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Effects of Photovoltaic Module Materials and Design on Module Deformation Under Load

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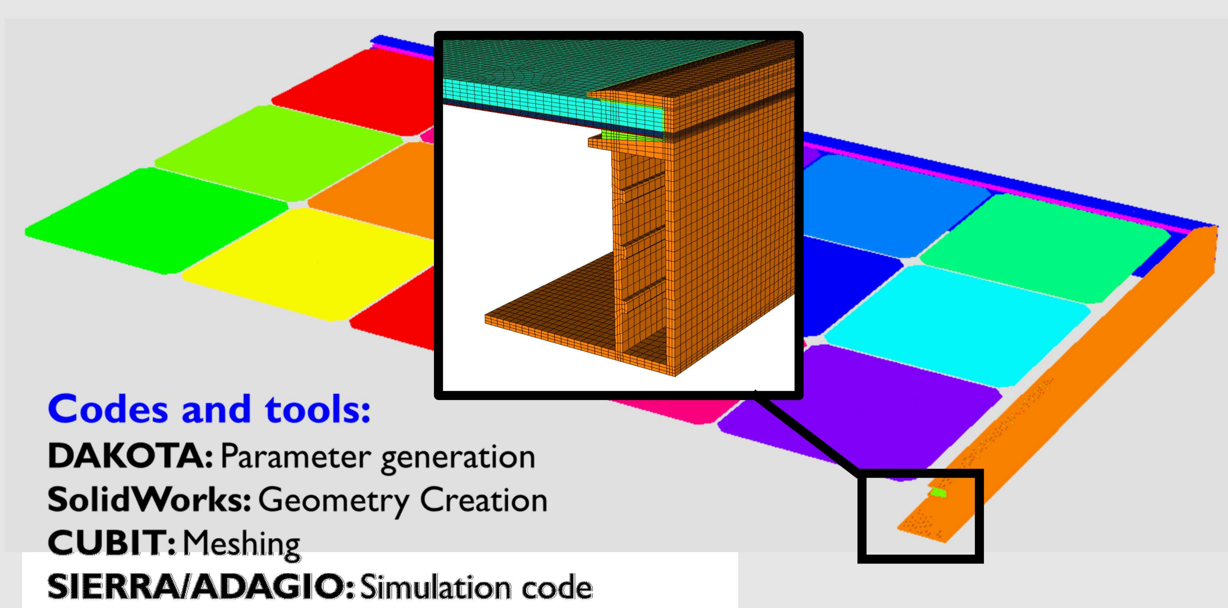
Abstract

Static structural finite element models of an aluminum-framed crystalline silicon (c-Si) photovoltaic (PV) module and a glass-glass thin film PV module were constructed and validated against experimental measurements of deflection under uniform pressure loading. Parametric analyses using Latin Hypercube Sampling (LHS) were performed to propagate input uncertainties into simulated deflection uncertainty and find the parameters most correlated to simulated deflection.

Methods

Finite element models of two distinct module designs were created: A 60-cell c-Si module and a glass-glass thin-film module. Models were developed directly from module design data.

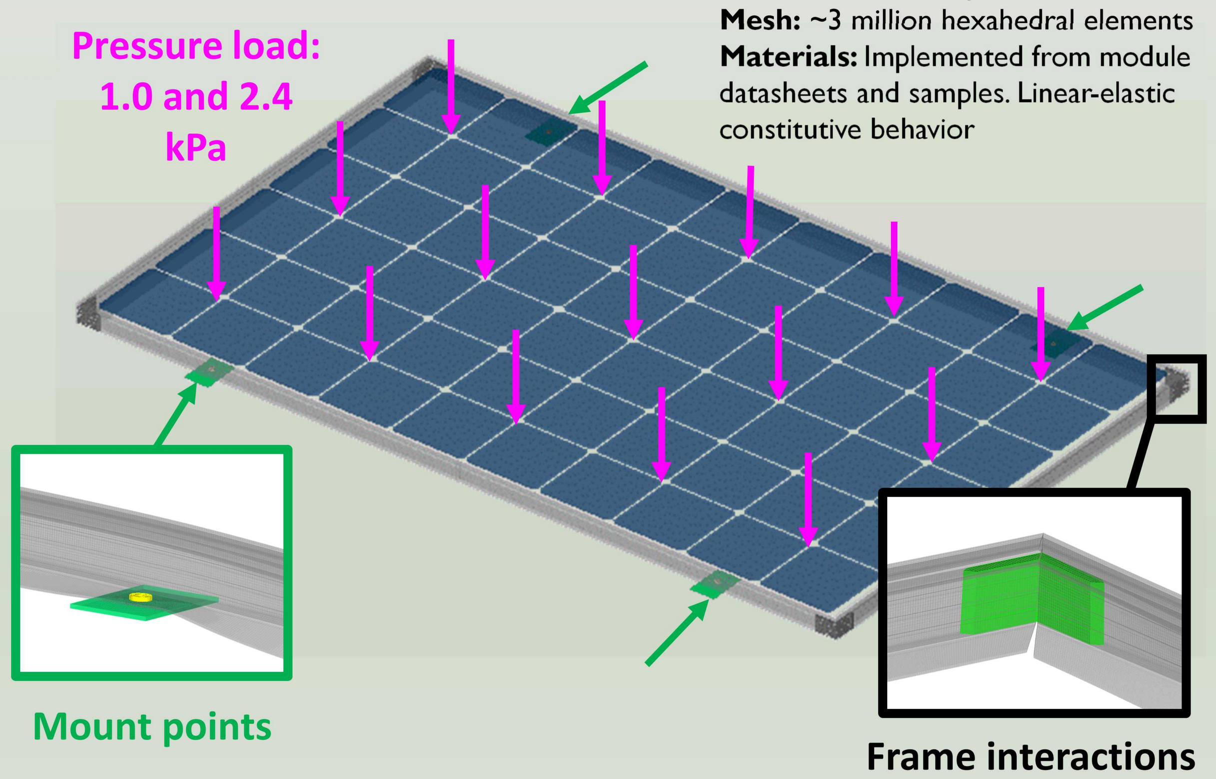


Codes and tools:
DAKOTA: Parameter generation
SolidWorks: Geometry Creation
CUBIT: Meshing
SIERRA/ADAGIO: Simulation code

Simulated c-Si module geometry and mesh details

Experiments applying uniform pressure loading to physical examples of each modeled module design were conducted. Weighted bags were uniformly stacked on each module to achieve pressures up to 2.4 kPa, while measurements of deflection were collected. This load case was replicated in simulation to allow direct comparisons between predicted and experimental deflection to be made.

Domain: Quarter-symmetric
Mesh: ~3 million hexahedral elements
Materials: Implemented from module datasheets and samples. Linear-elastic constitutive behavior

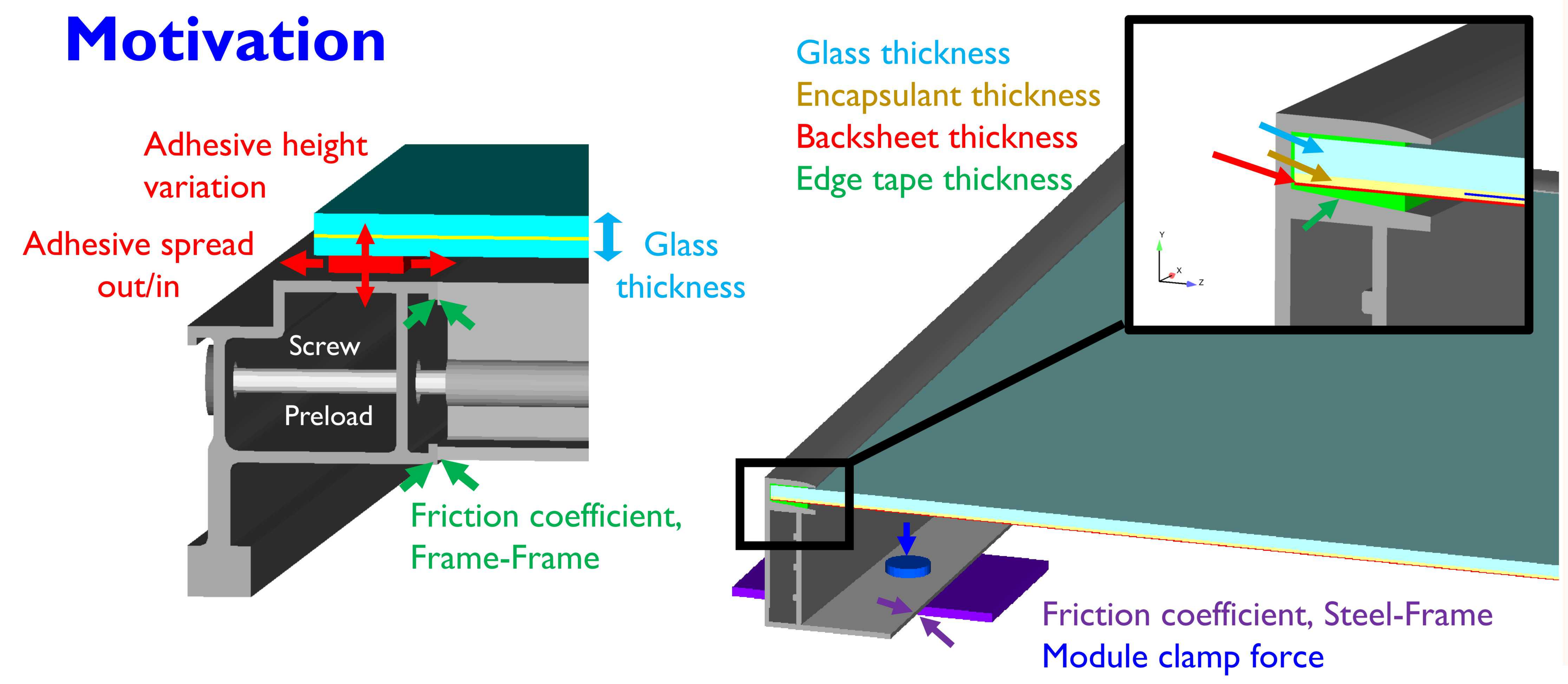


Simulated boundary conditions and interactions

Simulated interactions were developed to best represent actual module construction and mounting, including:

- Frictional contacts at frame joints and clamp interfaces
- Appropriate clamping forces and screw preloads
- Conformal meshing for fully adhered interfaces

Motivation



Finite element models are useful for analyzing and optimizing mechanical systems without the need for physical hardware, but should be validated against experimental data to be used with high confidence.

The goals of this study are to:

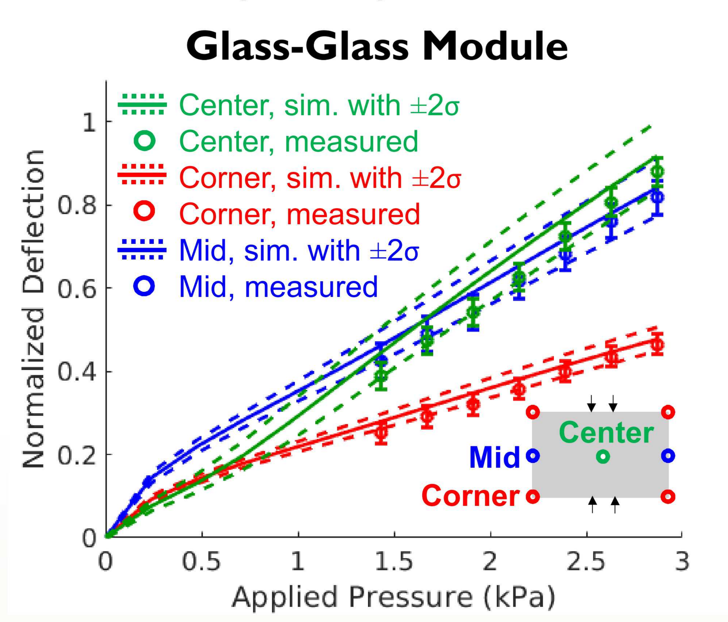
1. Validate models of 2 different module architectures against experimental deflection measurements
2. Propagate uncertainties in material properties and assembly tolerances into predicted deflection uncertainty
3. Assess which parameters are most correlated to predicted deflection

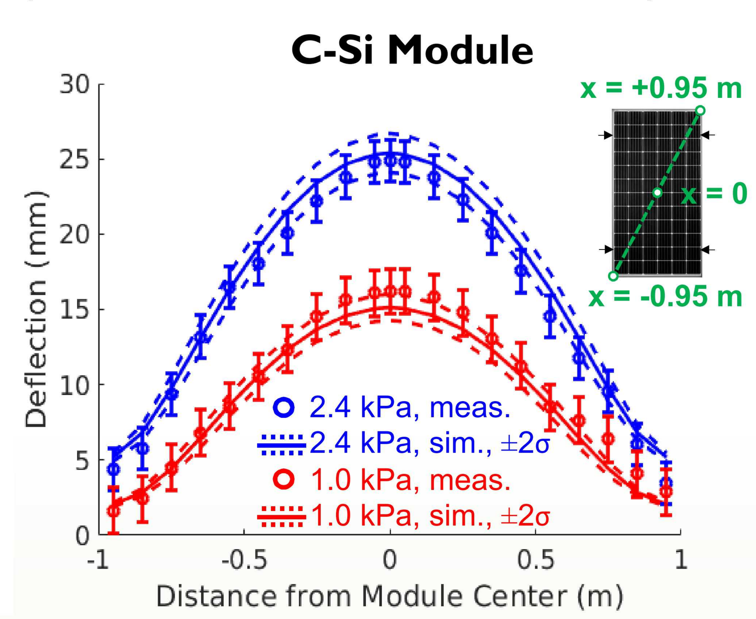
Validated models may be used for design optimization including materials selection, and analyses of deployment environments.

Which design parameter has the largest influence on module stiffness?

Results and Uncertainty Quantification

A suite of 120 simulations were run for each module using Latin Hypercube Sampling to select input parameters between bounds. Mean simulated results are shown below vs. experimental measurements, with simulated uncertainty represented as 2 standard deviations away from the mean. Experimental uncertainties were based on maximum observed asymmetry in the modules, to represent module-to-module variability.





Measured vs. simulated deflection at key module locations and input parameter uncertainties and bounds

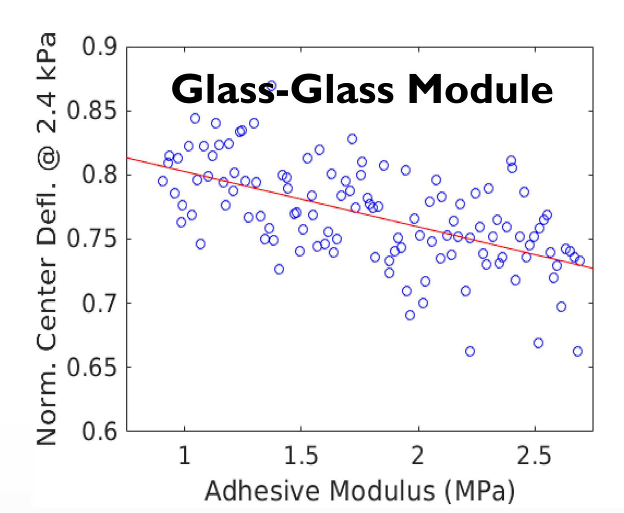
#	Glass-Glass Mod. Parameters	Lower	Upper
1	Steel, Elastic Modulus [Pa]	1.8×10^{11}	2.0×10^{11}
2	Steel, Poisson's Ratio	0.276	0.305
3	Front Glass, Modulus [Pa]	6.2×10^{10}	7.6×10^{10}
4	Front Glass, Poisson's Ratio	0.216	0.264
5	Front Glass Thickness [mm]	2.0	2.4
6	Rear Glass, Modulus [Pa]	6.2×10^{10}	7.6×10^{10}
7	Rear Glass, Poisson's Ratio	0.216	0.264
8	Rear Glass Thickness [mm]	2.7	2.9
9	Encapsulant, Modulus [Pa]	1.3×10^{7}	1.9×10^{7}
10	Encapsulant, Poisson's Ratio	0.450	0.499
11	Edge seal, Modulus [Pa]	2.4×10^{6}	2.8×10^{6}
12	Edge seal, Poisson's Ratio	0.400	0.499
13	Aluminum, Modulus [Pa]	6.5×10^{10}	7.1×10^{10}
14	Aluminum, Poisson's Ratio	0.314	0.347
15	Frame clamp, Modulus [Pa]	1.3×10^{8}	2.0×10^{8}
16	Friction, Frame-Frame	0.2	1.2
17	Friction, Screw-Frame	0.2	1.2
18	Screw preload artificial strain	-0.001	-0.005
19	Adhesive, Modulus [Pa]	0.9×10^{6}	2.7×10^{6}
20	Adhesive, Poisson's Ratio	0.400	0.499
21	Adhesive height [mm]	-0.5	+1.0
22	Adhesive #1 spread, out [mm]	-2.0	+2.0
23	Adhesive #1 spread, in [mm]	-2.0	+2.0
24	Adhesive #2 spread, out [mm]	-2.0	+2.0
25	Adhesive #2 spread, in [mm]	-2.0	+2.0
26	Adhesive #3 spread, out [mm]	-2.0	+2.0

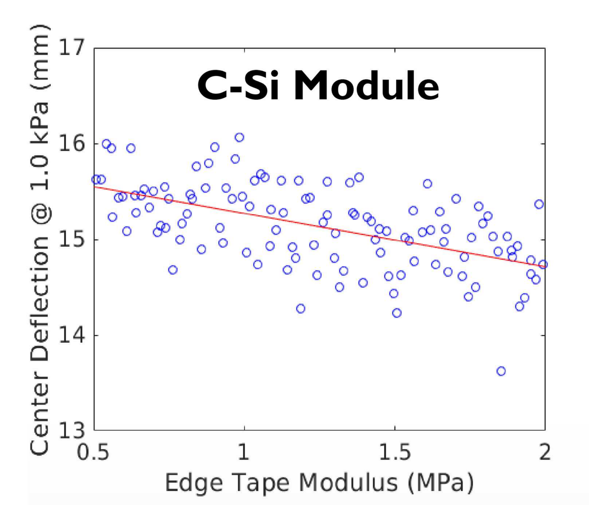
#	C-Si Module Parameters	Lower	Upper
1	Steel, Elastic Modulus [Pa]	1.8×10^{11}	2.0×10^{11}
2	Steel, Poisson's Ratio	0.276	0.305
3	Glass, Elastic Modulus [Pa]	6.3×10^{10}	7.7×10^{10}
4	Glass, Poisson's Ratio	0.216	0.264
5	Glass Thickness [mm]	3.10	3.30
6	Backsheet, Modulus [Pa]	1.0×10^{9}	4.0×10^{9}
7	Backsheet, Poisson's Ratio	0.400	0.499
8	Backsheet Thickness [mm]	0.10	0.20
9	Encapsulant, Modulus [Pa]	1.2×10^{7}	1.8×10^{7}
10	Encapsulant, Poisson's Ratio	0.450	0.499
11	Encapsulant Thickness [mm]	0.90	1.00
12	Edge tape, Modulus [Pa]	0.5×10^{6}	2.0×10^{6}
13	Edge tape, Poisson's Ratio	0.300	0.499
14	Edge tape thickness [mm]*	0.25	0.45
15	Aluminum, Modulus [Pa]	6.5×10^{10}	7.1×10^{10}
16	Aluminum, Poisson's Ratio	0.314	0.347
17	Silicon, Elastic Modulus [Pa]	1.5×10^{11}	1.9×10^{11}
18	Silicon, Poisson's Ratio	0.252	0.308
19	Friction, Frame-Frame	0.2	1.2
20	Friction, Steel-Frame	0.2	1.2
21	Module clamp force [N]	800	1600

*Derived parameter, not independently sampled

Sensitivity Analysis Results

Pearson's Correlation Coefficient (R) was computed for each parameter at 1.0 and 2.4 kPa pressures against deflection at module center locations, with top results shown below. Plots of sampled parameter values vs. resulting simulated deflection for each module are shown to demonstrate correlation strengths.





Deflection results vs. highly correlated input parameter values

1.0 kPa Load		2.4 kPa Load	
Parameter	|R|	Parameter	|R|
Edge tape, E	0.630	Glass, E	0.561
Glass, E	0.532	Edge tape, E	0.553
Edge tape, v	0.336	Edge tape, v	0.361
Glass, t	0.286	Glass, t	0.321
Encap., t	0.132	Encap., t	0.111

1.0 kPa Load		2.4 kPa Load	
Parameter	|R|	Parameter	|R|
Adhesive, E	0.557	Adhesive, E	0.582
Front glass, t	0.373	Front glass, E	0.476
Adhesive, h	0.363	Adhesive, h	0.291
Adh. #3 Spread	0.338	Adh. #3 Spread	0.280
Aluminum, E	0.215	Back glass, E	0.238

Legend: E = Elastic modulus; v = Poisson's ratio; h = Height; t = Thickness

Conclusions

For both modeled architectures, finite element models were able to match experimental results within uncertainties for predicted deflection under pressure loads. Sensitivity analyses found that polymeric adhesives and seals were highly correlated to module deflection. These results validate the applicability of finite element models, independent of module architecture, and suggest that polymer materials are an important parameter influencing module stiffness.

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