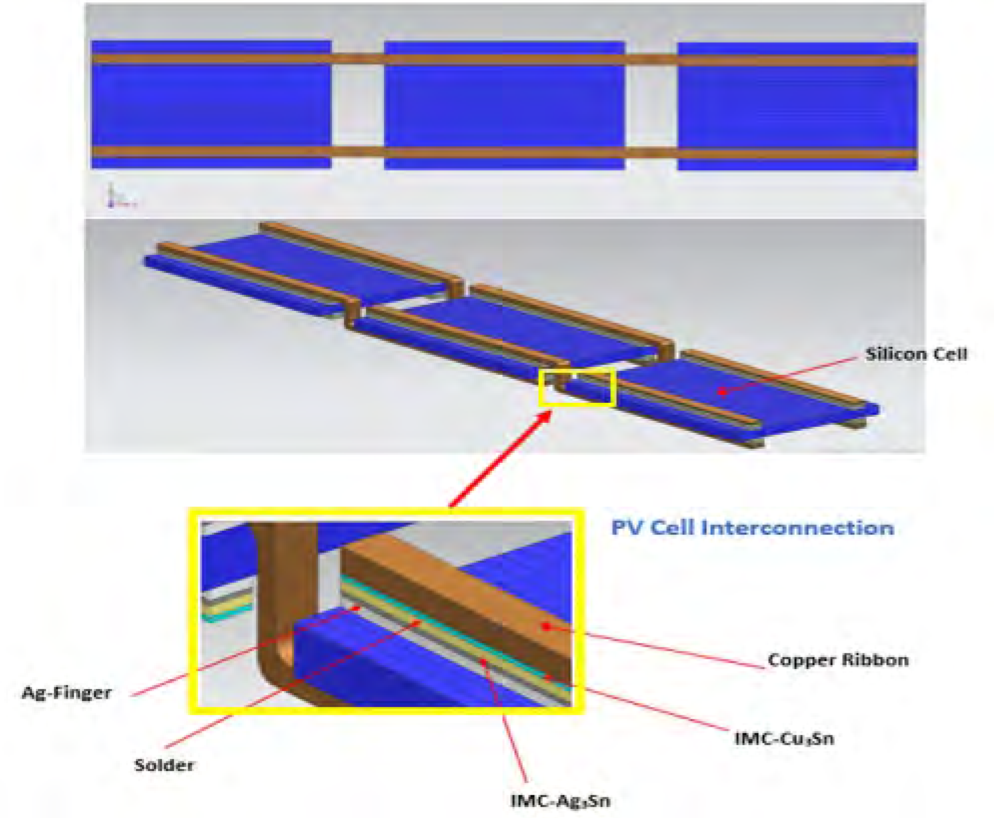
Modelling Solar Photovoltaic cell interconnections for improved reliability in Sub-Saharan Africa .



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RESEARCH AREA:
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PRESENTATION OUTLINE

- BACKGROUND AND JUSTIFICATION OF THESIS WORK
- AIMS AND OBJECTIVES
- OVERVIEW OF METHODOLOGY
- RESULTS AND DISCUSSIONS
- PROGRESS STATUS

BACKGROUND

- Increased warranty of Solar Photovoltaic Modules (SPM) in recent years.
- GOAL: photovoltaic system that can attain a thirty-year (30yr) service life by the year 2020 (*Hulstrom, 2005; Quintana, King, McMahon, & Osterwald, 2002*).
- POSSIBLE: when the rate of power degradation of the modules per year is between 0.5% and 1.0% maximum.
- HOWEVER: installed modules experience annual power degradation rates of about 0.5% to 10% .

BACKGROUND

DEGRADATION FACTORS

Several factors account for the degradation of installed SPV modules:

- Exposure of modules to a range of cyclic temperatures coupled with elevated temperature operations. (Induced thermo-mechanical stresses)
- Increased Moisture Accumulation ; corrosion of the solder joints and Ag fingers leading to significant losses in PV module performance *(Dhere & Raravikar, 2001; Polverini, Field, Dunlop, & Zaaiman, 2013)*
- Operations under a wide range of operating currents and voltages , huge variation in weather conditions
- (*Macben Makenzi, 2015*)reported degradation and failure mechanisms of SPV are location dependent

Fig 1: Moisture accumulation in SPV

RESEARCH FOCUS

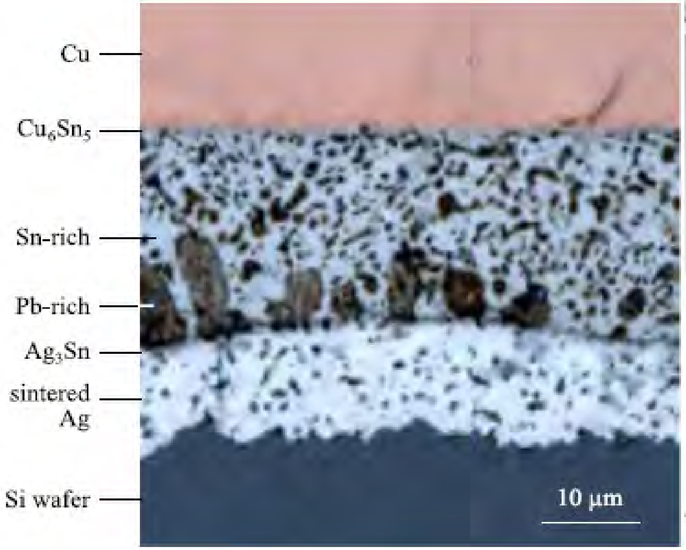
BACKGROUND

SPV modules are exposure to a range of cyclic temperatures

- Field SPV modules installed in sub-Saharan ambient experience temperature swings of about 45 ^{o}C each day.
- The outdoor weathering effects expose PV modules to direct sunlight in an alternating day/night cycles which exposes modules to thermal loading.
- The variation in the co-efficient of thermal expansion of constituent materials forming the individual cells in the module.
- The daily temperature swings induce fatigue related failure mechanism occasioned by mismatch of the respective temperature co-efficients of thermal expansion (CTE) of **silicon, EVA, glass, copper** and **solder bonded** together.
- Formation of micro-cracks leading to increase resistance across solder joint area (output power loss).

BACKGROUND

RESEARCH FOCUS



Si wafer-Ag-Solder-Copper interface

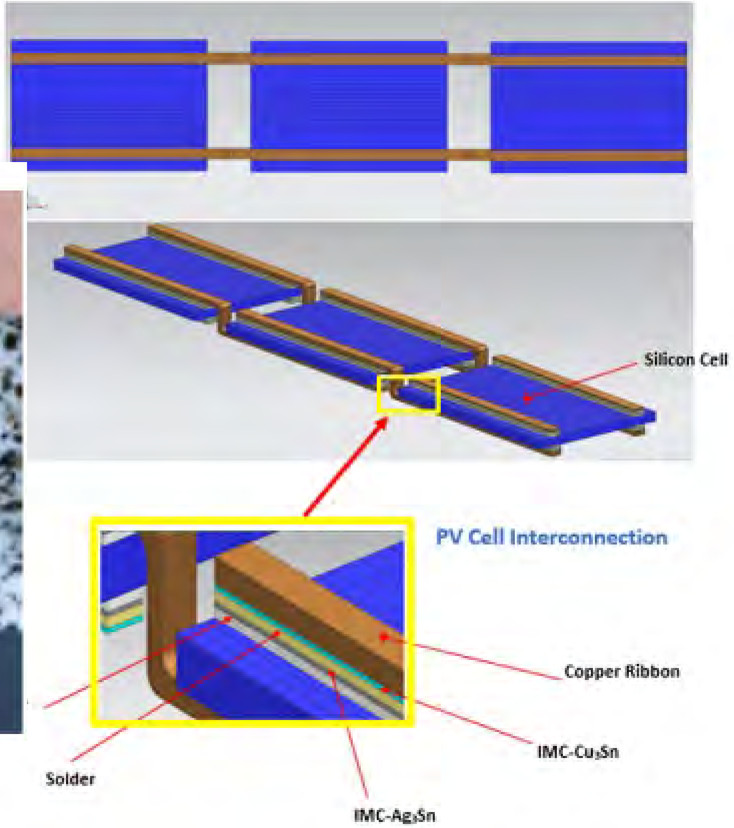


Fig2. **Conventional front-to-back cell interconnection in c-Si PV module**

JUSTIFICATION/PROBLEM STATEMENT

The development of indoor tests that have the ability to predict real outdoor conditions accurately is quite challenging. A number of research findings suggest various methods which include:

- Expanding on the certification procedures outlined in IEC 61215 thermal cycling test (TC 200) by increasing the number of cycles, increasing the temperature range or ramp rates(Owen-Bellini, Zhu et al. 2015).

Other studies have also used field data for PV reliability prediction:

- For instance (Cuddalorepatta, Dasgupta et al. 2010) in their study of the durability of Pb-free solder between copper interconnect and silicon in PV cells used a field condition with a temperature range between 63°C and 17°C from a data provided from a sponsoring company
- (Park, Jeong et al. 2014) used field data with a cycle time of 24 hours: 23-67°C; 390 minutes ramp up and 330 minutes ramp down; 2 hours dwell in high temperature and 10 hours in low temperature to estimate the degradation rate of multi-crystalline silicon.
- Different Constitutive models of EVA (ethylene Vinyl Acetate) have been used in various modelling studies: (Linear elastic, Temperature dependent Young's Modulus, Linear Viscoelasticity)

RESEARCH AIM AND OBJECTIVES

The aim of this research work is to Study the interconnections in photovoltaic modules for improved thermo mechanical reliability in Sub-Saharan Africa.

The Objectives of the study are:

I. to generate temperature cycle profile from in-situ climatic condition for accurate prediction of thermo-mechanical degradation of c-Si photovoltaic module in a Sub-Saharan Africa Ambient.

II. to evaluate the impact of encapsulant (EVA) constitutive behaviour on interconnect damage in C-Si Solar PV Modules installed at a Test site in Sub-Saharan Africa region.

III. to evaluate the effect of IEC 61215 thermal cycle and operating module temperature cycle(test region thermal cycle) on creep damage and fatigue life of interconnection in photovoltaic modules.

IV. to evaluate the effects of temperature ramp rates and dwell times on degradation of interconnections on SPV modules operating in sub-Saharan African region.

OVERVIEW OF METHODOLOGY

- Data was obtained from a test site (The site location is at College of Engineering, KNUST, Ghana; on latitude 6º 40" N and longitude 1° 37" W, at an elevation of 250 m above sea level) .
- The modules are unshaded and mounted on an inclined rooftop with a tilt angle of 5°, and oriented toward the equator (southwards)
- Calibrated Platinum sensors (PT100) with measurement accuracy of ±0.5 °C, resolution of 0.1°C and positioned at the center of each module (on the backside) measured the module temperatures.

Fig 3: Test Rig

OVERVIEW OF METHODOLOGY

- A rainflow counting algorithm developed using a MATLAB program to determine the number of temperature cycles experienced by the modules each year.
- An algorithm was also developed in MATLAB to select the temperatures at the peaks.

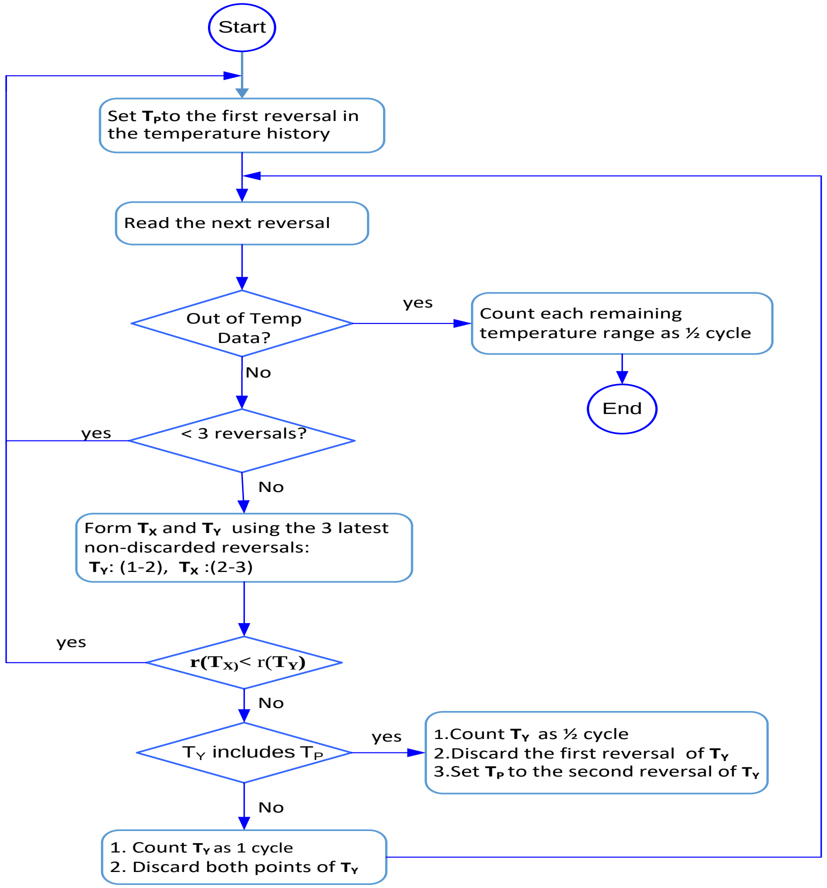


Fig. 4: Flowchart for rainflow counting

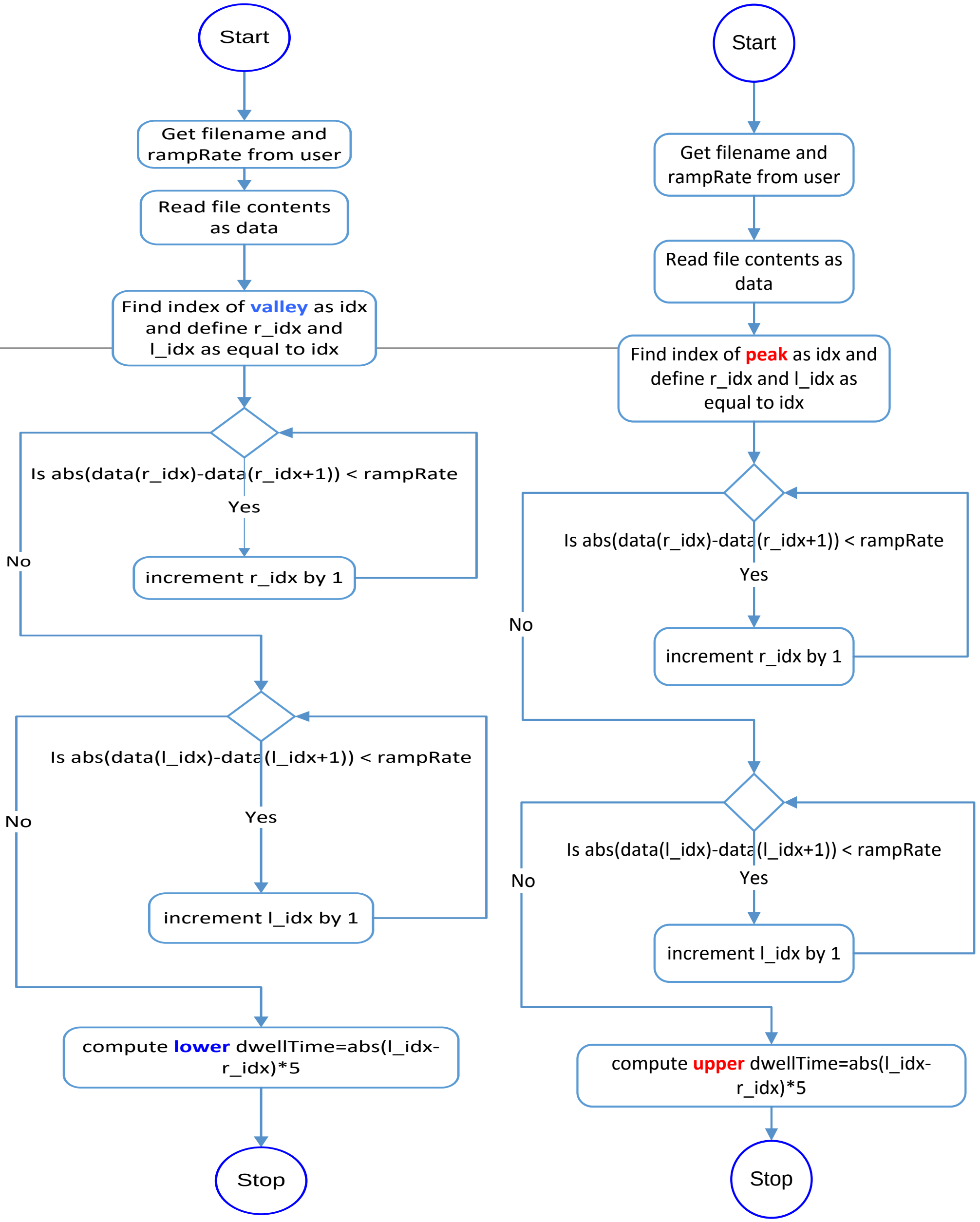
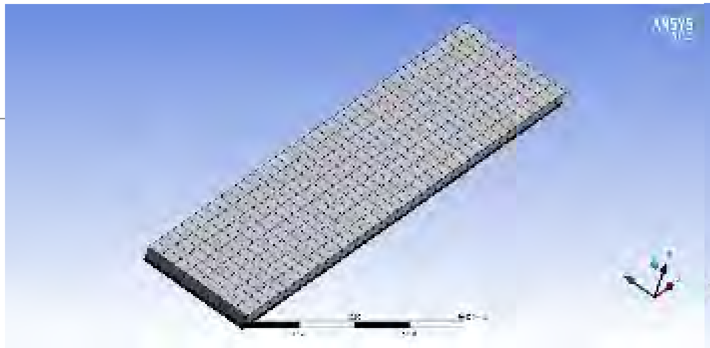
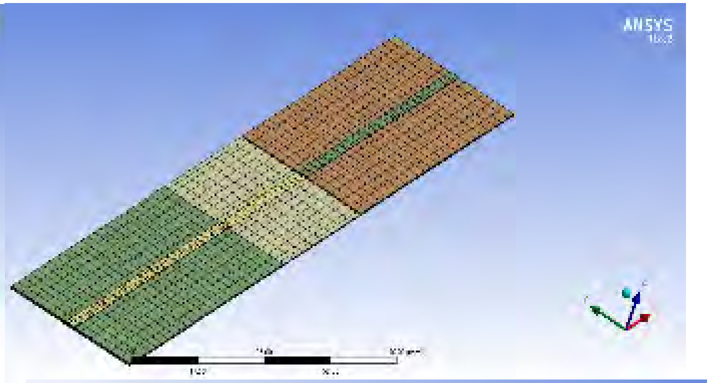


Fig5: Flowchart for computing dwell times; (a) lower dwell (b) upper dwell

FINITE ELEMENT MODELLING (FEM) OF SOLAR CELL

- 3-D representative geometric models were created by using a combination of Constructive Solid Geometry (CSG) and Boundary Representation (B-Rep) modelling technique.
- Simulation was optimized for accuracy and computational speed within the power of the computing resource, a quarter of meshed cell-to-cell interconnect model for simulation (FEA).





Mesh Statistics:
Nodes: 63937
Elements:12852

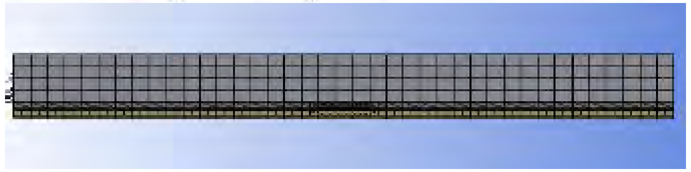


Fig 6: Meshed Model of Solar cell

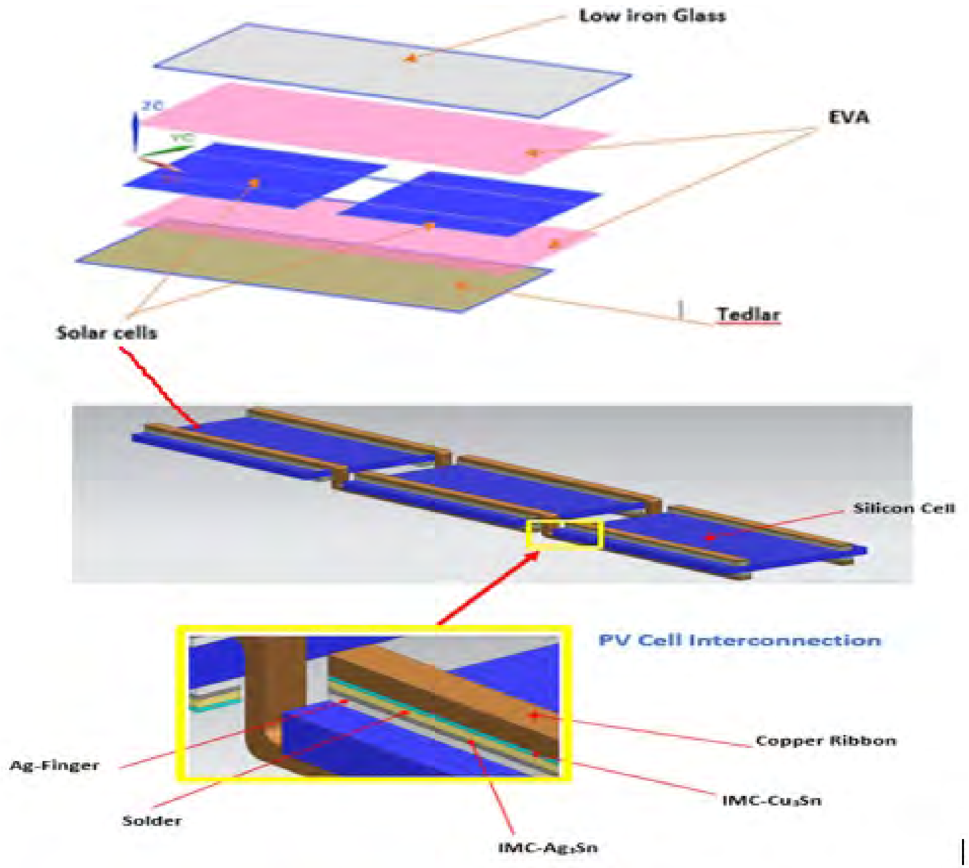
Table 1: Geometric Parameters of Solar cell materials

Layer Material	Size (Length x Width)	Thickness(μm)
Glass	0.352 m x 0.156 m	3600
EVA	0.352 m x 0.156 m	450
Silicon	0.156 m x 0.156 m	175
Copper Ribbons	0.156 m x 0.003 m	150
Solder	0.156 m x 0.003 m	20
IMC (Ag_3Sn, Cu_3Sn)	0.156 m x 0.003 m	4
Aluminium Rear Contact	0.156 m x 0.156 m	25
Silver (Ag) Busbars	0.156 m x 0.003 m	50
Tedlar Backsheet	0.352 m x 0.156 m	175

OVERVIEW OF METHODOLOGY

Table 2: Cell Material Modelling

	Layer	Material	Constitutive Behaviour
1	Glass	Glass	Isotropic linear elasticity
2	Encapsulant	EVA (Ethelyne vinyl Acetate)	1. Linear elasticity 2. Temperature dependent Young's Modulus 3. Linear Viscoelasticity
3	Solar Cell	Silicon	Anisotropic Material with different elastic constants in different loading directions
4	Interconnector	Copper	Bilinear Model (Young's modulus temperature dependent)
5	Busbar	Silver fingers	Isotropic Linear elastic
6	Rear contact	Aluminium	Isotropic Linear elastic
7	Interconnecting Material	Solder (SnPb, SnAgCu)+ IMC (Cu_3Sn, Ag_3Sn)	Creep (Generalised Garafalo creep model)
8	Backsheet	Tedlar	Isotropic linear elasticity



OVERVIEW OF METHODOLOGY

- A bonded contact type formulation with default trim tolerance was used in modelling all the contacts created by the different materials in the cell assembly.
- A direct solver was employed in the computation of the numerical solution to improve the accuracy of simulation results.
- A high performance computing resource (HPC) at The Energy Center (TEC), KNUST was used for the study. **(Procured by EnPE)**

Specs:

- 40 core Intel Xenon 2.65 GHz Processors
- 128 GB RAM, NVIDIA Graphics

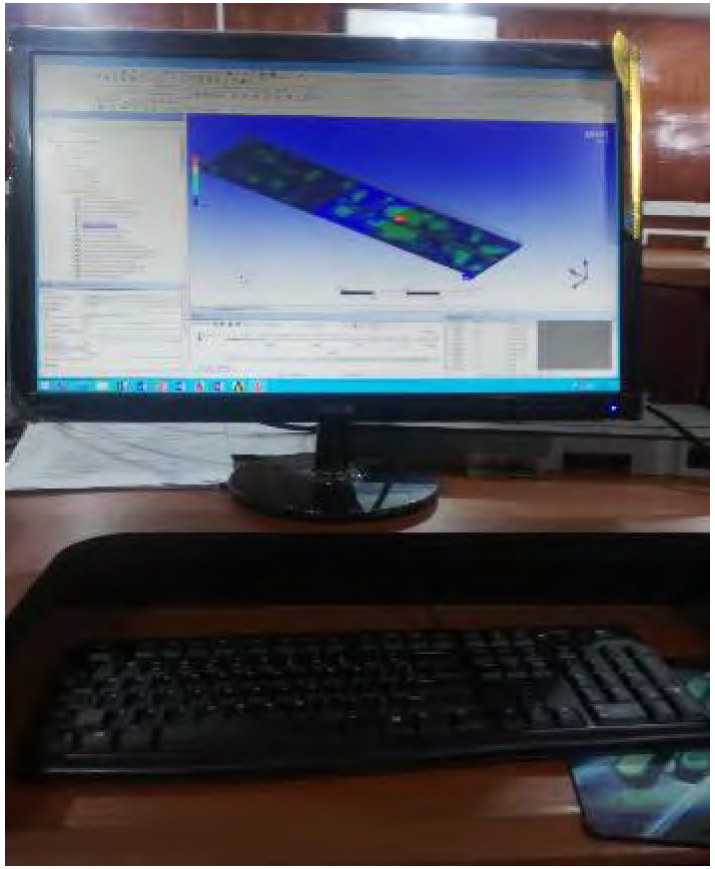


Fig 7: HPC Workstation

OVERVIEW OF METHODOLOGY

THERMAL LOADS AND BOUNDARY CONDTIONS

- Generate Thermal loads and boundary conditions from real-time temperature signals recorded for 2012, 2013, 2014.
- Generate Test Region Average (TRA) Thermal loads and Boundary conditions.
- Generete IEC 61215 thermal cycle (85°C to -40°C, 100°C/min ramp, 10 min dwell (Hot &Cold dwell))
- Generate Ramp rates, dwell times and temperature gradients.

OVERVIEW OF METHODOLOGY

LIFE PREDICTION OF SOLDER JOINTS

Accumulated Creep Energy Density (ACED)/Accumulated Strain Energy Density (ASED) Method

- Creep strain energy density is based on the deformation that is internally stored throughout the volume of the joint during thermal loading.
- In practice, the change in accumulated creep energy density per cycle (ΔW_{acc}) averaged over the volume of solder is used for predicting the cycles of failure

$$\Delta W_{ave} = \frac{\sum_i^n W_2^i V_2^i}{\sum_i^n V_2^i} - \frac{\sum_i^n W_1^i V_1^i}{\sum_i^n V_1^i}$$

Where $\boldsymbol{W_2^i}, \boldsymbol{W_1^i}$ is the total accumulated strain energy density in one element at the end point and the starting point of one thermal cycle respectively.

$\boldsymbol{V_2^i}$, $\boldsymbol{V_1^i}$ is the volume of element at the end point and start point of one cycle respectively (Syed 2004)

RESULTS AND DISCUSSIONS

SOE 1: To generate temperature cycle profile from in-situ climatic condition for accurate prediction of thermo-mechanical degradation .

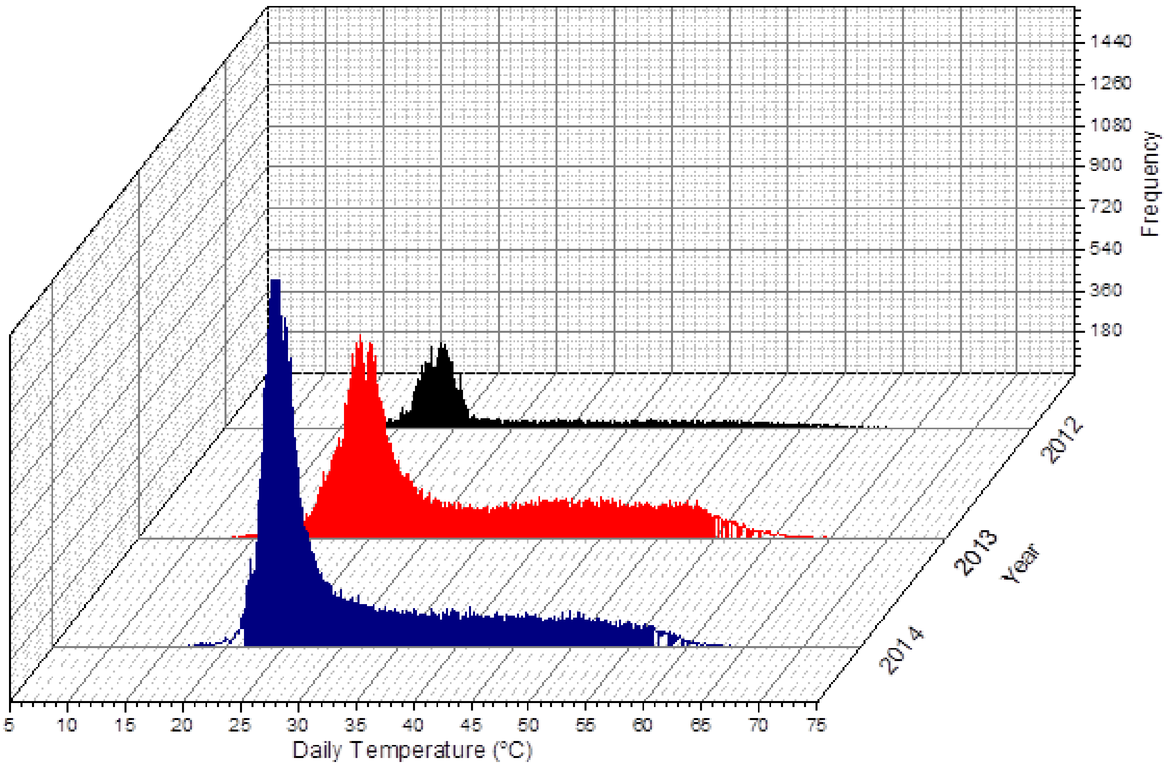


Figure 8 Distribution of observed daily module temperatures for 2012, 2013 and 2014

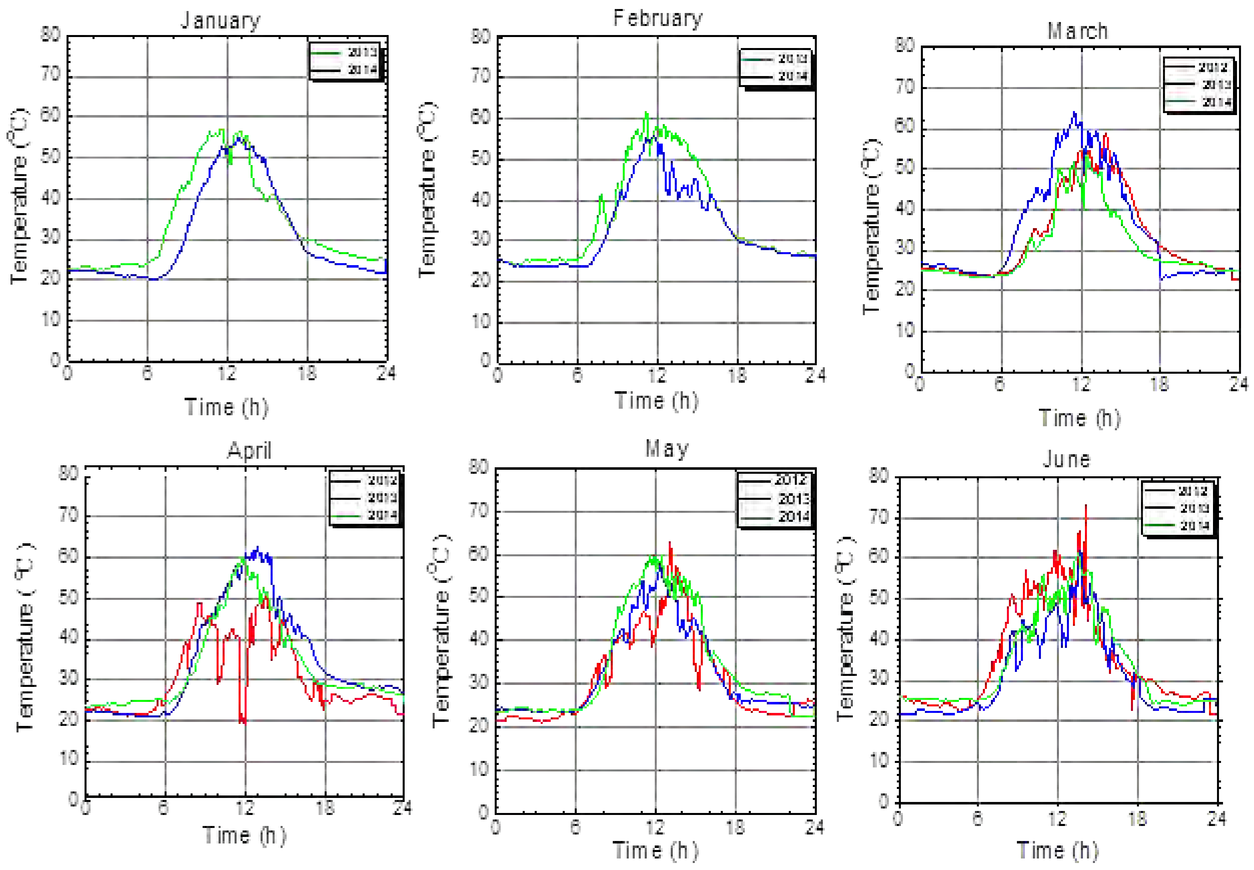


Fig. 9: Daily temperature profile (monthly average) observed for 2012 - 2014

RESULTS AND DISCUSSIONS

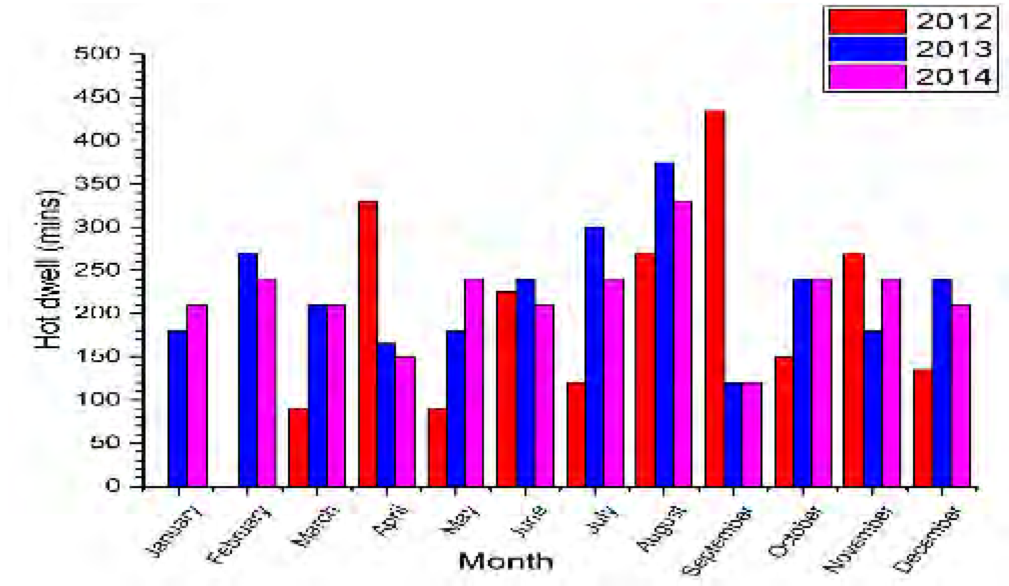


Figure 10: Monthly average distribution of hot dwell times (2012-2014)

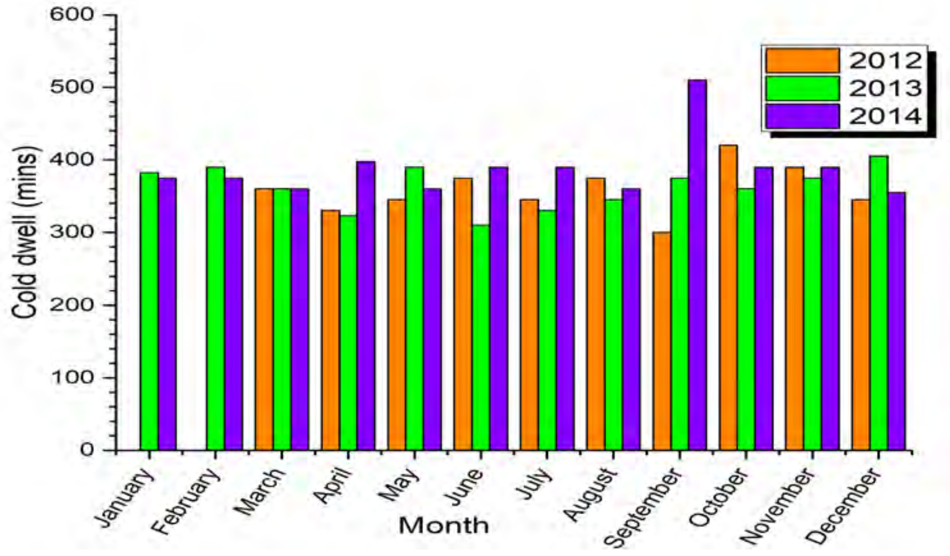


Figure 11: Monthly average distribution of cold dwell times (2012-2014)

Table 4: Summary of the parameters of the temperature cycle profile of the years

Test Year		2012	2013	2014	IEC 61215
Dwell time (min)	Mean Hot dwell	212	225	219	10
	Mean Cold dwell	359	357	390	10
Ramp rate ($°C/hr$)	Mean. ramp rate	9.51	8.65	8.82	100
Mean module Hot Dwell Temperature (HDT)/ ($°C$)		63.7	57.9	56.1	85
Mean module Cold Dwell Temperature (CDT)/ ($°C$)		23.5	23	24.4	-40
Temperature gradient		40.2	34.9	31.7	125

RESULTS AND DISCUSSIONS

GENERATED IN-SITU THERMAL CYCLE PROFILES

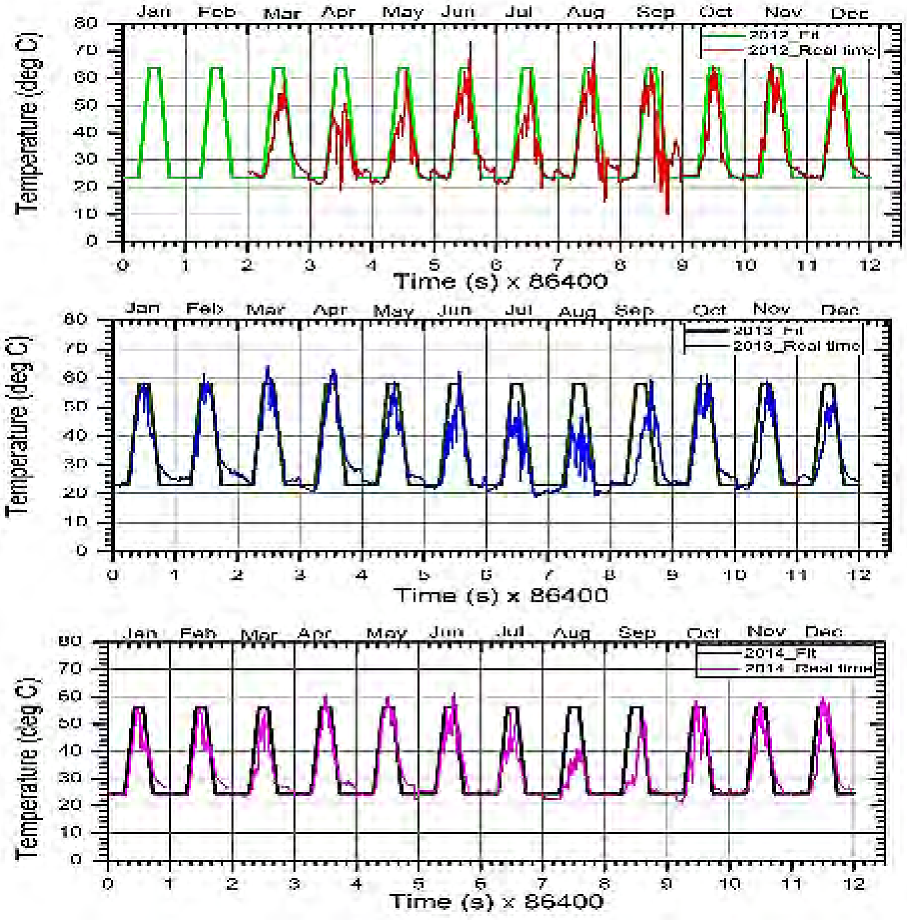


Figure 12: in-situ thermal cycle profiles fitted onto real time module temperature profile for 2012-2014.

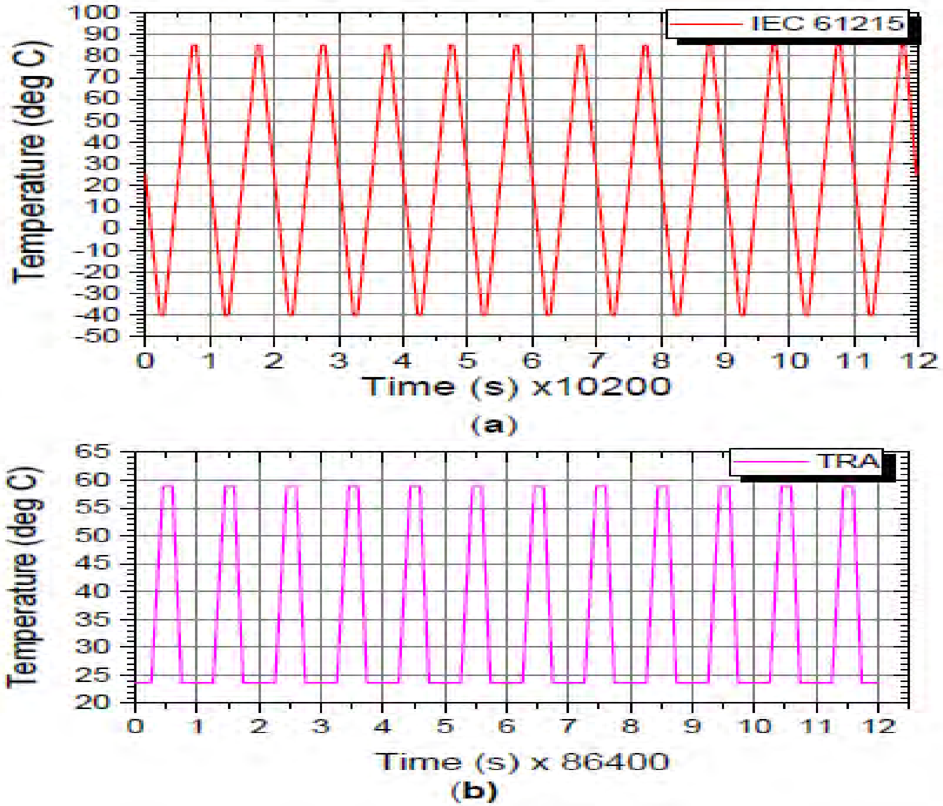
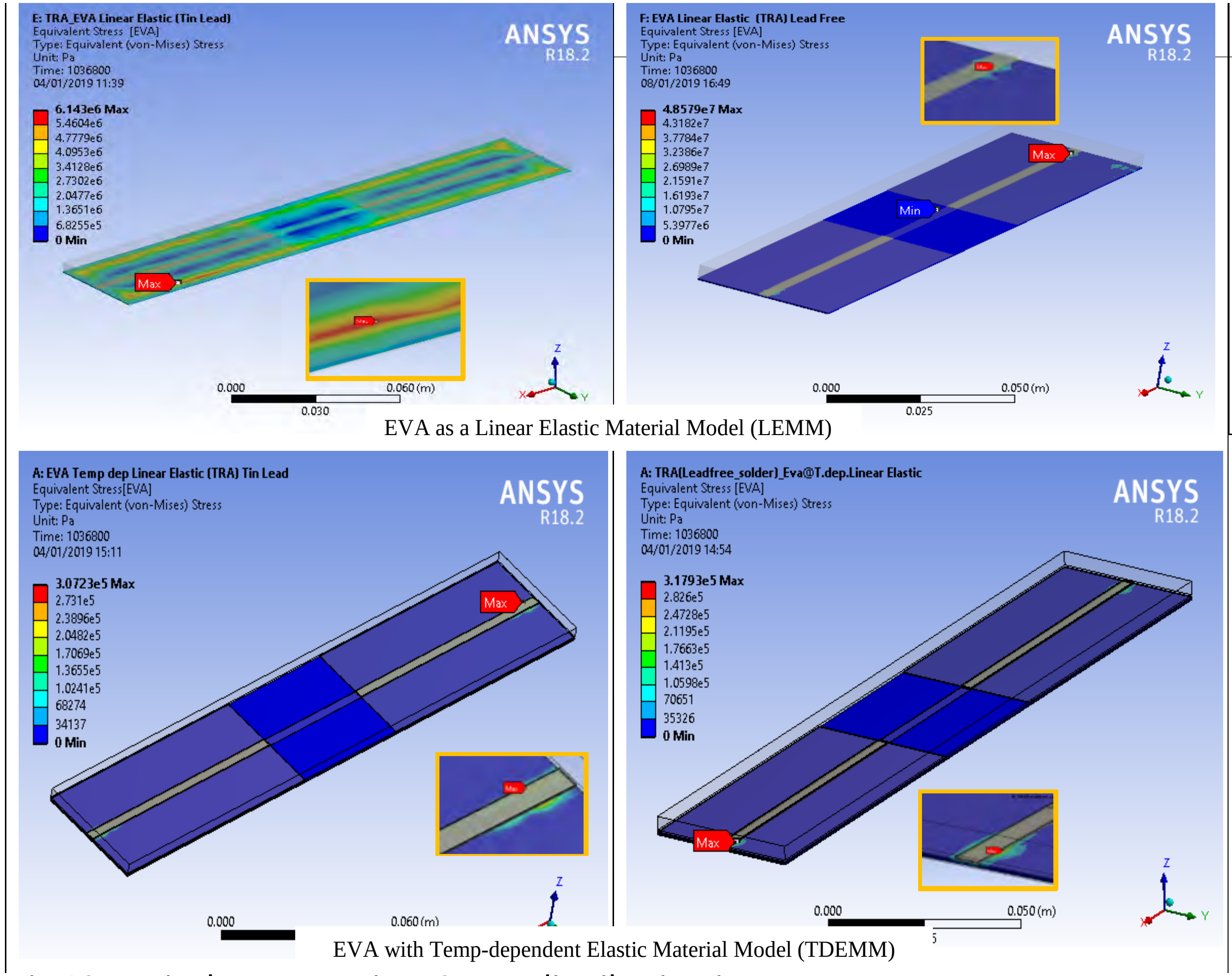


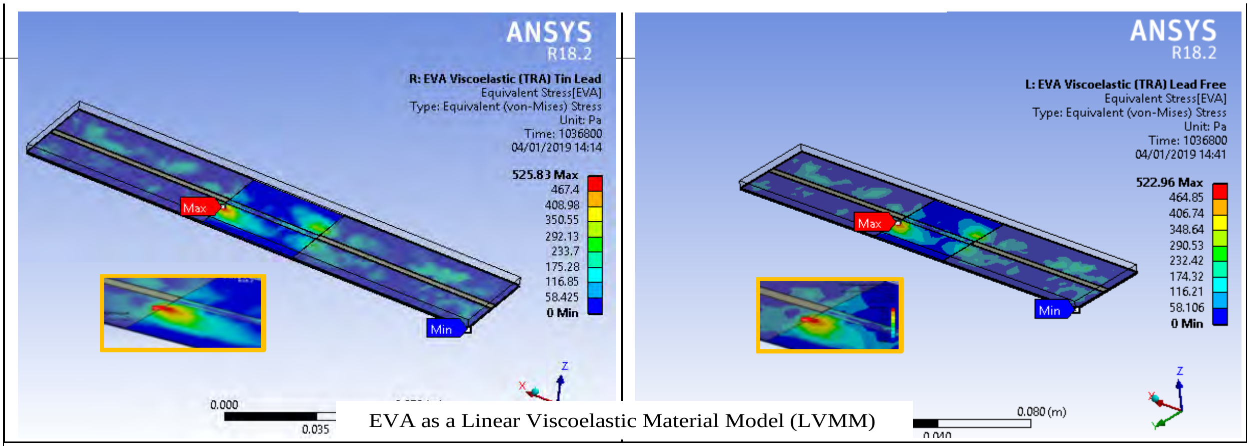
Fig.13: Plots of twelve-cycle profile of (a) the IEC 61215 Test Qualification and (b) the Test Region Average (TRA).

RESULTS AND DISCUSSIONS

SOE 2: To evaluate the impact of encapsulant (EVA) constitutive behaviour on interconnect damage in C-Si SPVM.

(a) Tin Lead solder Interconnections | (a) Lead free solder Interconnections | (a) Tin Lead solder Interconnections | (a) Lead free solder Interconnections





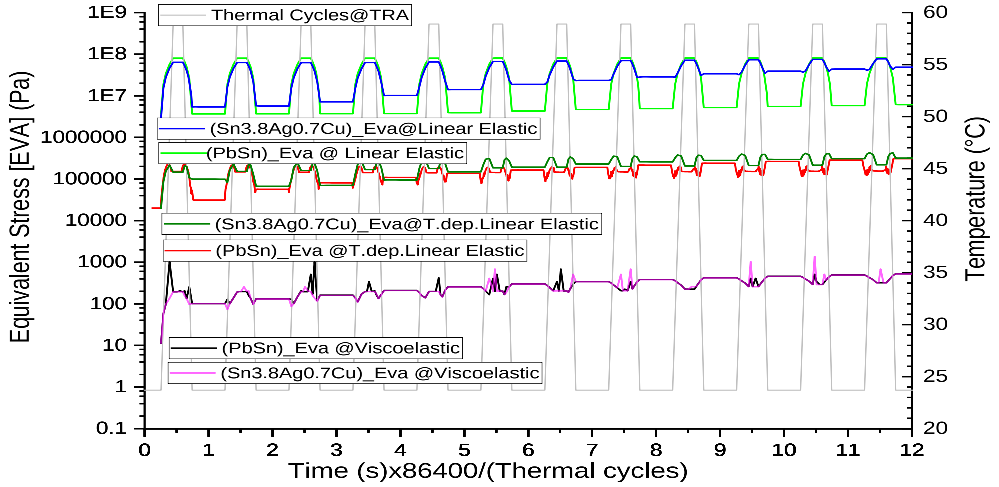


Fig 12:Equivalent von-Mises Stress distribution in EVA

Fig 13:Equivalent von-Mises Stress vrs Thermal Cycles

RESULTS AND DISCUSSIONS

KNUST

SOE 2: To evaluate the impact of encapsulant (EVA) constitutive behaviour on interconnect damage in C-Si SPVM.

(a) Tin Lead solder Interconnections | (a) Lead free solder Interconnections

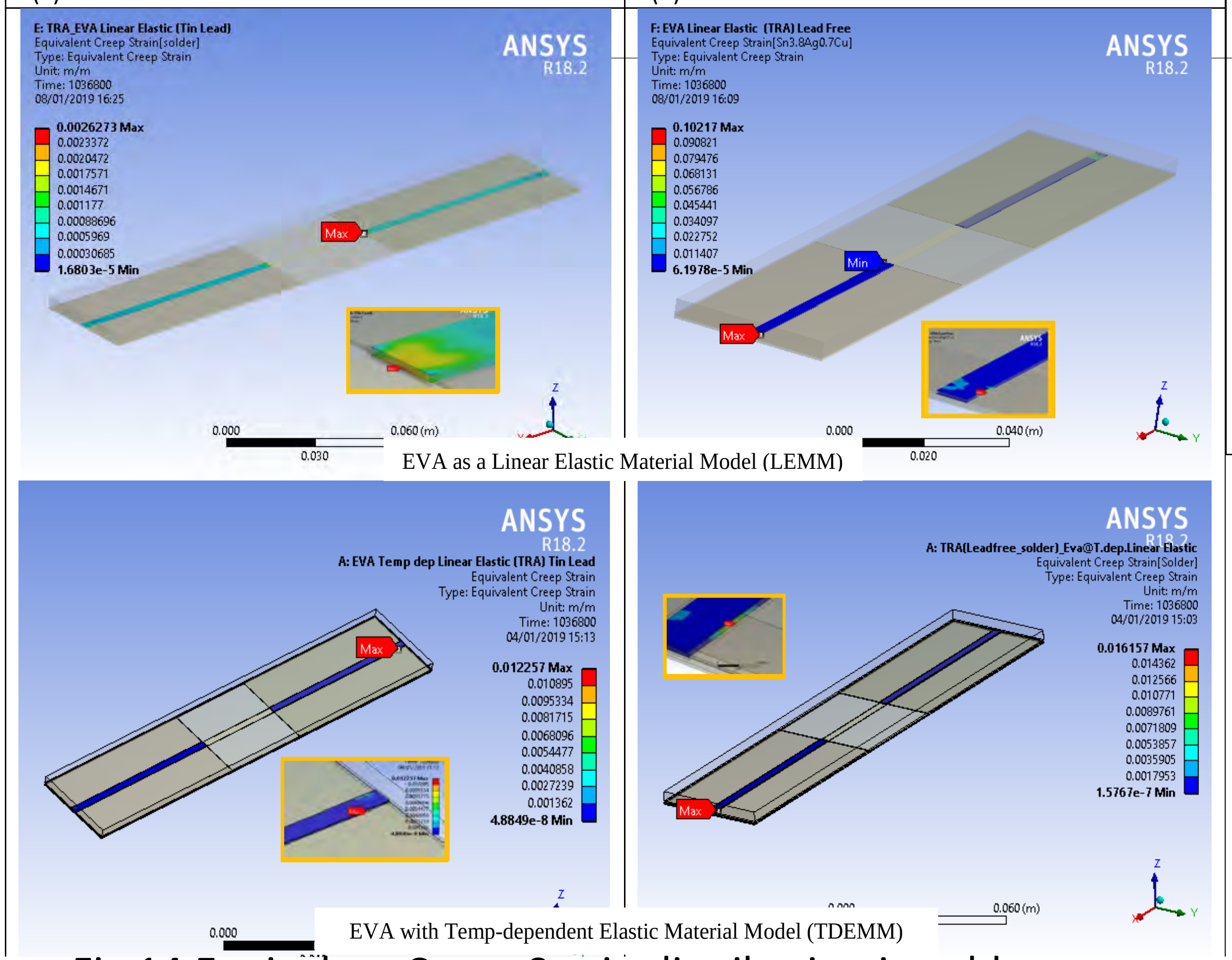
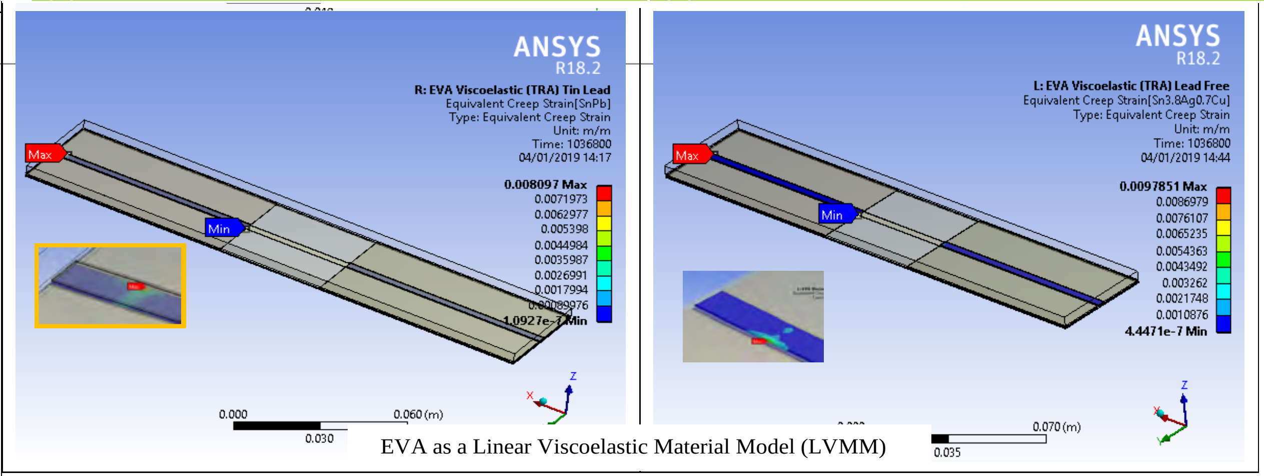
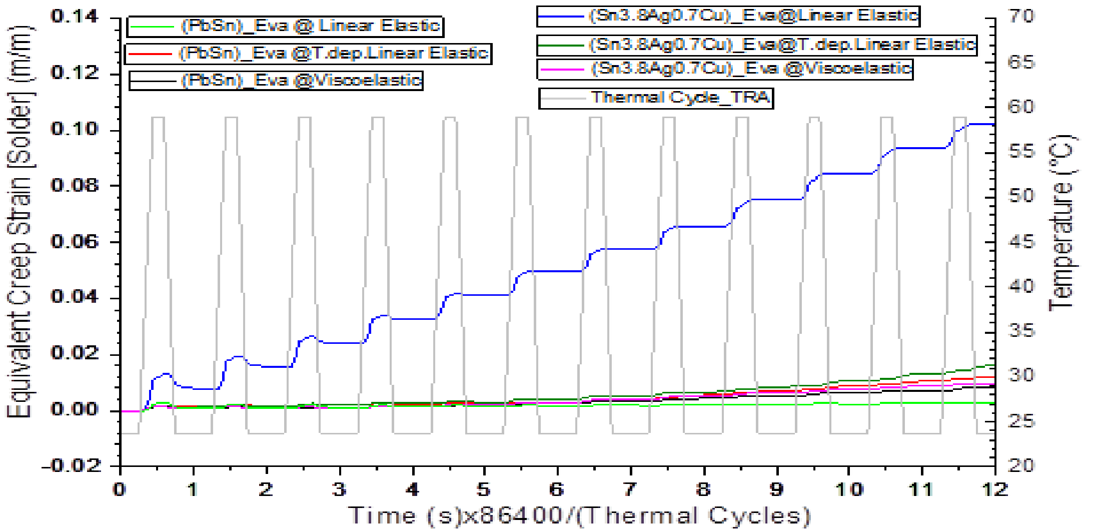


Fig 14 Equivalent Creep Strain distribution in solder

(a) Tin Lead solder Interconnections | (a) Lead free solder Interconnections

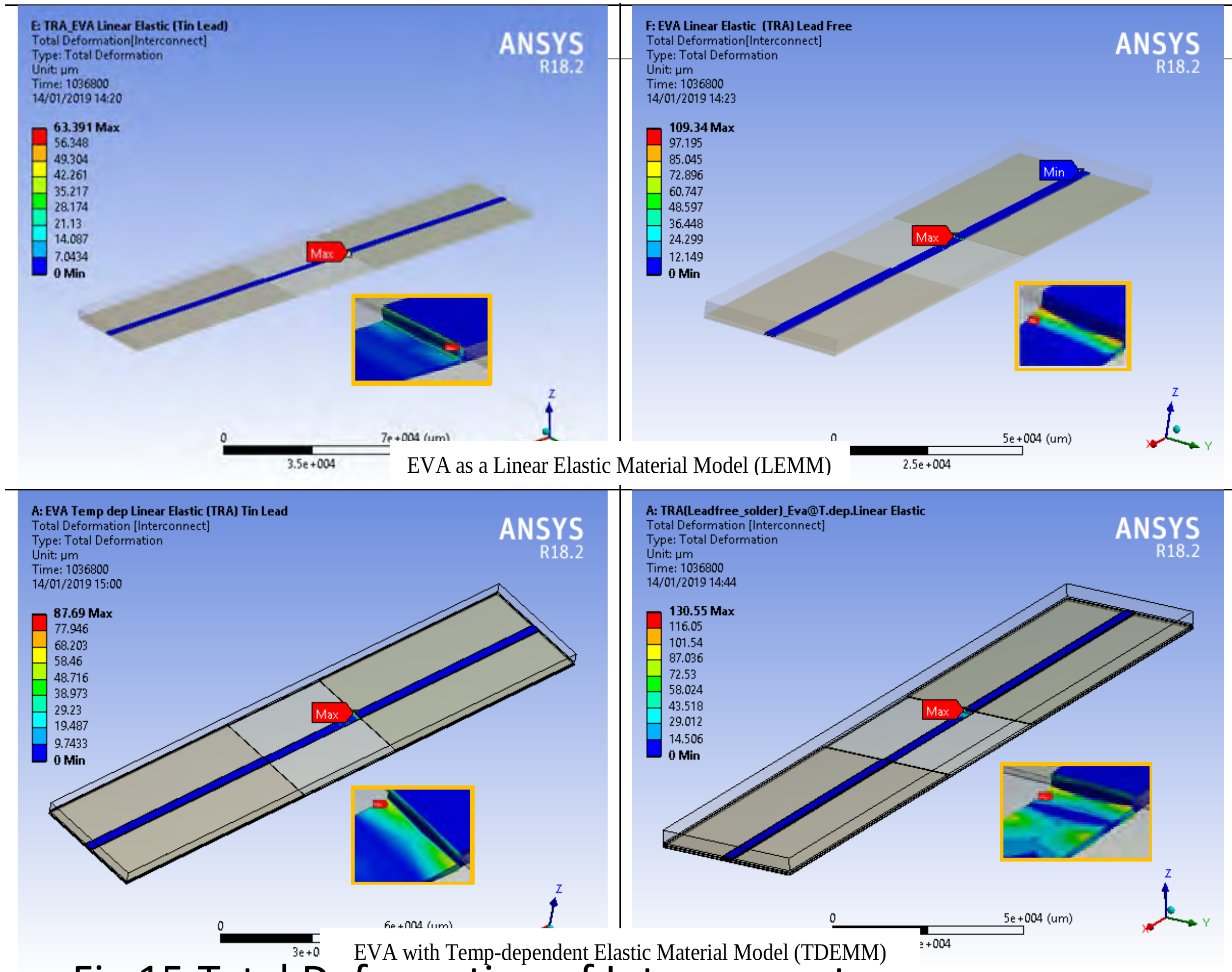




RESULTS AND DISCUSSIONS

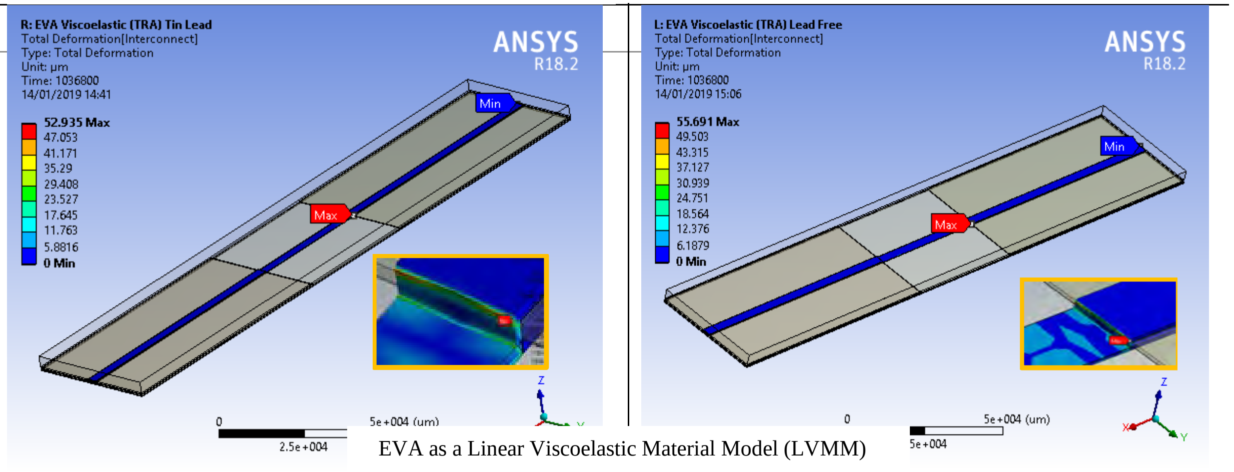
SOE 2: To evaluate the impact of encapsulant (EVA) constitutive behaviour on interconnect damage in C-Si SPVM.

(a) Tin Lead solder Interconnections	(a) Lead free solder Interconnections	(a) Tin Lead solder Interconnections	(a) Lead free solder Interconnections



EVA as a Linear Elastic Material Model (LEMM)

EVA with Temp-dependent Elastic Material Model (TDEMM)



EVA as a Linear Viscoelastic Material Model (LVMM)

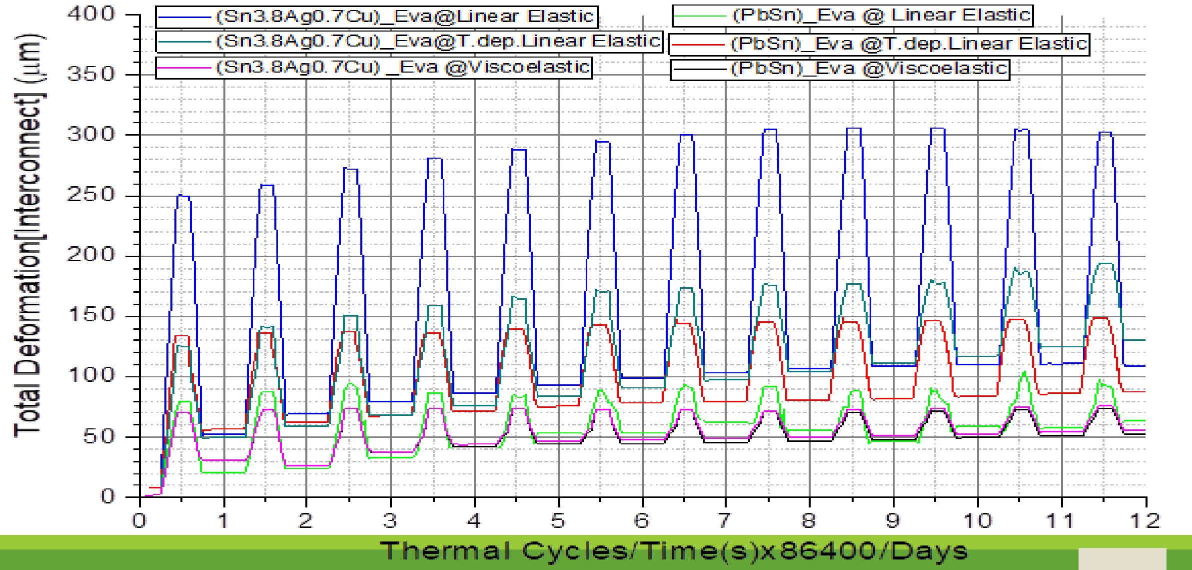


Fig 15:Total Deformation of Interconnect

CONCLUSION

PROGRESS STATUS:

Five (5) Manuscripts:

1. Review Paper: **Literature :** (Manuscript submitted)

Ms. Ref. No.: MEE-D-18-00310
Title: **Robust crystalline silicon photovoltaic module (c-Si PVM) for the tropical climate: future facing the technology**. https://ees.elsevier.com/mee/.

Page: 1 of 1 (1 total submissions) Display 10 results per page.

Action	Manuscript Number	Title	Initial Date Submitted	Status Date	Current Status
Action Links	MEE-D-18-00310	Robust crystalline silicon photovoltaic module (c-Si PVM) for the tropical climate: future facing the technology	May 30, 2018	Feb 04, 2019	Under Review

Page: 1 of 1 (1 total submissions) Display 10 results per page.

2. Nyarko, F. K. A., Takyi, G., Amalu, E. H., & Adaramola, M. S. (2018). Generating temperature cycle profile from in-situ climatic condition for accurate prediction of thermo-mechanical degradation of c-Si photovoltaic module. *Engineering Science and Technology, an International Journal*. doi:https://doi.org/10.1016/j.jestch.2018.12.007

CONCLUSION

PROGRESS STATUS:

Five (5) Manuscripts:

3. **Impact of Encapsulant constitutive behaviour on thermomechanical damage in crystalline silicon (C-Si) Solar PV Modules (SPVM). (Manuscript ready for proof reading)**
4. **Fatigue life prediction of Pb-free (SnAgCu) and SnPb solder joints in c-Si Solar PV Cell interconnect under in-situ field thermal cycling. (Manuscript under development)**
5. **Effects of Ramp rates, dwell times and temperature gradient on solder Joints degradation in c-Si solar PV under field thermal cycling (Manuscript under development)**

Tusen Takk