the specimen mounted at the zone that Delta Wing vortex applies which it is not the case of this study.

To study on the mentioned case the drag and lift force computed with respect to the whether characteristic, plus the specimen modeled with FEM software CSi SAP 2000 as much accurate as it was possible. Meanwhile, the solar panel instrumented with 26 strain gauges to measure the displacement and influence of open wind load on specimen at particular mentioned condition. Afterwards, it needs to apply the computed load and compare the results with the values measured by the datalogger.

5.1. Finite Element Simulation

The procedure FEM modeling of PV solar system described in chapter 4, which two different frames with respect to the place they worked plus 5 layers solar panel assembled with pin and fix connection instead of washers and screws. Meanwhile, the advantages of three Rod, Link and Equal commands were taken to model connection between support structure and frame surrounding the solar panel. Finally, four fully fixed supports considered to transfer distributed load from structure to the attached roofing system.

According to the second section, the various parameters influence the wind load described step by step to compute the applied load on different members depend on whether they are located at the sheltered area or not. All parameters recorded for each minute to graph large data of wind load for drag and lift components of each member induced wind flow for two month of January and February. This type of load computation versus time, caused to do the Static, Modal and Time History Non-Linear Modal Analysis to figure out the most suitable case with the most accurate results.

5.1.1 Static Analysis

As it mentioned previously one procedure to compute the displacement of PV solar system induced wind load is the static analysis where run for the load applied to system within January and February. With respect to the table 4-7 about the maximum wind load, the drag and lift components of wind load need to apply in particular direction.

To do this it needs to apply the maximum load to each member uniformly with respect to sheltered area provided by different members. According to the section 4.2.3 the lift force applied to all member except the multilayer solar panel is equal to zero. Moreover, the drag component of wind load applied to member number 3 and 6 considered equal to nothing due sheltered area provided by member number 1 and 2 respectively. The same condition considered for member 4 that sheltered by number 1 where wind reaches to the PV solar system from the backside. The figure 5-1 shows the particular location of different elements used to install PV solar panel.

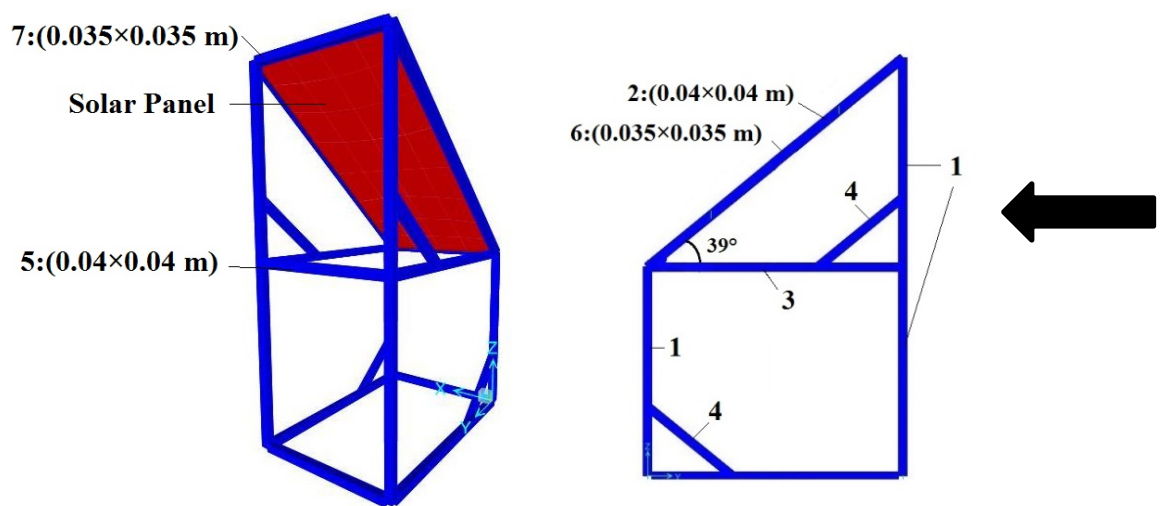


Figure 5-1 Different members used to install PV solar system

Although the wind flow reattached after separation occurs by vertical column stands in front, the horizontal direction of third member plus the small length of member number 4 is other points considered for drag force elimination. The same considerations need to apply for number 2 but due to the length and angle of this member, the relative drag component of wind load applied. The figure 5-2 shows how the uniform drags and lift components of wind load applied to the specimen.

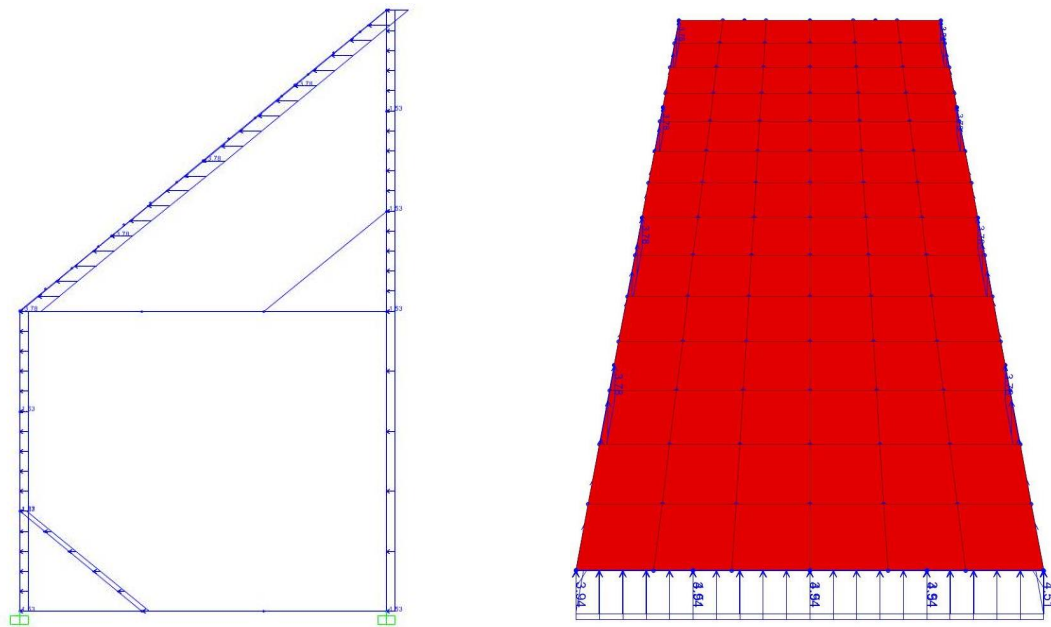


Figure 5-2 Uniform drags load application to the model

The next assignment need to be considered is the temperature application. With respect to the study conducted in chapter 3, the significant vulnerability of solar panel on negative temperatures proven. Therefore, according to the data collected within two months the average temperature equal to -7°C applied to the model as uniform load to all members and materials. For this assignment, the first procedure was introducing the temperature characteristics of all

materials. Hence, the advantages of Frames material temperature and Area material temperature commands were taken to apply 20° C to all elements and materials.

Finally, a linear load combination that consist dead load from the weight of structure and the equivalent static wind load defined to the software. Afterwards, the FEM software run for 5mm mesh size with respect to the 12 different cases depend on type of connection and joint. The table 5-1and 5-2 summarized the load application on each element and the maximum displacement computed by CSi-SAP 2000 respectively where the F_D stands for drag and F_L for lift components of wind load.

Table 5-1 Drag and lift components of wind load applied to different elements for January and February

January 2014	5-layers solar panel	1	2	3	4	5	6	7
Lift component (N)	50.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Drag component (N)	27.25	2.04	5.06	0.00	1.70	6.05	0.00	5.28

February 2014	5-layers solar panel	1	2	3	4	5	6	7
Lift component (N)	37.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Drag component (N)	20.34	1.53	3.78	0.00	1.27	4.51	0.00	3.94

Table 5-2 Maximum Displacement (Unit: m) computed by CSi-SAP 2000 with respect to Linear Static Analysis for 12 different models under January and February load application

Month	Fix-Equal	Pin-Equal	Fix-Link	Pin-Link	Fix-Rod	Pin-Rod
	0.001	0.002	0.091	0.098	0.063	0.336
January	0.001	0.002	0.025	0.070	0.063	0.308
February	0.001	0.002	0.025	0.070	0.063	0.308

Table 5-2 illustrates the maximum displacement computed regard to different simulations of models that takes advantages of pin and fix connection for frames, and Equal, Link and Rod constrain instead of screws to connect support structure to surrounding frame of solar panel.

According to the table 5-2, Fix connections and Equal options, exhibits the least value of displacement equals to 1.4 mm. Numerous factors could influence the behavior of PV solar structure form temperature and stiffness of different members to the accuracy of modeling. Therefore with respect to the maximum values of displacement computed regard to the effect of temperature and uplift load described in chapter 3, 2.24 mm and 1.68 mm displacement for the Pin-Equal type of modelling seems to be more accurate values that are for January and February respectively. It is caused due to very small distance between support structure and surrounding frame of solar panel (2mm) the screw used to connect tends to behave more fix rather than as pin support. Therefore, the Rod joist with idea of load distribution along one direction did not provide the sufficient accuracy looking for. Figures 5-3 and 5-4 show how PV solar system deformed regard to Fix-Equal connections-joints installation for January and February 2014. The rest of the figures are attached at the appendix A subsection Static Analysis Simulations.

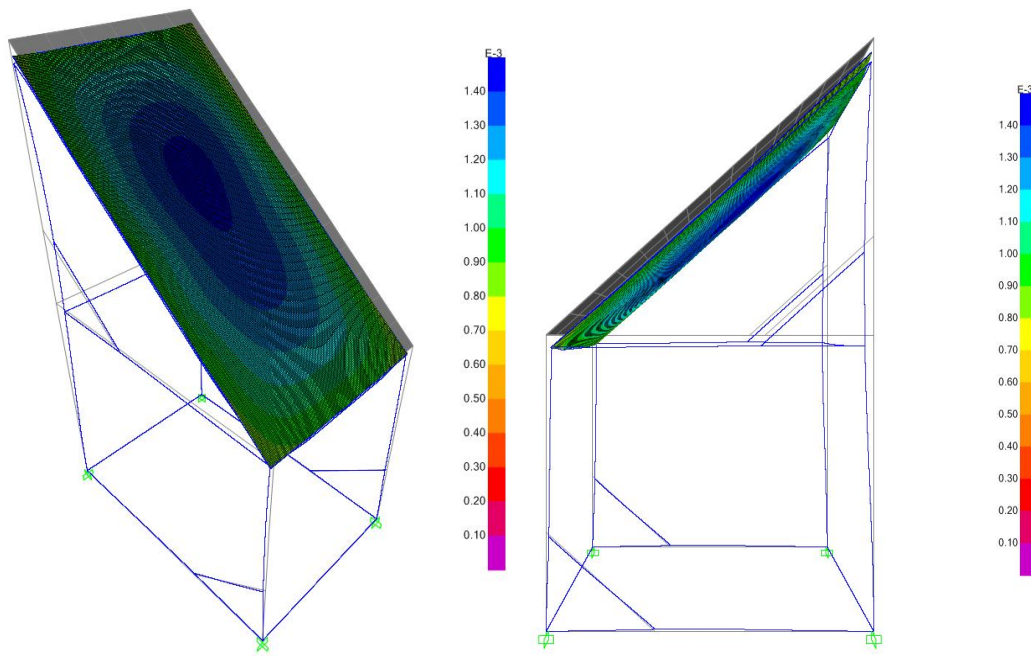


Figure 5-3 Amplitude of displacement variation according to Fix-Equal connections-joints installation analyzed statically for January 2014 load application

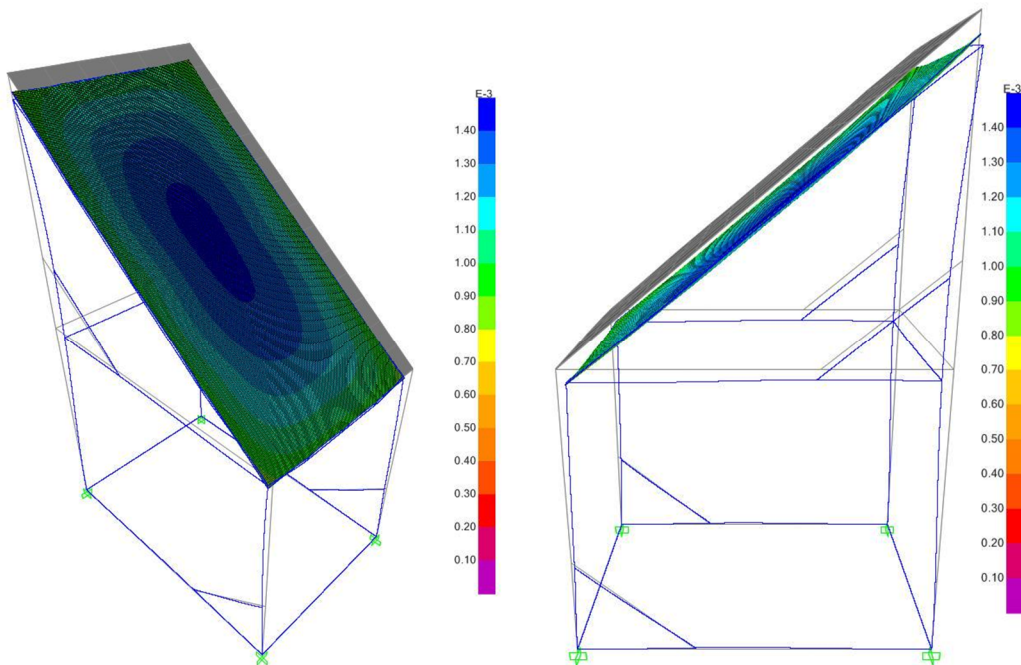


Figure 5-4 Amplitude of displacement variation according to Fix-Equal connections-joints installation analyzed statically for February 2014 load application

5.1.2 Modal Analysis

In the Static analysis most of basic parameters defined to analyze the behavior of structure, however one more case need to be consider which is the vibration modes of a structure. Due to the unpredictable and random vibration made by wind load with respect to hundreds of changing direction within a stream, different modes of structure need to be analyzed for better understanding of the behavior of structure. The advantages of linear modal analysis were taken to determine vibration modes of structure.

To study on different modes the FEM software SAP 2000 use two types of modal analysis, Eigenvector and Ritz-vector. “Eigenvector analysis determines the undamped free-vibration mode shapes and frequencies of the system. These natural modes provide an excellent in-sight into the behavior of the structure. Ritz-vector analysis seeks to find modes that are excited by a particular loading. Ritz vectors can provide a better basis than do eigenvectors when used for response-spectrum or time-history analyses that are based on modal super position” CSI Analysis Reference Manual page 230[37]. However, due to the ability of the software to prepare any algorithm at Ritz-vector analysis only for link connection, it is preferred to choose Eigenvector analysis with advantages of Static correction-modes.

The Static correction-modes are a group of static solution of the particular load that could be very important for getting accurate response at stiff supports. According to the hydrodynamic loading of thin structure it is mentioned by Fitch that “the use modal method without static correction can lead to substantial errors in frequency, amplitude and character of the structural response” page 9 [38]. Therefore, the Rayleigh quotient method advantages

were taken to calculate a frequency which assigned to Static correction-mode by FEM Software.

The generalized Eigen value solution before static correction application relied on equation 5-1[37]:

$$[K - \Omega^2 M]\Phi = 0 \quad (5-1)$$

[K] : Stiffness matrix

[M] : Diagonal mass matrix

$[\Omega^2]$: Diagonal matrix of Eigen values

$[\Phi]$: Mode shape

Where the square of the natural circular frequency, ω , considered as Eigen-value and the cyclic frequency, f , and period, T , of the Mode are related to ω by [37]:

$$T = 1/f \quad (5-2)$$

$$f = \omega/2\pi \quad (5-3)$$

According to the type of analysis (Eigen Vector), the natural behavior of structure studied with respect to the weight of structure only. Therefore, the FEM software run for the first 20 modes of with respect to 5 mm mesh size and 12 different cases depend on type of connections and joints. Table 5-3 shows the maximum displacement of first mode of different types of simulation. Same as static analysis the value shown under Equal case determined more reasonable value particularly in the Fix-Equal type of connection that with the same tend as static analysis shows least value of displacement for first mode of analysis.

Table 5-3 Maximum Displacement (Unit: m) computed by CSi-SAP 2000 with respect to Linear Modal Analysis for 12 different models of first mode under January and February load application

Month \ Joints & Frame connections	Fix-Equal	Pin-Equal	Fix-Link	Pin-Link	Fix-Rod	Pin-Rod
January	0.025	0.126	0.027	0.196	0.056	0.063
February	0.025	0.126	0.027	0.196	0.056	0.063

In the opposite side of static analysis, a model with Pin-Equal connections shows significant values of displacement rather other cases that could be cause of large displacement in the pin connection between members in support structure. However, the maximum value of displacement goes to Pin-Link case. With brief look at the relative figures of first mode of analysis, it is clear that the Link command, which provide a degree of freedom in Z direction could not simulate the accurate behavior of specimen, induced wind load. Rod joint shows more moderate values for first mode of analysis rather the value gained in Static Analysis section. However, taking advantages of automatic introduction of degree of freedom to FEM software did not yield to accurate behavior of model particularly in the case of how solar panel deformed or displaced in first mode of analysis. The incompatible behavior of model to real specimen appears in first mode of Fix-Link case where it seems the PV panel move .Figures 5-5 and 5-6 show how PV solar system deformed regard to Fix-Equal connections-joints installation for January and February 2014. The rest of figures attached at the appendix A subsection of First Mode of Modal Analysis.

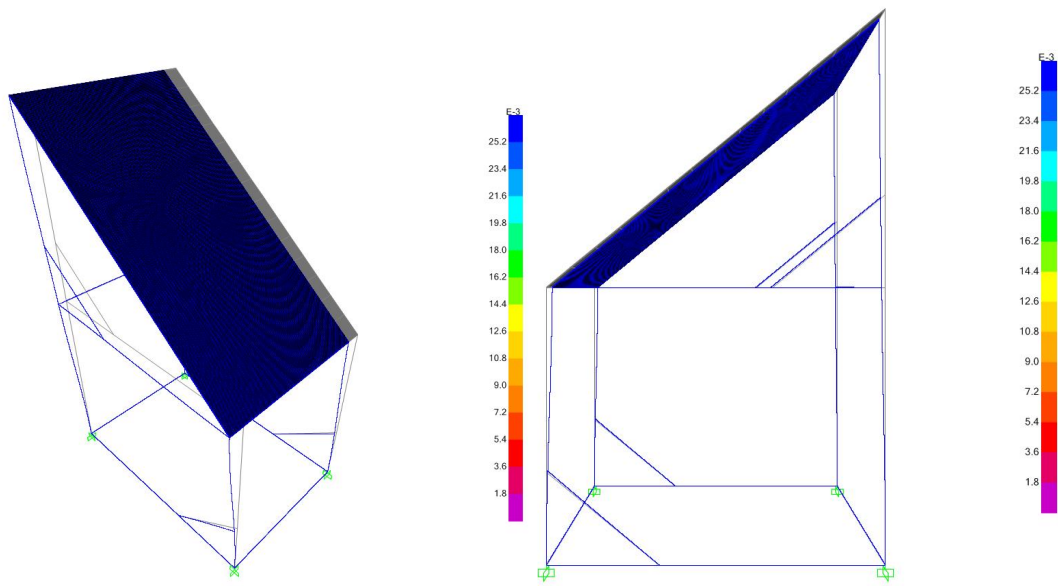


Figure 5-5 Amplitude of displacement variation according to Fix-Equal connections-joints installation analyzed by Linear Modal Analysis for January 2014 load application

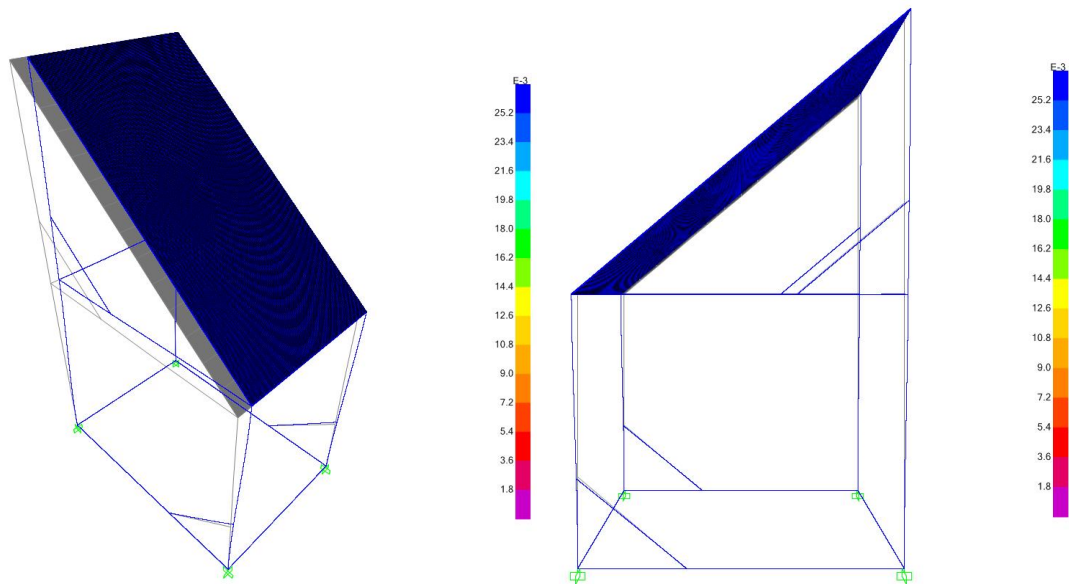


Figure 5-6 Amplitude of displacement variation according to Fix-Equal connections-joints installation analyzed by Linear Modal Analysis for February 2014 load application

5.1.3 Nonlinear Direct-Integration Time-History Analysis

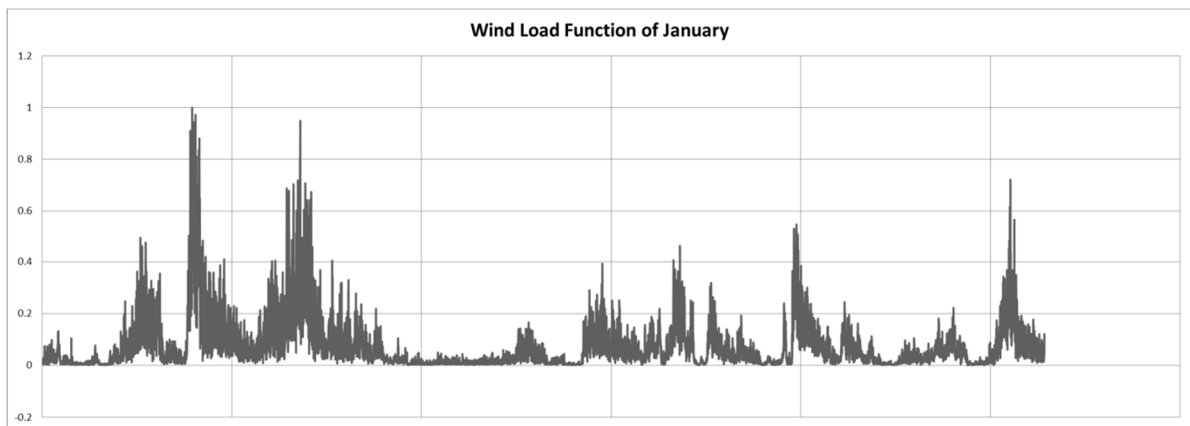
According to the section 4.2.3, the variation of drag and lift components of wind load with respect to the time lag of 60 seconds for each member computed. However the same procedure of load application such as what described in Static and Static Modal Analysis for each particular member depends on whether it placed at sheltered area or not considered , the most important difference is how this load applied to the model and what was the dynamic response of the structure to arbitrary loading.

Based on the section 5.1.2, when the wind load applies to any structure it produces a vibration that caused to different modes and respectively different response. However these considerations presented for one type of loads before, it needs to apply all loads recorded each 60 seconds. It is shown before that the application force on any structure produced by a wind stream, is a function various parameters such as contact area and direction of element stands in front. In opposite side, by elimination of geometric criteria and with respect to weather parameters such as temperature, density, wind speed and the flow direction, the wind load forced the system with unique load distribution for a portion of time.

The mentioned uniqueness is the main concept of preparing a function of wind load behavior based on record data for each one minute. It means there was a function of stream with respect to the period that data recorded, which described the variation of wind load distribution. This function helped to distribute more accurate wind load on each member that caused to increase the accuracy of dynamic analysis according to particular period. To compute the function of flow the drag and lift components of wind load applied to each member divided by the maximum respective component's value within all period of time. This means that the

function wind stream was in the range of nothing to one for every minute. The advantages of time history command were taken to introduce the function of wind load to the program. The table 5-4 summarize of load function computation which attached to the figure 5-7 (a, b) that shows the scattering of periodic wind load function for January and February.

a)



b)

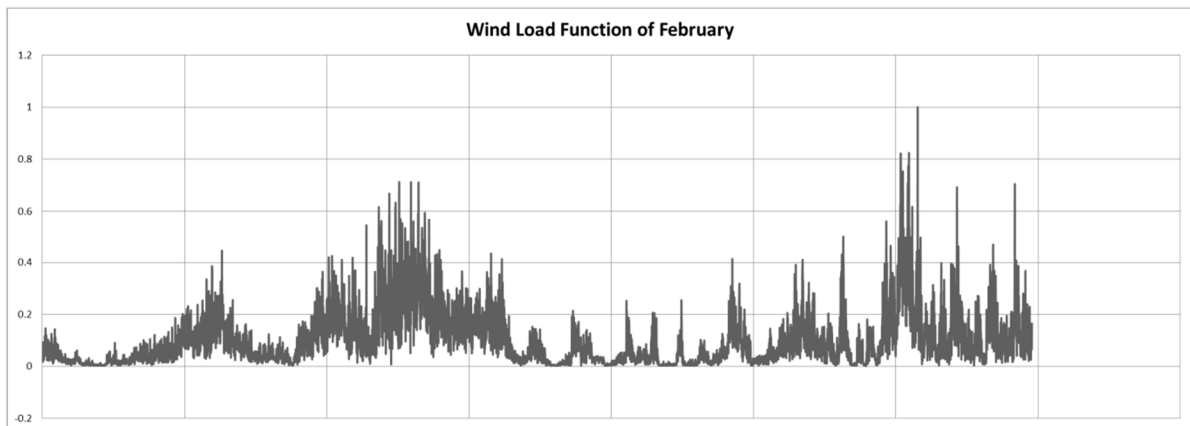


Figure 5-7 Amplitude of a variable wind load function with respect to the particular period of time on a) January 2) February

Table 5-4 The Wind load function for different members of PV solar structure-
January2014

Load Function									
Time	F _{Ds}	F _{Ls}	F _{D1}	F _{D2}	F _{D3}	F _{D4}	F _{D5}	F _{D6}	F _{D7}
60	0.02083	0.02083	0.02083	0.02083	0	0.02083	0.02083	0	0.02083
120	0.00612	0.00612	0.00612	0.00612	0	0.00612	0.00612	0	0.00612
180	0.00646	0.00646	0.00646	0.00646	0	0.00646	0.00646	0	0.00646
240	0.00544	0.00544	0.00544	0.00544	0	0.00544	0.00544	0	0.00544
300	0.01454	0.01454	0.01454	0.01454	0	0.01454	0.01454	0	0.01454
360	0.00802	0.00802	0.00802	0.00802	0	0.00802	0.00802	0	0.00802
420	0.00659	0.00659	0.00659	0.00659	0	0.00659	0.00659	0	0.00659

The FEM software multiplied the load function to the maximum load applied on each member that computed for relative month for any time step (Table5-1). This maximum load applied to any member of the PV solar structure same as what did in the static analysis procedure (Figure 5-2). Another load pattern need to assign to the model was the dead load produced by the weight of the structure. A linear load combination which consist dead load from the weight of structure plus Time History Non-Linear produced by wind load, introduced to the software to analyze the behavior and different modes.

Another important parameter need to be defined to run the analysis was the nonlinearity. According to the CSI Analysis Reference Manual pages 412-413[37] the nonlinearity types considered by the software classified to Material and Geometric nonlinearity. The former types considered for nonlinear Link or Support elements, limits in Tension and compression of Frame elements plus the existence of Plastic hinges. The latter focused on effect of P-Delta and large displacement.

Various methods could employ to study on Nonlinear Direct-Integration Time-History Analysis. However, the advantages Hilber-Hughes-Taylor alpha (HHT) method suggested to be taken by CSI Analysis Reference Manual CSI Analysis Reference Manual at page 370 and

noted that “The HHT method uses a single parameter called alpha. This parameter may take values between 0 and -1/3. Using alpha: 0 offers the highest accuracy of the available methods, but may permit excessive vibrations in the higher frequency modes, i.e., those modes with periods of the same order as or less than the time-step size. However, it is often necessary to use a negative value of alpha to encourage a nonlinear solution to converge”. The convergence of equilibrium influenced the large displacement analysis significantly that the closer value of alpha to zero could made some errors in the computation even it is mentioned the highest accuracy prepared by the zero value of alpha. To solve this problem the FEM software sap prepared a command of Line-Search Control which influenced on better convergence behavior that leads to better determine the optimum displacement [37]. This command prepared a trial and error procedure regards to the default tolerance of software Step Factor to find large displacement incrementally.

Finally, the Hilber-Hughes-Taylor alpha (HHT) method with alpha equal to zero, plus the Line-Search Control employed to run the Nonlinear Direct-Integration Time-History Analysis to compute different parameters of behavior. Table 5-5 illustrates the maximum displacement computed regard to different simulations of models that takes advantages of pin and fix connection for frames, and Equal, Link and Rod constrain instead of screws to connect support structure to surrounding frame of solar panel.

Table 5-5 illustrates the maximum displacement computed regard to different simulations of models that takes advantages of pin and fix connection for frames, and Equal, Link and Rod constrain instead of screws to connect support structure to surrounding frame of solar panel. Same as previous analysis the least displacement goes to Fix-Equal case where the maximum displacement is 1.54 mm. However, the value of displacement for Pin-Equal case

for both month increases by 0.2 mm that is not significant value, although it could be more reasonable. In the opposite side, both Pin-Rod and Fix-Rod cases of simulation show very large unreasonable values of displacement. Finally, the displacement values for both link cases on each month are remarkably close to equal case which shows this type of connection could be consider as a scenario of modeling however the first mode of modal analysis showed different idea.

Table 5-5 Maximum Displacement (Unit: m) computed by CSi-SAP 2000 with respect to Linear Static Analysis for 12 different models under January and February load application

Month \ Joints & Frame onnections	Fix-Equal	Pin-Equal	Fix-Link	Pin-Link	Fix-Rod	Pin-Rod
January	0.00154	0.00168	0.00210	0.00308	0.39200	0.39200
February	0.00154	0.00168	0.00210	0.00308	-0.23400	0.39200

Figures 5-8 and 5-9 show how PV solar system deformed regard to Fix-Equal connections-joints installation for January and February 2014. The rest of figures attached at the appendix A subsection of Nonlinear Direct-Integration Time-History Analysis.

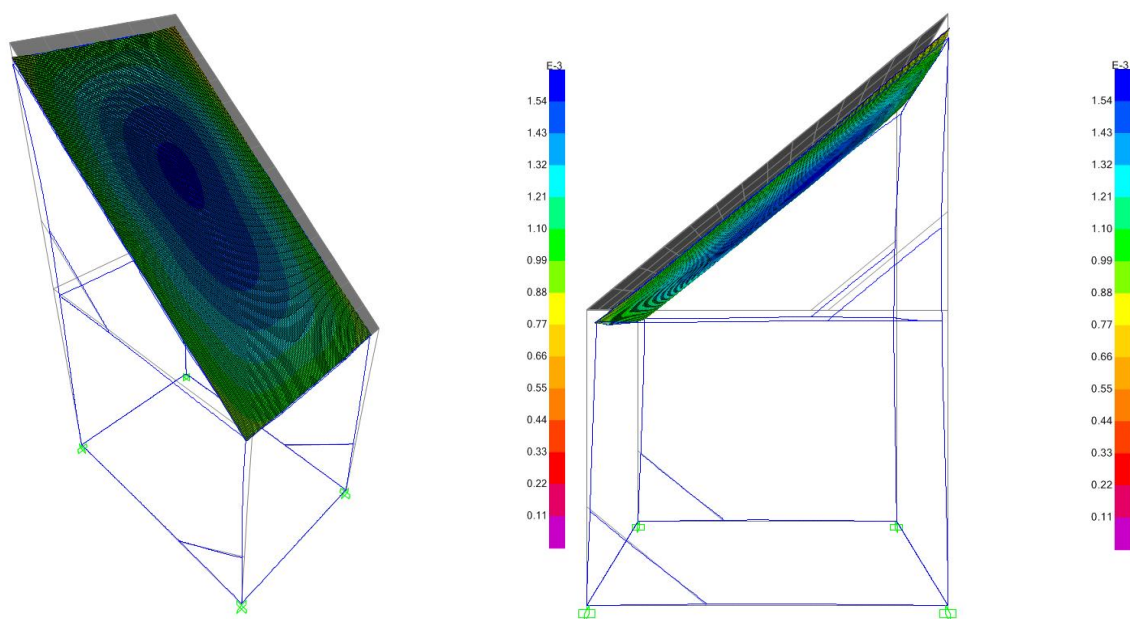


Figure 5-8 Amplitude of displacement variation according to Fix-Equal connections-joints installation analyzed by Nonlinear Direct-Integration Time-History Analysis for January 2014 load application

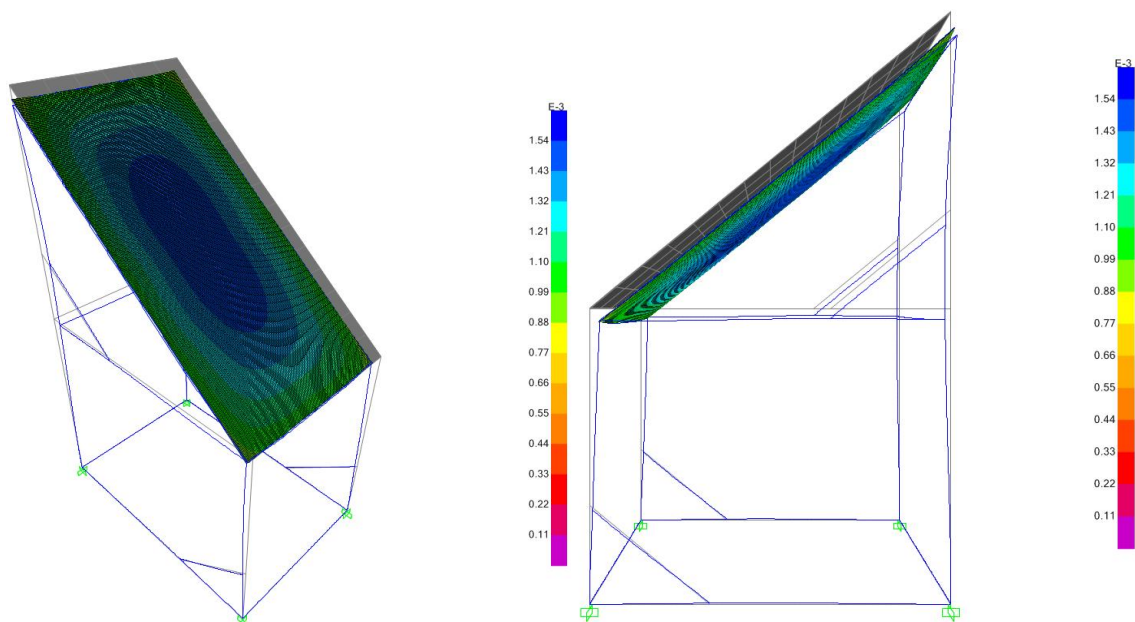


Figure 5-9 Amplitude of displacement variation according to Fix-Equal connections-joints installation analyzed by Nonlinear Direct-Integration Time-History Analysis for February 2014 load application

5.2 Data measurement, Strain computation

According to the objective section, this study conducted to compare data computed by FEM simulation and data collected from instrumented specimen mounted at the rooftop of Mann parking at the University of Ottawa. With respect to the different weather characteristic and geometric conditions 36 models for two month of January and February simulated to find the most compatible model to computed strain based on measured electrical resistance.

As it mentioned in forth chapter, the specimen instrumented with twenty 120 Ω WFLA-3-11 strain gauges (26 sensors) were placed in the center cross line of solar panel at equal distance of about 26.8 cm starting from both ends along the shorter side. They were connected to the datalogger through the multiplexer where all wires connected together and plugged to one input channel of datalogger that programed for 26 sensors through 13 lines with data time lag of 2 minutes with the accurate measurement. The accuracy of measurement is increased by a stop in operation when the primary power drops below 9.6V and extend the temperature compatibility to the range of -55° to +85° C where the standard operating is between -25° to +50° C.

Finally, the advantages of accurate measured data taken to compute the strain at the point of installation. However, before reading any data some calibration such as temperature effect upon the length of the wire, resistance induced by the lead wire and the gauge factor influenced by the sensor – wire attachments recommended by the instrumentation specifications [39]. The most important calibration went the changes in gauge factor due to the wiring of specimen.

5.2.1 Gauge factor calibration

Calibration of gauge factor was required to account number of parameters, such as length of lead wires and resistance of the strain gauge and lead wires. However the variation of temperature influenced the behavior of signal transfer, it was suggested by instrumentation specifications that by using quarter bridge with 3-wire system the unexpected effect of resistance change with temperature eliminated [40]. Therefore, the specification and length of leading wire and strain gauge considered to calibrate gauge factor.

The datalogger connected to 120 Ω WFLA-3-11 strain gauges by 5 meters 7/0.12 (number of cores/diameter) leading wire with the total resistance 0.44 Ω per meter. The total resistance in lead wire was 0.44 $\Omega/m \times 5m$: 2.2 Ω that was significant enough to influence the strain gauge signal. The equation 5-4 [39] determines the calibrated gauge factor with respect to the value equal to 2.1 employed in calculation as primary factor of strain gauge recommended by the producer [40].

$$K_0 = \frac{R}{R + \frac{r \times L}{2}} \times K \quad (5-1)$$

Where

r : Total resistance per meter of lead wires (Ω/m)

L : Length of lead wires (m)

K : Gauge factor

R : Gauge resistance

K_0 : Corrected gauge factor

By applying the respective values of each parameter to the equation the corrected gauge factor equal to 2.081 calculated.

$$K_0 = \frac{R}{R + \frac{r \times L}{2}} \times K = \frac{120\Omega}{120\Omega + \frac{0.44\Omega/m \times 5m}{2}} \times 2.10 = 2.081$$

5.2.2 Strain computation

According to section 2.3.3, a strain gauge is able to measure very small strain placed in a specimen with electrical resistance. “To measure such small changes in resistance, strain gauges are almost always used in a bridge configuration with a voltage excitation source.” [41] This voltage (V_x) applied to strain gauge and let the system records return voltage (V_r). Any changes in return voltage illustrate a change in strain value that needs to be compute with respect to type of strain gauge mounted on the surface of specimen. According to the type of instrumentation and experiment, a fractional of change in voltage [42] recorded for every 2 minutes time lag that called source zero.

According to the type of installation of strain gauges on the bottom and top face of solar panel, two quarter bridge strain gauges connect together one gauge parallel and the other normal to strain to provide more accurate result. This type of connection prepares a particular half bridge strain gauge that needs to consider in computation. Regard to the particular half bridge strain gauge, instrumentation specifications [42] provides the equation 5-2 to compute micro strain value.

$$\mu\varepsilon = \frac{-4 \times 10^6 \times V_r}{GF [(1+\nu) - 2V_r(1-\nu)]} \quad (5-2)$$

Where

$\mu\epsilon$: Micro strain

V_r : - 0.001×Source-Zero

GF : Gauge factor (corrected gauge factor need to consider $K_0 = 2.081$)

ν : Poisson's Ratio of strain gauge (it would be zero if not applicable)

As it mentioned previously with respect to the type of instrumentation (half bridge strain gauge where one is gauge parallel and the other normal to strain) plus the instrumentation specifications of datalogger [42] the source zero value computed by fraction of voltage of first gauge over second gauge. This value multiplied by -0.001factor to compute V_r .

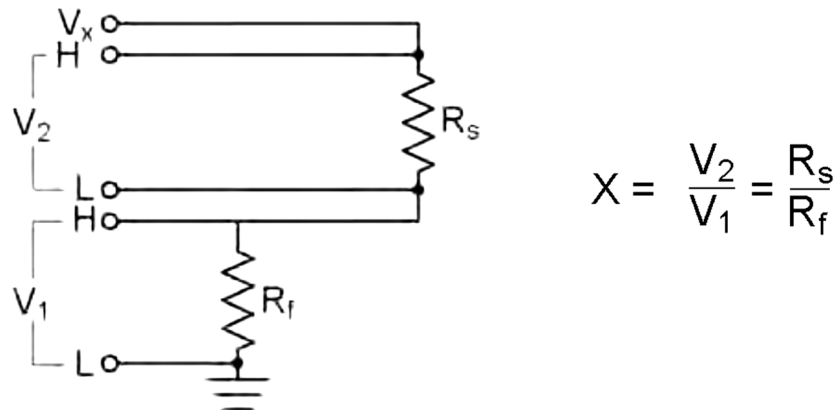


Figure 5-10 4 Wire Half Bridge strain gauge and respective source zero fraction value [42]

The corrected gauge factor that computed previously and zero value for poison's ratio of strain gauge (lack of applicability) employed to compute the value of micro strain of 13 strain gauges for every 2 minutes. The following mathematical procedures run to show how to approach to strain for one half bridge strain gauge at first two minutes where source zero value is equal to 0.493.

$$x = \frac{v_2}{v_1} = 0.4940582 \text{ So } V_r = -0.001x = -493 \times 10^{-6}$$

$$\mu\varepsilon = \frac{-4 \times 10^6 \times V_r}{GF [(1+v) - 2V_r(1-v)]} = \frac{-4 \times 10^6 \times -493 \times 10^{-6}}{2.081 [(1+0) - 2 \times -493 \times 10^{-6}(1-0)]} = 948.07$$

Table 5-6 The procedure of computation of micro strain measured by 13 strain gauges in February

Time period	Source Zero (BrHalf Resistive Bridge Circuits) $x=(v_2/v_1)$												
	1	2	3	4	5	6	7	8	9	10	11	12	13
2/4/2014 11:22	0.49372	0.49291	0.49291	0.49318	0.49237	0.49237	0.49183	0.49196	0.49183	0.49237	0.4925	0.49237	0.49291
2/4/2014 11:24	0.49372	0.49291	0.49318	0.49318	0.49237	0.49237	0.49183	0.4921	0.49183	0.49237	0.49264	0.49237	0.49318
2/4/2014 11:26	0.49372	0.49291	0.49318	0.49318	0.49237	0.49237	0.49183	0.4921	0.49183	0.49237	0.49237	0.49237	0.49318
2/4/2014 11:28	0.49372	0.49291	0.49304	0.49318	0.49237	0.4925	0.49183	0.4921	0.49183	0.4925	0.4925	0.49237	0.49318
2/4/2014 11:30	0.49385	0.49291	0.49318	0.49318	0.49237	0.49237	0.49183	0.4921	0.49183	0.49237	0.49237	0.49237	0.49318
2/4/2014 11:32	0.49385	0.49291	0.49318	0.49318	0.49237	0.49237	0.49183	0.4921	0.49183	0.4925	0.4925	0.49237	0.49318
2/4/2014 11:34	0.49399	0.49291	0.49318	0.49318	0.49237	0.4925	0.49183	0.4921	0.49183	0.4925	0.4925	0.49237	0.49318
2/4/2014 11:36	0.49399	0.49291	0.49304	0.49318	0.49237	0.4925	0.49183	0.4921	0.49183	0.49264	0.49264	0.49237	0.49318
Time period	Source calibration factor $v_r = -0.001x$												
	1	2	3	4	5	6	7	8	9	10	11	12	13
04/02/2014 11:22	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049
04/02/2014 11:24	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049
04/02/2014 11:26	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049
04/02/2014 11:28	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049
04/02/2014 11:30	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049
04/02/2014 11:32	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049
04/02/2014 11:34	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049
04/02/2014 11:36	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049	-0.00049
Time period	$GF=2.081, v=0$ Micro Strain $\mu\varepsilon = \frac{-4 \times 10^6 \times V_r}{GF [(1+v) - 2V_r(1-v)]}$												
	1	2	3	4	5	6	7	8	9	10	11	12	13
04/02/2014 11:22	948.07	946.51	946.51	947.03	945.48	945.48	944.44	944.70	944.44	945.48	945.73	945.48	946.51
04/02/2014 11:24	948.07	946.51	947.03	947.03	945.48	945.48	944.44	944.96	944.44	945.48	945.99	945.48	947.03
04/02/2014 11:26	948.07	946.51	947.03	947.03	945.48	945.48	944.44	944.96	944.44	945.48	945.48	945.48	947.03
04/02/2014 11:28	948.07	946.51	946.77	947.03	945.48	945.74	944.44	944.96	944.44	945.74	945.74	945.48	947.03
04/02/2014 11:30	948.33	946.51	947.03	947.03	945.48	945.48	944.44	944.96	944.44	945.48	945.48	945.48	947.03
04/02/2014 11:32	948.33	946.51	947.03	947.03	945.48	945.48	944.44	944.96	944.44	945.74	945.74	945.48	947.03
04/02/2014 11:34	948.59	946.51	947.03	947.03	945.48	945.74	944.44	944.96	944.44	945.74	945.74	945.48	947.03
04/02/2014 11:36	948.59	946.52	946.77	947.03	945.48	945.74	944.44	944.96	944.44	946.00	946.00	945.48	947.03

5.3 Data Calibration

According to section 5.1, Finite Element models employed for different linear and nonlinear methods to study on the behavior of models for each particular type of connections and joints. In addition, particular static and functional load application considered with respect to type of analysis for each months. Moreover, the effect of extreme weather applied on model with an average value for both months. This significant effect studied previously in chapter 3 for solar sandwich induced nominal uplift load that caused to generalize the mentioned effect for inclined model.

In the parallel scenario, it is mentioned that a real specimen instrumented with strain gauges and controlling systems. The advantages multiplexer as a terminal and datalogger as precision tool were taken to read any electrical change in resistance caused by elongation or shrinkage. For more accurate result and regard to type of installation of strain gauges, some calibrations and equation recommended in instrumentation specifications to apply in the computations.

Finally, displacement and strain values for both scenarios need to calibrate together to figure out what is the best type of modeling with respect to particular conditions of govern in experiment and modelling. According to different definitions of displacement and strain value, it is needed to figure out a reasonable relevance between different models and value measure by precision tools. Therefore, the idea of stress distribution along member discussed to figure out the most match model with the measured stress along the solar cell.

According to particular installation of strain gauges on top and bottom surface of PV solar panel, each face divided to 21 equal areas to study on stress distribution (Section 4.4).

One strain gauge installed at midpoint of bottom and top surface each patch. Therefore, the procedure of strain measurement and computation for 13 half-bridge strain gauges is mentioned in section 5.1.2 where 13 strain value read for each two minutes. Regard to the very tiny value of measured strain the Hook's law ($\sigma = E \times \mu\epsilon$) should be compatible to the case of study. Therefore, the uniform value Young's modulus (E) of solar wafer ($E = 53.48 \times 10^9$) that computed in the section 3.1.2 applied to the equation for each specific strain gauge with 2 minutes time lag. Table 5-7 describes the value of stress variation (unit: Pascal) within each 2 minutes for 13 strain gauges. Due to mechanical Issues between at February 7th 10th to 13th February data did not record. Figures 5-9 and 5-10 show the periodic scattering of stress distribution on January and February for half bridge strain gauges number 7 and 8 at the midpoint of solar wafer. The rest of figures attached at the appendix B subsection of Stress distribution.

Table 5-7 Distributed Stress along each area, measured by respective strain gauge

Time period	Stress Distribution (Pa) $\sigma = E \times \mu\epsilon$					
	1	2	3	4	5	6
04/02/2014 11:22	5.070E+07	5.062E+07	5.062E+07	5.065E+07	5.056E+07	5.056E+07
04/02/2014 11:24	5.070E+07	5.062E+07	5.065E+07	5.065E+07	5.056E+07	5.056E+07
04/02/2014 11:26	5.070E+07	5.062E+07	5.065E+07	5.065E+07	5.056E+07	5.056E+07
04/02/2014 11:28	5.070E+07	5.062E+07	5.063E+07	5.065E+07	5.056E+07	5.058E+07
04/02/2014 11:30	5.072E+07	5.062E+07	5.065E+07	5.065E+07	5.056E+07	5.056E+07
04/02/2014 11:32	5.072E+07	5.062E+07	5.065E+07	5.065E+07	5.056E+07	5.056E+07
04/02/2014 11:34	5.073E+07	5.062E+07	5.065E+07	5.065E+07	5.056E+07	5.058E+07
04/02/2014 11:36	5.073E+07	5.062E+07	5.063E+07	5.065E+07	5.056E+07	5.058E+07

Time period	Stress Distribution (Pa) $\sigma = E \times \mu\epsilon$						
	7	8	9	10	11	12	13
04/02/2014 11:22	2.560E+09	2.560E+09	2.557E+09	2.557E+09	2.557E+09	2.560E+09	2.560E+09
04/02/2014 11:24	2.561E+09	2.561E+09	2.558E+09	2.560E+09	2.558E+09	2.561E+09	2.562E+09
04/02/2014 11:26	2.561E+09	2.561E+09	2.558E+09	2.560E+09	2.558E+09	2.561E+09	2.561E+09
04/02/2014 11:28	2.561E+09	2.562E+09	2.558E+09	2.560E+09	2.558E+09	2.562E+09	2.562E+09
04/02/2014 11:30	2.561E+09	2.561E+09	2.558E+09	2.560E+09	2.558E+09	2.561E+09	2.561E+09
04/02/2014 11:32	2.561E+09	2.561E+09	2.558E+09	2.560E+09	2.558E+09	2.562E+09	2.562E+09
04/02/2014 11:34	2.561E+09	2.562E+09	2.558E+09	2.560E+09	2.558E+09	2.562E+09	2.562E+09
04/02/2014 11:36	2.561E+09	2.562E+09	2.558E+09	2.560E+09	2.558E+09	2.562E+09	2.562E+09

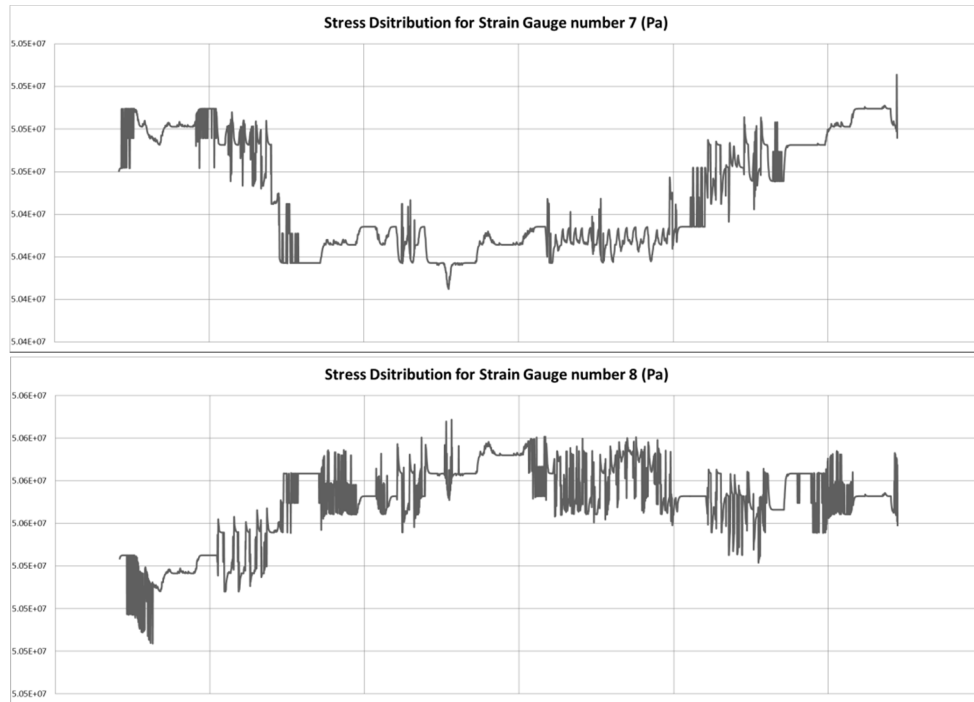


Figure 5-11 Periodic scattering of stress distribution (Pa) on January for half bridge strain gauges number 7 and 8

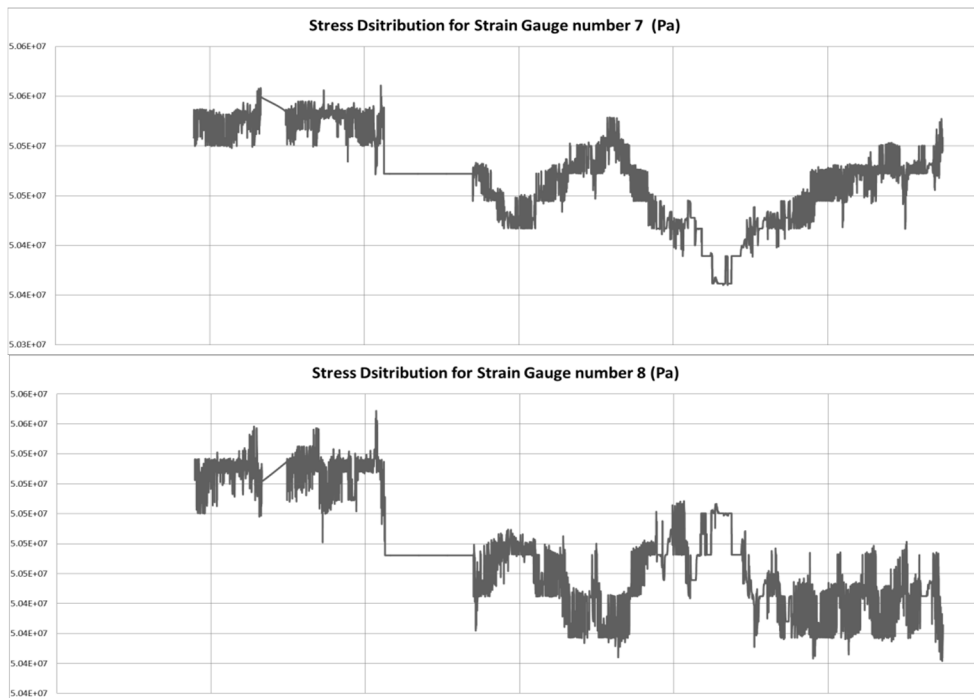


Figure 5-12 Periodic scattering of stress distribution (Pa) on February for half bridge strain gauges number 7 and 8

At the second phase of calibration, the stress distribution for 36 different models studied. Although FEM software did not provide enough ability to compute stress distribution for particular nodes, the possibility of computation stress distribution along different members and areas advanced. At second scenario to increase the accuracy and with respect to the way strain gauges installed and, each patch divided to 4 equal areas on the top and bottom surface of solar panel to study the stress distribution around on particular points of installed strain gauge. The procedure of parametric study in the FEM software based on numbering each patch and point to address how particular parameters changed. Figure 5-13(a,b,c) shows how each patch and nodes called.

a)						b)						c)							
15	29	43	57	71	85	16	81	96	36	124	139	15	16	35	54	36	82	97	15
14	28	42	56	70	84	80	79	95	109	123	138	151	31	29	53	67	81	96	109
13	27	41	55	69	83	78	77	94	108	122	137	150	28	27	52	66	80	95	108
12	26	40	54	68	82	76	75	93	107	121	136	149	26	25	51	65	79	94	107
11	25	39	53	67	81	74	73	92	106	120	135	148	24	23	50	64	78	93	106
10	24	38	52	66	80	72	71	91	105	119	134	147	22	21	49	63	77	92	105
9	23	37	51	65	79	70	69	90	104	118	133	146	20	19	48	62	76	91	104
8	22	36	50	64	78	39	68	89	103	117	132	33	39	18	47	61	75	90	33
7	21	35	49	63	77	67	66	88	102	116	131	145	17	12	46	60	74	89	103
6	20	34	48	62	76	65	64	87	101	115	130	144	11	10	45	59	73	88	102
5	19	33	47	61	75	63	62	86	100	114	129	143	9	8	44	58	72	87	101
4	18	32	46	60	74	61	60	85	99	113	128	142	7	6	43	57	71	86	100
3	17	31	45	59	73	59	58	84	98	112	127	141	5	4	42	56	70	85	99
2	16	30	44	58	72	57	2	83	97	111	126	140	3	2	41	55	69	84	98
						13	1	82	30	110	125	14	13	1	37	30	68	83	14

Figure 5-13 Solar panel FEM software numbering of a)devided area b)model with fix frame connections c)model with pin frame connections

The software computes stress distribution for each area depends on number of parameters affected, from type of connection to the value of wind load models induced with, and then it provides a table of respective result. Due to long time consumes to provide all tables

for 84 patches of 36 models, the table of stress distribution modified for 4 patches around the center nodes in fix (nodes number:101,103 and 105) and pin (nodes number:59,61 and 63) models. Table 5-8 illustrates the distributed stress on bottom and top surface of four areas around the node number 61 at Pin-Equal simulation.

Table 5-8 Distributed stress on bottom and top surface of four areas around the node number 61 in February 2014 (Pin-Equal Time History Simulation)

Stress Distribution (Node 61)						
Area	σ_x Top	σ_x Bottom	σ_x Ave	σ_y Top	σ_y Bot	σ_y Ave
	N/m2	N/m2	N/m2	N/m2	N/m2	N/m2
36	7.50E+07	7.63E+05	3.79E+07	1.22E+08	1.58E+06	6.20E+07
36	7.50E+07	7.60E+05	3.79E+07	1.22E+08	1.57E+06	6.19E+07
36	7.57E+07	7.86E+05	3.82E+07	1.22E+08	1.58E+06	6.20E+07
36	7.57E+07	7.89E+05	3.83E+07	1.23E+08	1.59E+06	6.21E+07
36	7.50E+07	7.62E+05	3.79E+07	1.22E+08	1.58E+06	6.20E+07
36	7.49E+07	7.59E+05	3.79E+07	1.22E+08	1.57E+06	6.19E+07
Stress Distribution (Node 61)						
Area	σ_x Top	σ_x Bottom	σ_x Ave	σ_y Top	σ_y Bot	σ_y Ave
	N/m2	N/m2	N/m2	N/m2	N/m2	N/m2
37	8.48E+07	1.07E+06	4.29E+07	1.19E+08	1.41E+06	6.00E+07
37	8.48E+07	1.07E+06	4.29E+07	1.19E+08	1.42E+06	6.01E+07
37	8.48E+07	1.07E+06	4.29E+07	1.19E+08	1.42E+06	6.01E+07
37	8.48E+07	1.06E+06	4.29E+07	1.19E+08	1.41E+06	6.00E+07
37	8.48E+07	1.06E+06	4.29E+07	1.19E+08	1.41E+06	6.00E+07
37	8.48E+07	1.07E+06	4.29E+07	1.19E+08	1.42E+06	6.01E+07
Stress Distribution (Node 61)						
Area	σ_x Top	σ_x Bottom	σ_x Ave	σ_y Top	σ_y Bot	σ_y Ave
	N/m2	N/m2	N/m2	N/m2	N/m2	N/m2
50	7.51E+07	7.71E+05	3.80E+07	1.20E+08	1.51E+06	6.06E+07
50	7.51E+07	7.71E+05	3.80E+07	1.20E+08	1.51E+06	6.06E+07
50	7.55E+07	7.86E+05	3.82E+07	1.20E+08	1.52E+06	6.07E+07
50	7.55E+07	7.86E+05	3.82E+07	1.20E+08	1.52E+06	6.07E+07
50	7.51E+07	7.70E+05	3.79E+07	1.20E+08	1.51E+06	6.06E+07
50	7.51E+07	7.70E+05	3.79E+07	1.20E+08	1.51E+06	6.06E+07
Stress Distribution (Node 61)						
Area	σ_x Top	σ_x Bottom	σ_x Ave	σ_y Top	σ_y Bot	σ_y Ave
	N/m2	N/m2	N/m2	N/m2	N/m2	N/m2
51	7.99E+07	9.30E+05	4.04E+07	1.18E+08	1.44E+06	5.97E+07
51	7.99E+07	9.30E+05	4.04E+07	1.18E+08	1.44E+06	5.97E+07
51	7.99E+07	9.30E+05	4.04E+07	1.18E+08	1.44E+06	5.97E+07
51	7.99E+07	9.30E+05	4.04E+07	1.18E+08	1.44E+06	5.97E+07
51	7.98E+07	9.29E+05	4.04E+07	1.18E+08	1.44E+06	5.97E+07
51	7.98E+07	9.29E+05	4.04E+07	1.18E+08	1.44E+06	5.97E+07

Maximum Stress distribution (Node 61)		
Area	σ_{xAve}	σ_{yAve}
m2	N/m2	N/m2
36	4.29E+07	6.21E+07
37	4.30E+07	6.21E+07
50	4.30E+07	6.21E+07
51	4.30E+07	6.21E+07

The value of distributed stress regard to the Equal case of simulation (Time history Analysis) shows the most accurate results which are calibrated sufficiently with the stress computed in the experiment section. However, the Rod and Link cases of study do not show enough accuracy which is expected from previous study. It is clear that due to numerous number of factors such as ; type of connections which are not pin or fix hundred percent , significant influence of temperature variation within two months ,possibility of existence residual stress due to previous loading ,elimination of coppers and electrical devices in modeling and many other parameters ,the ideal 100% calibrated value of distributed stress needs more time to study and leads more accurate results.

Chapter6: Conclusion and recommendations

6.1. Conclusion

Rapid growth energy consumption of tend to take advantages of renewable type of energy resources rather traditional one especially sun light caused to significant increase in installation of PV solar system on flat roofs which induced with wind load. However, lack of enough codes and documents regard to the design and analyze the behavior of structure of system with respect to the attached or ballast type of installation forced to introduce a case study and look how the particular specimen behaves.

Although the accuracy of mentioned case due to remarkable time spent for each particular case is high enough, technically it is not possible to introduce any specific case study and spent great budget for any installation. Therefore, demand in using other type of analysis and design has been raised day by day. One reasonable way is taking advantages of power of computers and different software products to simulate the behavior of members and PV Solar panel. However, the accuracy of simulation needs to calibrate with an experiment had run.

Different types of experiment considered to look at the various parameters from effect of air flow on scaled model in wind tunnel test to analyze dynamic or static load application on full scale specimen. However, the most accurate result gains when a full scale specimen employed to conduct a study with respect to open-air wind load induction. This type experiment ran within two months period on January and February 2014 on the rooftop of Mann parking at the University of Ottawa, where the PV solar system instrumented in unique case with 13 half bridge strain gauges on both faces of solar panel with the cross line format

of installation. The advantages of FEM commercial software SAP 2000 was taken to simulate the model and calibrate the behavior of instrumented specimen. Therefore, number of mechanical and thermal properties had defined to the software for more accurate results. The importance of accurate definition of material properties bolded with a brief look at the variable behavior of solar sandwich under nominal load uplift load application with respect to the large range of temperature from -40° to $+40^{\circ}$ Celsius in third chapter which in extreme cold weather shrinkage caused to negate the uplift uniform load applied on bottom surface of solar panel. This could be more resonated whether inhomogeneity of silicon layer had not eliminated due to an assumption.

Another case is the exactness of drawing of PV solar surrounding frame significantly influenced on the stiffness of structure and how load distribute along the model due to special shape which was noticed in forth chapter. However, it sheltered form drag and lift components of wind load applied form north by the support structure frames. Two components of wind load computed regards to record of weather parameters such as humidity, temperature, air pressure and wind speed with respect to the direction of wind flow and the area stand in front in every one minutes between January and February 2014. Therefore, the drag and lift force defined for each member depends on whether it was located in sheltered area by another member or not. Due to the dominant direction of wind load usually met PV solar system from behind in northern hemisphere, which cause to application of the most extreme load applied to members. The location of site provided this ability to study on behavior of PV solar system in wind stream reattachment zone approximately.

The type of data acquisition provides high records of induced wind load for every minute which exactly determine that what was the intensity and direction of wind load on each

member. However, the provided database of dynamic wind load was shown number of significant number of varieties for every minute for different members, due to very tiny period of recording data it was assumed that the source of wind flow for respective period was unique. Thus, unique dominant wind function should apply to all members in specific time. This idea generalized to all period of data acquisition, which means two main functions, governed to all members' behavior within period of experiment. Therefore, both function introduced to FEM software to take advantages of Time History Analysis.

Two more procedures of analysis considered besides the Nonlinear Direct-Integration Time-History Analysis, were Linear Static and Linear Modal analysis. To study the behavior of model with respect to both case of analysis the maximum value of wind load recorded applied on each respective member. The same load application consider for Nonlinear Direct-Integration Time-History Analysis with notable change that related to effect of wind load function that neglected in two other analysis. Another important load application was related to average temperature that met PV solar system within period of experiment, which was equal to -7° Celsius. Before running the software, one important consideration defined for all type of analysis whether the behavior PV solar panel under nominal uplift load simulated or whole PV solar system, which was the size of mesh.

The Finite Element method works with the ability of dividing a member to tons of elements with particular dimension, which called Mesh. More accurate results expected by generating more refined mesh which means provide smaller size but larger number confined area and compare with other mesh size to reach the most accurate results (mesh sensitivity). This effect studied in third chapter to find how a PV member displaced and compare results computed with respect to the three 5, 10 and 50mm mesh size. The accuracy

of results gained and the least dimension length of equal to 5 mm caused to run analysis relies on 5 mm most accurate mesh size. The importance mesh discretization yielded to choose alternative ways instead of making hole and modeling screws at connections and joints.

Therefore, 3 Equal, Link and Rod commands of FEM software taken to compute the behavior of PV solar system with respect to pin and fix connection between frames to stay far from imprecise results gain due to discretization errors. Moreover, two fix and pin connection between frames provides this ability to compare results together and another experiment ran simultaneously to gain the most accurate results.

Another experiment designed to measure the strain placed on solar panel within same period on January and February. The fractional values measured defined by changing in electrical voltage of each bridge of strain gauges, which used to compute micro-strain by equation provided in guidebook manual of the datalogger used to read data with some other recommended calibrations. The advantages of Hook's law taken to compute stress distribution for each specific node within period of experiment according to measured strain for every sensor which multiplied by uniform Young's Modulus computed in third chapter.

The stress values of both scenario compared together to figure out the most close stress value gain from 36 simulations to distributed stress got form designed experiment. It was shown that Nonlinear Direct-Integration Time-History Analysis with respect to Equal case of simulation was the most calibrated study to the value got form designed experiment.

6.2. Future Works

For future studies might be conducted according to the topic of simulation, it is recommended that:

- Ø Increase the accuracy of modeling by defining electrical devices used to in solar panel that increase the accuracy of simulation.
- Ø Due to significant influence of temperature variation on behavior of model, take advantages of some methods to apply periodic amplitude temperature in FEM simulation
- Ø According to the influence of screws on distribution of load parameters (stress, strain),the modeling the behavior of screws or taking advantages of partial fixity plus accurate translational and rotational spring might yield more precise results
- Ø Due structural view at load distribution on this type of study ,installation strain gauges on support structure is able to determine how much load transfer to roofing and Main Lateral Force Resisting System

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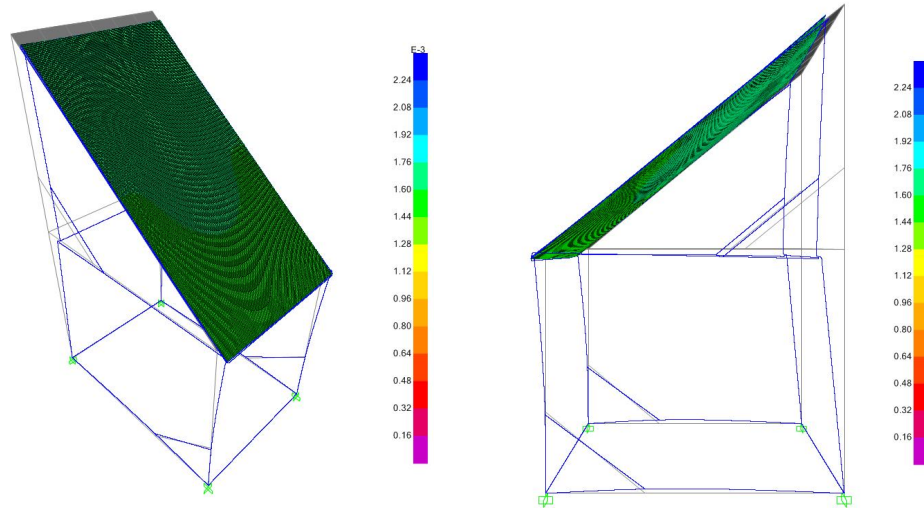
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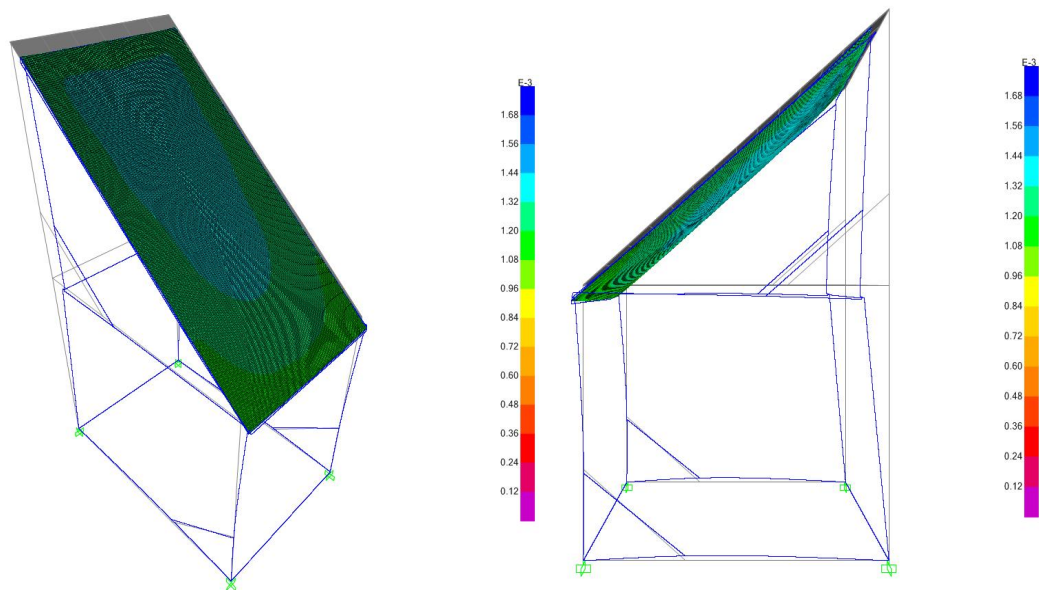
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Appendix A

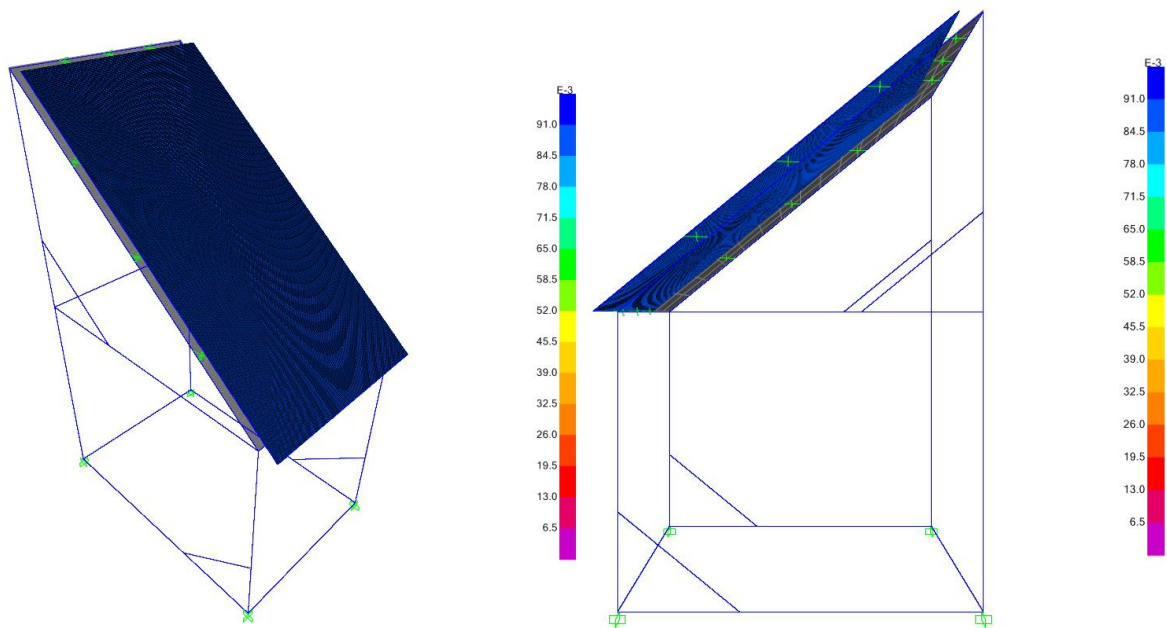
Static Analysis Simulations



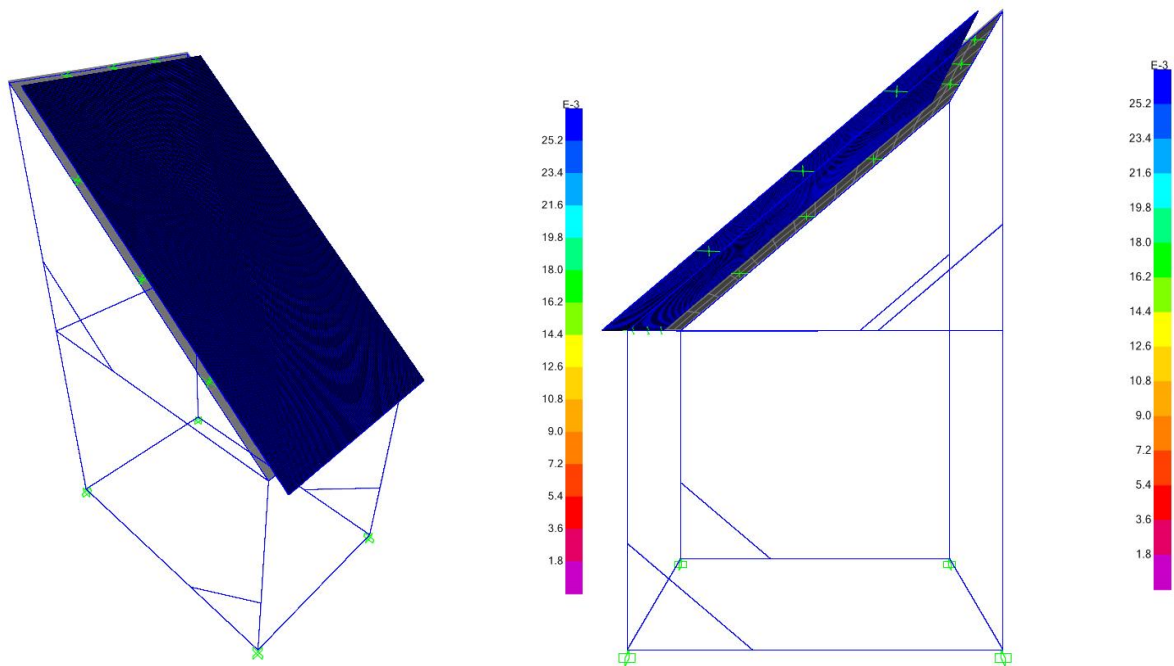
Amplitude of displacement variation according to Pin-Equal connections-joints installation
analyzed statically for January 2014-load application



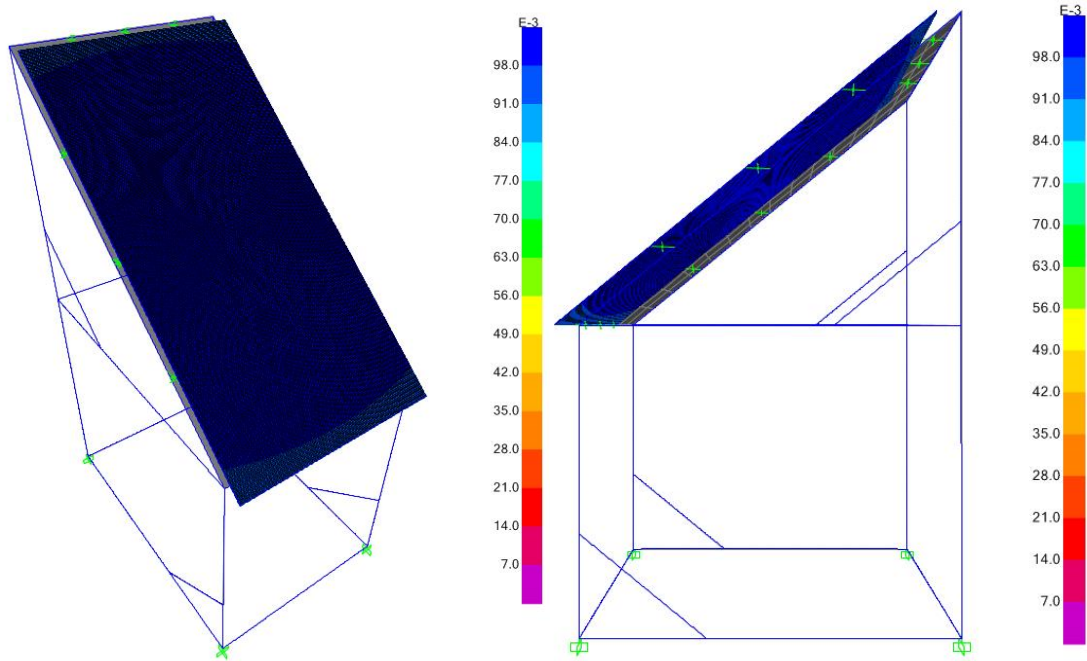
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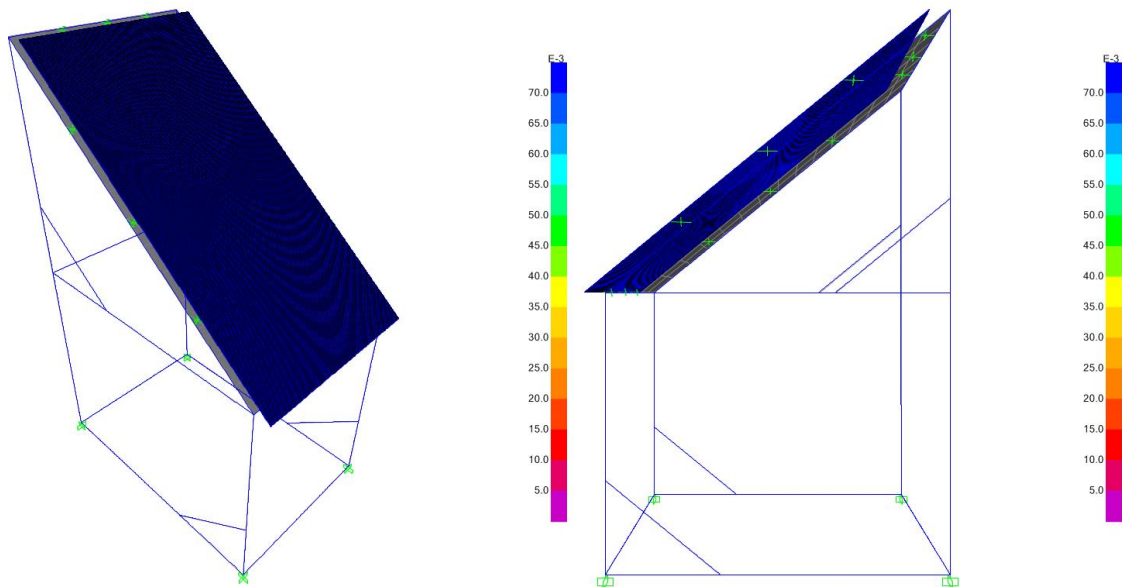
Amplitude of displacement variation according to Fix-Link connections-joints installation
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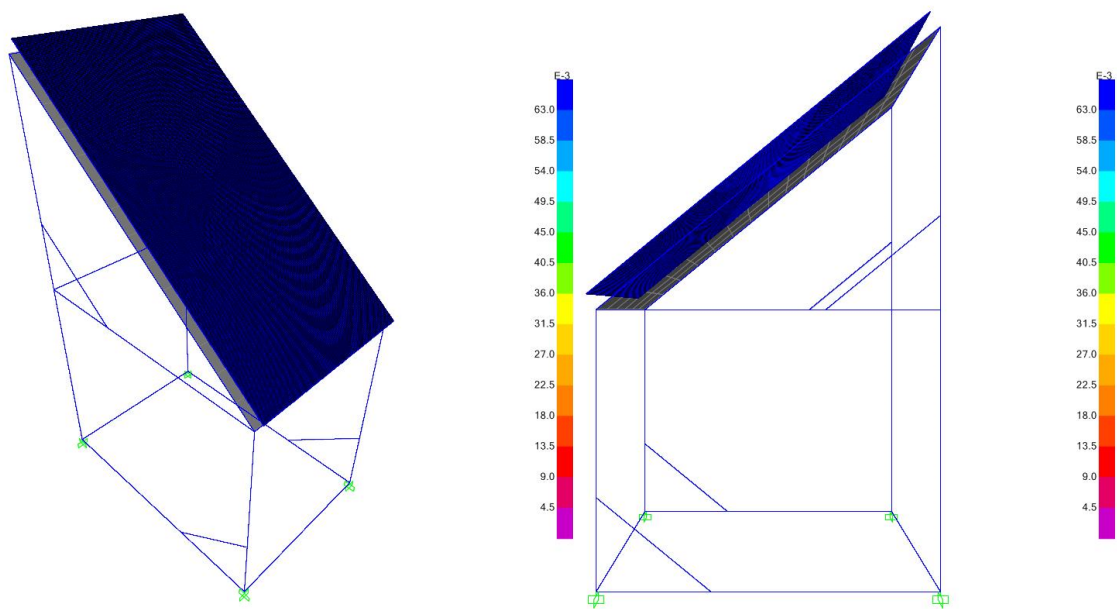
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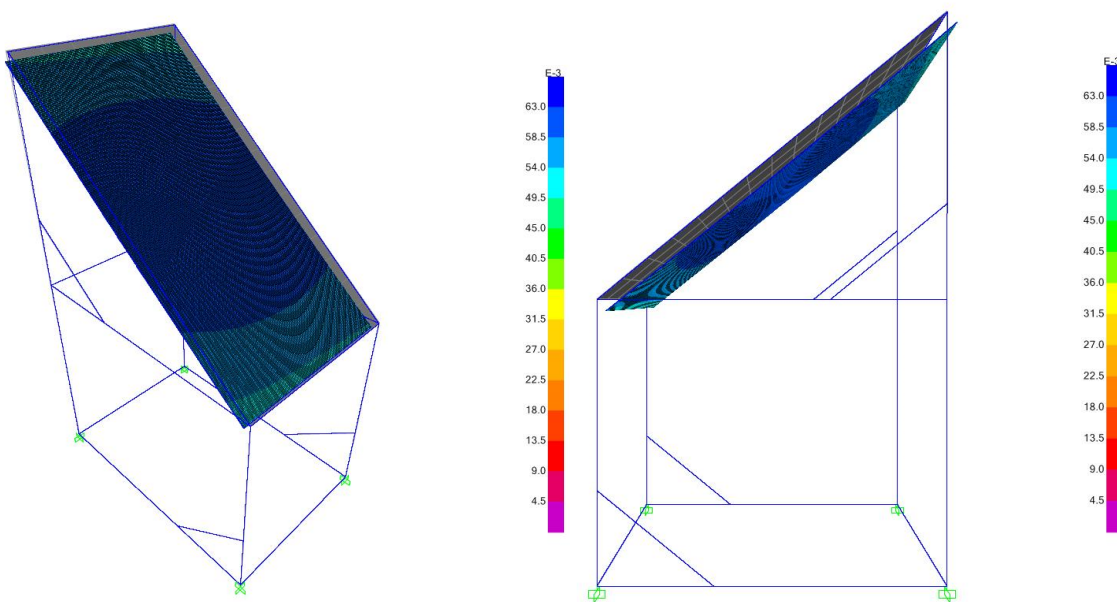
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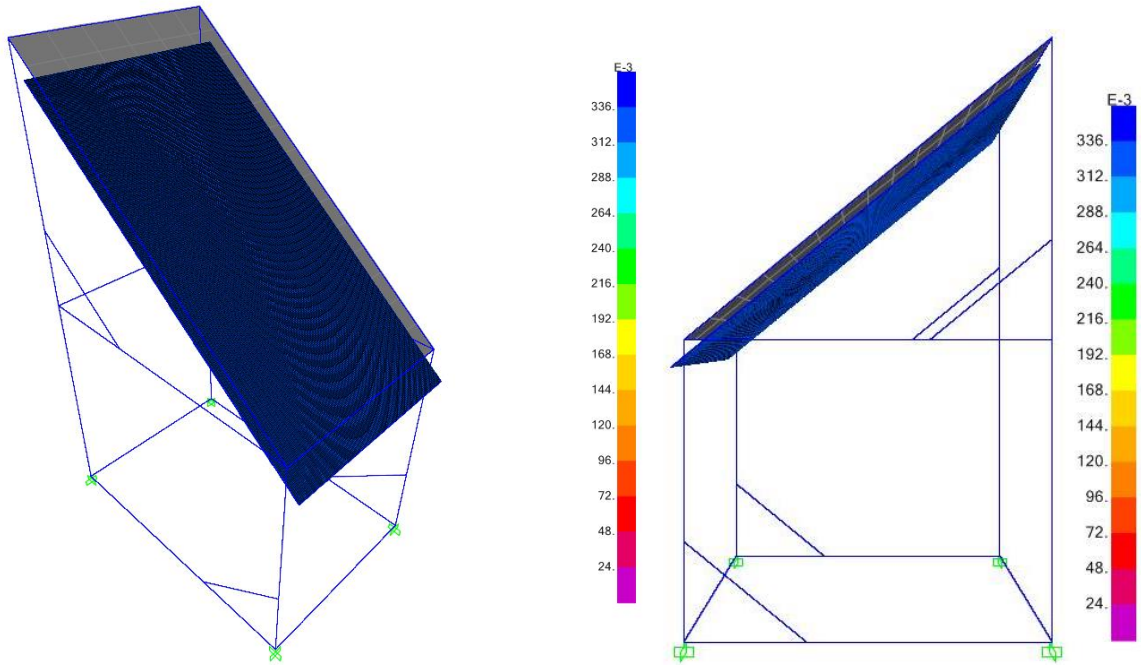
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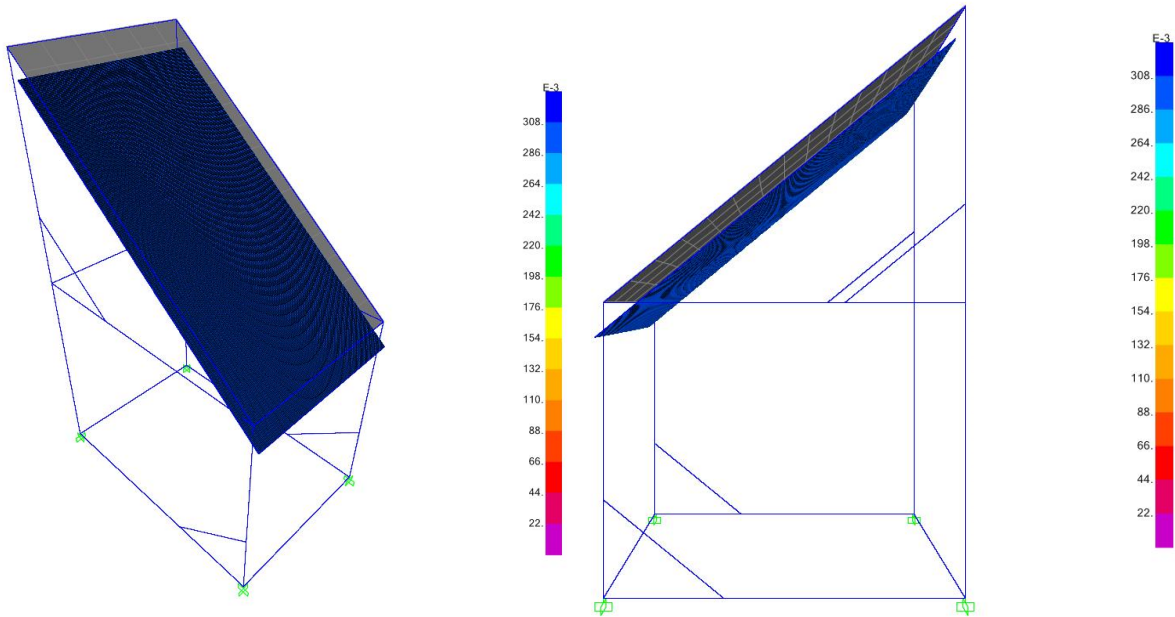
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analyzed statically for January 2014 load application



Amplitude of displacement variation according to Fix-Rod connections-joints installation
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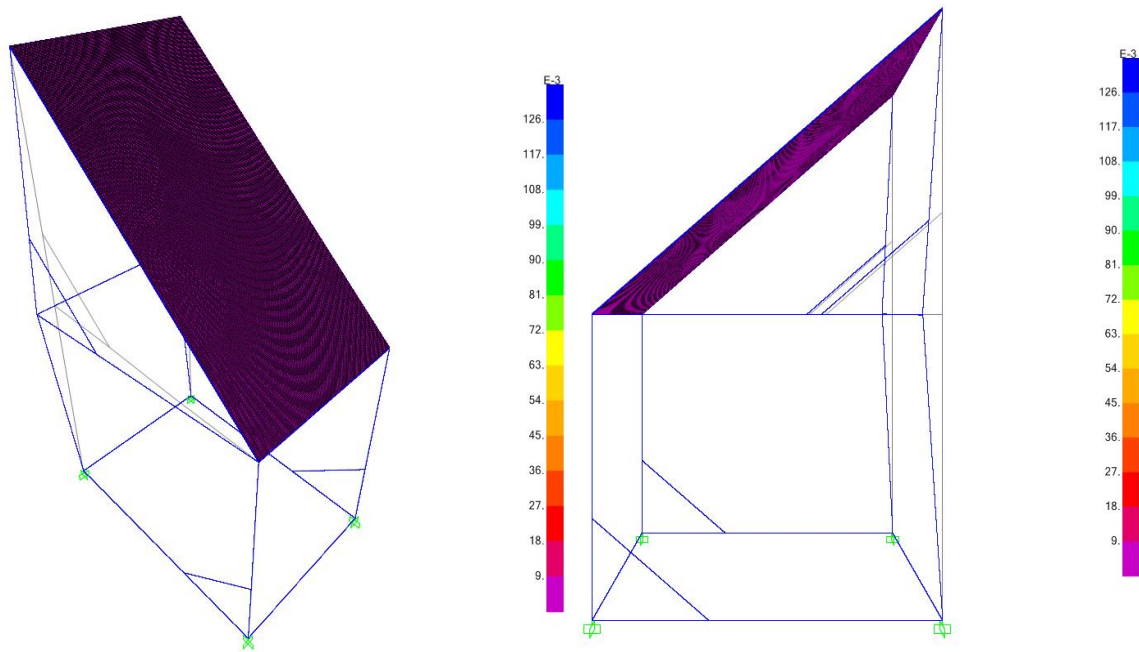


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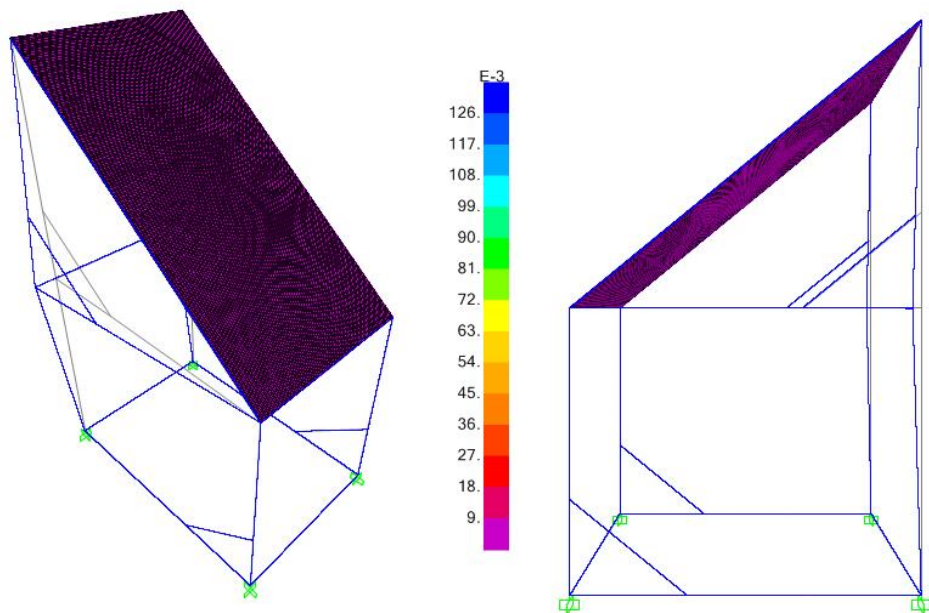


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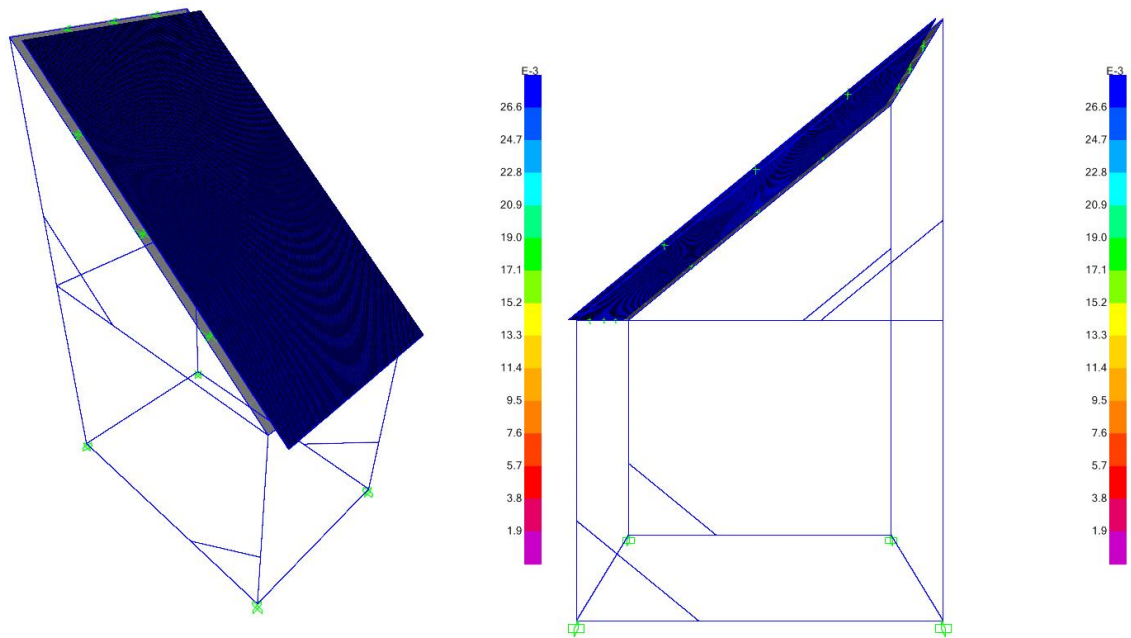
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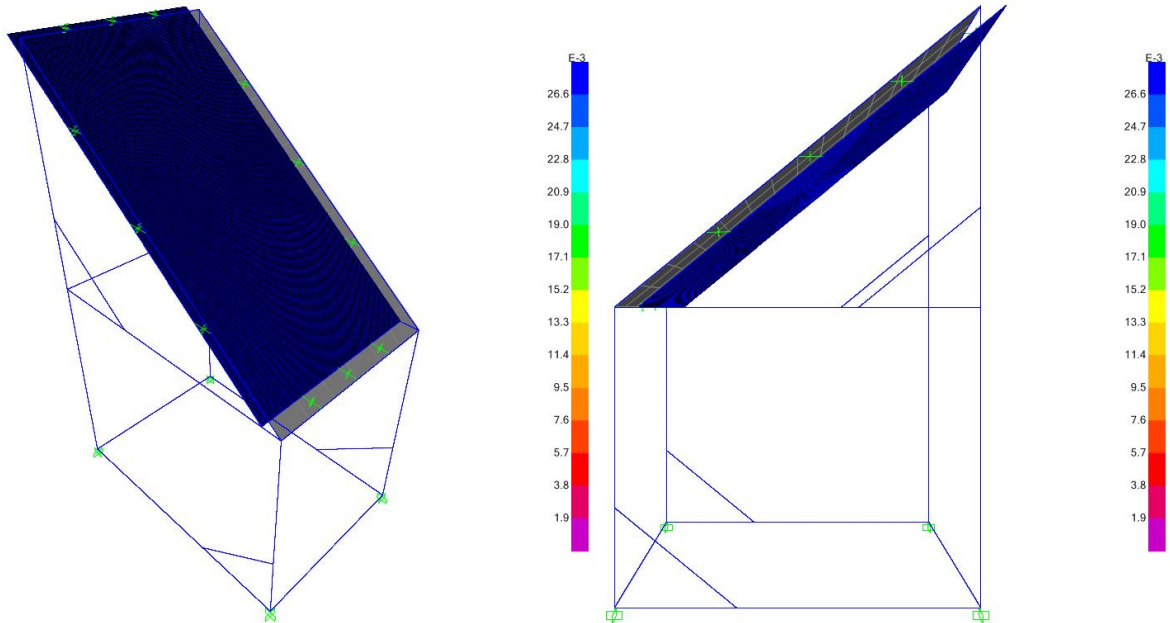
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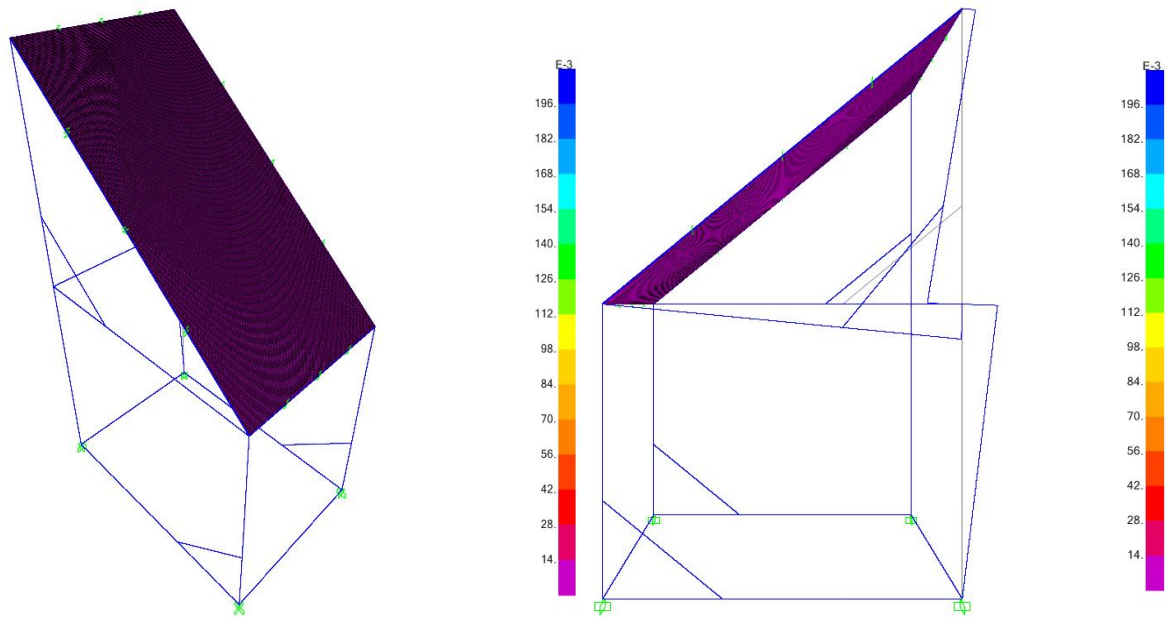
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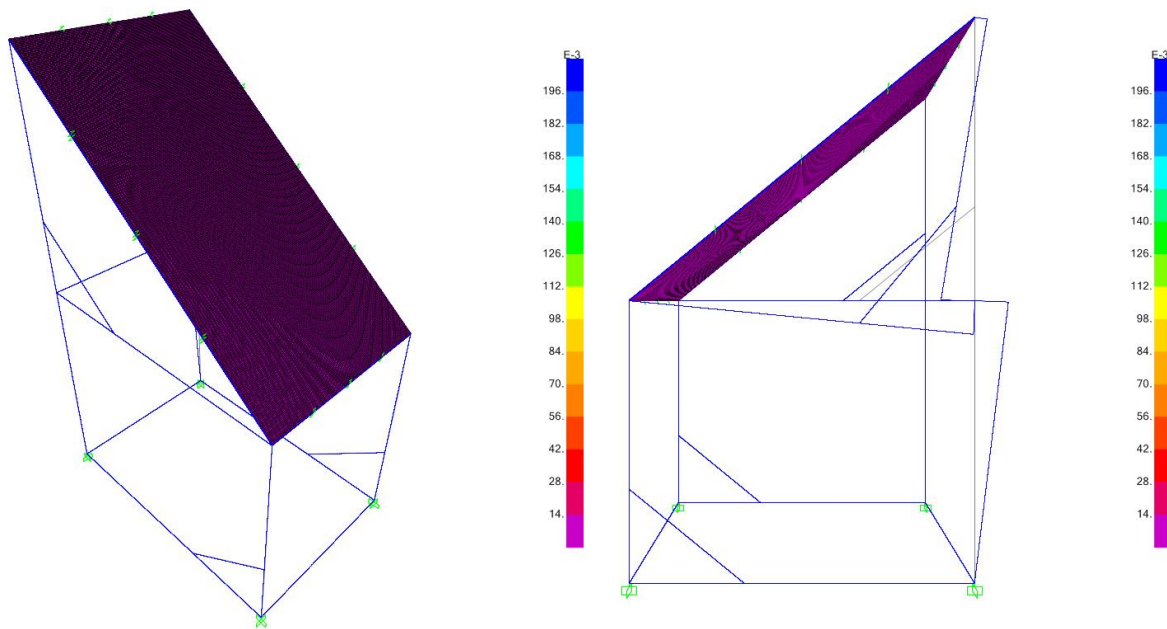
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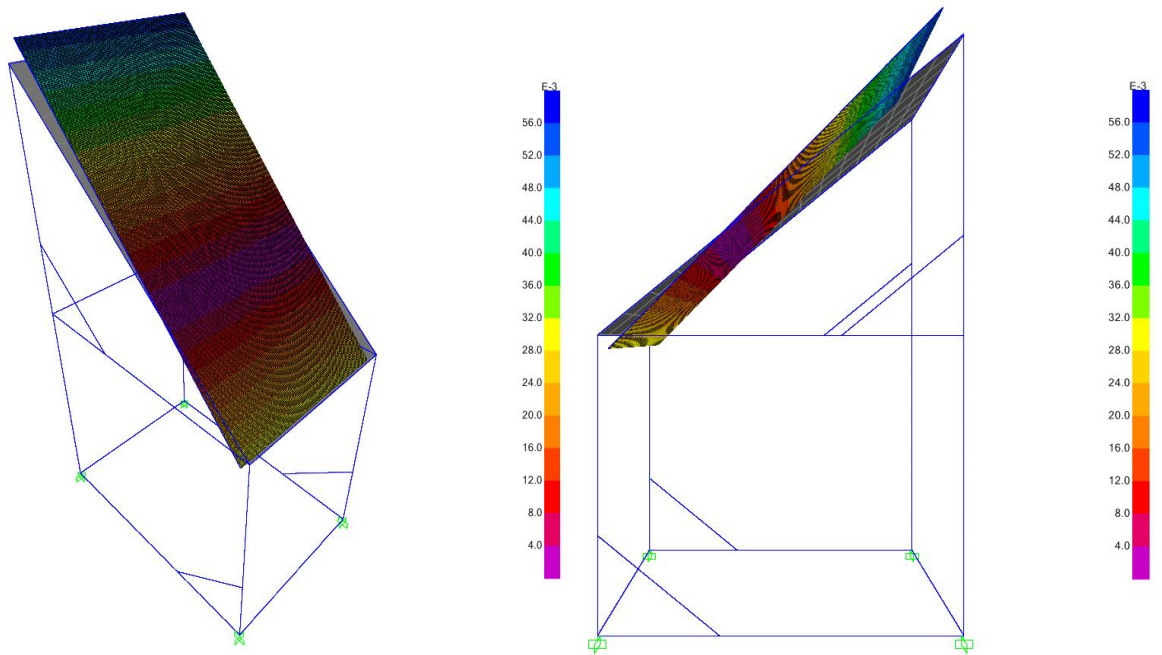
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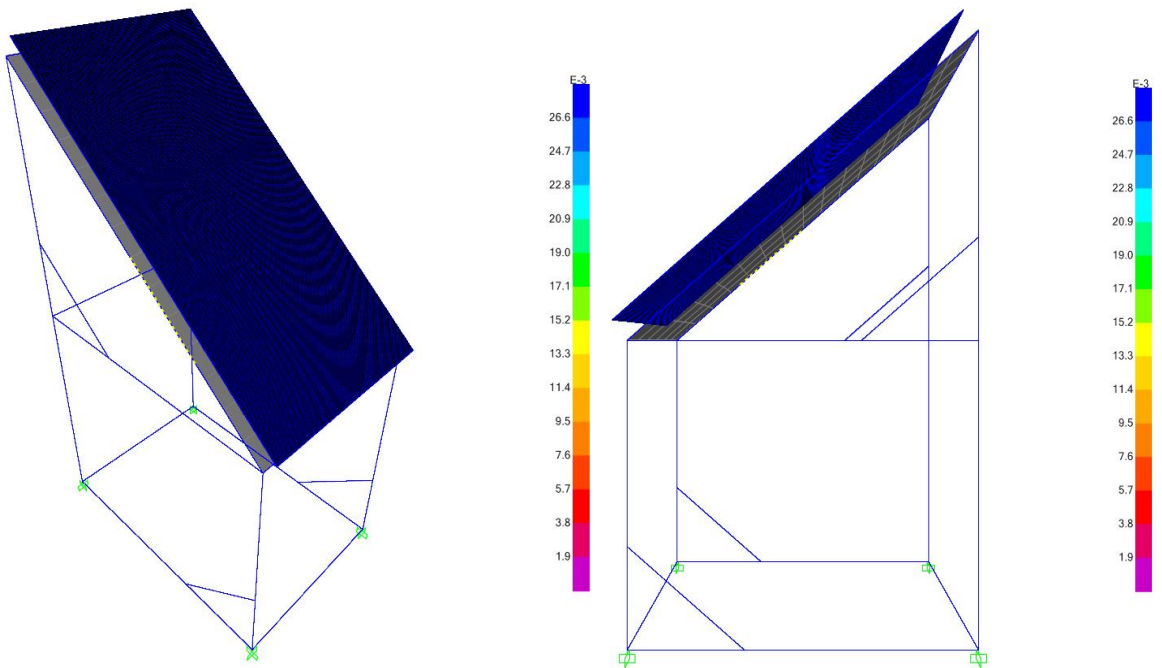
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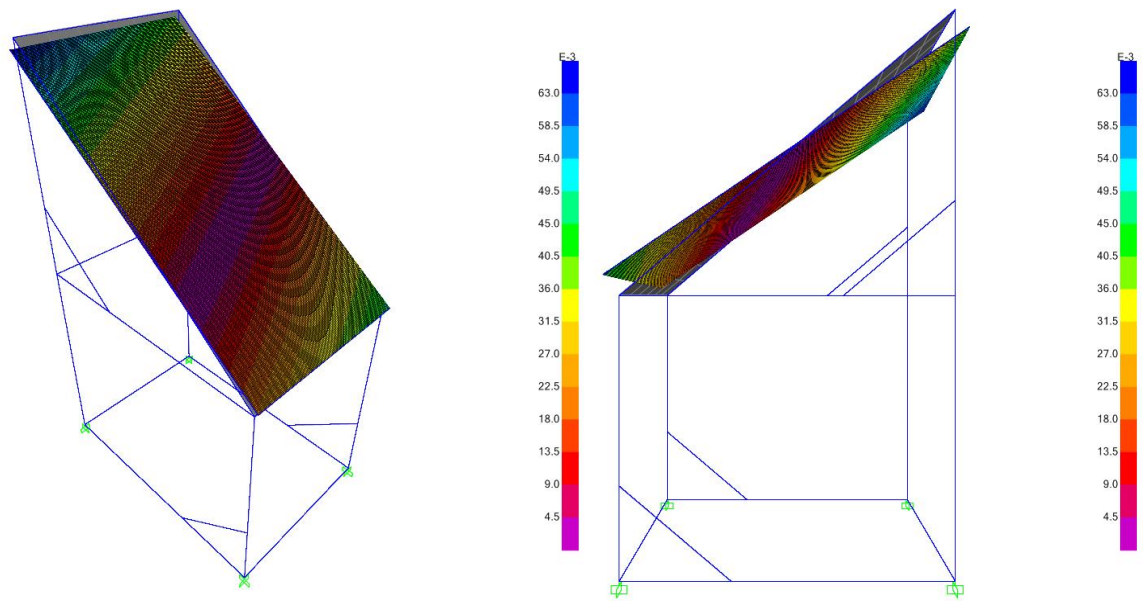
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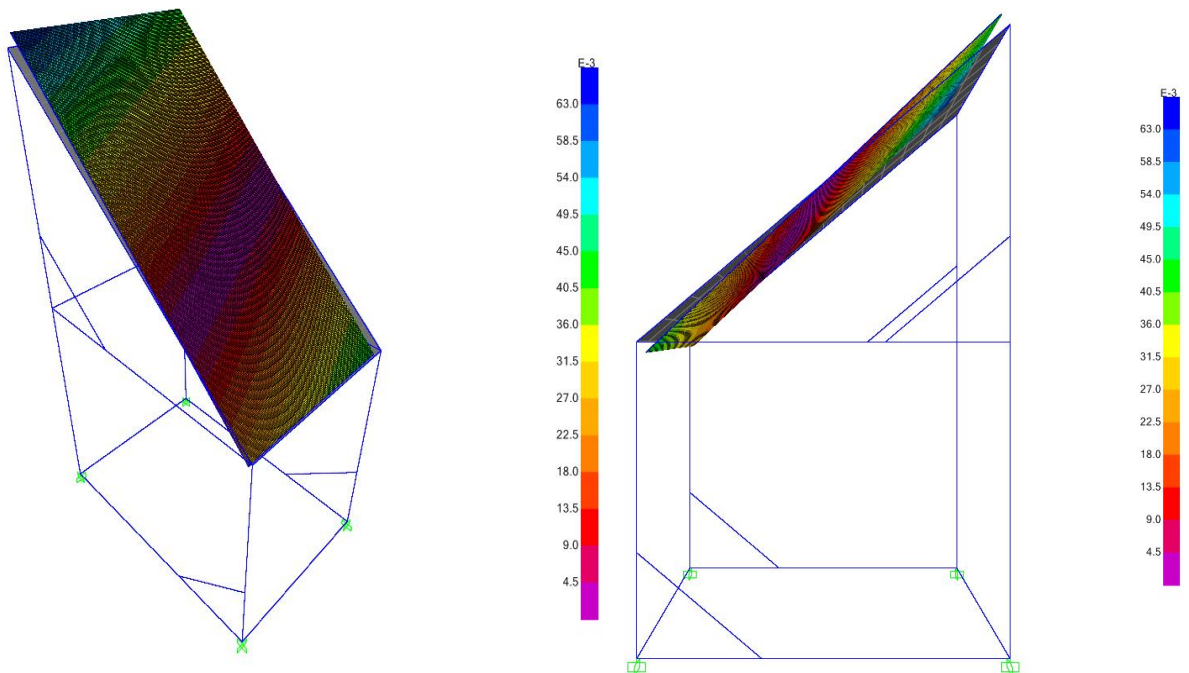
Amplitude of displacement variation according to Fix-Rod connections-joints installation
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Amplitude of displacement variation according to Fix-Rod connections-joints installation
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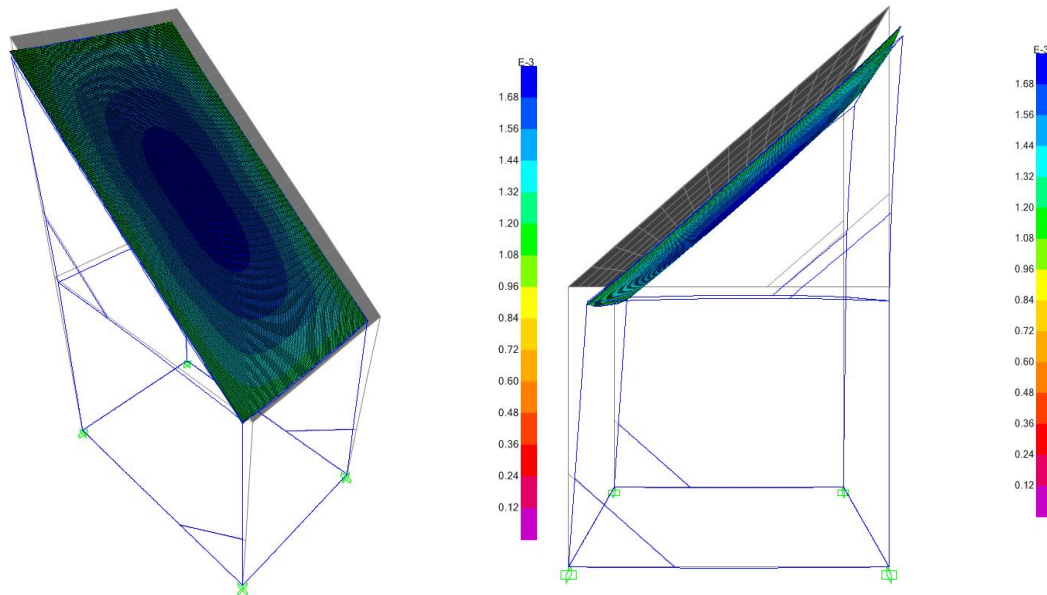


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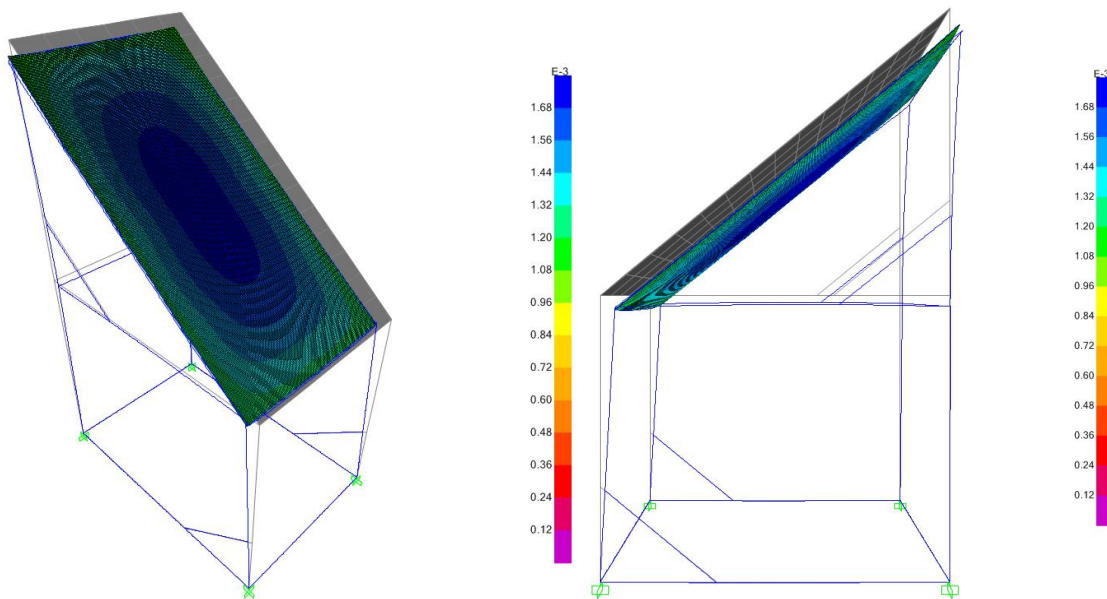


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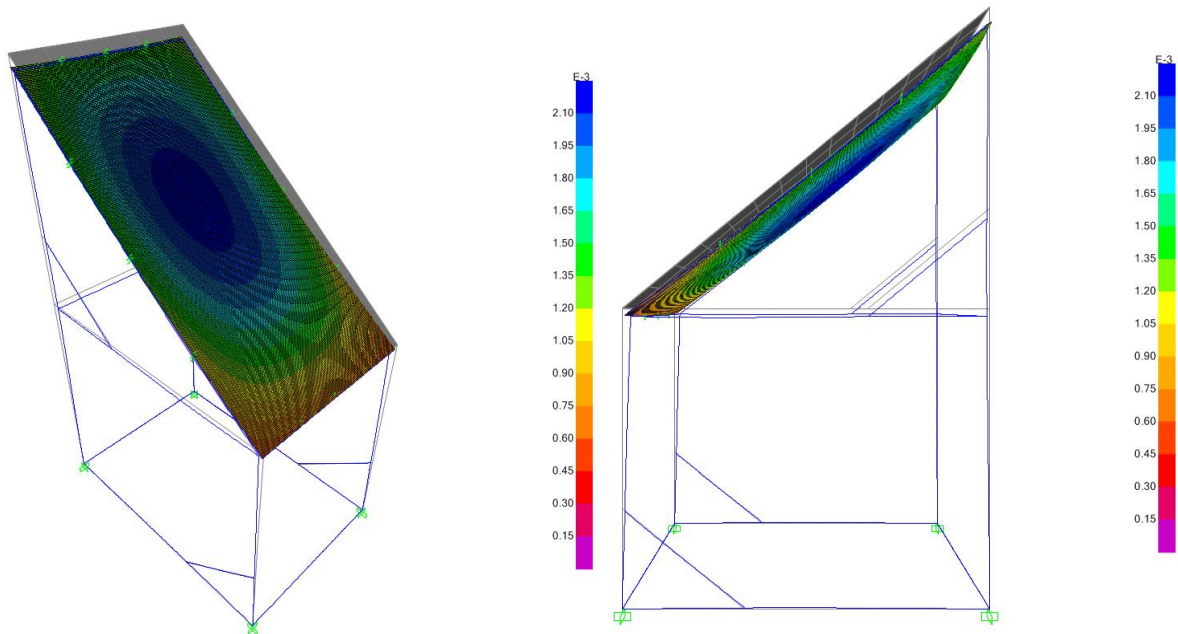
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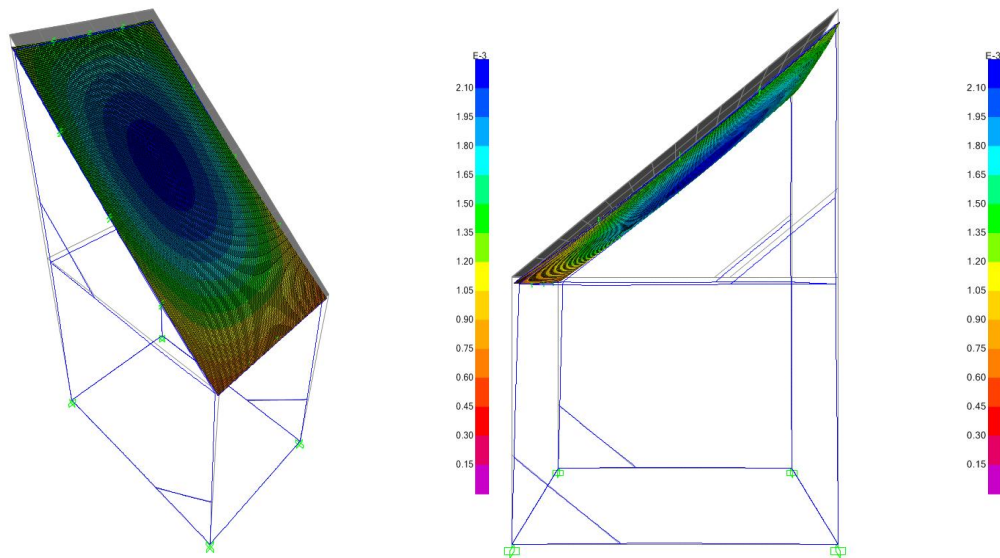
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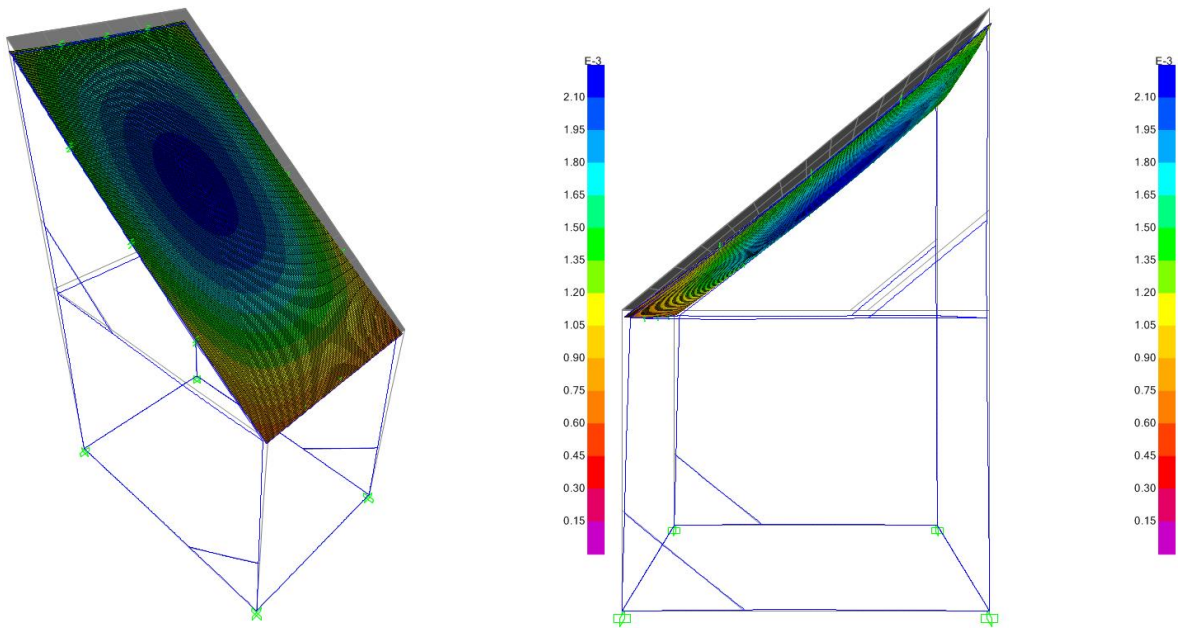
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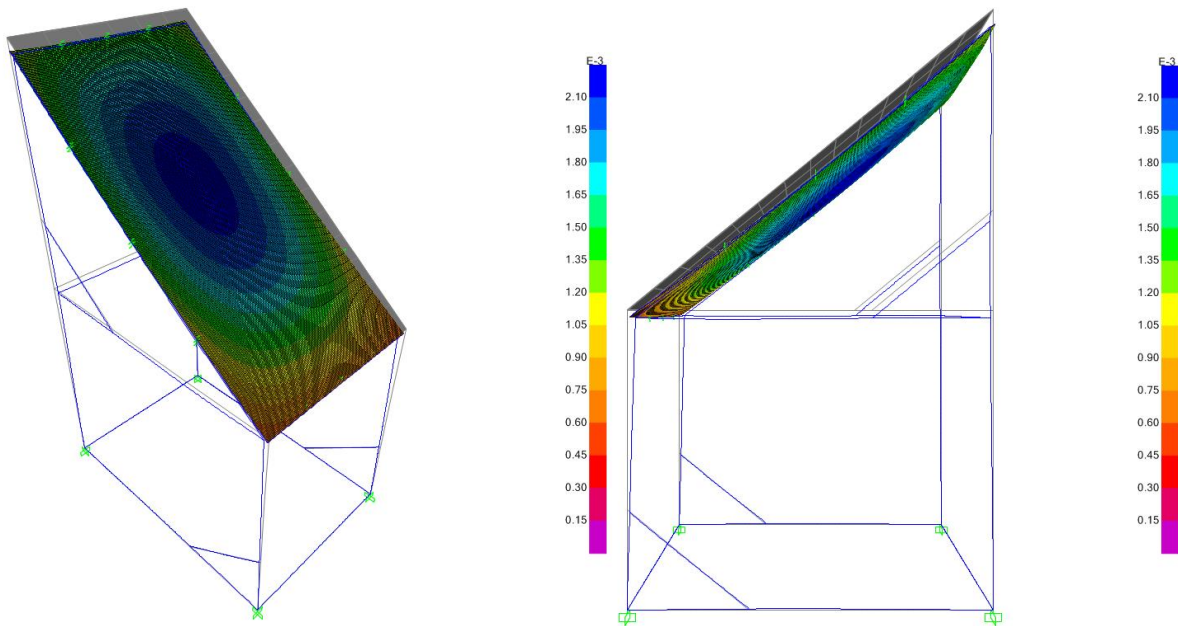
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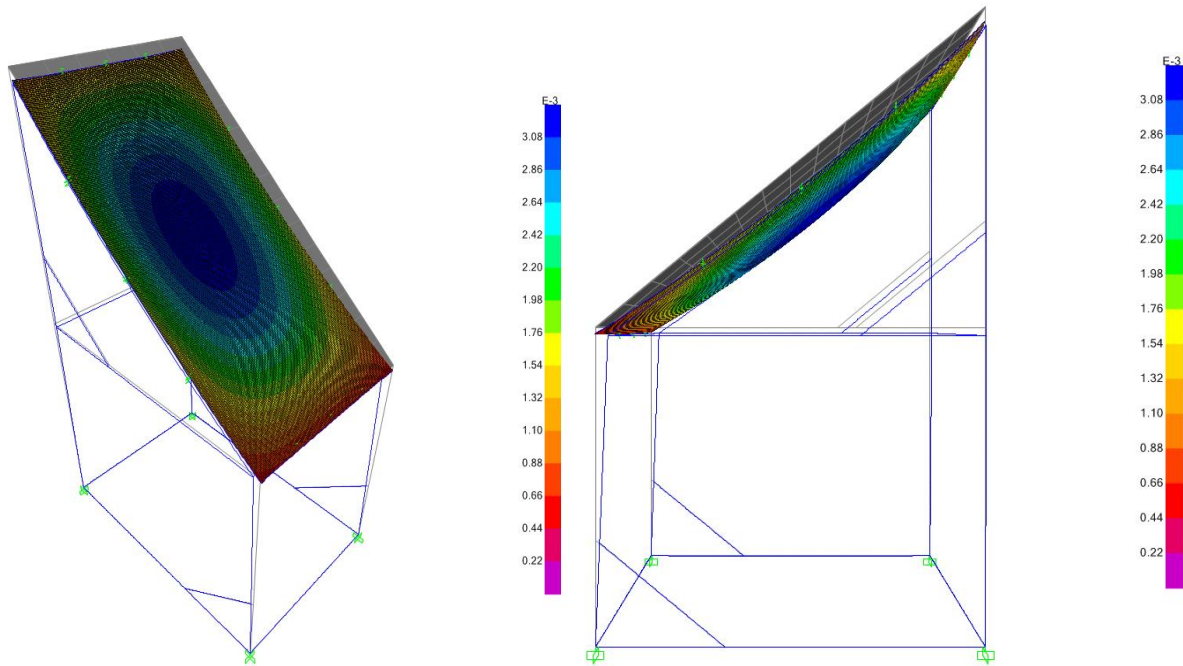
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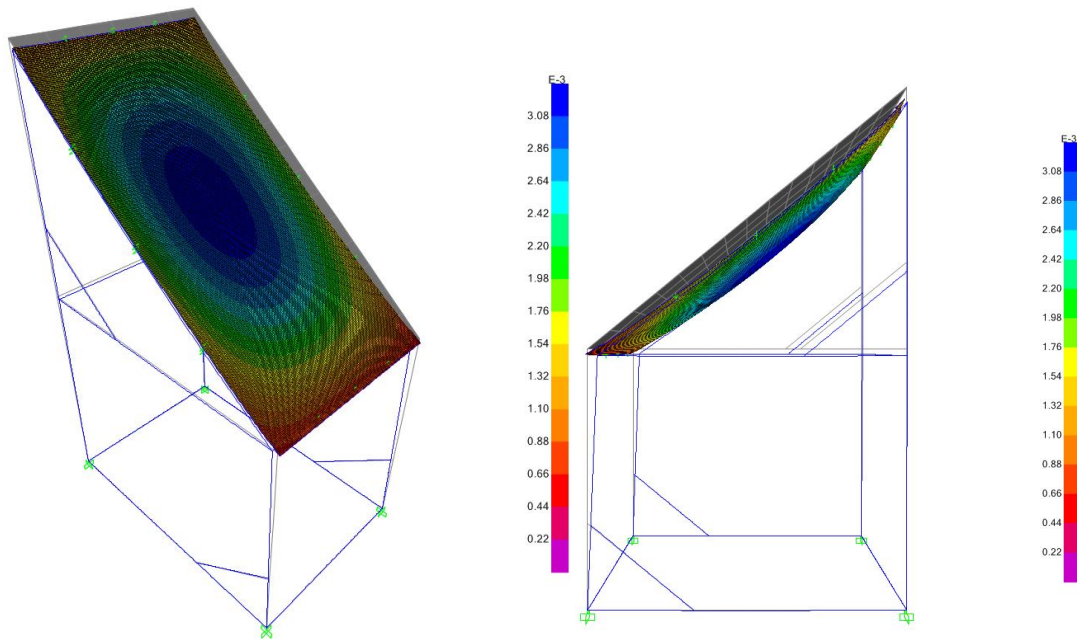
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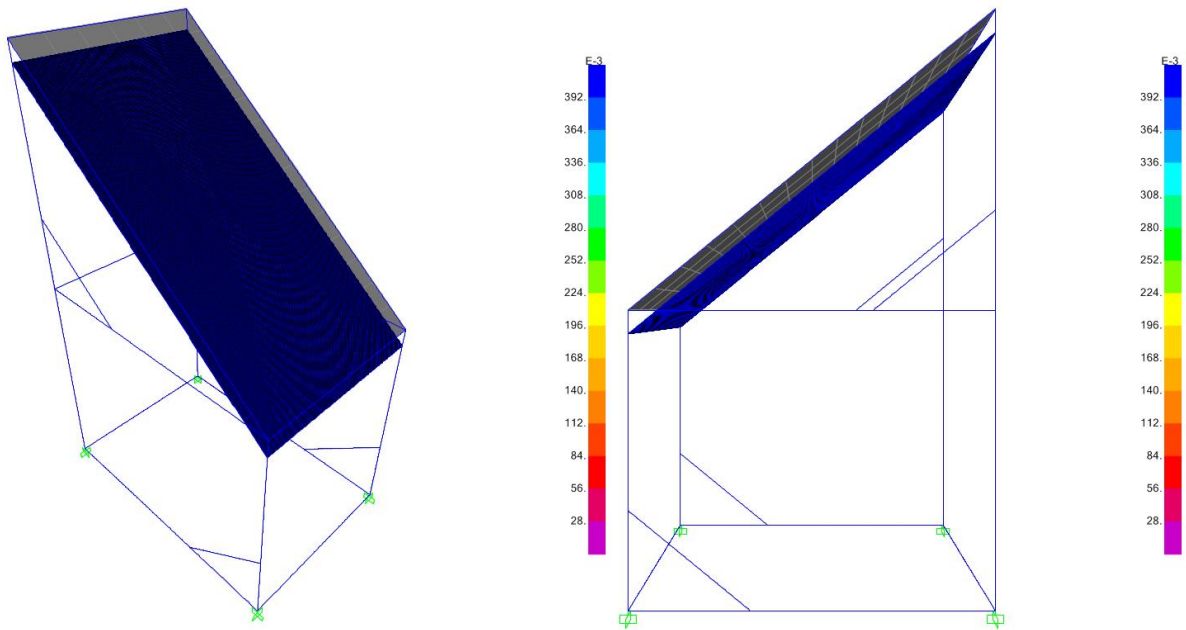
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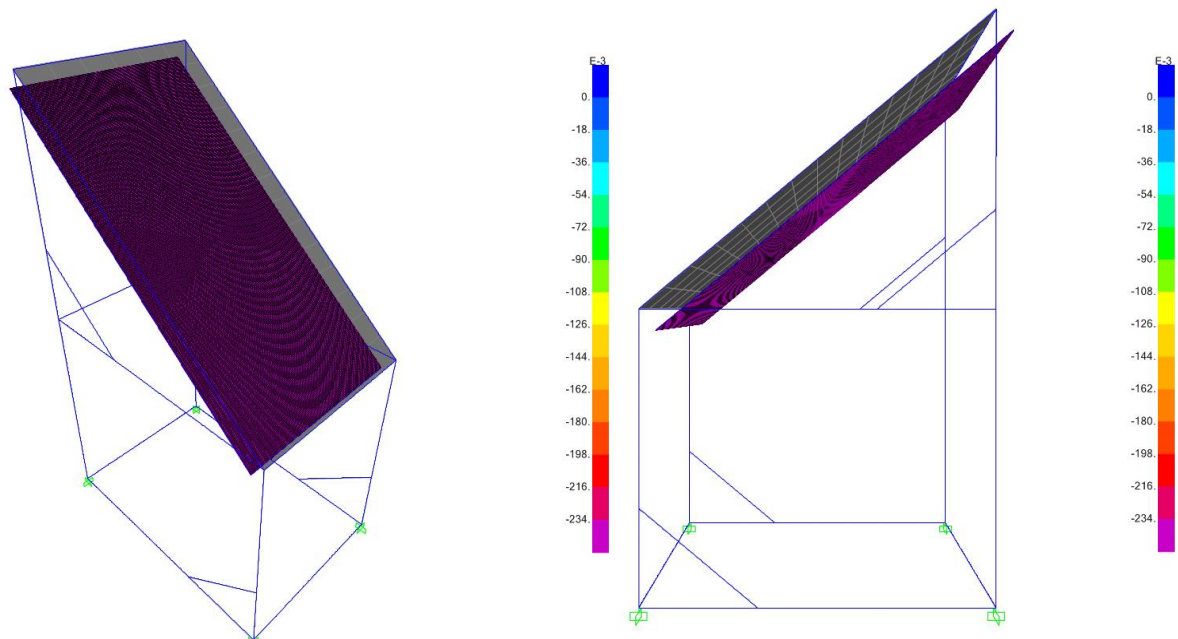
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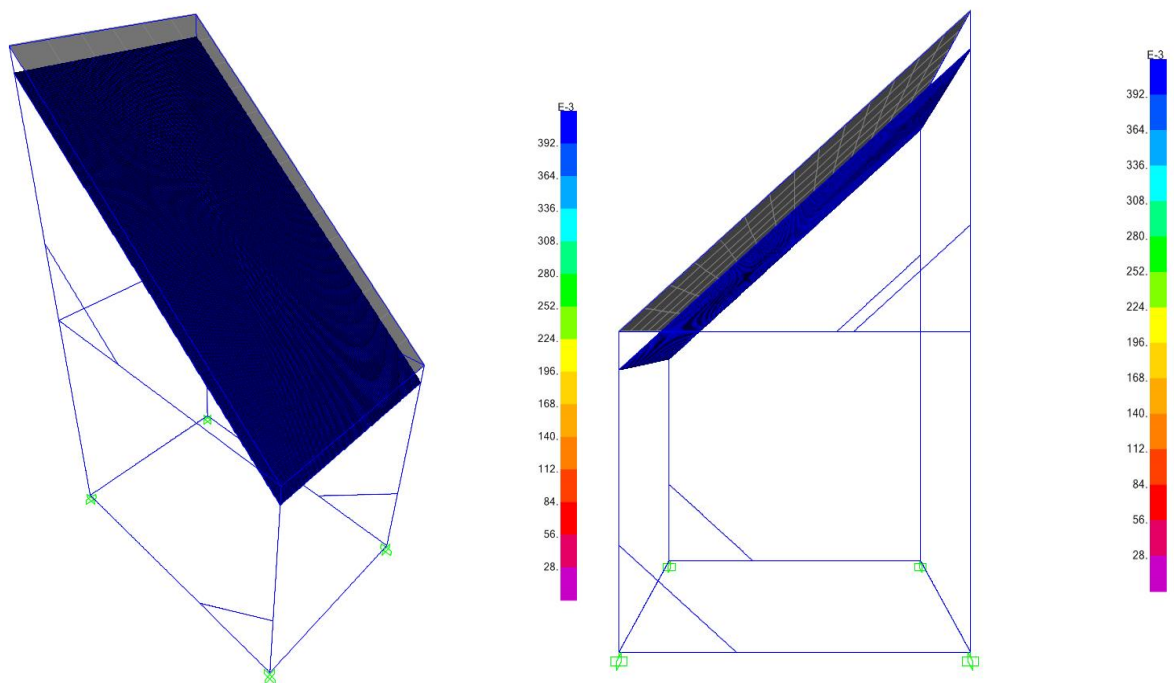
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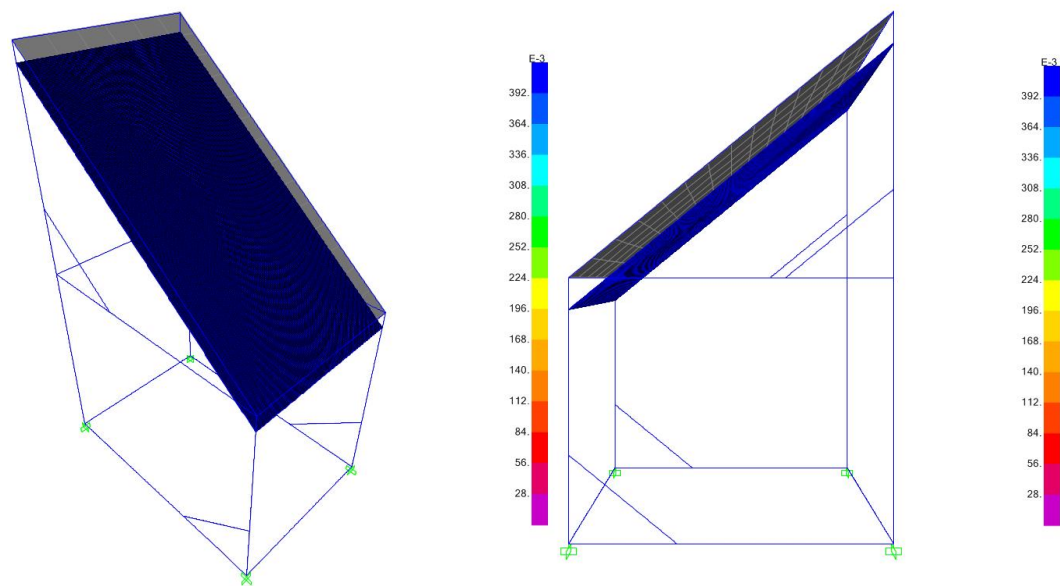
Amplitude of displacement variation according to Pin-Link connections-joints installation analyzed by Nonlinear Direct-Integration Time-History Analysis for February 2014-load application



Amplitude of displacement variation according to Pin-Link connections-joints installation analyzed by Nonlinear Direct-Integration Time-History Analysis for January 2014-load application



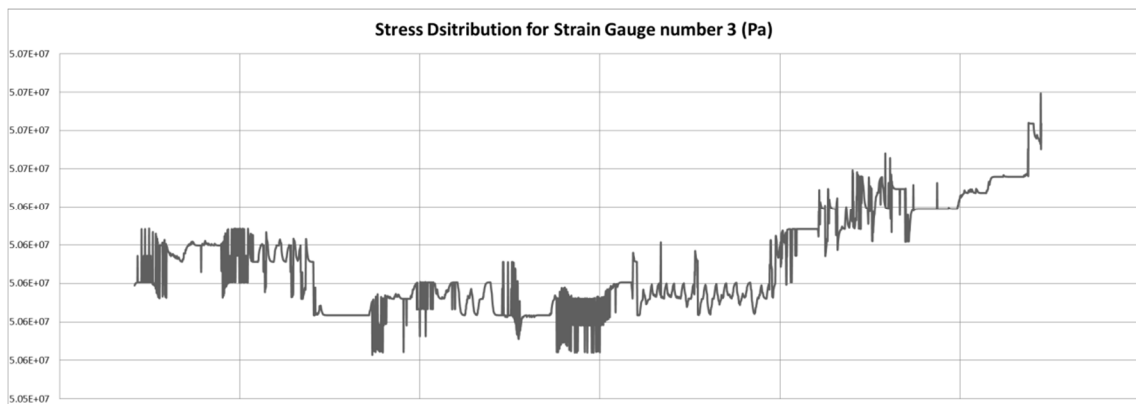
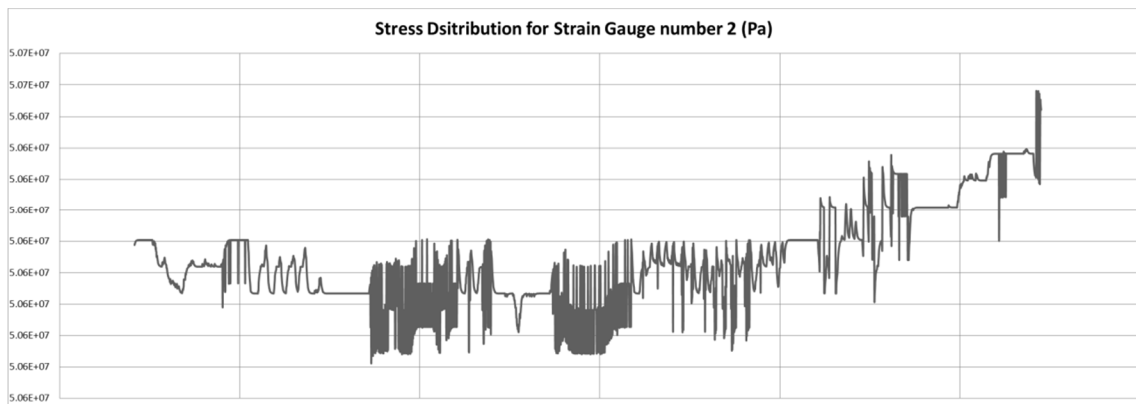
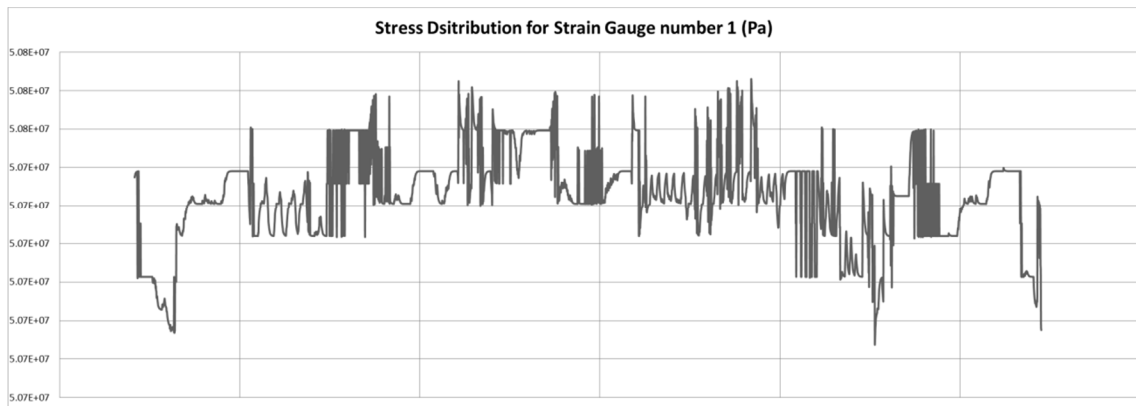
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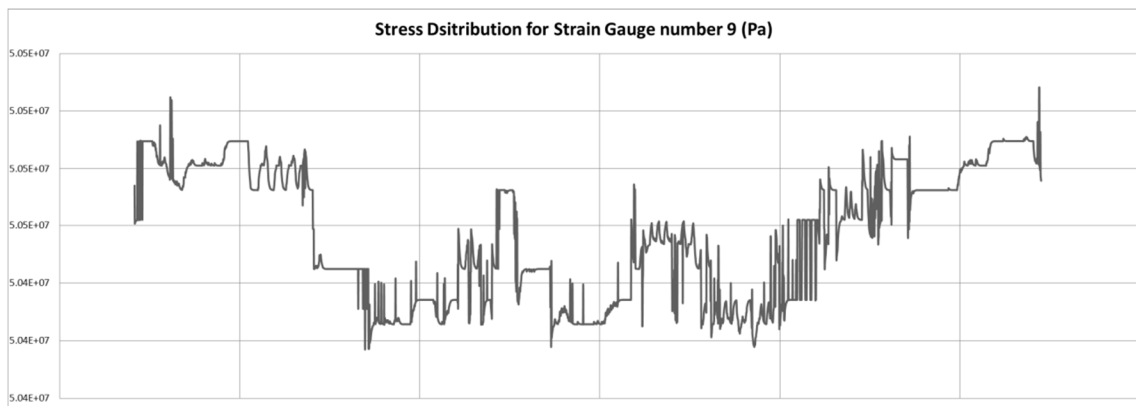
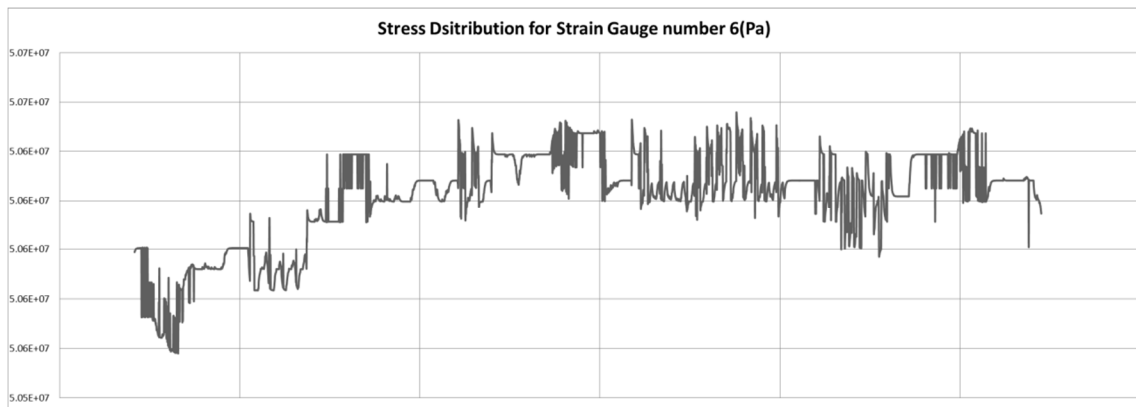
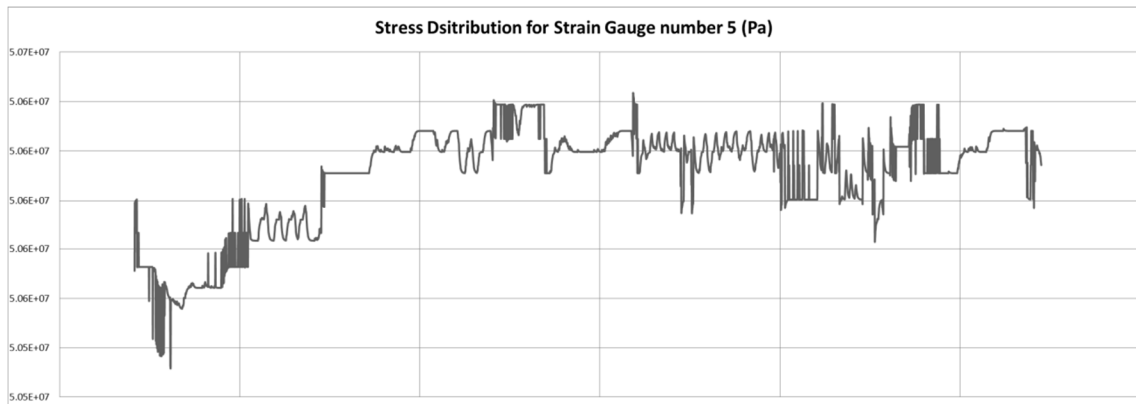
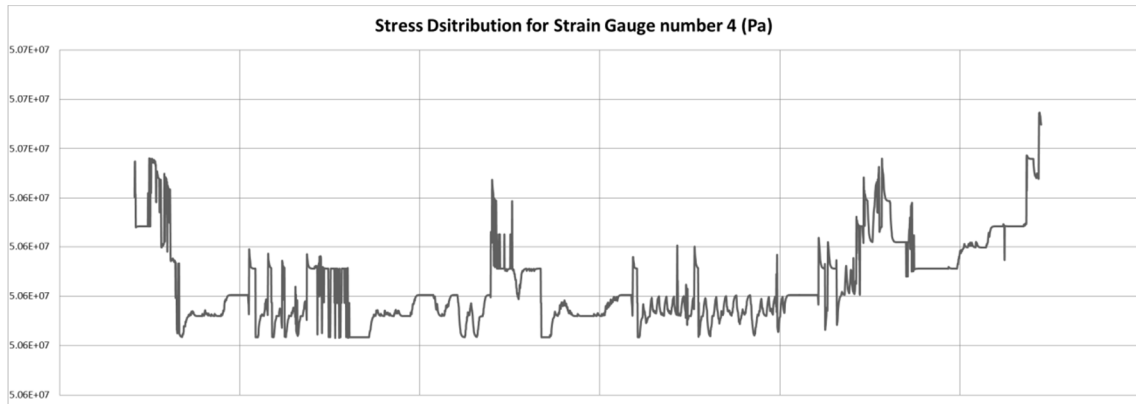


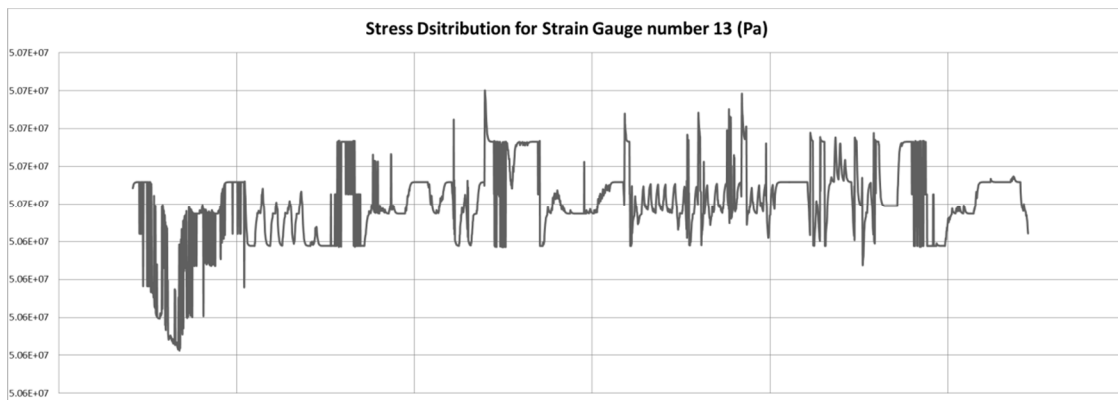
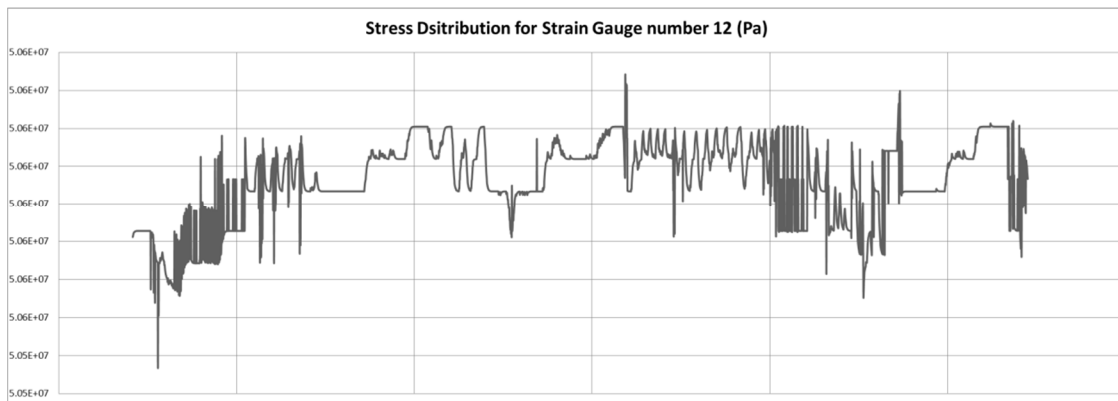
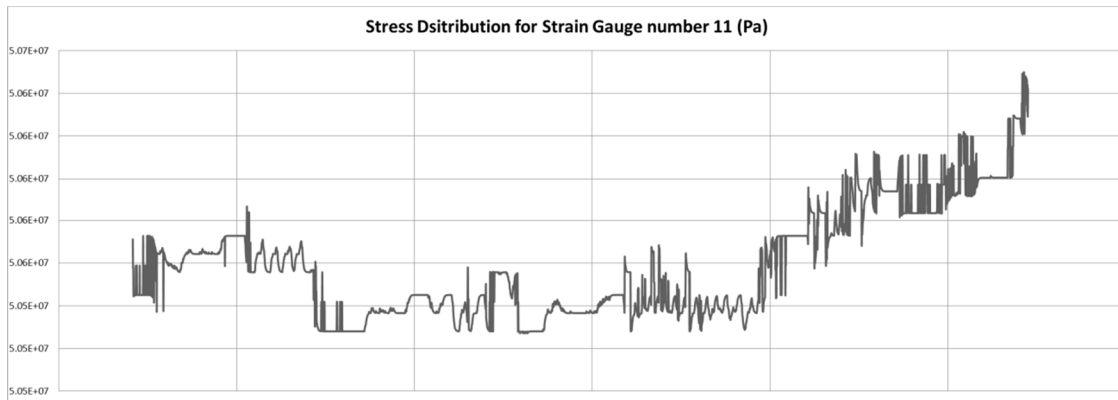
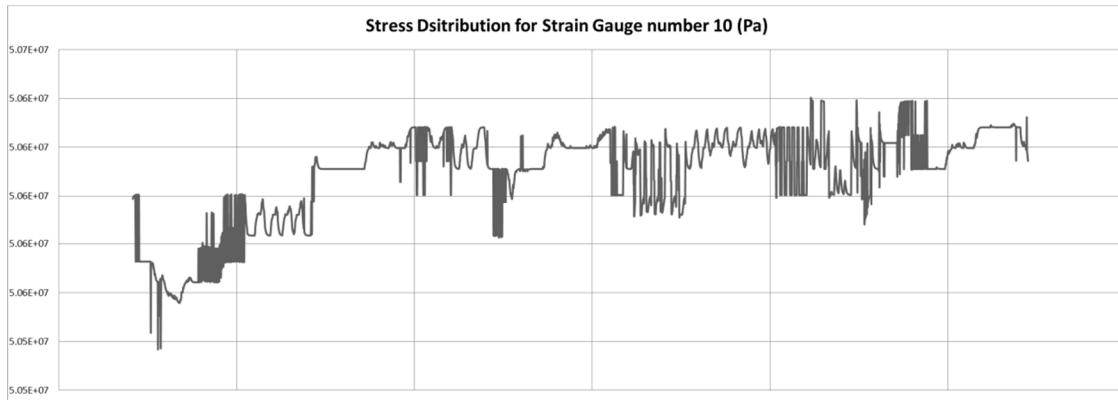
Amplitude of displacement variation according to Fix-Link connections-joints installation analyzed by Nonlinear Direct-Integration Time-History Analysis for January 2014-load application

Appendix B

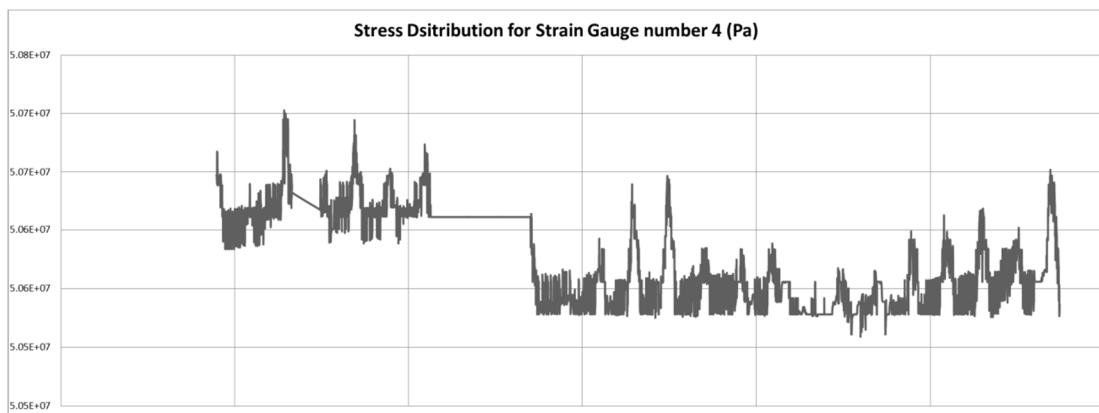
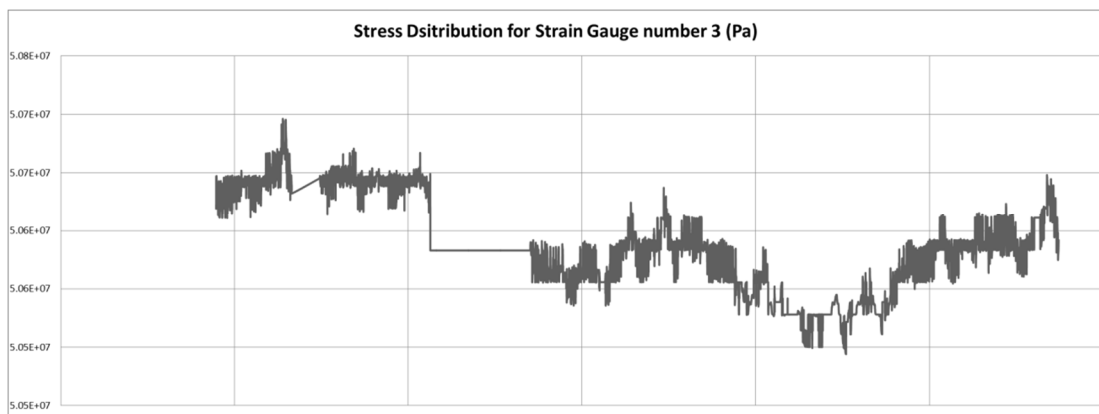
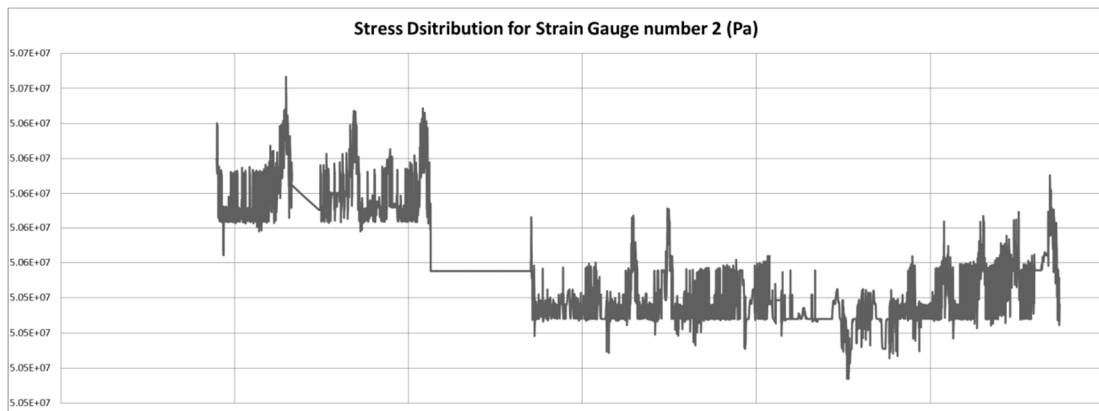
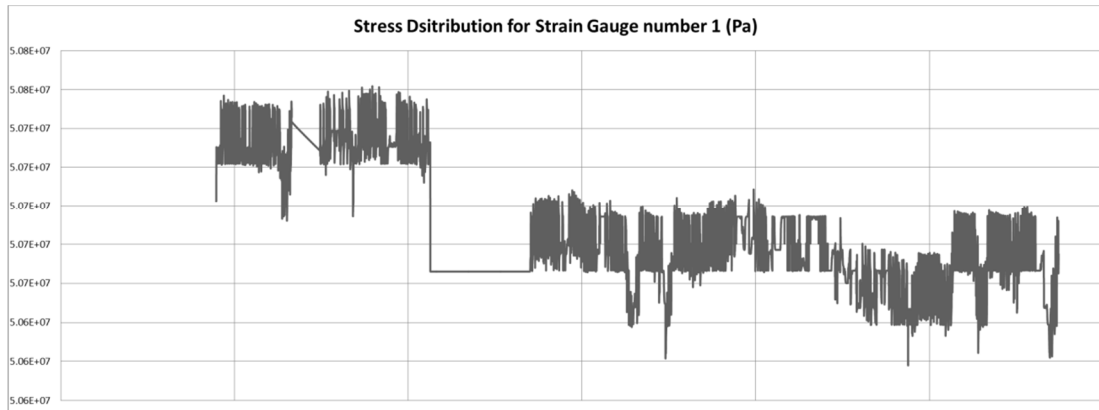
Stress distribution

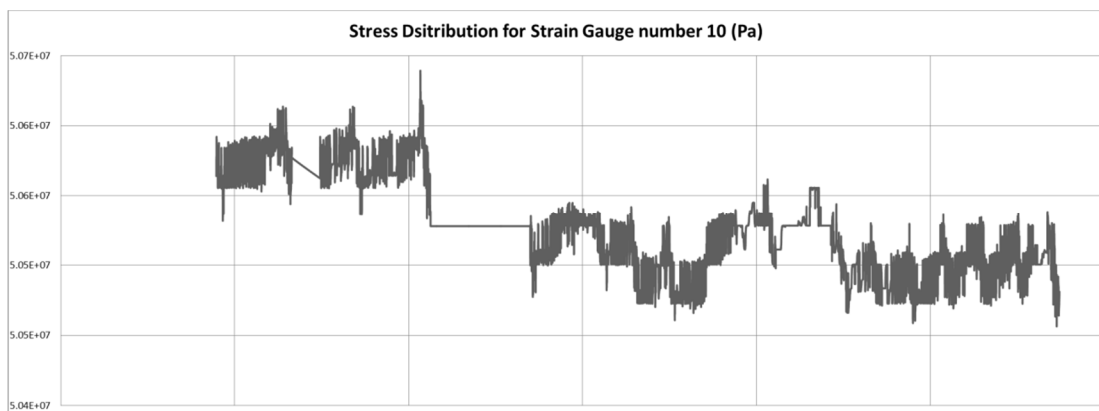
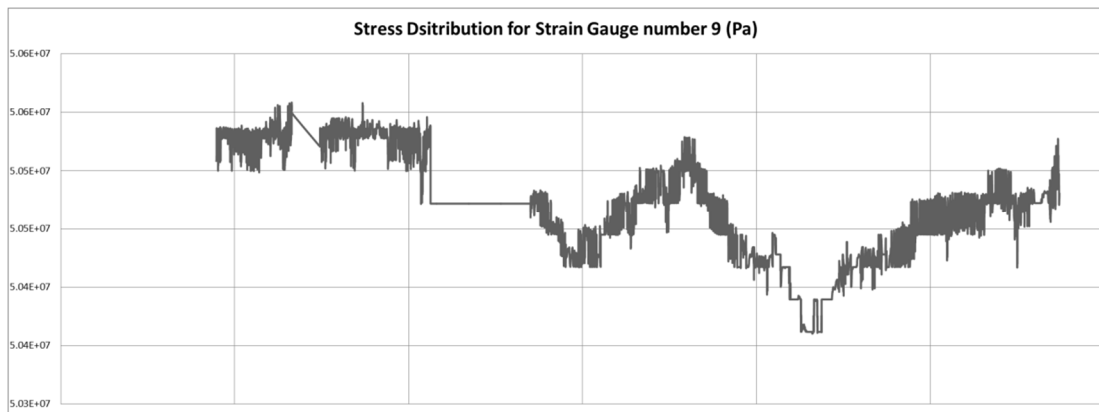
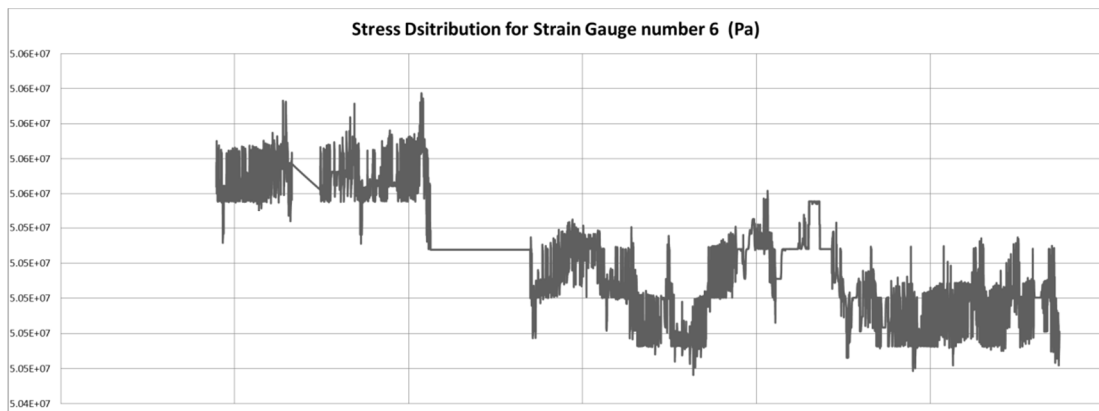
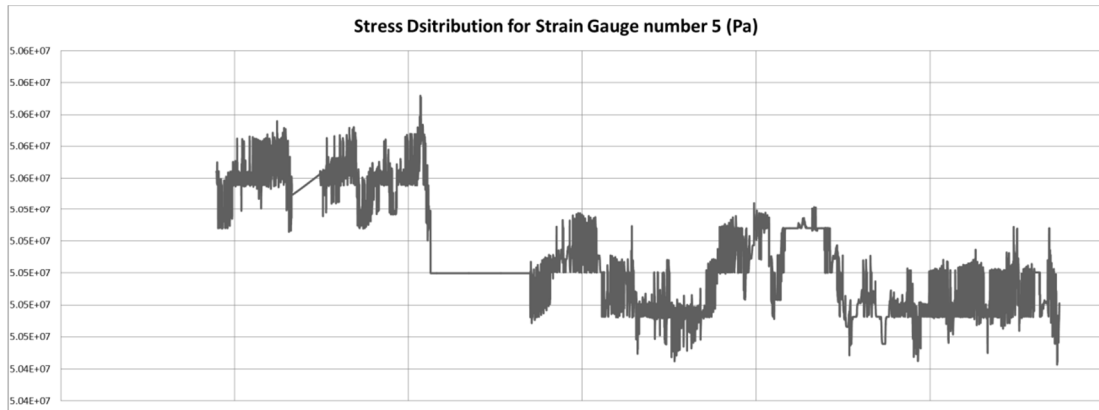


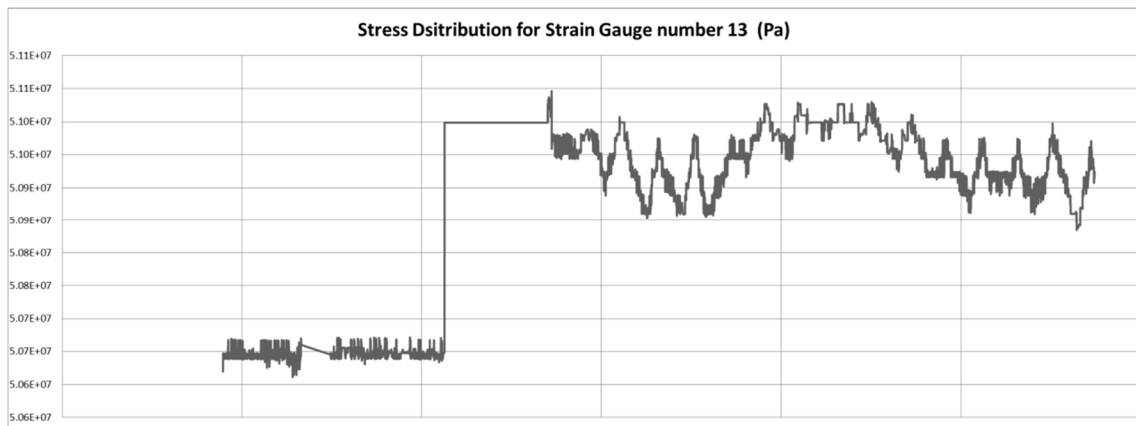
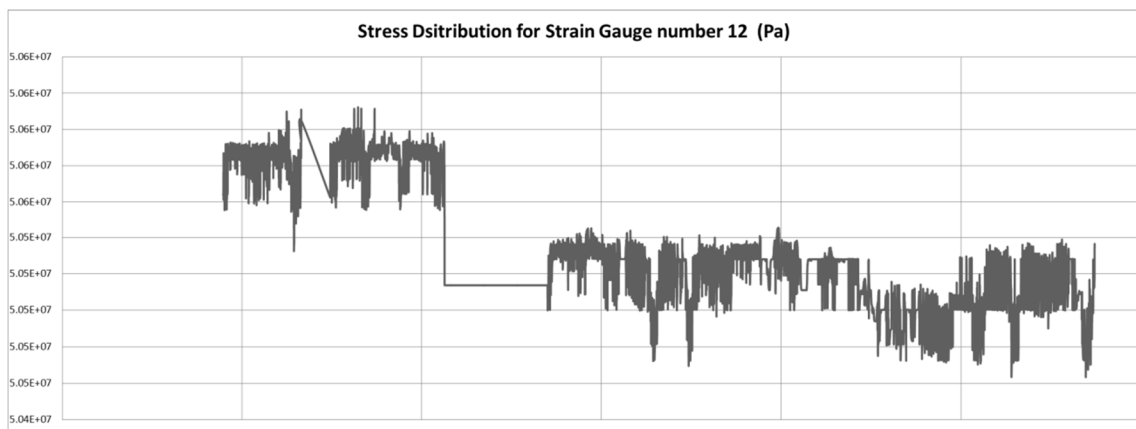
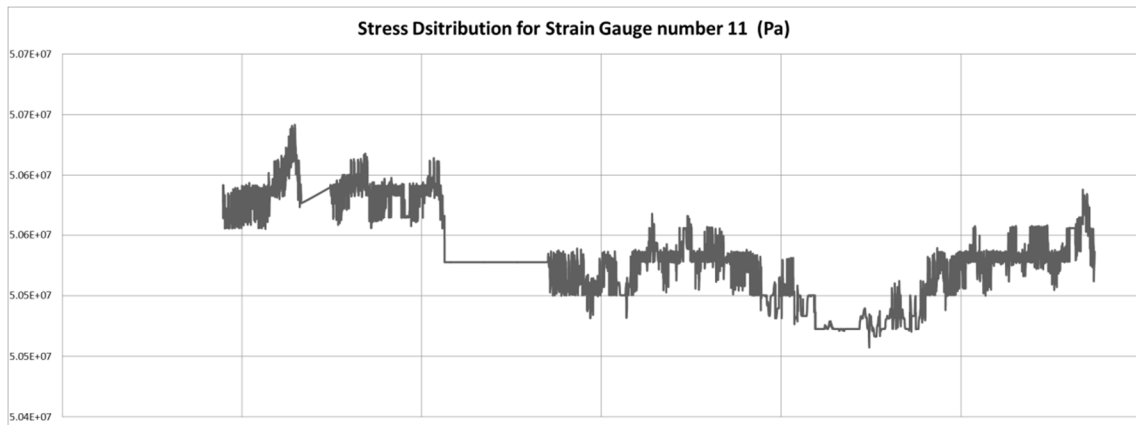




Periodic scattering of stress distribution (Pa) on January for 11 half-bridge strain gauges







Periodic scattering of stress distribution (Pa) on February for 11 half bridge strain gauges