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Instrumented Modules for Mechanical Environment Characterization and Simulation Model Validation

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***Abstract*—A group of crystalline silicon glass-backsheet photovoltaic modules was designed and fabricated with strain gauges directly encapsulated within the module laminate. These instrumented modules were subjected to uniform mechanical pressure loading in stepped experiments, to correlate recorded internal strains against deformed module shapes. Strain data will also be used to validate computational finite element models of module deformation under load. This work serves as a proof-of-concept assessment of whether embedded strain gauge instrumentation can be used to accurately characterize internal module states during mechanical loading, and discusses lessons learned with the instrumentation, fabrication, and data acquisition process. Additional applications for the instrumented module concept could include deployment into field environments, to record module response to weather events and better define packaging robustness requirements, or measurement of internal strains over time to assess the impact of material viscoelasticity on internal components.**

Keywords—Strain gauge, finite element modeling, validation, mechanical loading

I. Introduction

Mechanical loads are a typical part of the photovoltaic (PV) module deployment environment, from exposures to wind, snow, and installation handling, among others [REF]. As such, the module package is critical for improving durability and lifespan and is an unavoidable contributor to the overall module cost. Optimization of the module package to ensure survivability in deployment environments while minimizing costs is a persistent objective, evolving alongside developments of new materials and technologies.

Methods for optimizing a module package design can include prototyping and physical testing, with associated difficulties around materials and processing expenses, or computational simulation, which is limited by availability of applicable validation testing. Optimization may also be accomplished by better characterizing expected deployment environments, to avoid over- or under-designing against the actual mechanical exposures endured during a module lifecycle.

Strain gauges are thin, electromechanical devices which convert mechanical deformations into changes in resistance by altering the conductive path through a deformable foil pattern [1]. Their flat profile enables placement directly on substrates within a PV module laminate, and their simplistic, robust design are amenable to module lamination processes. Additionally, since strain data is electrically modulated, measurements can readily be made with high precision, continuously in time, and at high sampling rates. This enables detection of even small displacements of components within the module laminate, potentially as influenced by material creep, or due to fluctuating environmental loads such as wind.

In this work, PV modules were designed and built with strain gauges incorporated directly into the laminate in order to measure and record strain within the module at key locations while under mechanical load. Static, laboratory-imposed uniform pressure loads were used for this study, to enable comparison of strain outputs against both expected strains predicted from full module finite element models and externally measured module deflections. Also included are insights on the instrumentation, manufacturing, and data acquisition processes. Knowledge gained from this study is intended to enhance PV module packaging design efforts, by helping to validate computational modeling tools, and assessing the accuracy and robustness of the instrumented module concept. Future applications could include deployment of instrumented modules into field environments to characterize mechanical exposure during a module lifetime or capturing difficult-to-measure internal effects such as time-dependent component displacements due to encapsulant viscoelasticity.

II. Methods

A. Module platform description

Modules were designed to mimic commercially available modules, with a 60-cell, 5-busbar, monocrystalline, glass-backsheet architecture chosen as the baseline. Glass thickness was 2.75 mm, encapsulant chemistry was ethylene vinyl acetate (EVA), and a clear polyester (PE) backsheet was used, to enable a direct view of the module interior. A 45 mm aluminum frame with L-bracket corner keys was used, and electrical functionality was left intact including junction boxes and tabbing to enable diagnostics via electroluminescence (EL) imaging.

B. Strain gauge instrumentation

HBM linear (1-LY66-10/350) and XY-rosette (1-XY106-6/350) gauges were used in sizes selected to fit between bussing fixtures. Most strain gauges were adhered directly to the backsides of the cells using X280 two-part cold-curing adhesive. This was done to provide a stable substrate, required for repeatable strain output [1], although a couple gauges were deliberately left free-floating in the encapsulant layers to assess impacts on strain output. Gauges were selected to be thermally

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matched to silica to reduce expansion drift [2]. Each gauge was wired using 30-gauge polyimide-coated copper wires, soldered to gauge terminals with solder paste and routed away from the cell using both polyethylene (PE) alignment tape and Kapton® tape.

A quarter bridge circuit was completed for each gauge and included a 350 Ohm high precision resistor and a National Instruments (NI) 9949 bridge completion accessory. A NI CompactDAQ with NI 9237 modules was used for data acquisition. The CompactDAQ was in communication with an in-house Labview platform which controlled the excitation voltage, recorded the measured resistance across each circuit, and calculated strain.

C. Simulations

Finite element simulations of modules under load were based on models developed in [3,4], resolving the entire module and frame. Some variations existed between the simulated and constructed module designs, although displacement and strain *trends* were expected to be representative. A uniform pressure load of 2.4 kPa on the front glass surface was simulated to visualize expected strain distributions on cells along module long- and short- dimensions (Fig. 1). Gauge placements were selected to measure cell areas expected to have characteristic features such as large magnitudes or strain reversals.

D. Strain gauge placements

A total of four modules were constructed, with one module designated as an undisturbed control and the remaining modules containing instrumentation. Gauge placements were selected based on areas of interest identified in simulation results and distributed across modules to reduce the number of instrumentation wires exiting the module. Fig. 2 shows the instrumented module gauge layouts and the key observations to be made from each design.

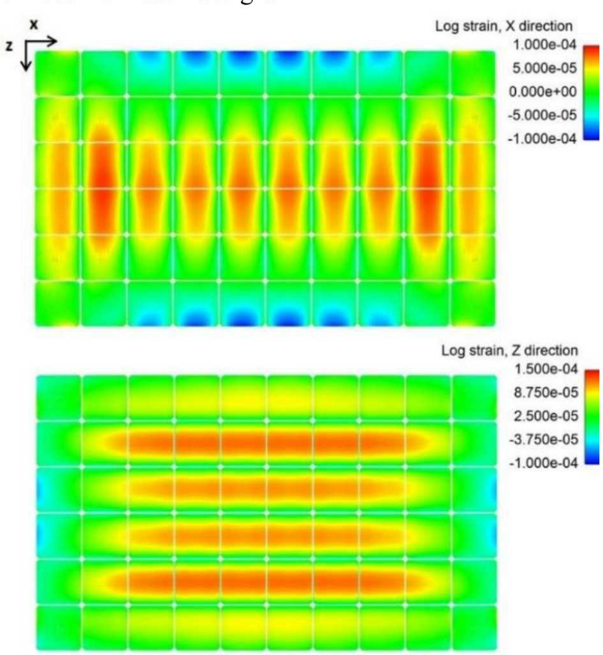

Fig. 1. Simulated log strain on cells, along module long (x) and short (z) dimensions, with a front-surface pressure load of 2.4kPa.

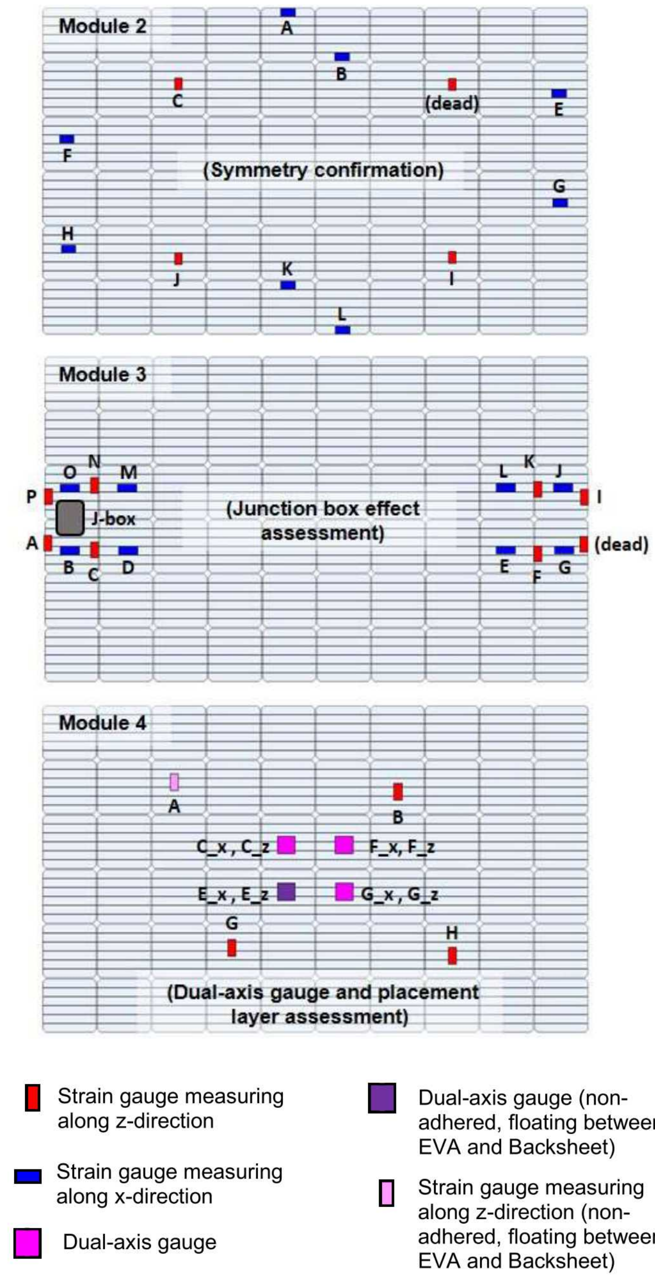

Fig. 2. Module strain gauge layouts including gauge letter IDs, with key data goals in paranthesis. Legend indicates gauge measurement direction and placement notes.

E. Experimental cases

A LoadSpot mechanical tester [5] was be used to conduct mechanical testing, with loading imposed by air pressure behind the module mounted with seals against the frame perimeter (Fig. 3). Two stepped ramp procedures of pressure loads were completed for each module design: the first reached a cautious maximum load of 1.0 kPa to reduce the risk of cell breakage, and the second reached a max load of 2.4kPa with extended 20-minute hold periods at 1.0 kPa and 2.4kPa (Fig. 4). Simultaneously, module deflection of the backsheet surface was measured with optical sensors built-in to the LoadSpot frame, and EL images were recorded at each 100 Pa step.

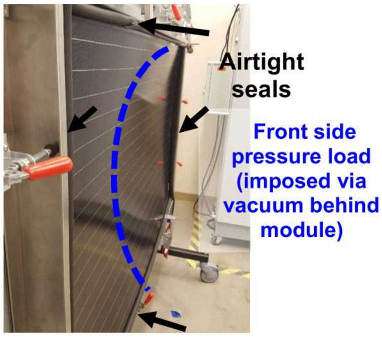

Fig. 3. LoadSpot module mechanical tester, imposing a front-side pressure load to test module by reducing air pressure behind module.

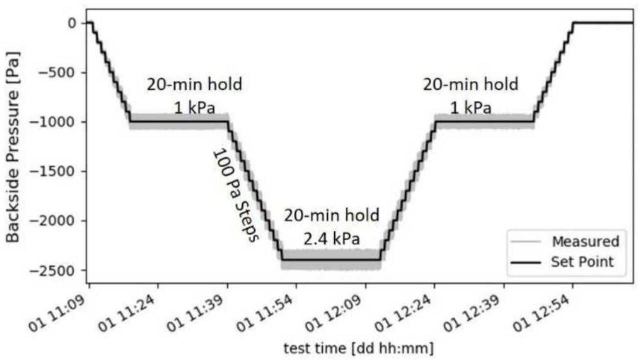

Fig. 4. Backside pressure set points and measured values for the 2.4kPa stepped ramp procedure

III. Results

A. Module fabrication process

Instrumented modules were laid up manually, beginning with the glass, top encapsulant sheet, and interconnected cells. Strain gauges were adhered to the positioned cells, and the adhesive was left to cure for at least 24 hours. Wires were routed to exit underneath the junction box and secured along their paths with PE alignment tape. Wire terminations were collected and fed through holes in the rear encapsulant sheet and backsheet during final sheet placement. The layup was then laminated through a commercially representative heating cycle, with no air bubbles or delamination sites observed in the finished module despite the quantity of wires and alignment tape used (Fig. 5). Resistances across strain gauge instrumentation wire terminations indicated that continuity was maintained for all except three test gauges, indicating good survivability through the lamination and shipping process. EL images of the completed modules (Fig. 6) indicated that no cell cracking occurred during lamination or shipping, suggesting that the package was tolerant of the strain gauge wiring, which at times crossed cell tabs, each other, or formed bundles due to the thin and flexible nature of the wires.

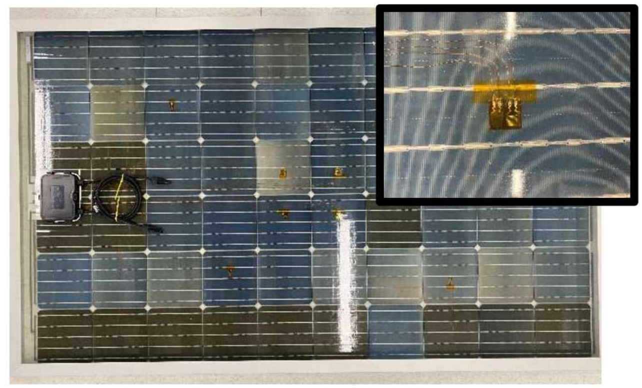

Fig. 5. Completed instrumented module with inset showing strain gauge placement and wire routing methodology.

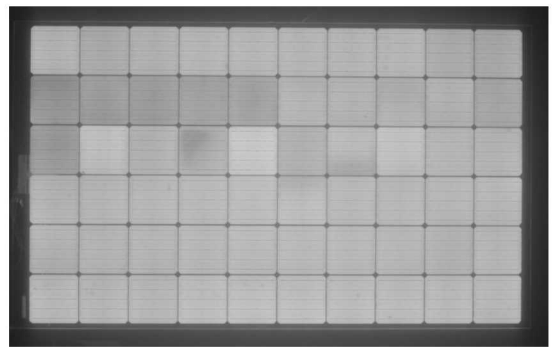

Fig. 6. EL image of completed module with embedded instrumentation and wiring (not visible), showing no cell cracks post-lamination.

B. Strain measurements

Strain data collected during the 2.4kPa stepped ramp procedure on Module 2 (Fig. 7), Module 3 (Fig. 8) and Module 4 (Fig. 9). Colors were selected based on predicted strain at the gauge locations using the strain map in Fig. 1. The largest strains are measured in the module center, as predicted by computational model. Edge-module gauges in Module 2 (“A” and “L”) and in Module 3 (“A”, “I” and “P”) measure strains opposite in direction to center module gauges, as expected. The slight drift in strain observed during the 20-minute holds is likely due to polymer relaxations of the viscoelastic encapsulant material.

Module 2 was designed to confirm symmetry of strain within in the module. If module symmetry were observed, strain readings of matching colors would be equal. The trends in symmetric gauges match, but strain magnitudes vary up to 20%, perhaps due to module imperfections or misaligned strain gauges.

Module 3 was designed to assess the effect of the junction box on strain in nearby cells. Generally, the results show less strain in cells around the J-box (e.g. z-direction “A” and “P”) as compared to their counterpart across the module (“I”). However, some gauges which were predicted to have matching results (e.g. x-direction “J” and “G”) actually measured strains as varied as the difference seen across the module with and without the junction box.

Module 4 was designed to assess the viability of dual-axis gauges in this application and to observe strain output when gauges were “floating” between the encapsulant and backsheet layers. The dual-axis gauges have similar levels of agreement across quadrants as single-axis gauges. Results from the “floating” gauges “E1” and “A” show similar strain magnitudes to their counterparts with a more pronounced relaxation behavior associated with polymer viscoelastic behavior during the long holds.

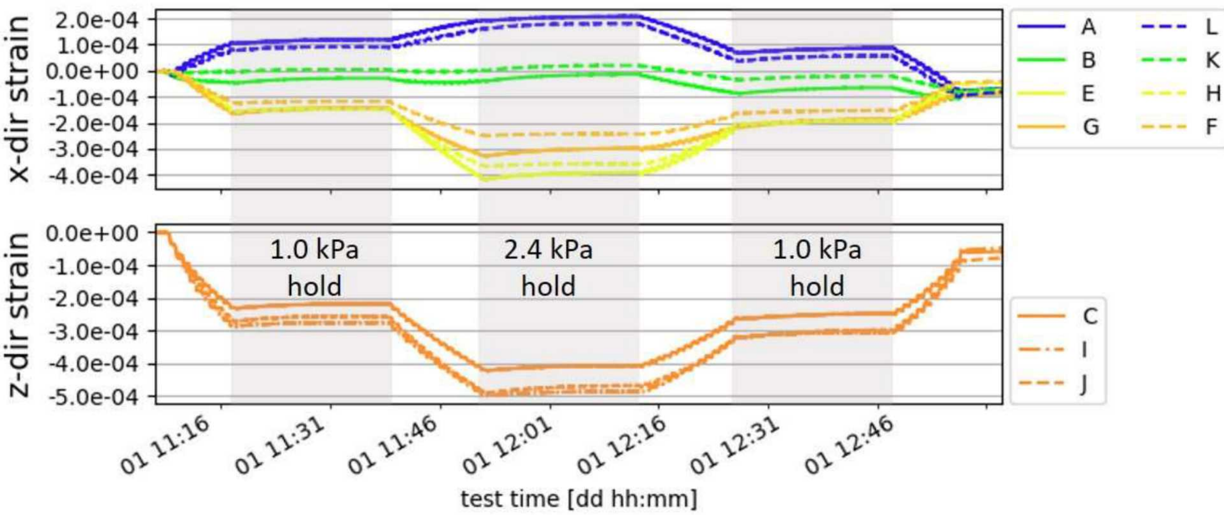

Fig. 7. X-direction and z-direction strain measurements from Module 2 durig the 2.4kPa stepped ramp procedure. Matching colors indicate symmetric locations.

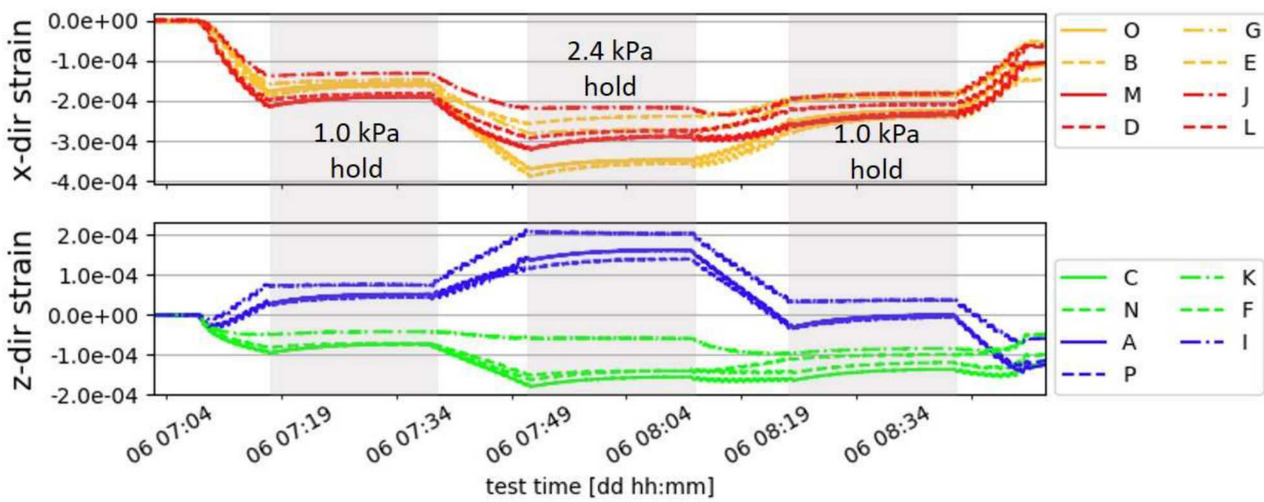

Fig. 8. X-direction and z-direction strain measurements from Module 3 durig the 2.4kPa stepped ramp procedure. Data colored based on model predicted strain at gauge location mapped in Fig. 1.

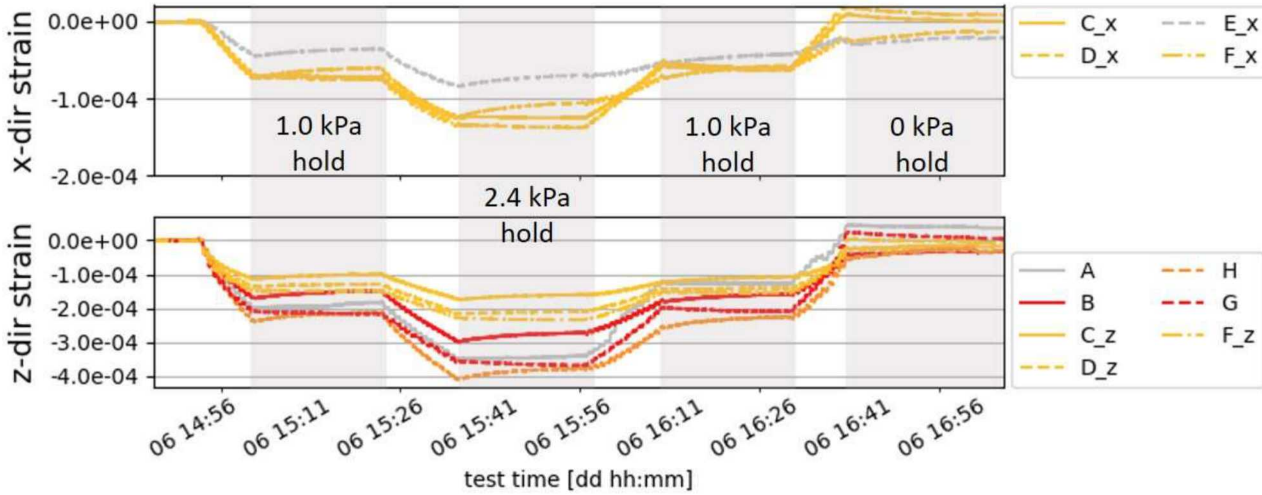

Fig. 9. X-direction and z-direction strain measurements from Module 4 durig the 2.4kPa stepped ramp procedure. Data colored based on model predicted strain at gauge location mapped in Fig. 1, except gray indicated unadhered gauges placed between encapsulant and backsheet.

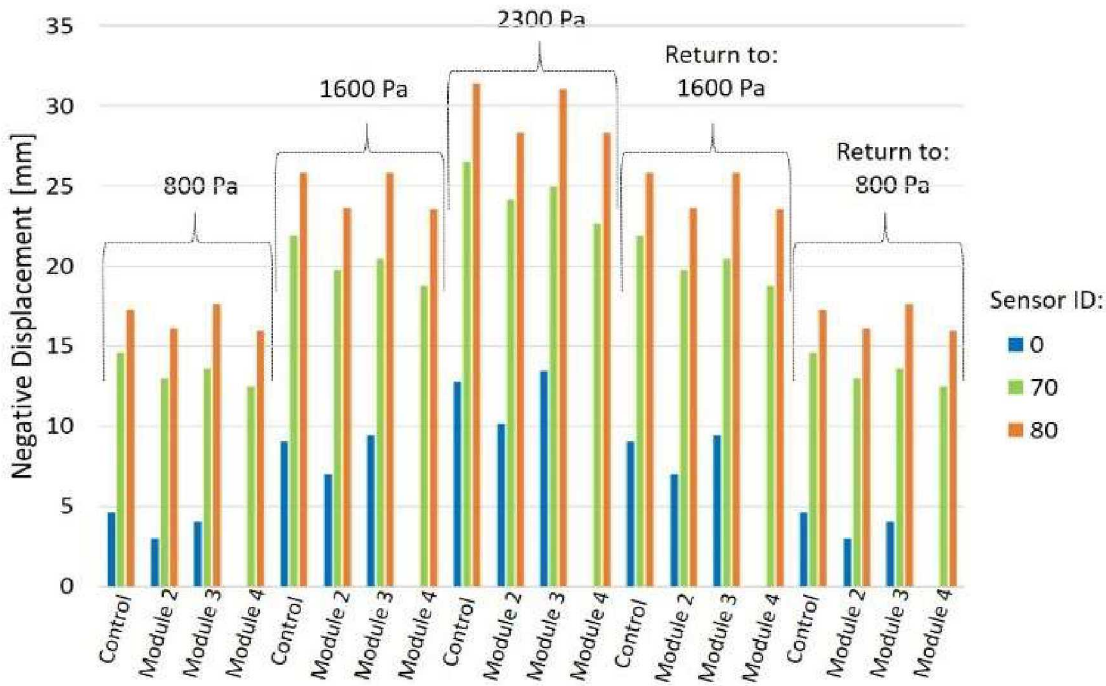

Fig. 10. Average measured negative displacement of the backsheet for all four modules under 800 Pa, 1600 Pa and 2300 Pa front-side load conditions. Sensors 00, 70 and 80 are located along the diagonal of the module.

C. Deflection measurements

Overall module deflection was observed by collecting data at nine locations using the LoadSpot optical displacement sensors. Data from three sensors along the module diagonal are included in Fig. 10 for all four modules at select pressure set points in the stepped procedure. Results show good agreement between all modules, demonstrating that adding gauges and wiring did not significantly alter the module behavior under these loading conditions. Also note that no significant difference is observed in the first half of the test compared to the second (no hysteresis). A map of simulated displacement at 2.4k Pa shows the expected shape of the loaded module with the highest displacement predicted at the center of the module (Fig. 11). Deflection along the module diagonal was measured and modeled in [4] with a center-point deflection of 25mm predicted under 2400 Pa front-side load. Although the magnitude of displacement measured here is slightly higher, perfect agreement between these experiments and the model was not expected due to differences in glass thickness and frame design. The deflection trends from edge to center do match well.

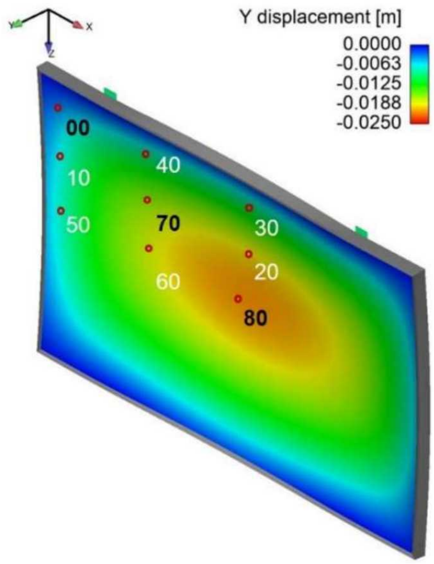

Fig. 11. Simulated displacement of front glass, with a front-surface pressure load of 2.4kPa. LoadSpot optical displacement sensor locations marked with red circles and labeled with sensor ID numbers.

D. *Embedded strain measurement insights*

These results demonstrate that it is possible to embed instrumentation within a PV module laminate without damaging cells and interconnects and without affecting overall module deflection under mechanical load. It should be noted that craftmanship is very important to gather representative data. Strain gauges are sensitive to exact positioning, complete adhesion to the substrate without excess adhesive, and precise soldering of gauge leads. Additionally, the expertise of D2Solar in constructing custom modules was critical in this project to produce four matching modules without the automation and process control common in commercial module manufacturing facilities.

A key lesson learned is that additional steps could be taken to avoid and/or correct for the effects of temperature on strain measurements over a long test procedure. Using a 3-wire design of strain gauge leads would have canceled out the effect of increased resistance in gauge lead wires due to heating. Imbedding thermocouples next to some of the strain gauges would allow strain measurements to be corrected to the local temperature conditions and help experimenters to select an excitation voltage that avoids gauge heating [2].

IV. Conclusions

Custom PV modules representative of commercial 60 cell crystalline silicon modules were designed and built with embedded internal instrumentation, to collect strain data. This data will be used to validate computational models. The fabrication process was found to be successful, with no adverse effects or observable damage to cells or gauges despite many gauge wires running throughout the backside layers of the module. The instrumented modules were tested under uniform mechanical pressure loading, to verify strain gauge data accuracy and repeatability, correlating data outputs to external module shapes. Results showed up to 20% strain variation across symmetric quadrants and reduced x- and y-direction strain around the junction box. Future work will specifically compare measured strain magnitudes against simulated strains for the test load configurations, which will be 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, or evaluation of the effects of design decisions, for example size and placement of the junction box.

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