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Instrumented Modules for Mechanical Environment Characterization and Simulation Model Validation

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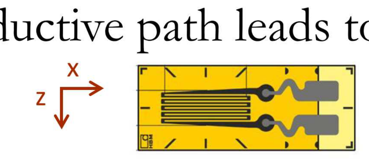
Introduction and Motivation

- This proof-of-concept project was designed to assess the viability of internal strain gauge instrumentation as a tool to assess internal states of modules experiencing external loads such as wind pressure or snow. Data will be compared to model predictions and useful for model validation.
- Strain gauges are thin, electromechanical devices where mechanical deformation of a conductive path leads to a change in resistance.

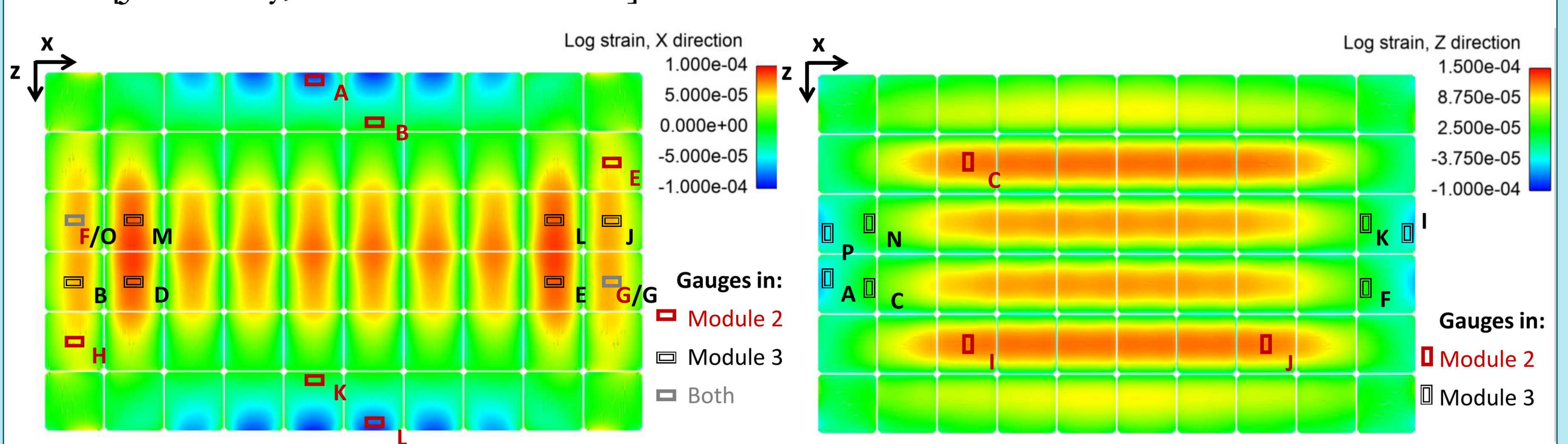


Linear gauge sensitive to strain in x-direction

- Strain gauges allow continuous high precision measurement at high sampling rates, making them well suited to monitor even small displacements of components. Their thin size allows them to be encapsulated in PV module laminates without disrupting stress states.
- Use of this capability in the future could include validation of collection of mechanical histories of modules in the field, or assessment of the representativeness of cell stress during accelerated test protocols.

Finite Element Model

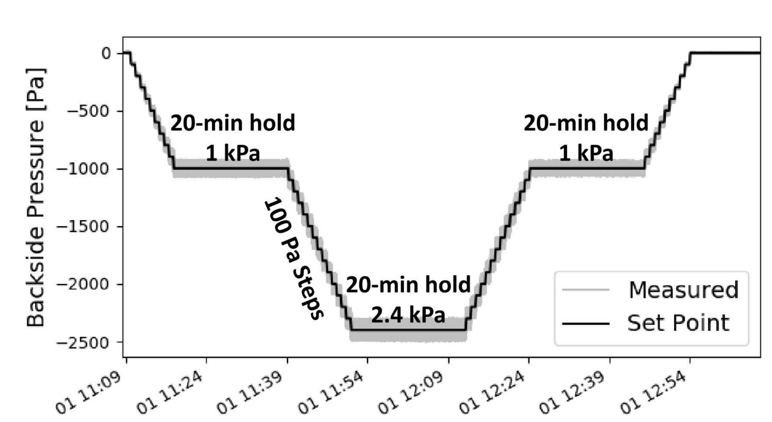
- Computational Finite Element Models (FEM) are useful for assessment and optimization of PV module designs. Full confidence in their results requires validation against experimental data from controlled test cases.
- Development of the FEM resolving the entire module and frame is detailed in [J. Hartley, 2019 IEEE PVSC]



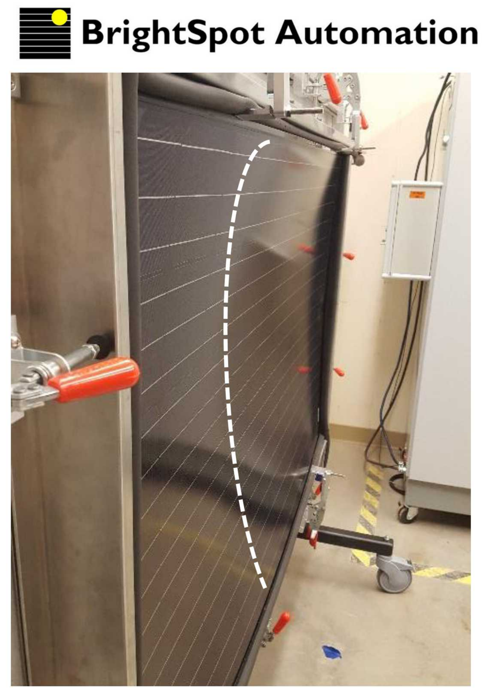
Model-predicted strain maps under 2.4 kPa frontside load with strain gauge locations

LoadSpot Module Mechanical Tester

- The LoadSpot is an air pressure based mechanical tester which enables repeatable, controlled loads with simultaneous internal and external data collection
- Identical load sequences were applied pulling vacuum on the back of each module:



BrightSpot Automation


Module deflecting under 5400 Pa load conditions (imposed via vacuum behind the module)

Instrumented Module Design and Fabrication

Module details:

- Module fabrication and design considerations completed in collaboration with D2 Solar LLC
- Modules are 60-cell, 5-busbar, monocrystalline, glass-backsheet architecture, with EVA encapsulant and a clear PE backsheet
- Four modules were constructed, one left un-instrumented as a control

Strain gauge instrumentation:

- Linear and XY-rosette strain gauges from HBM were selected with thermal properties matched to silicon. Output: bidirectional strain measurements.
- X280 cold-cure adhesive was used to adhere gauges to the back of cells

Strain gauge placements were selected for the following data objectives:

- Probe cells with maximum or minimum strain along module short edge and along module long edge
- Assess J-box effect on nearby cell strain
- Confirm symmetry across module quadrants

Successful fabrication:

- Wiring continuity checks and EL imaging confirmed the instrumentation survived the lamination process and did not cause cell cracks

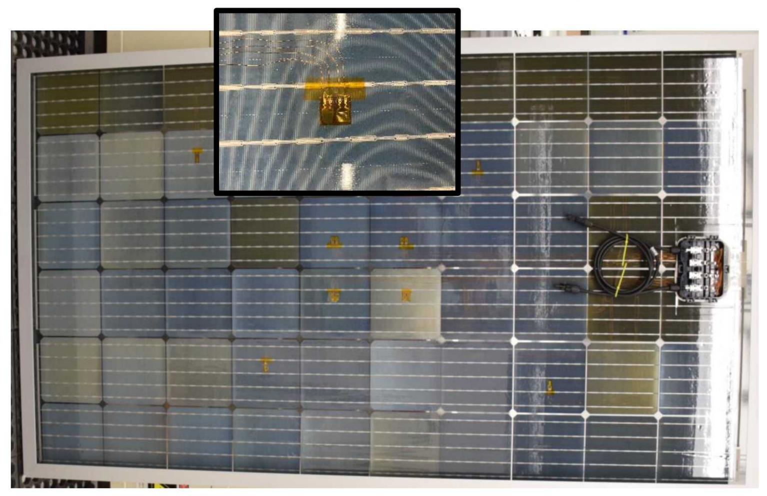
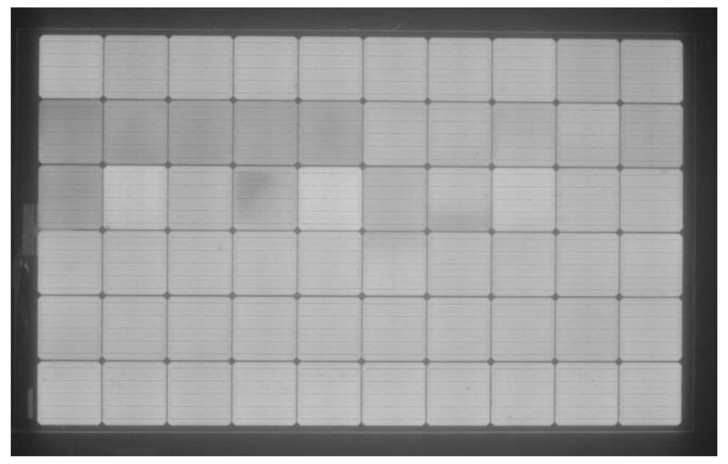
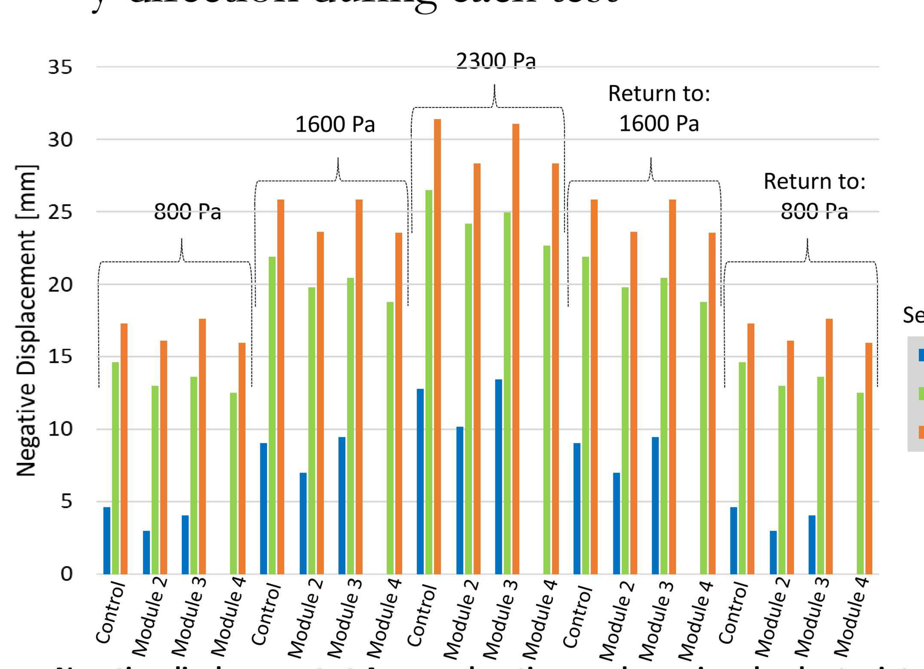


Photo of backside Module 4 w/ gauge and wiring inset

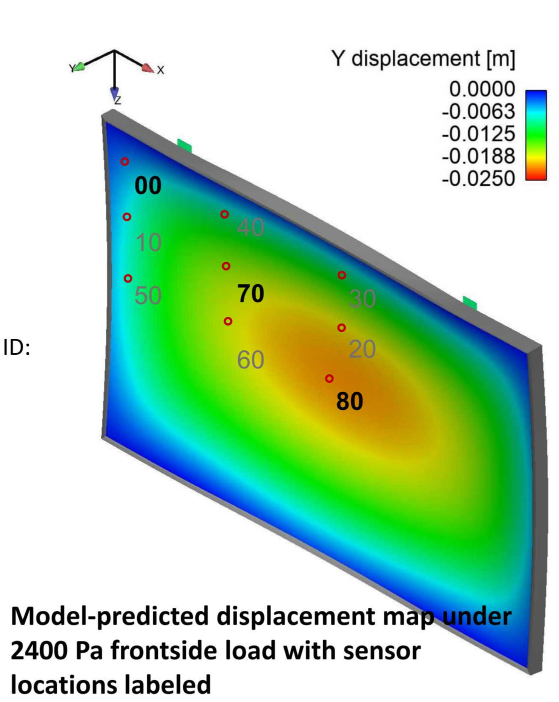

EL image of completed module showing no cracks post-lamination

Module Deflection Results

- Optical sensors measured displacement of the backsheet surface in the y-direction during each test



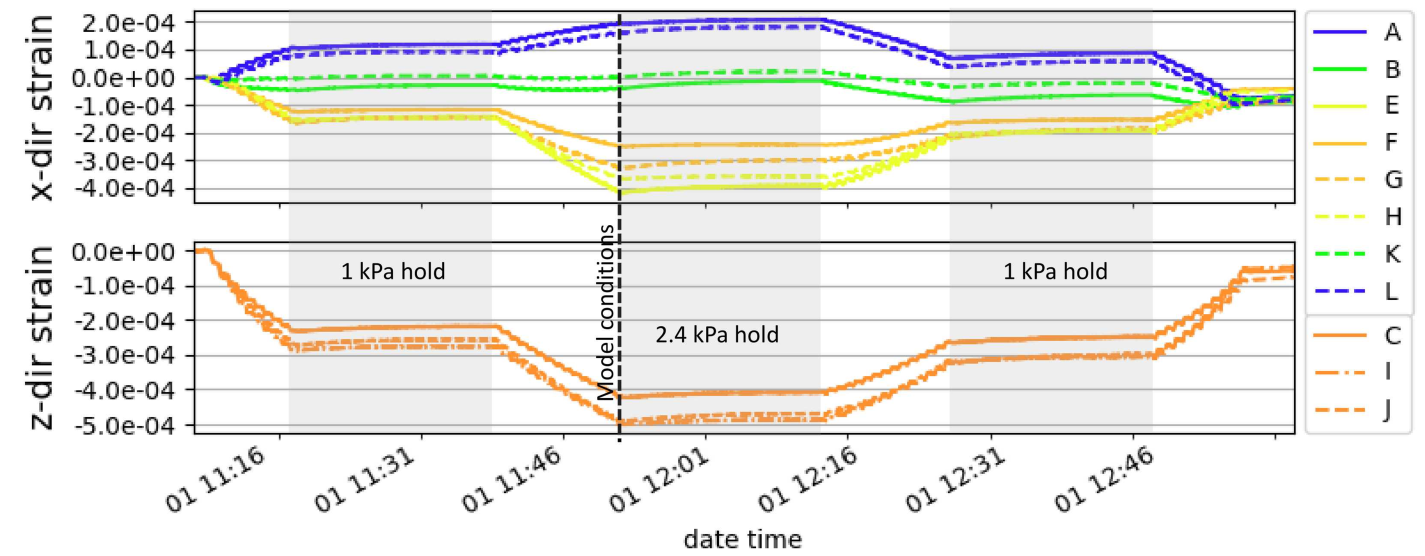
Negative displacement at 4 sensor locations under various load setpoints



Model-predicted displacement map under 2400 Pa frontside load with sensor locations labeled

Strain Measurement Results

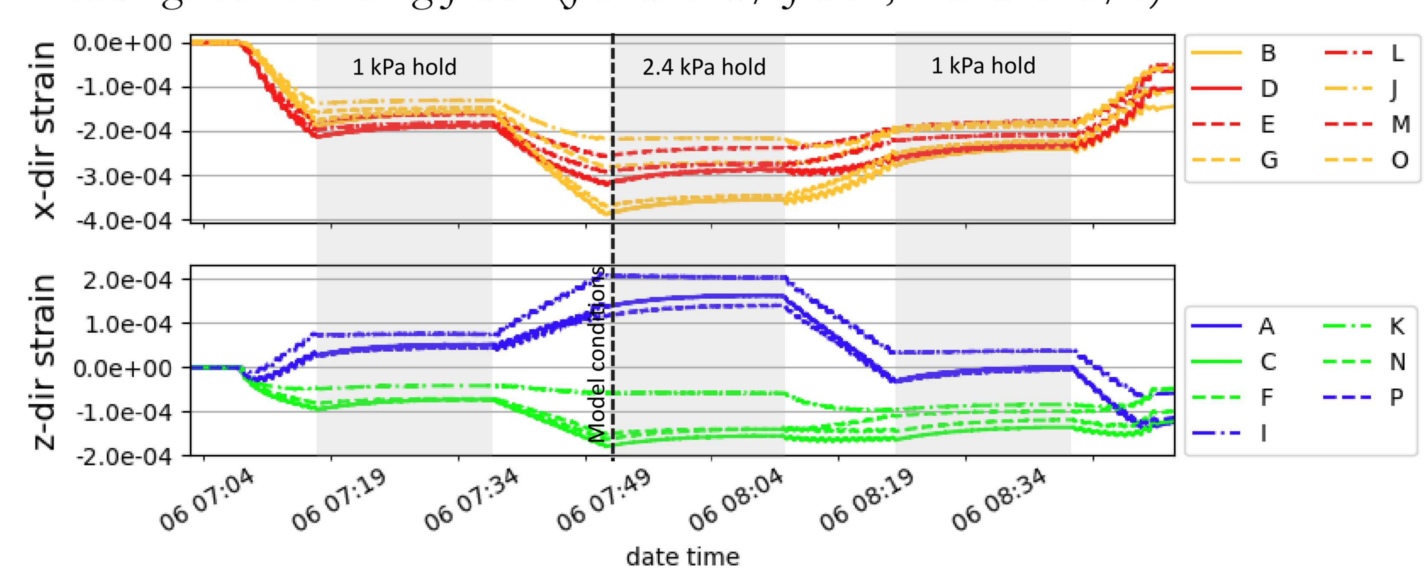
- Largest strains are measured in the module center, as predicted by computational model. Edge-module gauges "A" and "L" measure strains opposite in direction to center module gauges, as expected.
- If module symmetry were observed, strain readings of matching colors would be equal. Trends match but magnitudes vary up to 20%, perhaps due to module imperfections or misaligned strain gauges.



Module 2 strain gauge readings from 0 ->2.4 kPa -> 0 ramp experiment

Effect of junction box on nearby cell strain:

- Largest difference between module left/right sides observed in x-direction readings surrounding J-box (J and G w/ J-box, B and O w/o)



Module 3 strain gauge readings from 0 ->2.4 kPa -> 0 ramp experiment

Conclusions and Future Applications

- This work has produced detailed information about the strain state of the PV cells within the module architecture
- An area of further investigation is the irreversibility observed in the strain measurements. Strain after the return to zero load tends to remain below zero, likely due to a combination of temperature effects on instrumentation and irreversible changes in the mounting or module structure.
- These results are useful as model validation data to improve confidence in more complex FEM predictions of internal components
- Use of this capability in the future could include:
  - collection of mechanical histories of modules in the field under snow loading or high wind conditions
  - assessment of the representativeness of cell stress during accelerated test protocols.
  - effects of design decisions, for example size and placement of the junction box

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DuraMAT Durable Module Materials Consortium

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