Study of Impacts of Transportation on PV Modules

Submitted in partial fulfillment of
the requirements for the degree of

Master of Technology
(Microelectronics)

by

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Declaration

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Date: 30 June, 2021

Abstract

This work aims to understand the challenges faced by the photovoltaic (PV) industry in handling and transporting PV modules and bring solutions to the challenges. IEC 62759-1:2015 standard suggests to use ASTM D4169 Assurance Level-II for the laboratory simulation of PV module transportation. Köntges et al., reported that the ASTM D4169 standard fits the PV module transportation data from Europe well. Singh et al. reported in 2007 that the Power Spectral Density (PSD) profile of transportation vibration obtained from various vehicles in Indian roads were not compliant to ASTM D4169 standard. This work also attempts to devise a PSD profile suitable for the Indian road conditions.

For this study, transportation vibration data was collected from PV modules placed in different types of pallets, during transportation. PSD profiles were generated from the vibration data and benchmarked with the standards. The vibration profiles obtained for the PV module transportation on Indian roads were not fitting with the ASTM D4169 Assurance Level II, the main reference of IEC 62759-1:2015. The vibration levels were severe than ASTM D4169 for the lower frequencies. For the vertical placement of PV modules inside the pallet, it was found that the vibrations along the axis perpendicular to the module plane were severe in mid-frequencies (10-20 Hz). Hence, it is recommended to incorporate the laboratory simulation of the lateral/longitudinal vibration for PV module pallet in the IEC62759 standard. An electronic system has been developed to collect bulk amount of vibration data during the transportation of PV modules. The findings are important for the development of the vibration test profiles for road conditions in India and elsewhere.

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Chapter 1

Introduction

1.1 Motivation

This work focuses on understanding and solving the challenges faced by the photovoltaic (PV) industry in handling and transporting PV modules. After the manufacturing process, PV modules undergo manual handling and transportation before installation. Microcracks are one of the major causes for the power degradation in photovoltaic (PV) modules deployed in India [1]. Many large PV power plants in India are located in remote areas due to low land cost. The quality and condition of roads, leading to these locations are often poor. IEC 62759-1:2015 [2] suggests to use ASTM D4169 [3] Assurance Level-II for the laboratory simulation of PV module transportation. The vibration profiles are generated experimentally and most of these experiments are conducted in European and North American countries [4]. But the Indian road conditions seem to be different from Europe and North America. Hence the major aim of the work is to come up with a transportation vibration test profile suitable for Indian road conditions. This can be achieved by collecting transportation vibration data during PV module transportation and generating the Power Spectral Density profile from the collected data. This would enable the comparison of the vibration profile with the different international standards mentioned in IEC62759, including the main reference ASTM D4169. The subsequent section provides a brief overview of the chapters in this thesis.

1.2 Thesis Outline

The next (second) chapter describes different research publications relevant for this thesis. Chapter three explains the research methodology used in the experiments. The fourth, fifth and sixth chapters are about multiple experiments conducted with different industry partners. Chapter seven explains the prototype devised for collecting bulk amount of transportation vibration data. Finally, Chapter eight concludes the thesis with major takeaways from different research works and lists out the future works.

Chapter 2

Literature Review

IEC62759 standard describes simulation of transportation and handling of complete package units of PV modules [2]. It also describes the methods for the simulation of the subsequent environmental impacts of the PV modules. However, the standard does not include pass/fail criteria. The standard can be coordinated with IEC61215 or IEC61646. In this way, single set of samples may be used to perform both the transportation and handling simulation and performance evaluation of PV module design. Figure 2.1 shows the test sequence of IEC62759 for PV modules.

According to the IEC62759 standard, the transportation of PV modules can be simulated by random vibration test. For shipping goods, truck transportation is considered to be the most severe method of long distance transportation. The truck transportation test therefore covers most other means of transportation. The transportation simulation shall be performed in accordance with ASTM D4169, which is the main reference of IEC62759. The vibration profile is shown in Figure 2.2.

In 2016, Köntges et al., investigated how well the ASTM D4169 [3] standard fits the transportation in Europe [5]. The experiment was conducted on 60-cell glass to polymer backsheet modules with a cell size of 15.6 cm X 15.6 cm. All tested modules were stacked vertically in a box or horizontally with sunny side down. The work focused on PV modules transported in the manufacturer packaging and proper securing of the module stack in the truck. The sensor arrangement on both vertically and horizontally stacked pallets are shown in Figure 2.3.

Köntges et al. reported that the ASTM D4169 Truck Assurance Level II was a well-fitting PSD spectrum to simulate the vibration of PV modules in a PV module stack during transportation. The most pronounced power density was found in the range of 11–12 Hz. Figure 2.4 shows the vertical vibration profile obtained from the experiment. The work also reported that the vertical vibration profile would be different for vertical and horizontal placements.

In 2007, Singh et al. investigated the power spectral density profiles of the road and rail transportation in India. The experiments were performed on goods other than PV

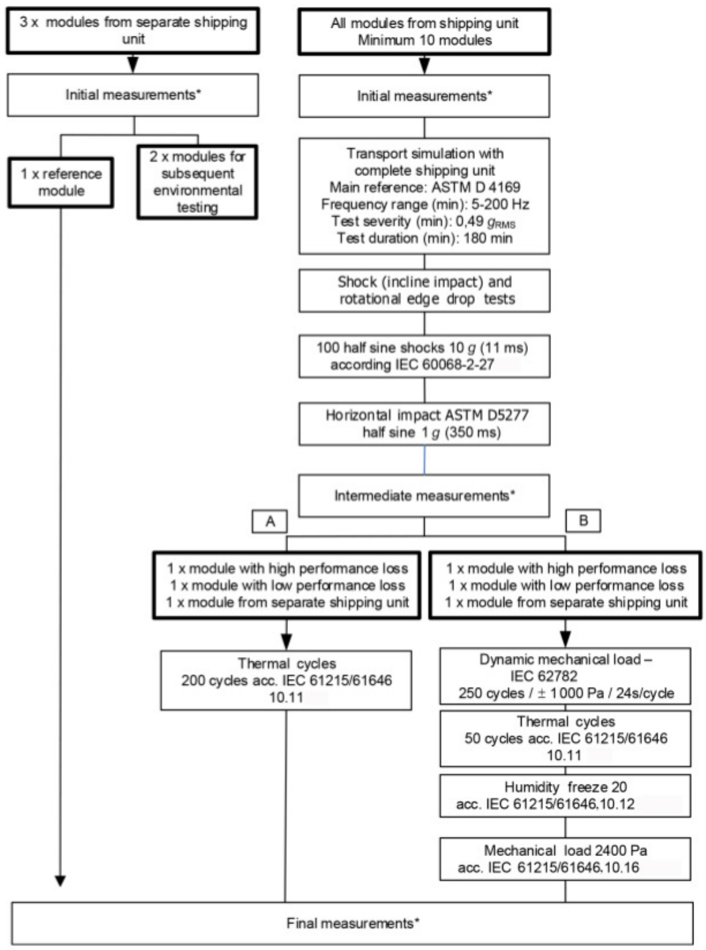


Figure 2.1: Transportation test sequences for PV modules as per IEC62759 [2].

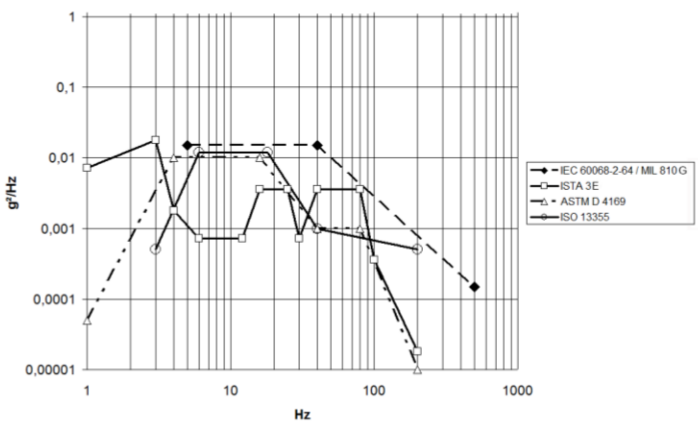


Figure 2.2: Appropriate vibration test profile for transportation testing of PV module as per IEC62759 [2].

modules. For this study, Lansmont SAVER 3X90 accelerometers were used. The recorders were mounted directly on to the vehicle (truck and rail) platform base. The truck was then driven through different roads in India. Figure 2.5 shows the PSD profile of the vertical vibration data obtained from this study. The work reported that the measured vertical vibration levels were more severe than levels used for existing test methods. The

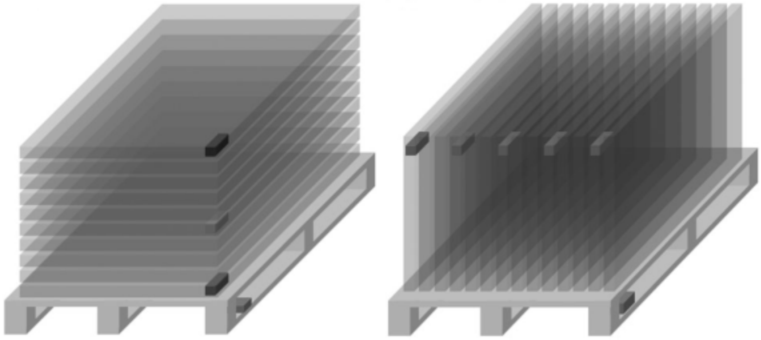


Figure 2.3: The standard positions of the data logger for the acquisition of acceleration data in horizontal and vertical PV module transport stack used by Köntges et al. [5].

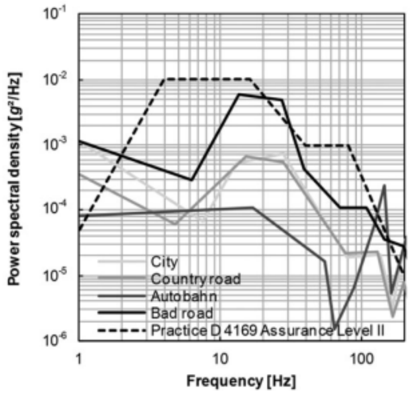


Figure 2.4: Measured reduced power spectral densities in a vertically stacked transport stack reported by Köntges et al. [5].

vibration intensity levels were higher in India as compared to those from North America and Europe. The truck and rail vibration profiles shows excessive lateral and longitudinal movement. Hence, a detailed study is necessary for the laboratory simulation of the transportation of PV modules on Indian roads .

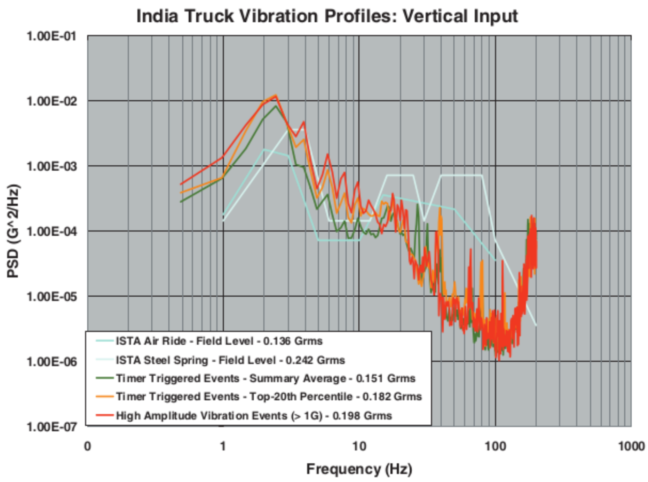


Figure 2.5: PSD profile for the truck vibration on Indian roads along the vertical axes reported by Singh et al. [4].

Chapter 3

Experimental Methodology

3.1 Introduction

All the experiments were carried out by monitoring different parameters of selected PV modules during transportation, starting from the manufacturing unit and ending at the installation site. The experiment starts with initial measurements, including EL imaging and IV tracing. PV modules would be selected randomly from the pallet. There are different varieties of PV module pallets available in the market. The number of PV modules in a pallet could vary from 2 to 30. In each pallet, 2 to 9 PV modules would be selected to keep under observation. The number of modules for observation is limited by the number of sensors available. Three EL images would be taken for each PV modules selected. One image with a bias current equal to the short circuit current (Isc), another one with 10% Isc and the final image with no bias current (open circuit). EL images were taken using Sensovation cool Samba HR-830 camera. IV tracing of the PV modules would be performed optionally. A quick analysis of the EL images needs to be performed for the selection of the PV modules for mounting sensors. This includes evenly distributing sensors among the PV modules with severe micro-cracks, moderate micro-cracks and no micro-cracks. This would give more insights to the micro-crack generation and/or transformation due the the transportation and handling.

3.2 Instrumentation

Gulf Coast Data Concepts (GCDC) X16-4 accelerometers (Figure 3.1) were used for the experiments [6]. This is a 3-axes accelerometer with ±16g acceleration range. It can sample the 3-axes acceleration data up to 800 Hz. The lifetime of the built-in batteries were limited for few hours. Hence, additional battery packs or power banks were used to extend the lifetime of the data loggers.

The battery pack consists of 10 pieces of 18650 Li-ion Samsung cells connected in parallel with a total capacity of 26 Ah. It was custom made from Robokits.com. It has

Figure 3.1: GCDC X16-4 accelerometers [6].

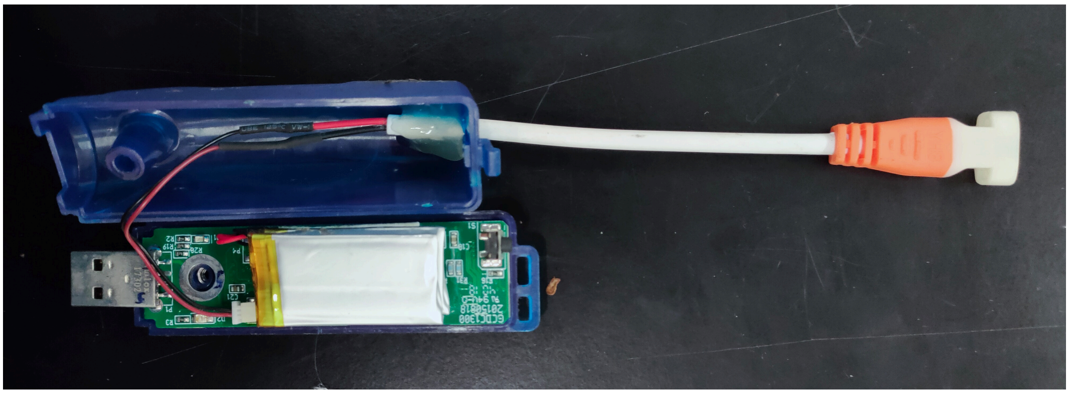


Figure 3.2: GCDC X16-4 accelerometer with connection for battery pack.

two connectors, one for charging (red) and other one for discharging (yellow). Figure 3.2 shows additional slot provided on the GCDC accelerometer board for connecting external battery packs. Figure 3.3 shows the connection between GCDC accelerometer and the battery pack. Voltaic always-on power banks were also used to extend the power supply. Figure 3.4 shows the connection between GCDC accelerometer and the Voltaic always-on power bank.

The range of frequency recommended by ASTM D4169 standard is from 1 Hz to 200 Hz. The data loggers were set to continuously record 3-axes vibration data at 800 Hz sample rate (4 times the required frequency). 3M 950 double sided adhesive tape was used to stick the data logger to the backside of the PV module. The accelerometers would be attached and turned-on before pallet packing. Figure 3.5 shows the GCDC accelerometer attached to the PV module with a battery pack connected. The pallet would be loaded to the truck from the manufacturing unit and unloaded at the installation site. The sensors would be accessible only after opening the pallet. The final measurement would

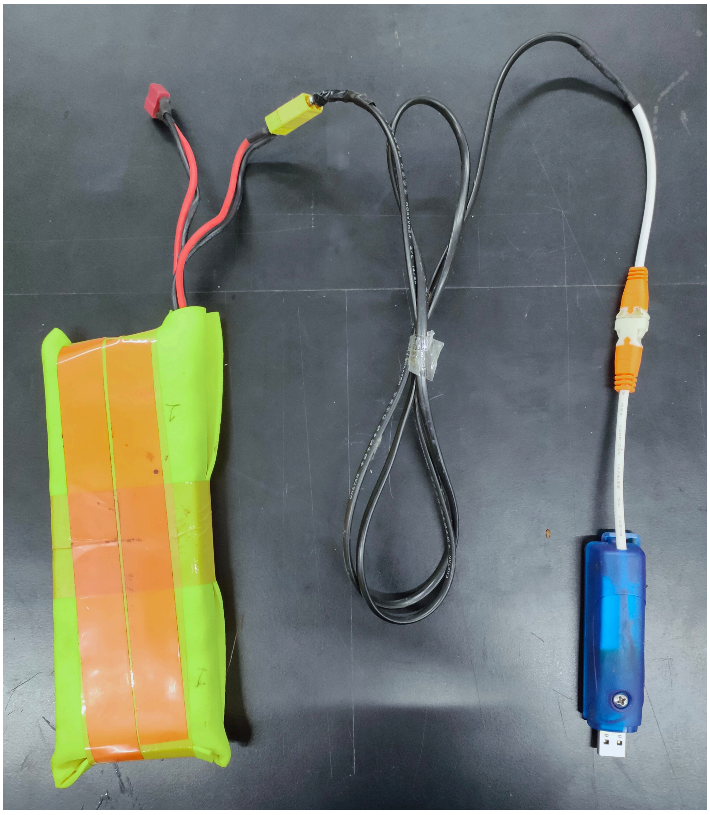


Figure 3.3: GCDC X16-4 accelerometer connected to battery pack.

Figure 3.4: GCDC X16-4 accelerometer connected to Voltaic power bank.

be performed at the site. This would be same as the initial measurements, EL at Isc, 10% Isc and at open circuit and optional IV tracing.

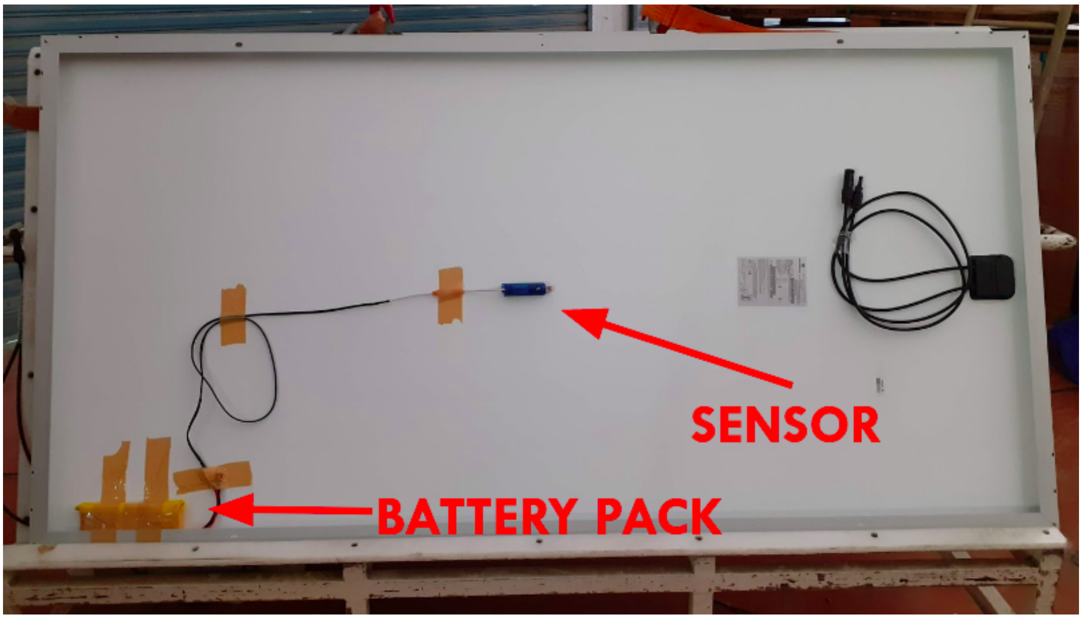
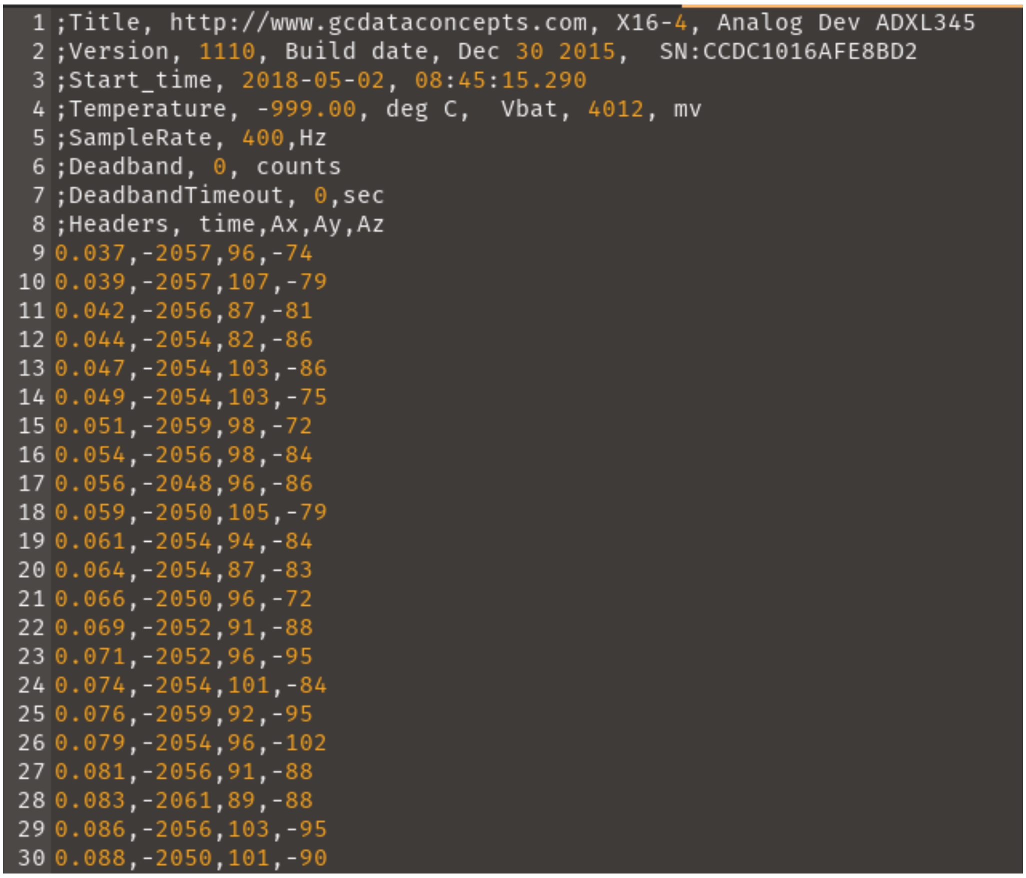


Figure 3.5: GCDC X16-4 accelerometers attached on a PV module with battery pack connected.



```
;Title, http://www.gcdataconcepts.com, X16-4, Analog Dev ADXL345
;Version, 1110, Build date, Dec 30 2015,  SN:CCDC1016AFE8BD2
;Start_time, 2018-05-02, 08:45:15.290
;Temperature, -999.00, deg C,  Vbat, 4012, mv
;SampleRate, 400,Hz
;Deadband, 0, counts
;DeadbandTimeout, 0,sec
;Headers, time,Ax,Ay,Az
0.037,-2057,96,-74
0.039,-2057,107,-79
0.042,-2056,87,-81
0.044,-2054,82,-86
0.047,-2054,103,-86
0.049,-2054,103,-75
0.051,-2059,98,-72
0.054,-2056,98,-84
0.056,-2048,96,-86
0.059,-2050,105,-79
0.061,-2054,94,-84
0.064,-2054,87,-83
0.066,-2050,96,-72
0.069,-2052,91,-88
0.071,-2052,96,-95
0.074,-2054,101,-84
0.076,-2059,92,-95
0.079,-2054,96,-102
0.081,-2056,91,-88
0.083,-2061,89,-88
0.086,-2056,103,-95
0.088,-2050,101,-90
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Figure 3.6: An example raw data collected from GCDC X16-4 accelerometer.

3.3 Power Spectral Density Analysis

From the continuously recorded data, few events were sampled for the analysis in two ways, signal-triggered events and time-triggered events. Signal triggered data would be collected when the magnitude of the vibration data crosses the threshold of 1.5g (15 m/s^2). The sample consists of 2 sec data, starting from 1 sec before triggering. This means that each vibration data sample would consists of 1 sec of pre-triggered data (before triggering) and 1 sec of post triggered data. This would make sure that the peak of the vibration would be at the middle of the event. In case of time-triggered events, a vibration data sample of 2 seconds duration were sampled once in every 10 minutes. This methodology was adopted from Singh et al. [4]. Figure 3.6 shows an example of the raw data collected from GCDC X16-4 accelerometers.

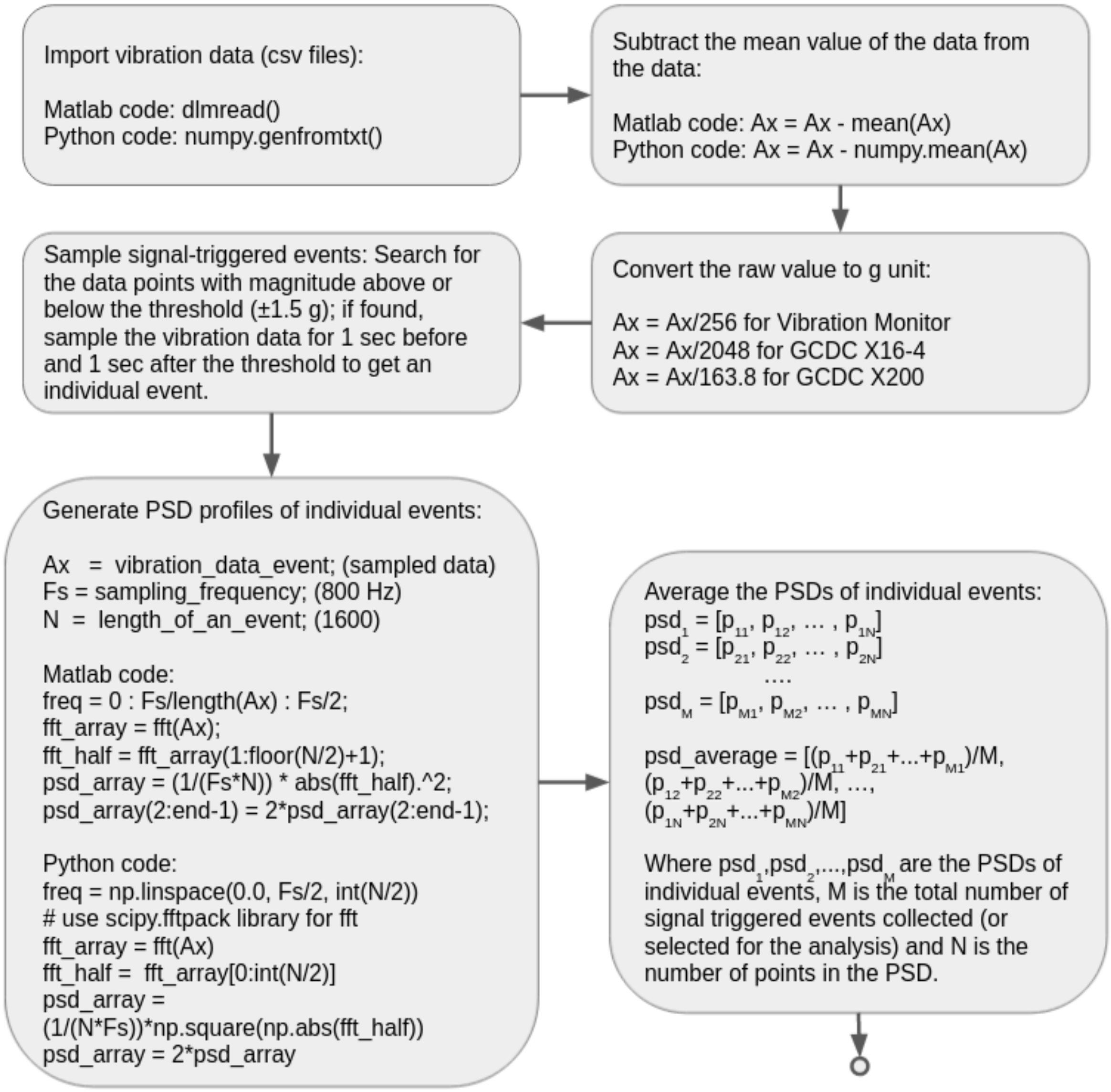


Figure 3.7: Flow chart explaining PSD plot generation (part 1 of 2) [7].

Transportation vibration data were analyzed using Power Spectral Density (PSD) profiles. From the continuously recorded data, static data files (when the vehicle was not travelling) were removed. This can be performed by viewing the entire data in the time domain and manually separating the files where the truck was travelling and stationery. This is not important when signal-triggered events were sampled. Signal-triggered and

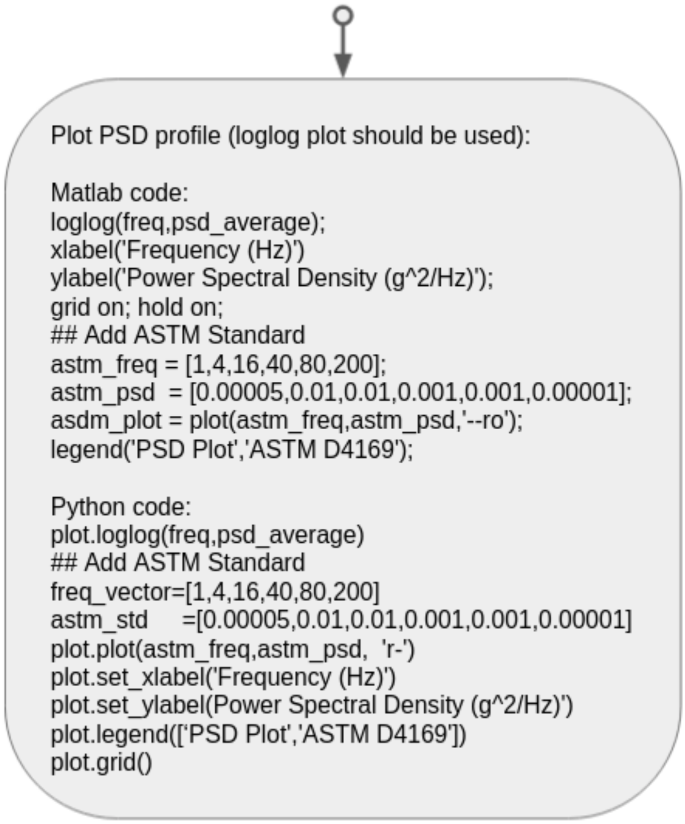


Figure 3.8: Flow chart explaining PSD plot generation (part 2 of 2).

time-triggered data of X, Y and Z axis were cropped from the vibration data. The number of events would depend upon the parameters like duration of the travel, severity of the vibration, etc. PSD describes the distribution of power into frequency components composing that signal. Figure 3.7 and 3.8 shows a flow chart that explains the procedure for plotting PSD profile [7]. Mathematically it can be calculated by taking the Fast Fourier Transform (FFT) of the event and squaring it, followed by dividing it by the total number of data points and the sampling frequency. After taking the PSD of the individual events, they averaged to get the final PSD profile. More detailed information on the PSD calculation is available with the documentation of the program for plotting PSD profiles from the vibration data.

3.4 An updated methodology

In case of time-triggered samples collected when the truck was stationary, it does not make any sense to consider that event for the analysis. Hence another method that may be considered for the analysis would be selecting the events based on the root mean square (RMS) value of the vibration data (G_{RMS}). The RMS is defined as the square root of the mean square (the arithmetic mean of the squares of the vibration data). G_{RMS} can be calculated using the formula,

$$\sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \tag{3.1}$$

where 'x_i' is the acceleration values of an event and 'n' is the length of the event.

This method was explored in the latest python code developed for the data processing. More details about this analysis can be found in Chapter 7. In Chapters 4 and 5, the analysis was performed with all the signal-triggered and time-triggered events which were sampled from the continuously recorded acceleration data. But this includes the time-triggered events which may not be severe enough to be included in the analysis (for example, a time-triggered event captured when the truck was stationery). In Chapter 6, this updated methodology was used. Only the signal-triggered samples were considered in the analysis. All the PSD profiles were compared with the ASTM D4169 Assurance Level II, which is the main reference of IEC62759. Next chapter describes a preliminary attempt to collect vibration data from PV modules during transportation.

Chapter 4

Impact of Transportation on Indian Roads, on PV Modules

4.1 Introduction

An experiment was conducted that aims to understand how well the ASTM D4169 Assurance Level II standard for the laboratory simulation of the vibrations experienced by PV modules during transportation, prescribed in IEC62759-1:2015, emulate the transportation conditions in India. For this study, transportation vibration data was collected from the field for standard 20 module pallet which are commonly used for large scale applications and from cassette type of packing which contains PV modules and are suitable for low volume residential applications.

4.2 Experimental methods

4.2.1 PV Module Packaging Methods

Multi-crystalline silicon PV modules of size 1.96 m X 1 m with 72 cells were used in this study. Two types of module packages were used. First one was a standard PV module pallet packing consisting of a wooden pallet as the base, followed by a thick cardboard as a damper. 20 PV modules were placed vertically on top of the cardboard. The sides aligned to the plane of the modules were secured with cardboard sheets at the ends of the package. Subsequently the package was wrapped in plastic sheets. All four corners of the package were secured by thick cardboard sheets. The packet was then secured by plastic straps. This packaging method, shown in Figure 4.1, is widely used for transporting PV modules to large power plants.

The second type of packing used was Cassette type of packing which contained only two modules, placed with front glass facing each other. There would be a thick cardboard in between the two to separate them. This would be covered on the top and bottom

Figure 4.1: A standard pallet containing 20 PV modules.

using cardboards and tightened with plastic straps or adhesive tapes, as shown in Figure 4.2. This packaging method is mainly followed for transporting modules for low volume residential applications.

Figure 4.2: A stack of 10 cassette type of packages containing 2 modules each.

4.2.2 Instrumentation

Two GCDC X16-4 accelerometers with extended battery backup were used for this study [6]. The accelerometers were attached to the center of the backsheet with double sided tapes. Samples of vibration data (events) were collected in two ways: (i) time-triggered events in which vibration data sample of 2 seconds duration were recorded once in every 10 minutes, and (ii) signal-triggered events in which the events are triggered when the acceleration value exceeded 1.5g. Two different experiments were conducted to understand the vibrations experienced by the modules during transportation. In the first experiment (Experiment-1), sensors were placed inside the pallets and cassettes. 2 pallets of 20 modules each and 2 cassette packages of 2 modules each were transported in a 6-wheel leaf-spring truck (see Figure 4.3). In the second experiment (Experiment-2), sensors were placed inside 2 cassette packages and there were 22 cassette packages transported in the truck (see Figure 4.4).

4.2.3 Experiment-1

Experiment-1 started from the manufacturing unit of Waaree Energies Ltd., Sachin, Gujarat to NCPRE Module Lab, IIT Bombay, Mumbai, Maharashtra, covering a distance of 270 km. 6 modules were under observation, and accelerometers were attached to 2 of those modules, one each in the bottom pallet and in the cassette, before packing. The pallets were loaded to the truck using a forklift. Cassette packets were handled manually. EL images of the 6 modules were taken before and after transportation to quantify the damages due to transportation and handling.

This experiment was then repeated by keeping one more sensor on the base of the truck to collect the vibrations generated on the truck base. It was useful in understanding the vibrations generated from the trucks on Indian roads, during PV module transportation. This vibration data would be independent of the packaging methods.

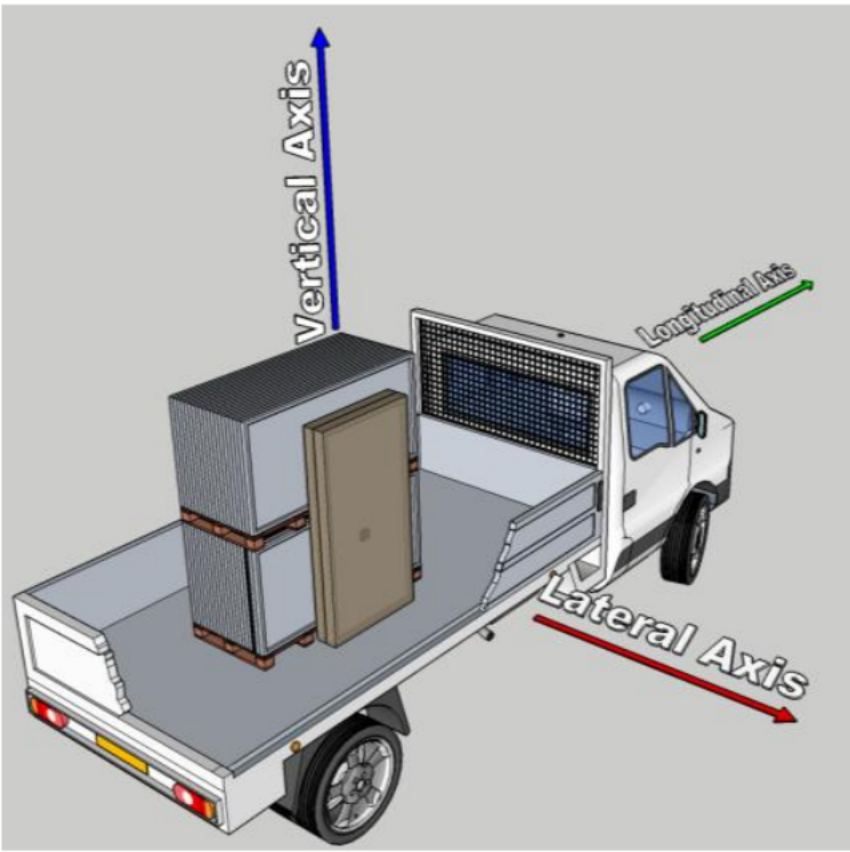


Figure 4.3: Experiment-1 setup: 2 standard pallets of 20 modules (Accelerometer placed on the module highlighted with a different shade, in the bottom pallet, 3rd from right) and 2 cassette packages of 2 modules with a module attached with an accelerometer.

4.2.4 Experiment-2

In Experiment-2 the transportation was from NCPRE Module Lab, IIT Bombay, Mumbai, Maharashtra to the manufacturing plant of Waaree Energies Ltd., Sachin, Gujarat covering 270 km. All modules were packed in cassette type of packing. Out of 22 cassette packages, 19 were kept vertically with the module plane perpendicular to the lateral axis of the truck and 3 were kept with the module plane perpendicular to the longitudinal axis of the truck. All cassettes were handled manually before and after transportation. 6 modules were under observation, out of which three modules already had less than 3 micro-cracks and the other three had more than 3 micro-cracks. Accelerometers were attached to two modules out of the 19 cassettes. EL images of the modules were taken before and after transportation.

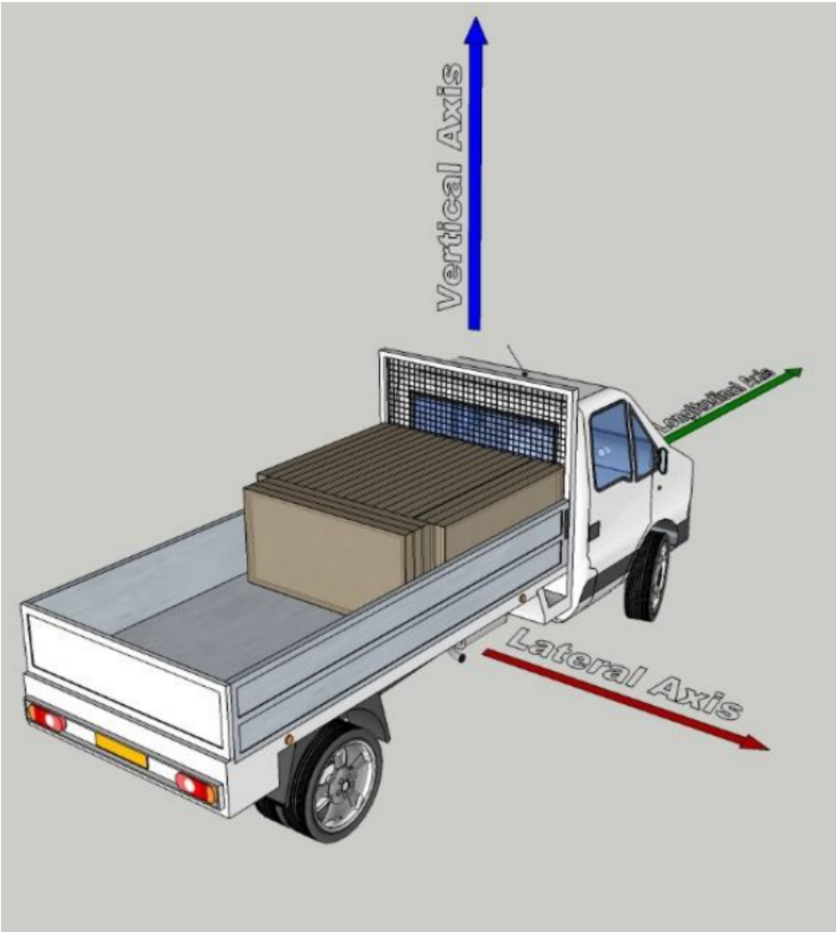


Figure 4.4: Experiment-2 setup: 22 cassette packages of 2 modules with accelerometers attached on 2 modules.

4.3 Results and Discussions

In Experiment-1, the EL images before and after transportation were compared to detect micro-crack generation during transportation. None of the modules in the pallet developed micro-cracks during transportation and handling. In the case of cassette package, one module showed Mode-A crack (hair line crack) in one of the cells [8]. The transportation vibration profile from the accelerometer inside the pallet and on the truck floor were shown in Figure 4.5. The events were sorted in ascending order, i.e. from the most severe vibration event to the least severe event. PSD of the vibration events were computed and the average value of PSD of the most severe 30% of the events was plotted in Figure 4.5. It was seen that the magnitudes of low frequency (1-3 Hz) vibrations were higher than the reference ASTM D4169. This was same for the vibration collected from the floor of the truck. The vertical vibration PSD profile (Figure 2.5) reported by Singh et al. [4] also shows similar trends. He reported a peak at 1-3 Hz range in the PSD profile of the vertical vibration data. The pallet was able to absorb the high frequency vibrations, above 10 Hz.

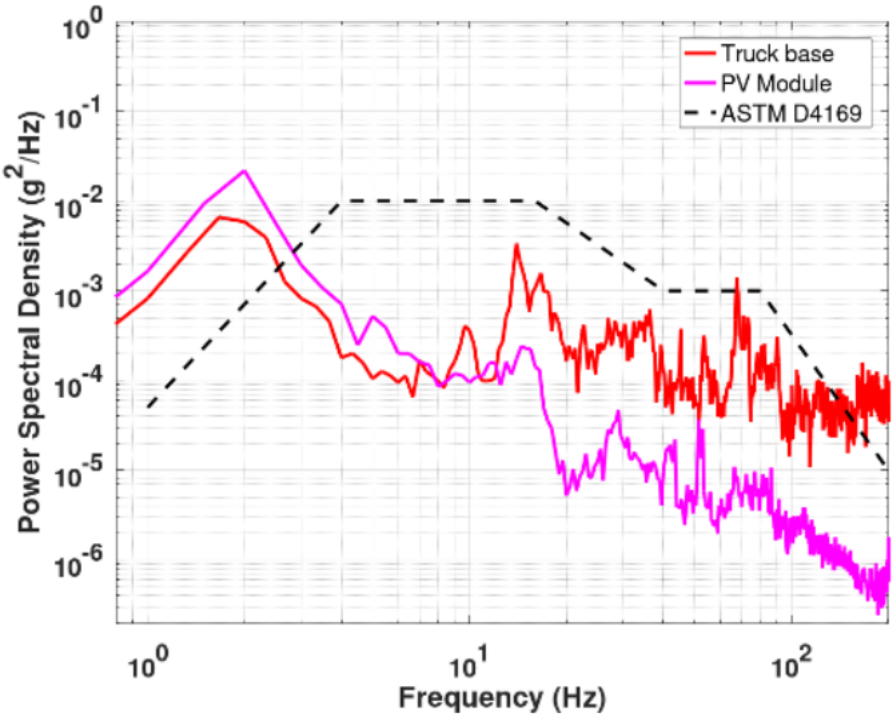


Figure 4.5: PSD of vertical vibration data collected from a PV module inside the pallet and from the truck floor in Experiment-1.

In Experiment-2, the PSD of vertical, lateral and longitudinal vibration are shown in Figure 4.6. The vertical vibrations at low frequency were seen to be higher than specified in the ASTM standard. A peak at around 15 Hz was also seen in the PSD profile of lateral vibrations. Similar results were observed for the pallet package transportation where the module plane was perpendicular to the lateral direction. From this observation, we may understand that using a general transportation standard like ASTM D4169 is inadequate for PV applications. Not only the vertical axis vibrations, but the vibrations from the axis that was perpendicular to the module plane also gives mechanical stresses to PV module. Many PV module manufacturers in India are preferring vertical placement of PV modules inside the pallet to avoid the severe vibrations along the vertical axis. In that case lateral axis vibration may be included for the laboratory simulation of PV module transportation.

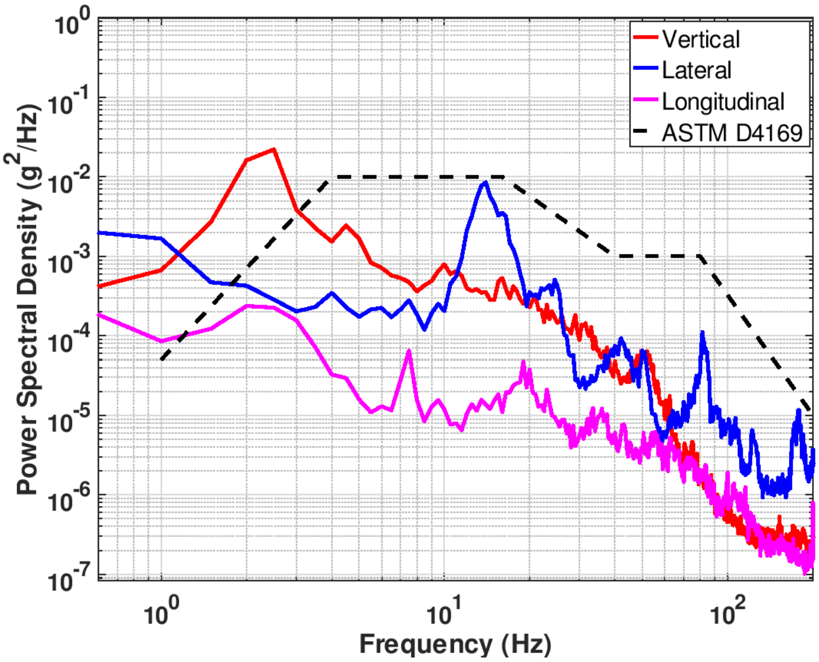


Figure 4.6: PSD of vertical, lateral and longitudinal vibration data collected from a cassette packing for Experiment-2 (A new crack generation and 6 crack transformations were detected from EL images).

Figure 4.7 shows the histogram of accelerations recorded for manual handling of the cassette packing for the Experiment-2. In IEC 62759 standard, it is prescribed to conduct a half sine shock test as part of the transportation simulations at 10g. The histogram clearly shows that the handling exerts heavy amplitudes of acceleration on the modules (up to 15g).

5 modules out of the 6 under observation in Experiment-2, showed at least 1 micro-crack after transportation. Comparison of the EL images of one of the 6 modules before and after transportation are shown in Figure 4.8. The nature and count of cracks are listed in Table 4.1. In this experiment, most of the modules were placed with its plane perpendicular to the lateral axis of the truck. This would lead to an increase in lateral vibrations experienced by the modules.

4.4 Summary

The vibration profile obtained for the PV module transportation on Indian roads are not fitting with the ASTM D4169 Assurance Level II, the main reference of IEC 62759-1:2015. The vibration levels are severe than ASTM D4169 for the lower frequencies (1-3 Hz). The PSD plots for vertical placement of modules shows immoderate lateral vibrations. Manual handling of modules was found to result in high values of acceleration, up to 15g. The

Table 4.1: List of cracks observed in experiment-2 (Cassette type packing).

Module No.	List of cracks generated or profile propagated during transportation and handling	PSD Profile
1	1 new Type-A crack and 2 new Type-B cracks were generated.	Not available.
2	No cracks generated.	Not available.
3	37 new Type-A cracks and 7 new Type-B cracks were generated (The module had 4 Type-A cracks before transportation).	Vertical vibration profiles available, not shown.
4	6 new Type-A cracks were generated (The module had 4 Type-B cracks before transportation).	Not available.
5	1 new Type-A crack was generated; 2 existing Type-A cracks were transformed into Type-B and 4 existing Type-B cracks were transformed into Type-C (The module had 23 Type-A cracks and 30 Type-B cracks before transportation).	Vertical, lateral and longitudinal vibration profiles (see Fig. 6).
6	2 new Type-A cracks were generated.	Not available.

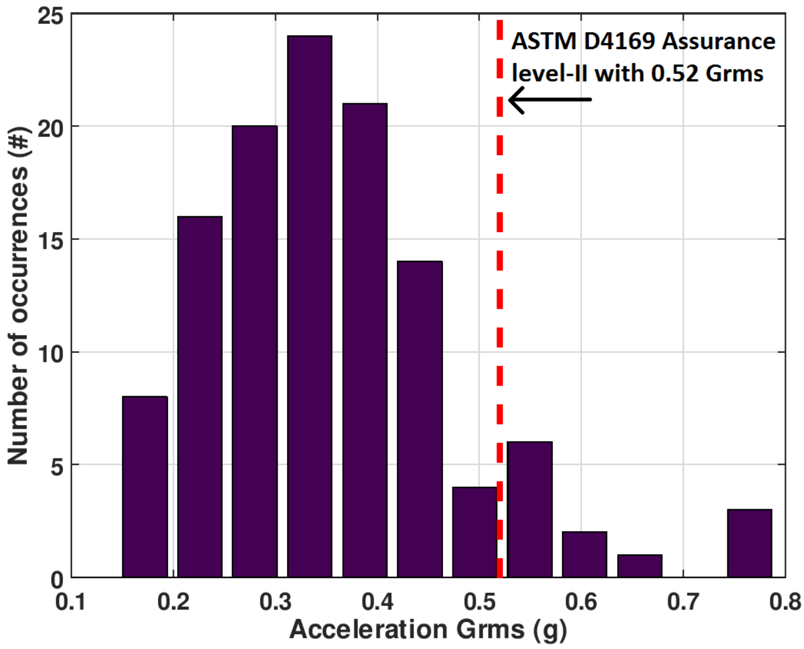


Figure 4.7: Histogram of the accelerations from Experiment-2 for the manual handling of a cassette packing.

standard pallets were safer for the transportation of PV modules through good roads, but the cassette packing was not sufficient to absorb the impacts of transportation. For vertical placement of PV modules inside the pallet, it was found that the lateral vibrations were severe in mid-frequencies (10-20 Hz), hence may be included in the laboratory simulation of PV module transportation. Next chapter describes another experiment that specifically focus on the lateral vibrations.

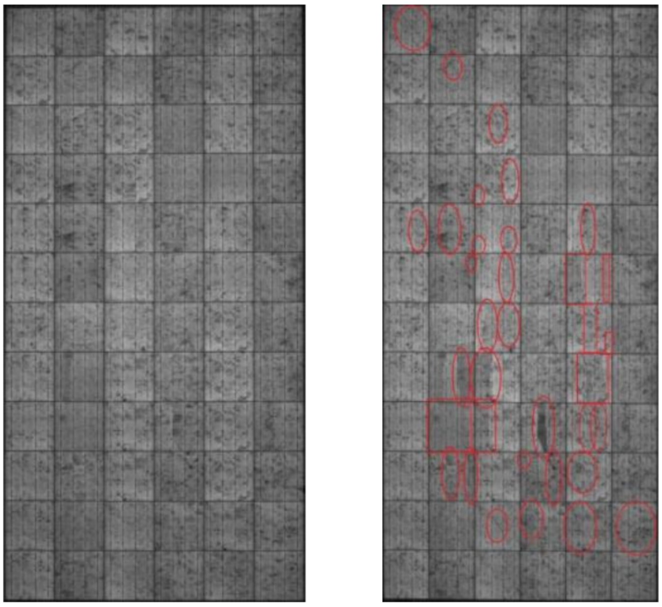


Figure 4.8: EL Images of module-3 from Experiment-2 before (left) and after (right) transportation. The shapes with red outline enclose the cracks generated during transportation and handling.

Chapter 5

Lateral vibrations experienced by vertically placed PV modules in the pallet during transportation

5.1 Introduction

Previous experiment on transportation of PV modules on Indian roads showed that the vibration profile obtained from Indian roads was not compliant with the ASTM D4169, the main reference of IEC62759-1:2015 [2]. Also, the lateral vibrations which were oriented perpendicular of the module plane were severe. IEC62759 recommends to conduct the same series of tests for horizontally and vertically stacked PV modules. Many of the PV module manufacturers in India prefers vertical placement of PV modules to avoid the severe vertical vibrations acting directly on the axis perpendicular to the module plane. For a vertically placed PV module pallet, using a general standard like ASTM D4169 may not be adequate for the laboratory simulation of the PV module transportation. Hence, an experiment was conducted to study the severity of lateral vibrations generated during the transportation of vertically placed PV module pallets. This work focus on the vibration profiles obtained from PV modules placed at different places in the vertically stacked pallets.

5.2 Experimental methods

5.2.1 PV Module and Pallet

Crystalline silicon PV modules of size 1.96 m X 1 m with 72 cells and maximum power of 380 W were used for this study. A standard pallet containing 25 PV modules was used. All the modules were placed vertically in the pallet (Figure 5.1). The standard pallet consists of a wooden pallet as the base, followed by a thick cardboard sheet. All four corners of the PV module were secured with thin card board corners. They were then placed on the thick cardboard on the wooden pallet. A bottom-open cardboard box was then inserted to secure the modules from all four sides and the top. The final package was then secured by plastic straps. This packaging method is widely used in the PV industry, suitable for transporting PV modules to large volume applications in utility scale power plants.

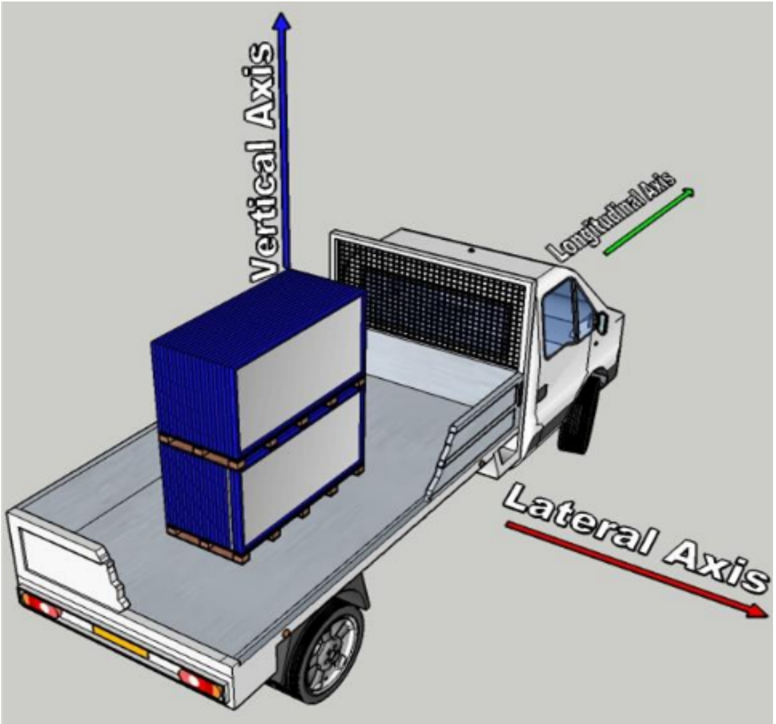


Figure 5.1: Experiment setup: 2 standard pallets of 25 PV modules.

5.2.2 Instrumentation

Seven GCDC X16-4 accelerometers were used for this study [6]. The accelerometers were attached to the center of the backsheet with 3M 950 double sided adhesive tape. The sensors were set to continuously record 3-axes vibration data at 800 Hz sampling rate. From the continuously recorded vibration data, few events were sampled for the analysis in two ways, (i) signal-triggered events in which vibration data sample of 2 seconds duration were recorded when the acceleration value exceeds 1.5g. (ii) time-triggered events in which vibration data sample of 2 seconds duration were recorded once in every 10 minutes. In a pallet, three sensors were placed on the PV modules placed at the center and at both the edges of a pallet (Figure 5.2). Six sensors were distributed in two pallets and the seventh sensor was placed on the floor of the truck. This sensor data would be independent of the packaging method.

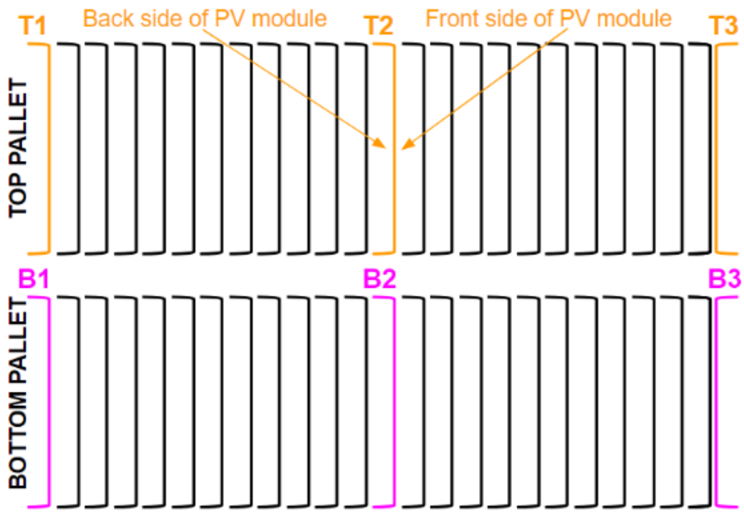


Figure 5.2: PV module arrangement inside the top and bottom pallets. Accelerometers were attached to the PV modules placed at the middle and at both the edges.

5.2.3 Truck Transportation

Four-wheel leaf-spring truck was used for this experiment. The truck travelled around 250 km within the state of Gujarat, India. Individual PV modules were handled manually and the fully packed pallets were handled with a forklift. Two pallets, placed one on top of other were used for this experiment (Figure 5.1). Six PV modules with accelerometers were under observation.

In a pallet of 25 PV modules, 24 were aligned in the same way, front side of the PV module facing backside of another module (Fig. 2). The last module was placed front side facing front side of another module. In Figure 5.1, PV modules T1 and T2 in the top pallet were aligned front side facing backside of another module and PV module T3 was aligned front side facing front side of another module. Similarly, in the bottom pallet, PV modules B1 and B2 were aligned front side facing backside of another module and PV module B3 was aligned front side facing front side of another module. Sensors were attached on B1, B2, B3, T1, T2 and T3.

5.3 Results and Discussions

Vibration data was analyzed using Power Spectral Density (PSD) profiles. Individual PSD profiles were generated for every sampled vibration data event. The final PSD was then generated by taking linear averages of the individual PSDs. The analyzed data was compared with the ASTM D4169 Assurance Level II.

The lateral vibration profiles of all PV modules shows a peak value at around 15 Hz (Figures 5.3,5.4). Similar results were observed in previous experiments. Comparing the PSD profiles of lateral vibrations experienced by the PV modules T1 and T3 shows that the module T2 experienced lesser vibrations compared to module T1. i.e., the vibration

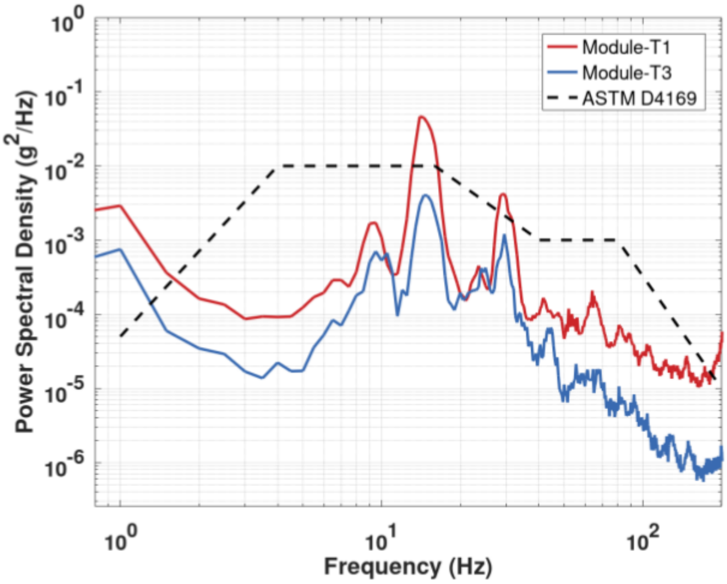


Figure 5.3: Lateral vibration profile of the PV modules T1 and T3.

experienced by the PV module placed glass facing glass was lesser than the vibration experienced by the PV module placed front side facing backsheet (Figure 5.3).

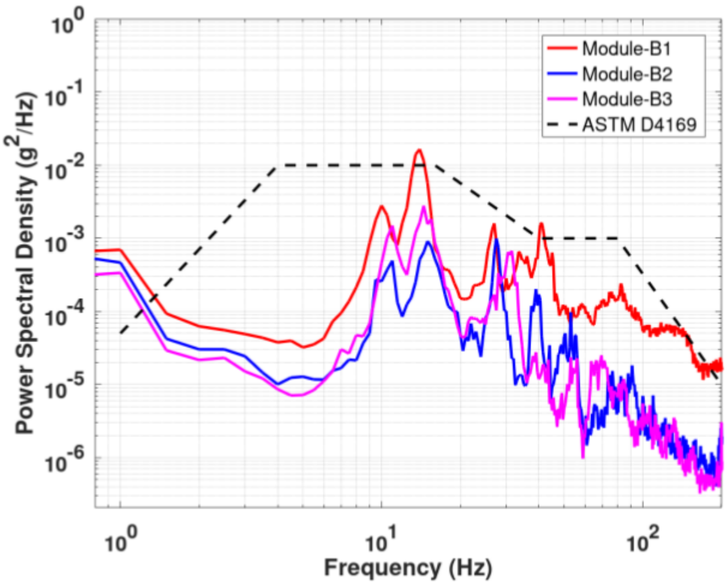


Figure 5.4: Lateral vibration profile of the PV modules B1, B2 and B3.

Lateral vibration data collected from three PV modules B1, B2 and B3 from the bottom pallet were compared together (Figure 5.4). The lateral vibration experienced by the module B1 was the highest, followed by module B3 and the least amount of vibration was experienced by the module B2. It indicates that, irrespective of the orientation, the PV module placed at the middle (where front side was facing backside of another module) experienced lesser vibration compared to the PV modules placed at both the edges.

The vibration data collected from the floor of the truck shows insignificant lateral vibrations compared to that of PV modules (Figure 5.5). The occurrence of peak in the

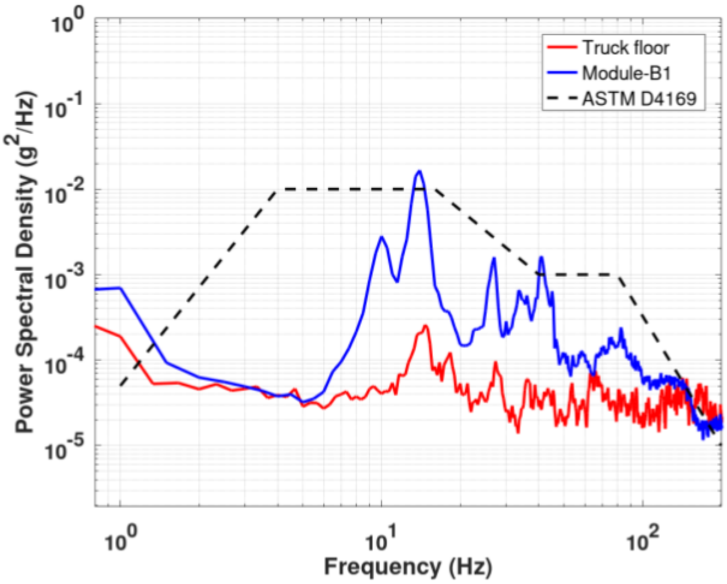


Figure 5.5: Lateral vibration profile of the PV module B1 and the floor of the truck.

PSD profiles of PV modules may be due to the vibration of the PV modules at its natural frequency. Hence, the natural frequency of the PV module may lie in 10-20 Hz range.

5.4 Summary

Lateral vibrations generated during the transportation of vertically placed PV module pallets were seen to be immoderate. The peak in the lateral vibration was sometimes higher than the vertical vibration test profile provided by ASTM D4169, the main reference of IEC62759. It is recommended to incorporate the laboratory simulation of the lateral vibration for PV module pallet in the IEC62759 standard. The natural frequency of the PV module may lie in 10 - 20 Hz frequency range. The PV modules placed front side facing front side of another module shows lesser lateral vibration compared to the module placed front side facing backside of another module. But the module placed at the middle experienced even lesser vibration compared to the PV modules placed at the edges. Next chapter describes another experiment performed to collect vibration data from a field transportation over a longer distance.

Chapter 6

Transportation study over a longer distance

6.1 Introduction

This experiment focused on understanding the shocks and vibrations generated during a field transportation. All the previous experiments were planned and hence the truck, the number of pallets, etc, were different from the actual scenario. The experiment was conducted on two fully packed containers. The transportation started from the manufacturing unit at Bangalore and ended at Hyderabad covering around 800 kms.

6.2 Experiment details

6.2.1 PV Module, Pallet and Container

Crystalline silicon PV Modules of size 1.95 m X 0.99 m with 72 cells and maximum power of 320 W were used in this study. Two containers were used for transporting 35 PV module pallets. One container had wooden floor (Figure 6.1) and other container had metal floor (Figure 6.2). The transportation started from the manufacturing unit of Company X, Bangalore and ended at the installation field at Hyderabad covering around 800 kms. Out of 35 PV module pallets transported, 34 of them were packed with 27 PV modules and 1 of them packed with 18 PV modules. This was just to match their total number of PV modules for shipping. 25 PV modules were kept under observation. These 25 PV modules were distributed in 5 pallets. In these 5 pallets, 5 PV modules which were under observation distributed as two PV modules at both the ends and one PV module at the middle.

Figure 6.3 shows the arrangement of PV module pallets inside two containers. The circle at the top right corner of the images of both containers indicates the driver's side. Each box represent the top view of the pallet. 5 PV modules under observation are

Figure 6.1: Dark room setup made for EL imaging inside the container (wooden floor).

Figure 6.2: PV module pallets loaded inside the container (metal floor).

marked in red. The pallets were handled using a forklift, electric pallet truck and hand pallet truck as shown in Figure 6.6. Figure 6.1 shows the dark room setup for the EL imaging inside a container. Figure 6.4 shows the arrangement of PV modules inside the pallets P1, P4 and P5. Figure 6.5 shows the arrangement of PV modules inside the pallets P2 (bottom) and P3 (top).

6.2.2 Instrumentation

Seven GCDC X16-4 accelerometers [6] with extended battery backup were used (Figures 3.3, 3.4). The accelerometers were attached to the center of the backsheet with 3M 950

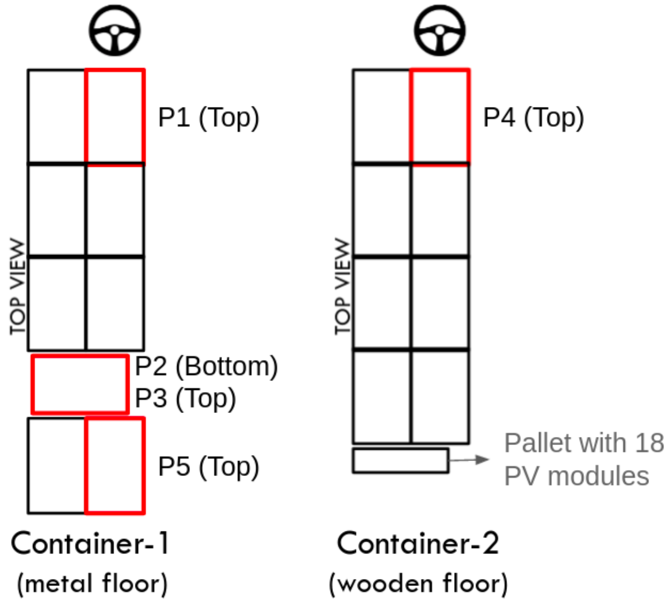


Figure 6.3: Pallets arranged over 2 containers, red boxes indicates the PV module pallets under observation.

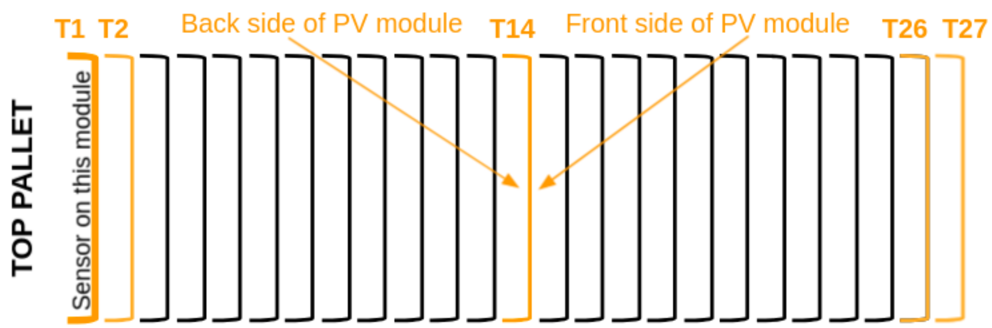


Figure 6.4: Arrangement of PV modules inside the pallets P1, P4 and P5; PV modules colored in yellow represents the PV modules under observation.

double sided adhesive tape. The sensors were set to continuously record 3-axes vibration data at 800 Hz sample rate. Out of seven sensors, five were placed on PV modules and two were placed on the floor of the truck.

6.3 Results and Discussions

EL images taken before and after transportation were compared to detect crack generation or propagation due to transportation and handling. Figure 6.7 shows some interesting images from the EL analysis: a new mode A crack generation, mode B to mode C transformation, mode A to mode C transformation and a mode B crack was disappeared after transportation [8].

In previous experiments, the PSD was plotted from the events sampled by both time-

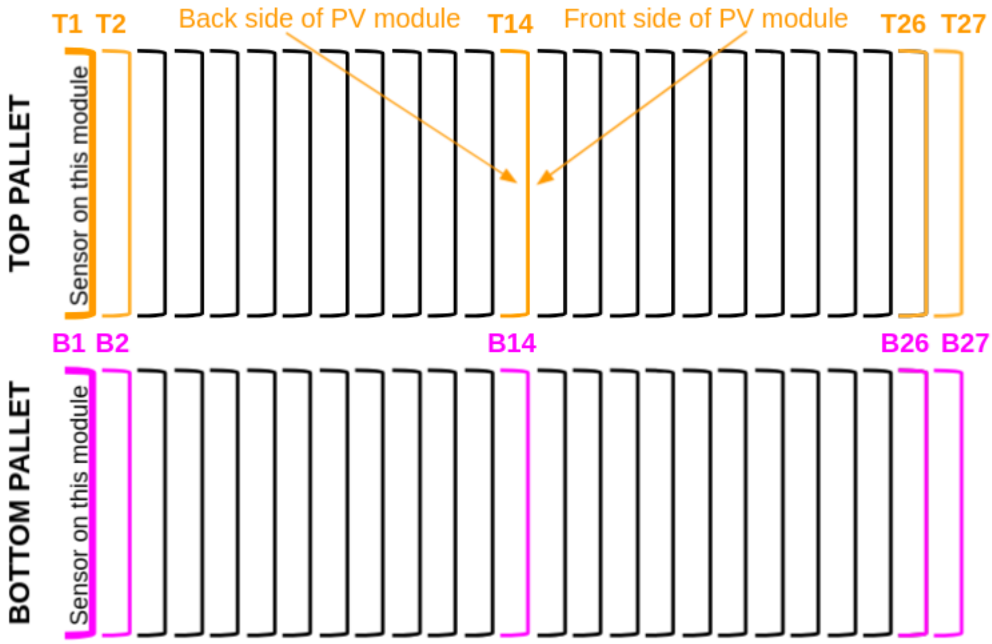


Figure 6.5: Arrangement of PV modules inside the pallets P2 (bottom) and P3 (top); PV modules colored in yellow and pink represents the PV modules under observation.

Figure 6.6: Different pallet handling practices used in the industry.

triggered and signal-triggered sampling methods. But this methodology resulted in PSD profiles which were not severe as the PSD profiles obtained from previous experiments. Hence, a detailed analysis of the time-triggered and signal-triggered data was carried out. Figure 6.8 shows an example vibration data representing signal-triggered events at 1.5 g threshold. Figure 6.9 shows an example vibration data representing time-triggered samples of 10 minutes interval. In both of the plots, the blue color data indicates continuous acceleration data recorded by GCDC accelerometers and the sampled events are marked in red.

From the Figure 6.8 and 6.9, it may be observed that there were more number of many time-triggered events than signal-triggered events which were not severe enough to be included in the analysis. Samples were collected even when the truck was stationery.

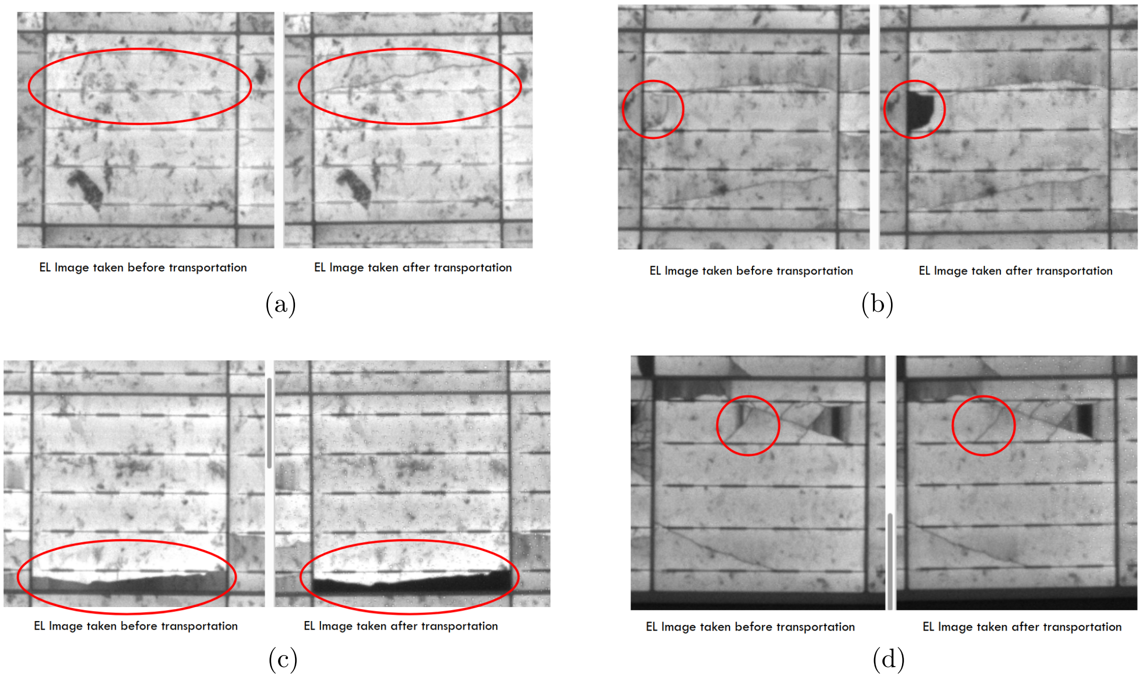


Figure 6.7: Few interesting images from the EL analysis with (a) new mode A crack generation, (b) mode A to mode C transformation, (c) mode B to mode C transformation and (d) a mode B crack was disappeared due to transportation and handling.

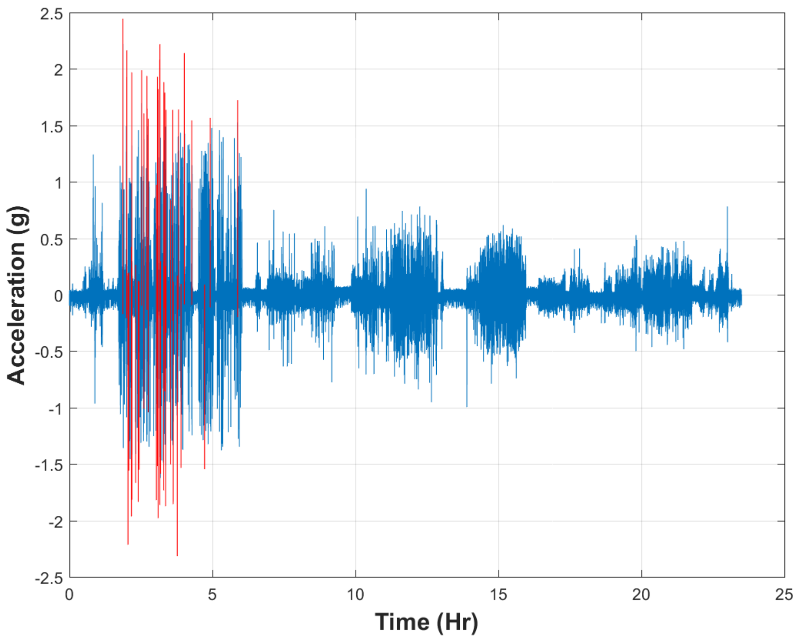


Figure 6.8: Example vibration data representing signal-triggered events at 1.5 g threshold; The blue color data indicates continuous acceleration data recorded by GCDC accelerometers and the sampled events are marked in red.

In order to understand the impacts of the analysis scheme, the PSD profiles of these data was plotted. Figure 6.10 shows the PSD profile plotted from the signal-triggered events alone and the time-triggered events alone. A clear difference in the severity of the PSD

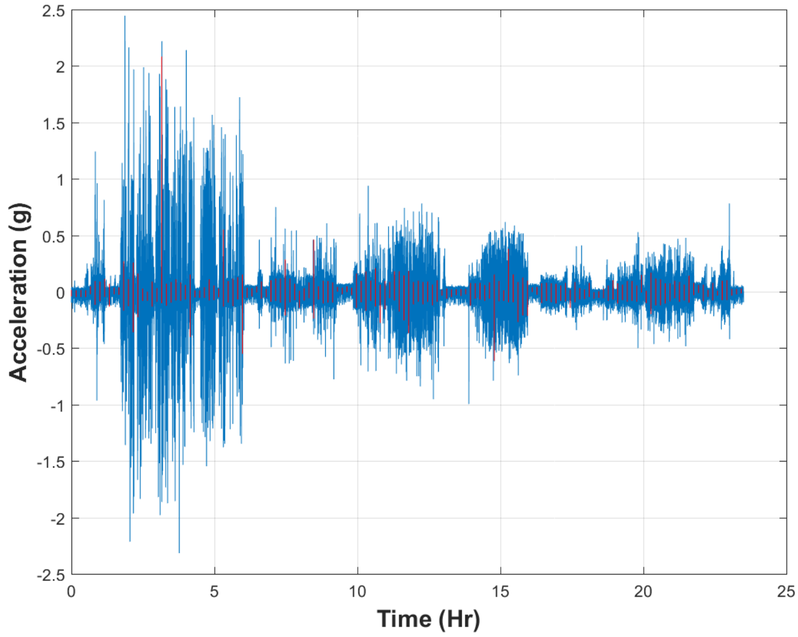
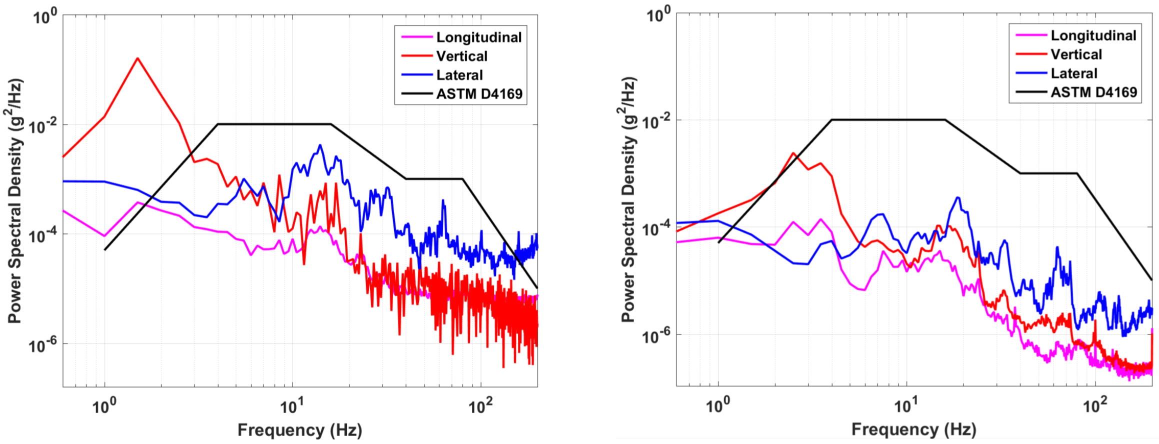


Figure 6.9: Example vibration data representing time-triggered samples of 10 minutes interval; The blue color data indicates continuous acceleration data recorded by GCDC accelerometers and the sampled events are marked in red.

profiles was observed. Hence, for the analysis used in this chapter, only signal-triggered events were used.

Figure 6.11 shows the comparison between PSD plots of the vertical vibration data from the PV module placed in the container with metal floor (inside pallet P1) and wooden floor (inside pallet P4). At lower frequency (1-3 Hz), vertical vibration magnitude was severe for the PV module placed in container with wooden floor. But a peak in the vertical vibration data was observed at 11 Hz for the data from the PV module placed in container with metal floor. But it was absent in case of the PV module placed in container with wooden floor. Figure 6.12 shows the comparison between PSD plots of the lateral vibration data from the PV module placed in the container with metal floor (inside pallet P1) and wooden floor (inside pallet P4). From 10 Hz onwards, lateral vibrations from the PV module placed in container with metal floor were severe than the vibrations from the PV module placed in container with wooden floor.

Table 6.1 shows crack statistics of 5 PV modules each from pallets P1 (placed in container with metal floor) and P4 (placed in container with wooden floor). The 5 PV modules placed in the container with wooden floor had 151 cracked cells, but only 6 cells were damaged out of 5 modules during to transportation and handling. In case of container with metal floor, it had only 53 cracked cells out of 5 PV modules, but 22 cells out of 5 modules were damaged during transportation and handling. Hence, it may be observed that the PV modules placed in container with metal floor shows more damage as compared to the PV modules placed in container with wooden floor. But there were other



(a) (b)

Figure 6.10: Example PSD plots generated from (a) signal-triggered events alone and (b) time-triggered events alone.

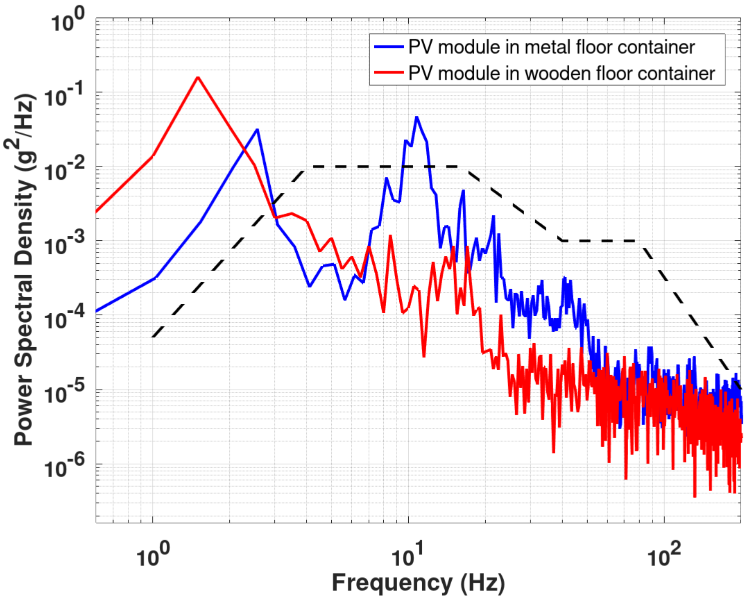


Figure 6.11: A comparison between the PSD profile of vertical vibration data collected from PV module placed inside the pallet P4 (placed in container with wooden floor) and pallet P1 (placed in container with metal floor).

parameters like the condition of the container, skills of the driver, etc different between two containers.

Figure 6.13 shows the 3-axes PSD profile of the vibration data collected the PV module inside pallet P3. The axis perpendicular to the PV module plane was oriented towards longitudinal direction of the container. In the PSD profile, a peak in the longitudinal vibration data was observed in 10-20 Hz range. Previous experiments had similar peak in the lateral direction when the axis perpendicular to the PV module plane was along lateral direction of the truck. Hence, it may be observed that, irrespective of the direction of the truck, PV module experiences vibration in 10-20 Hz range along the axis perpendicular

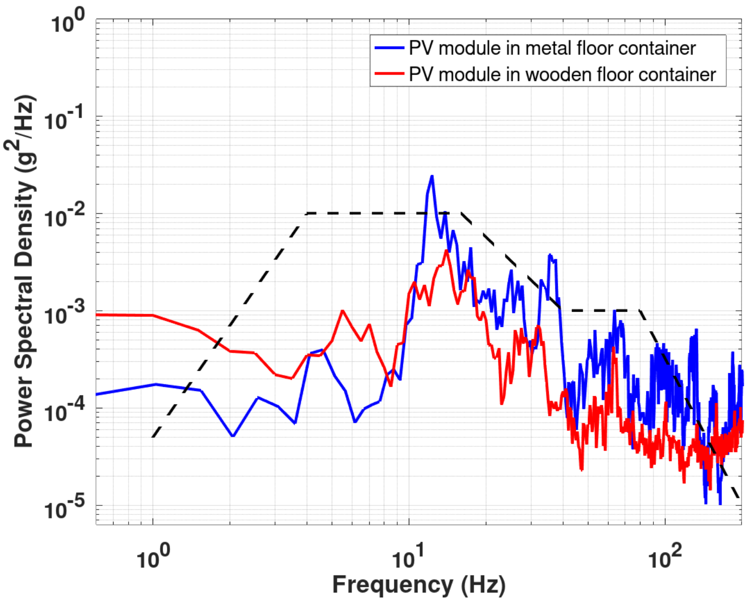


Figure 6.12: A comparison between the PSD profile of lateral vibration data collected from PV module placed inside the pallet P4 (placed in container with wooden floor) and pallet P1 (placed in container with metal floor).

Table 6.1: Crack statistics of 5 PV modules each from pallets P1 (placed in container with metal floor) and P4 (placed in container with wooden floor).

Micro-crack type	Number of cracks from PV modules in P1 (metal floor)	Number of cracks from PV modules in P4 (wooden floor)
New mode A cracks generated	19	0
New mode B cracks generated	0	0
New mode C cracks generated	1	0
Mode A transformed to mode B	1	5
Mode A transformed to mode C	1	0
Mode B transformed to mode C	0	1
Number of existing damaged cells before transportation (out of 5 PV modules)	53	151
Number of damaged cells during transportation (out of 5 PV modules)	22	6

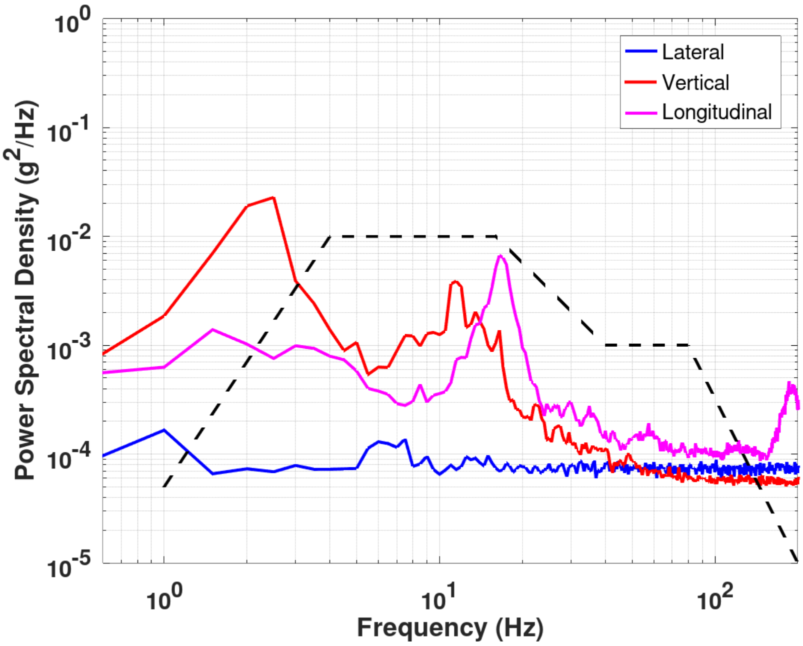


Figure 6.13: PSD profile of 3-axes vibration data collected from the PV module inside pallet P3; The axis perpendicular to the PV module plane was oriented towards longitudinal direction of the container.

to the module plane.

6.4 Summary

PSD profiles obtained from time triggered analysis underestimate the severity of vibrations experienced by the goods transported. The PV modules placed in the container with wooden floor showed lower amount of micro-crack generation or transformation as compared to the PV modules in the container with metal floor. The lateral vibration was studied in Chapter 5. That study concluded that the lateral vibration may be included for the laboratory simulation of PV module transportation. But from this chapter, it was observed that irrespective of the direction of travel of the truck, PV module experiences vibration in 10-20 Hz range along the axis perpendicular to the module plane. Hence, the vibration along the axis perpendicular to the module plane aligned over lateral/longitudinal axis may be included for the laboratory simulation of PV module transportation.

Next chapter describes an electronic system developed for collecting bulk amount of transportation data.

Chapter 8

Conclusions and Future Works

The vibration profiles obtained for the PV module transportation on Indian roads from different experiments mentioned in chapters 4, 5 and 6 were not fitting with the ASTM D4169 Assurance Level II, the main reference of IEC 62759-1:2015 standard. The vibration levels were severe than ASTM D4169 for the lower frequencies (1-3 Hz). Manual handling of modules was found to result in high values of acceleration, up to 15g.

For the vertical placement of PV modules inside the pallet, it was found that the vibrations along the axis perpendicular to the module plane were severe in mid-frequencies (10-20 Hz). Hence, it is recommended to incorporate the laboratory simulation of the lateral/longitudinal vibration for PV module pallet in the IEC62759 standard. The PV modules placed front side facing front side of another module shows lesser lateral vibration compared to the module placed front side facing backside of another module. But the module placed at the middle experienced even lesser vibration compared to the PV modules placed at the edges. Vibration events should be sampled by signal-triggered events alone for the PSD analysis of PV module transportation. The PV modules placed in the container with wooden floor showed lower amount of micro-crack generation or propagation as compared to the PV modules placed in the container with metal floor.

An electronic system has been developed and tested to collect bulk amount of vibration data during the transportation of PV modules. More investigation on the transportation of PV modules to remote locations are necessary for devising an appropriate vibration test profile for Indian road conditions.

This work can be extended by deploying the prototype developed to collect bulk amount of vibration data. Before that, there are some minor works that needs to be completed in the prototype like: make an enclosure for the server unit, drill holes for the battery connector on the enclosure of sensor unit and fix the PCB to the enclosure with proper screws. An updated version of the server unit can be designed to save cost and power by using Raspberry Pi 3 and installing lightweight operating systems like Raspbian lite or Ubuntu Server. The PV module transportation data may be benchmarked with ISTA 3E test profile which is more likely to represent Indian road conditions. From the

PSD profile generated, the test spectrum may be developed according to DIN EN 15433-5 standard.

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List of Publications

International Conferences

1. **D. P. Vasudevan**, P. Bhatt and A. Kottantharayil, "Impact of Transportation on Indian Roads, on PV Modules," *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, 2019, pp. 1529-1532, doi: 10.1109/PVSC40753.2019.8980720.

2. **D. P. Vasudevan**, P. Bhatt and A. Kottantharayil, "Lateral vibrations experienced by vertically placed PV modules in the pallet during transportation," presented at *XX^{th} International Workshop on The Physics of Semiconductor Devices (IWPSD), December 17-20, 2019.*

3. **D. P. Vasudevan**, P. Bhatt and A. Kottantharayil, "Lateral vibrations experienced by vertically placed PV modules in the pallet during transportation," *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, 2020, pp. 1323-1325, doi: 10.1109/PVSC45281.2020.9301001.

Appendix A

Electroluminescence Image Analysis

Electroluminescence imaging (EL) is a widely used technique to evaluate the quality of the electrical contacts of solar cells. In order to visualize the cracks generated or propagated during transportation and handling, a classification scheme was developed.

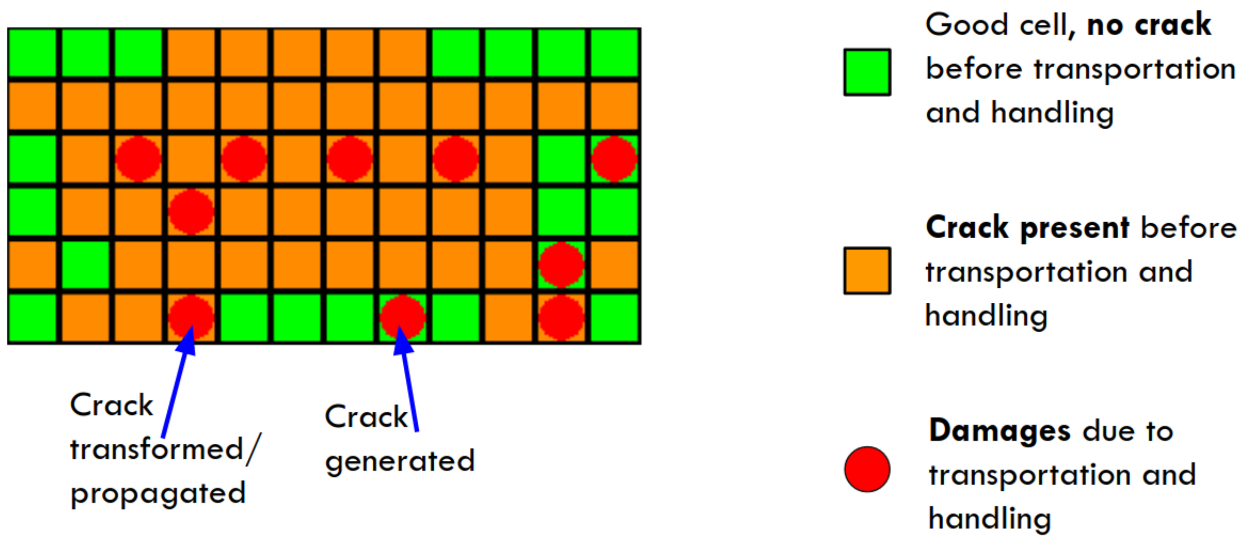

Figure A.1: Analysis of EL image – classification scheme.

Figure A.1 shows the classification scheme generated from the micro-crack analysis of the PV module from EL images taken before and after transportation. It contains boxes corresponding to each cell of a PV module. A green box indicate a good cell, with no cracks before and after transportation. An orange cell indicate a cell with one or more cracks present before transportation. A red circle indicates damages due to transportation or handling. Here a red dot on green box indicates crack generation and a red dot on orange square may indicate a crack transformed or propagated.

Appendix B

Amendments to IEC62759 to account for Indian road conditions

It was decided that to provide recommendations based on the research on transportation of PV modules on Indian roads, to the BIS standard committee for adopting IEC62759 standard. From the experiments described in chapter 4, it was found that the vibration profile obtained from Indian roads were not fitting with the ASTM D4169 Assurance Level II, the main reference of IEC62759. Magnitudes of low frequency (1-3 Hz) vibrations were higher than ASTM D4169 standard. The severity of the low frequency vertical vibrations experienced by PV modules during transportation on Indian roads was higher than the ASTM D4169 standard. Hence, it is recommended to raise the test limit at the lower frequencies.

IEC62759-1 recommends to conduct same series of tests for horizontally and vertically placed PV module pallets. ASTM D4169 is a transportation standard for general goods. But PV module unlike many other goods, has directional dependence on the vibrations. The vibrations experienced perpendicular to the module plane may have severe impact compared to other axes. The study of transportation on vertically placed PV modules (chapter 5) indicate that the vibrations along the axis perpendicular to the module plane (towards lateral) was immoderate. Modules tend to vibrate more along lateral axis than vertical axis above 10 Hz and it peaks at 15 Hz. Experiment data indicates that the natural frequency of the PV module was around 15 Hz. Simulated transportation of fully packed PV module pallet also indicates that 15 Hz was the first mode of vibration. Hence, it can be concluded that the natural frequency of the PV module was around 15 Hz. Hence the second amendment is that the severe lateral vibrations experienced by PV modules placed vertically in the pallet during transportation on Indian roads needs to be accounted in the standard. In case of uni-axial vibrators, the vibrations may be applied to the axis perpendicular to the module plane.

IEC62759-1 recommends to simulate shocks generated during handling through half sine shock tests. The amplitude of shock is 10 g or 98 m/s^2. The acceleration data during manual handling indicates very severe shocks with amplitudes as high as 15g. The histogram in the figure indicates the number of occurence of shock amplitudes. The histogram clearly shows that the handling exerts heavy amplitudes of acceleration on the modules (up to 15g). Hence, the third recommendation is to use higher magnitudes for the half sine shock test.

Appendix C

Manual handling

Different manual handling practices are used in the industry to move PV modules starting from the manufacturing unit to the installation site. Some of the improper handling methods stresses the module and may results in micro-cracks. Figure C.1 shows a person carrying PV modules on his head. This might exert heavy mechanical load on the PV module.

Figure C.2 shows shifting the PV modules from the ground to the terrace using ropes. The modules were hitting the wall which may exert mechanical stress on the PV module. Hence, proper manual handling practices needs to be established and the workers must be trained, to reduce the mechanical stress exerted on the PV modules during manual handling.

(a) (b)

Figure C.1: Improper manual handling practices noticed.

Figure C.2: Risky manual handling practice.

Appendix D

Brief information about the documentation of the code

The documentation for all the codes used for this study is explained in 3 documentation files; documentation-sensor.pdf for the sensor unit, documentation-server.pdf for the server unit and documentation-psd.pdf for the data processing. The documentation for the server unit contains the software installation guide for setting up the SDK of ESP8266 and the explanation of the code. The documentation for the server explains the python code written for TCP server. The data processing documentation explains how to process GCDC accelerometer data and the Vibration Monitor data.