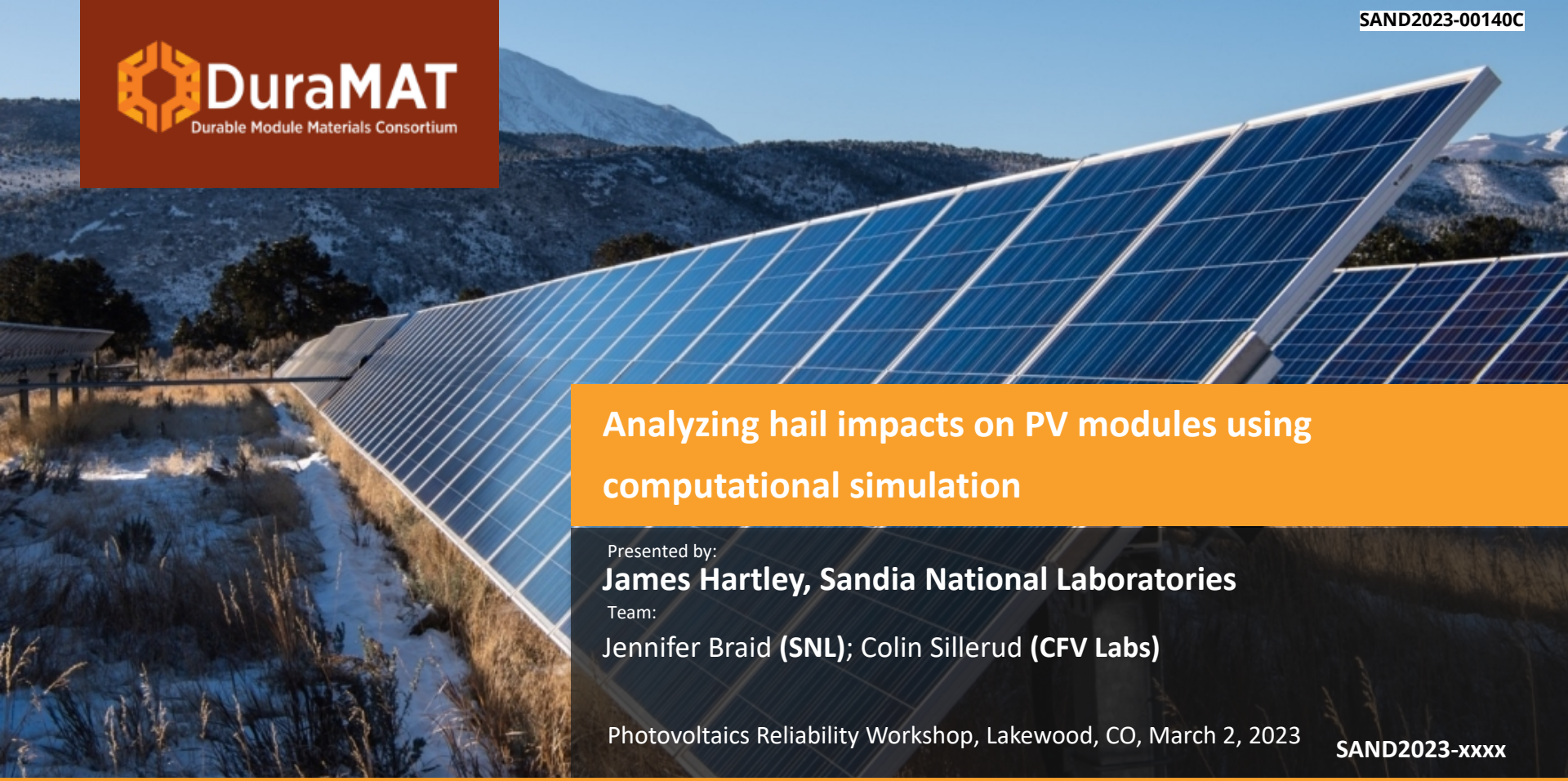
SAND2023-00140C

DuraMAT
Durable Module Materials Consortium



Analyzing hail impacts on PV modules using computational simulation

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Photovoltaics Reliability Workshop, Lakewood, CO, March 2, 2023

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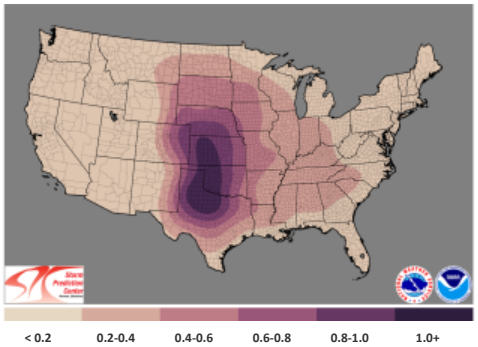
CFV Labs

Motivation and goals

- A 30+ year module will most likely experience a large hail event in its design lifespan
- Damage due to hail is measured as pass or fail, which is insufficient resolution for calculating risk
- **A method for *quantifying* module damage risk is needed**



Mean days per year with a hail size greater than 2” (1986-2015)

IEC61215-2:2016 MQT17 (Hail Test) Standards

Diameter mm	Mass g	Test velocity m/s
25 PASS	7,53	23,0
35 PASS	20,7	27,2
45 FAIL	43,9	30,7

Most modules are here. Would they survive 38 mm?

Qualification standards do not fully describe damage risk

Goal: Model the hail vs. module impact in simulations to enable a more continuous understanding of hail risk and quantify parameters which influence module survivability

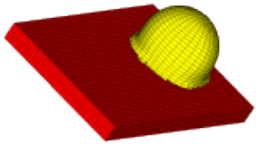
Project scope and overview

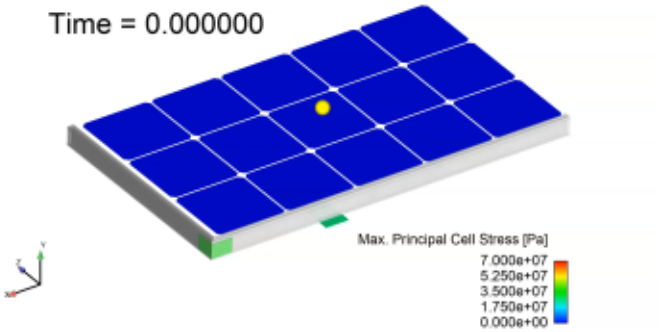
- Capture the hail impact vs. module event in simulation
- Validate that the simulation matches reality
  - **Ice ball material model**
  - **Module dynamic response model**
  - **Module damage model**
- Use validated simulations to conduct parametric studies to find what physical characteristics correlate to damage probability

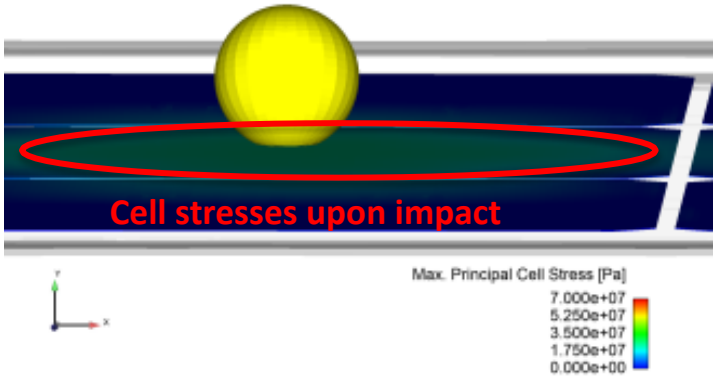
A quantitative understanding of module damage probability enables informed decision making for both module design and deployment

Capture the hail impact vs. module event in simulation

- Impact simulations require both the projectile (**hail**) and target (**module**) to be modeled
- **Hail model:** Exists in literature and previously implemented at Sandia for other applications
  - Elastic-plastic with rate-dependent yield and supplemental failure criteria
- **Module model:** Previously developed under DuraMAT 1 projects







A combined hail vs. PV module simulation. Capturing both hail ice material properties and module deformation upon impact is needed to accurately predict damage

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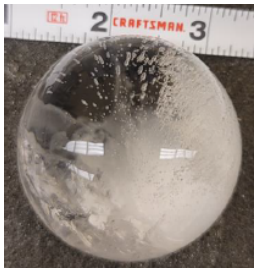
Validating the simulation: The ice material model

- Force vs. time profiles were recorded for impacts against an instrumented target:
  - IEC-standard hail from 25 mm to 75 mm
  - Non-ideal ice (to probe real-life hail variability)
  - Non-ice objects (to baseline measurements)
- Comparing measured results to simulations gives confidence in model applicability



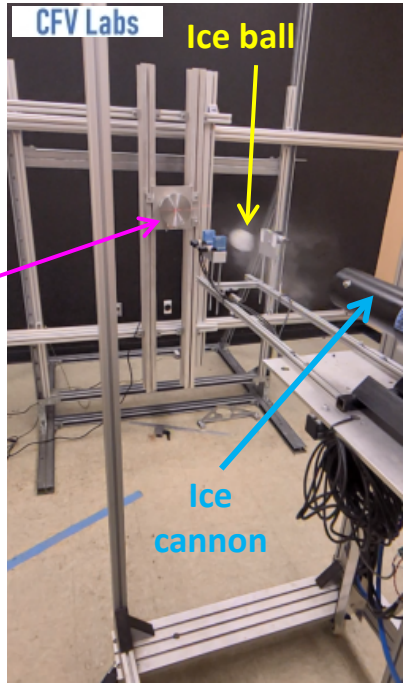
IEC-defined ice ball


Conglomerate ice ball


Non-ice projectiles

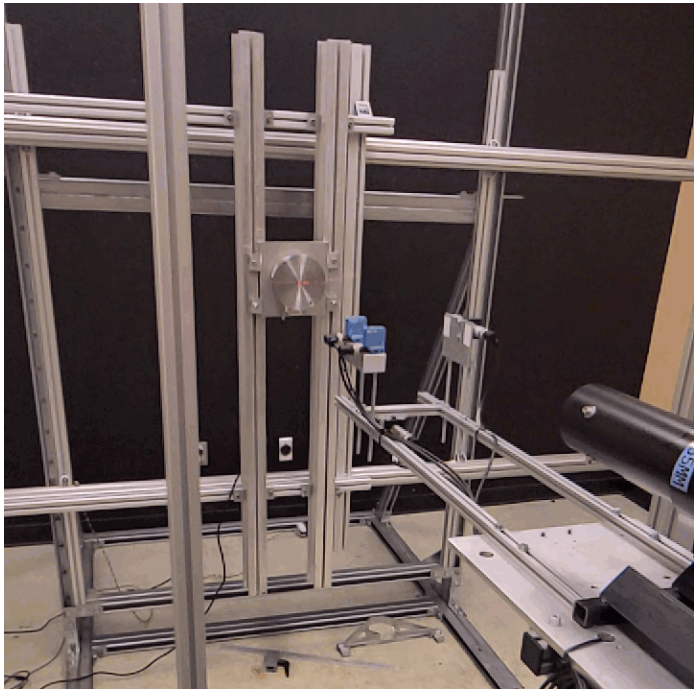


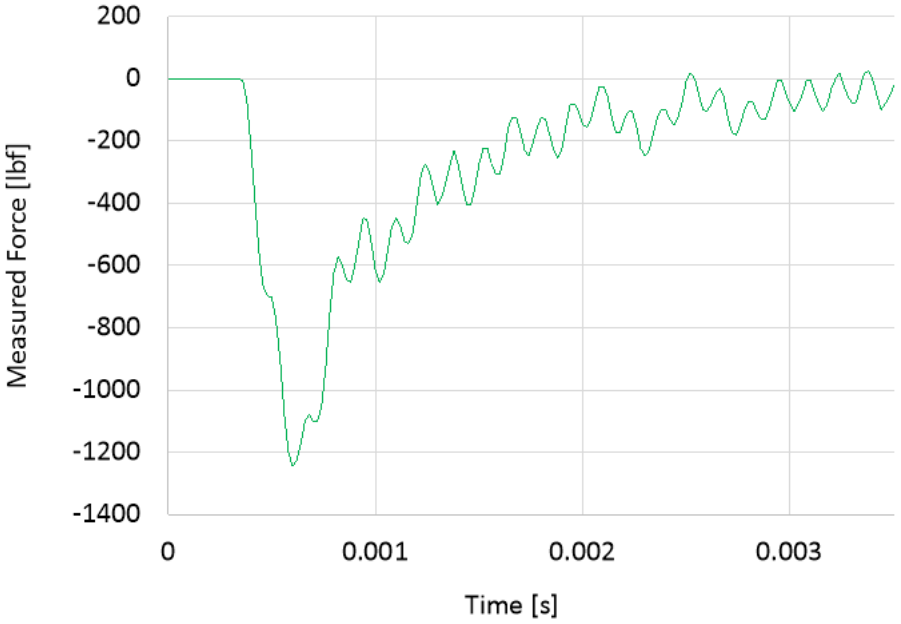
50 kHz force sensor



Impact force setup @CFV Labs

Example force vs. time profile (65mm IEC-standard ice ball)

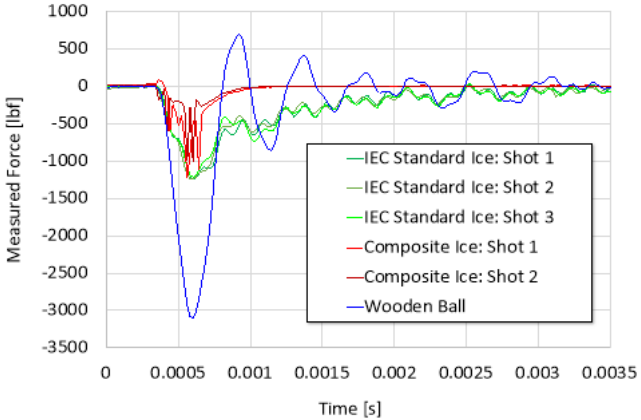




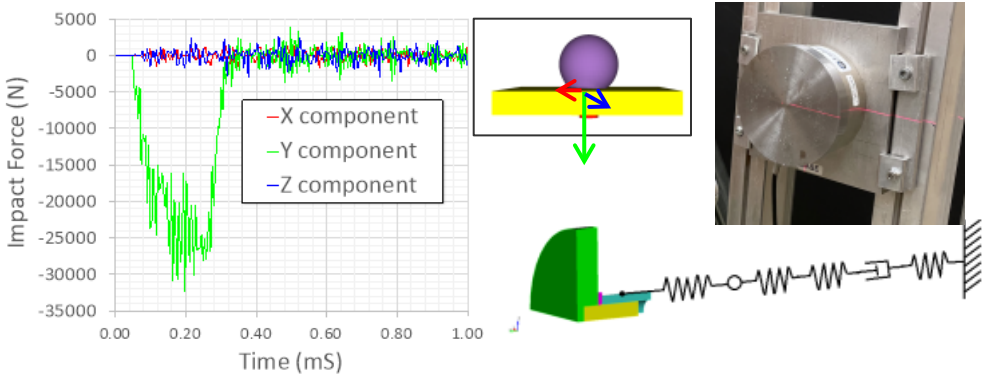
Measured force vs. time profile

Measured impact observations and project next steps

- All ice impacts were surprisingly repeatable
- IEC-standard ice balls are a worst case scenario, but perhaps not excessive:
  - Very repeatable impact force profile despite variable appearance, bubbles, density
- Project next steps: adjust for test fixture dynamics to complete material model validation



Comparison of force vs. time profiles for various 65mm impacts



Modeled ice impact against rigid target. Direct comparison requires modeling of non-rigid test fixture dynamics

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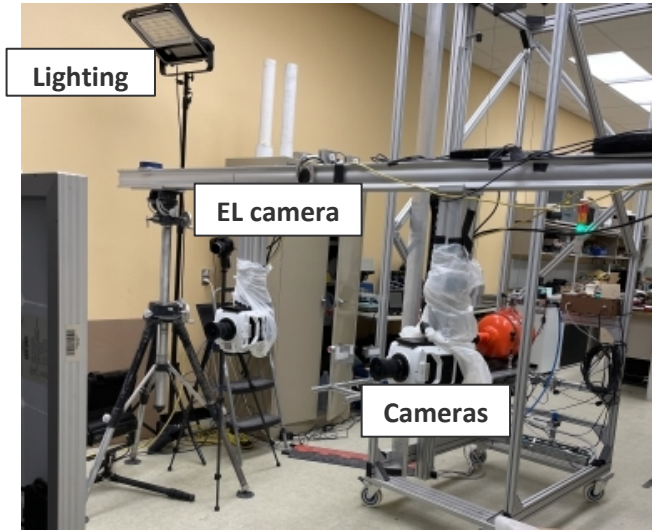
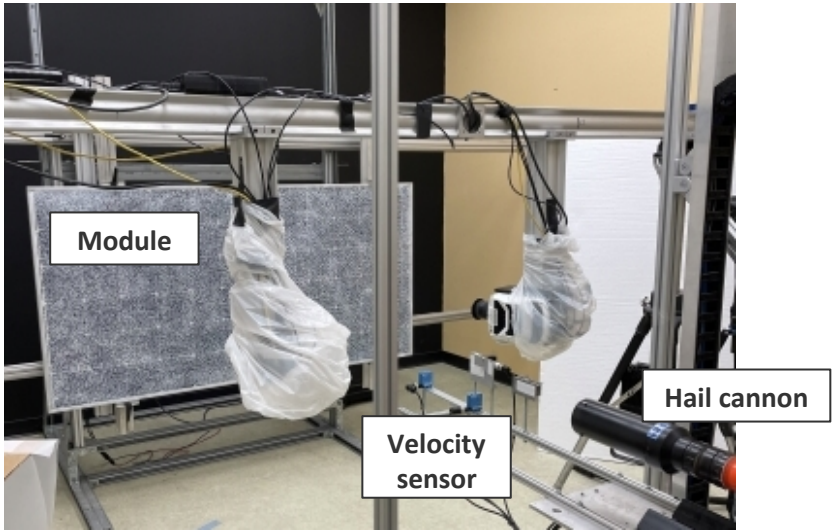
Validating the simulation: Module dynamic response

- Stereo high speed video of a hail impact was recorded for analysis with digital image correlation to process module deflections vs. time
- Matching dynamic response to simulations provides confidence in model applicability



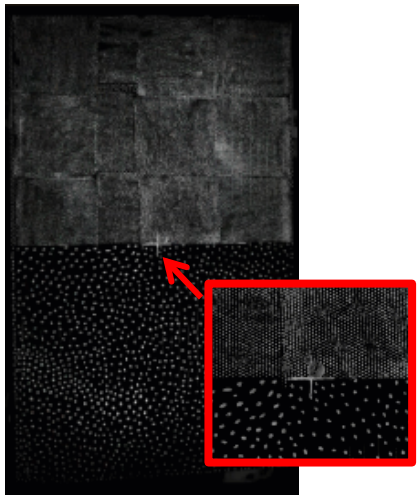
Test setup: Module view



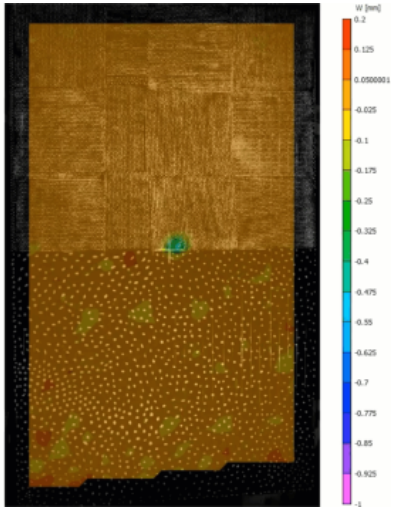
Test setup: Cannon view

Module dynamic response observations and project next steps

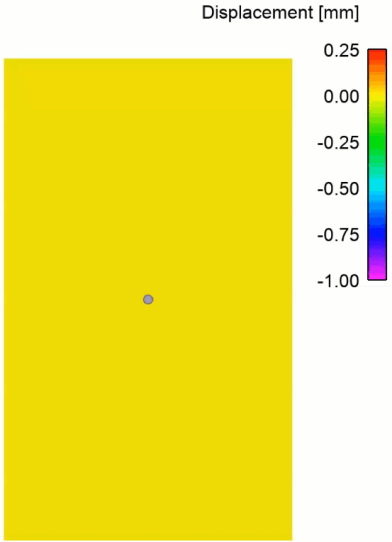
- Proof-of-concept has been demonstrated for the experimental technique
- Collection of validation datasets (2 module designs, 96 shots each) is underway



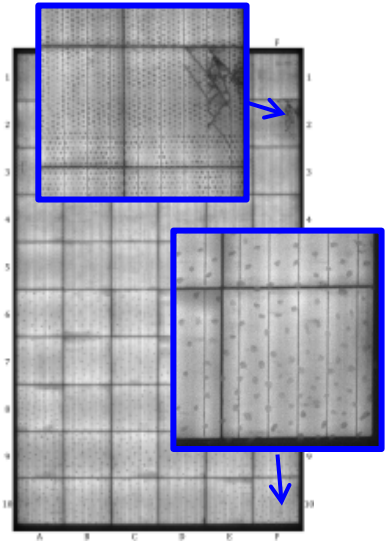
Visual video of hail impact



Video processed for displacements



Simulated impact event showing displacements



EL images able to show cracks under DIC patterning

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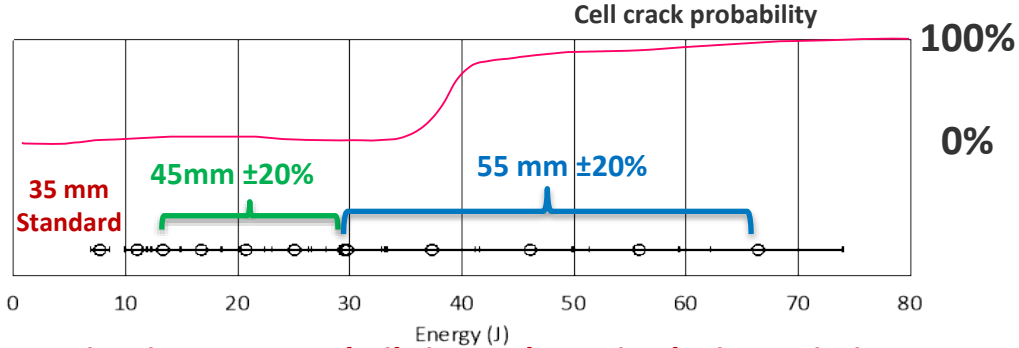
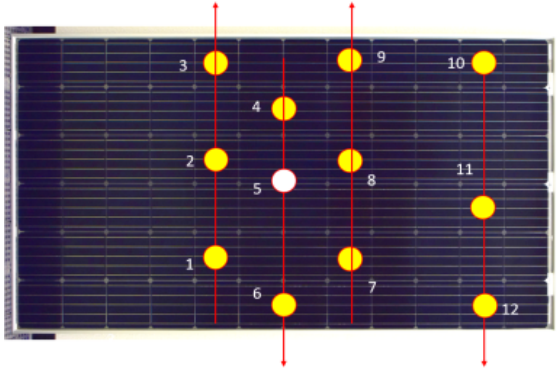
Validating the simulation: Module damage model

- Pre- and Post-impact electroluminescence (EL) imaging can be applied to identify cell damage
- A battery of hail tests is underway to collect cell and glass failure statistics (in tandem with high speed video and digital image correlation for dynamic response)
  - 8 samples of a 72-cell, 3.2mm glass-backsheet module, ~12 shots per module
  - 8 samples of a 144-cell, half-cut, 2mm/2mm glass-glass module, ~12 shots per module



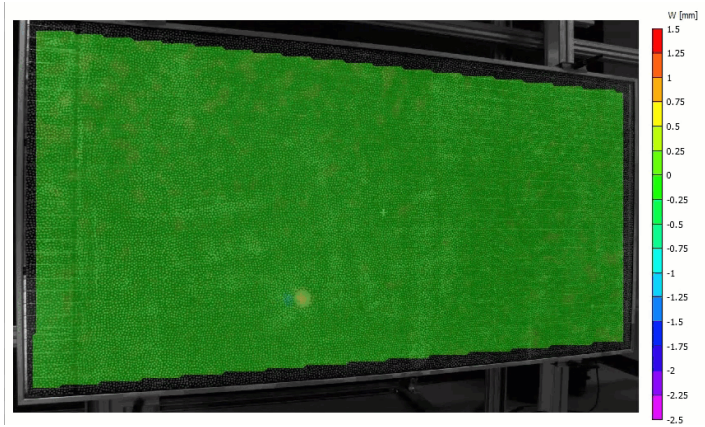
Kinetic energy vs. hail size and ±20% velocity variation
With sufficient tests, damage trends begin to emerge



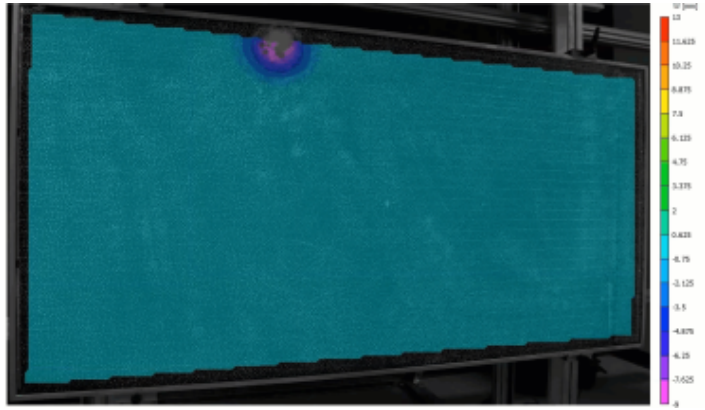
Testing a variety of locations improves simulation and damage model validation

Module damage model observations and project next steps

- Module damage is complex! Full data collection currently underway for both module designs
  - Cell damage is defect-driven (remote damage occurs with lower strain than impact site)
  - Cell- and glass- failure thresholds often overlap
  - Existing cell damage is accelerated by hail impacts



A 45mm IEC standard impact



A 55mm IEC standard impact resulting in glass failure

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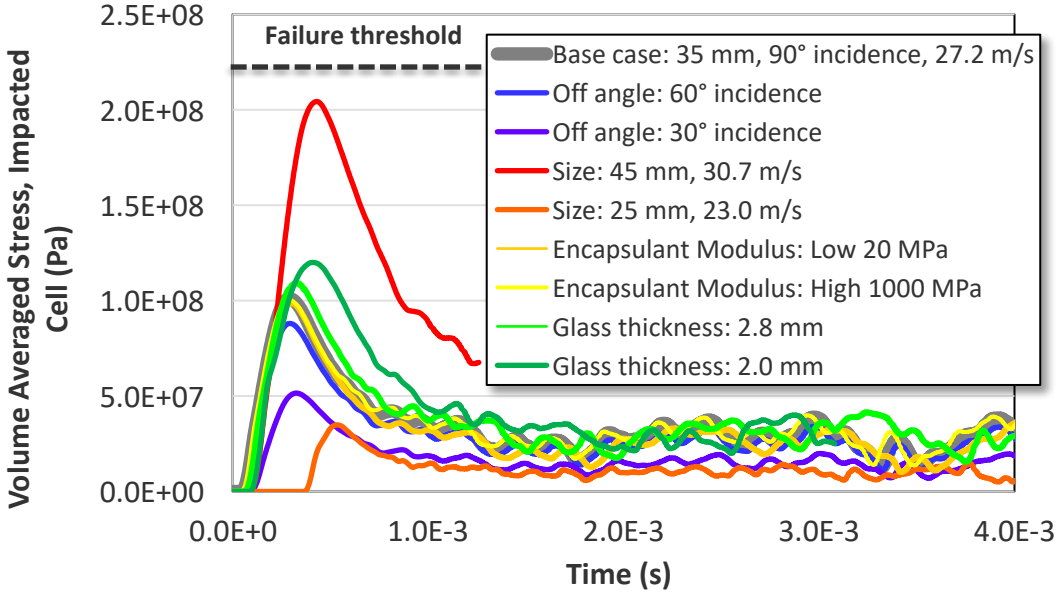
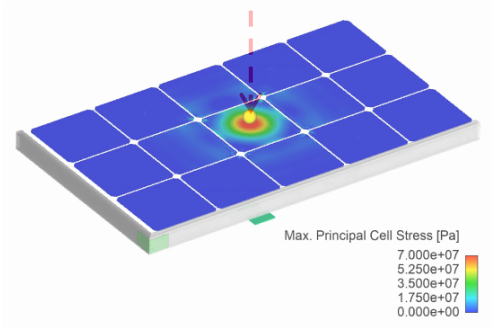
  - Module damage model
- **Use validated simulations to conduct parametric studies to find what physical characteristics correlate to damage probability**

Conduct parametric studies using validated models to find which characteristics correlate to module damage

- Parametric studies with validated models can quantitatively inform module design and operation to maximize hail survivability (or optimize insurance decision making)





Initial parametric studies demonstrate the effect of various inputs on cell stress

Summary

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A quantitative understanding of module damage probability enables informed decision making for both module design and deployment

Questions or comments?

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