CRACK INVESTIGATION OF ENCAPSULATED SOLAR CELLS UNDER THERMAL AND MECHANICAL STRESSES

Martin Sander
Fraunhofer Center for Silicon Photovoltaics CSP, Otto-Eissfeldt-Strasse 12, Halle (Saale), Germany
Tel: +49 (0) 345 5589-5216, Fax: +49 (0) 345 5589-5999, martin.sander@csp.fraunhofer.de

Workshop "Impact of mechanical and thermal loads on the long term stability of PV modules"
Institute for Solar Energy Research Hamelin (ISFH), Hamelin, 05th November 2013

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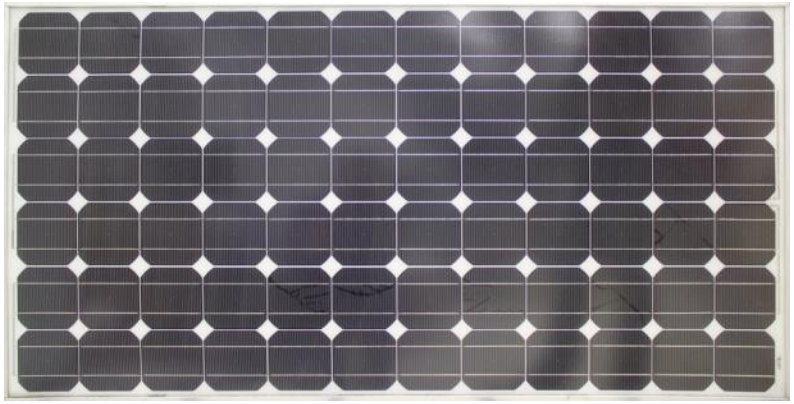
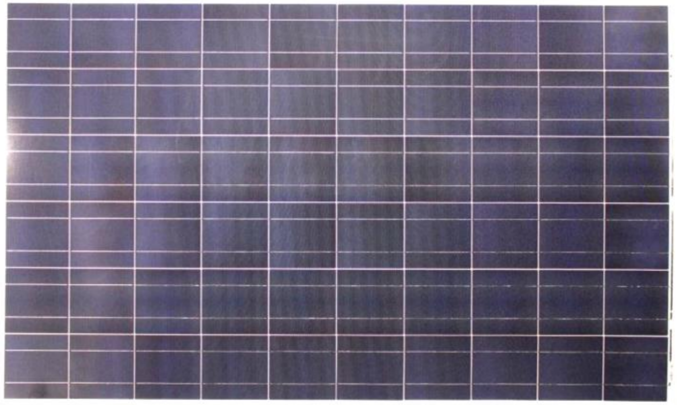
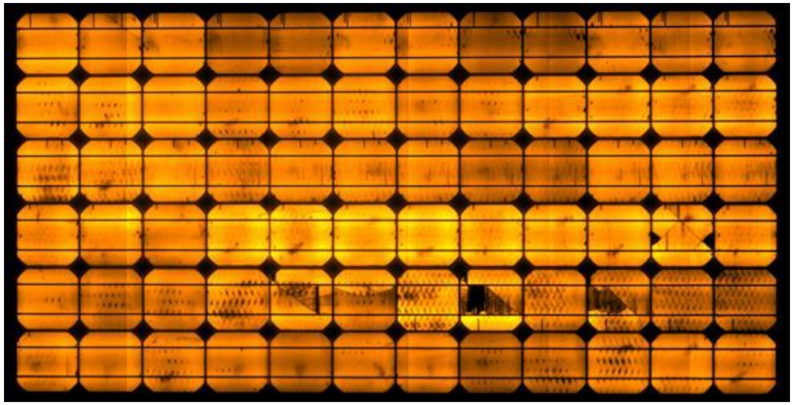
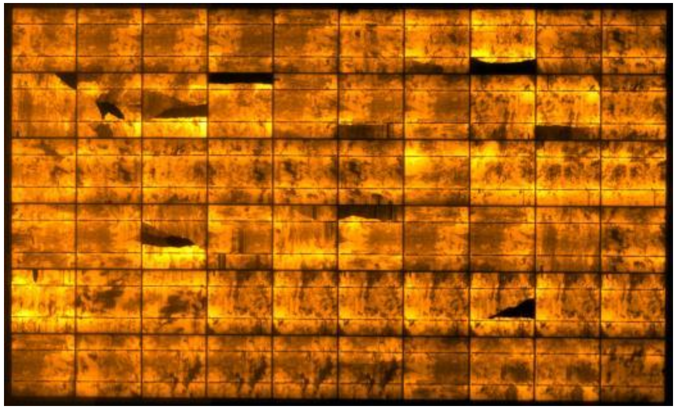
Motivation







Electroluminescence



Electroluminescence

0 255

Luminescence intensity [-]

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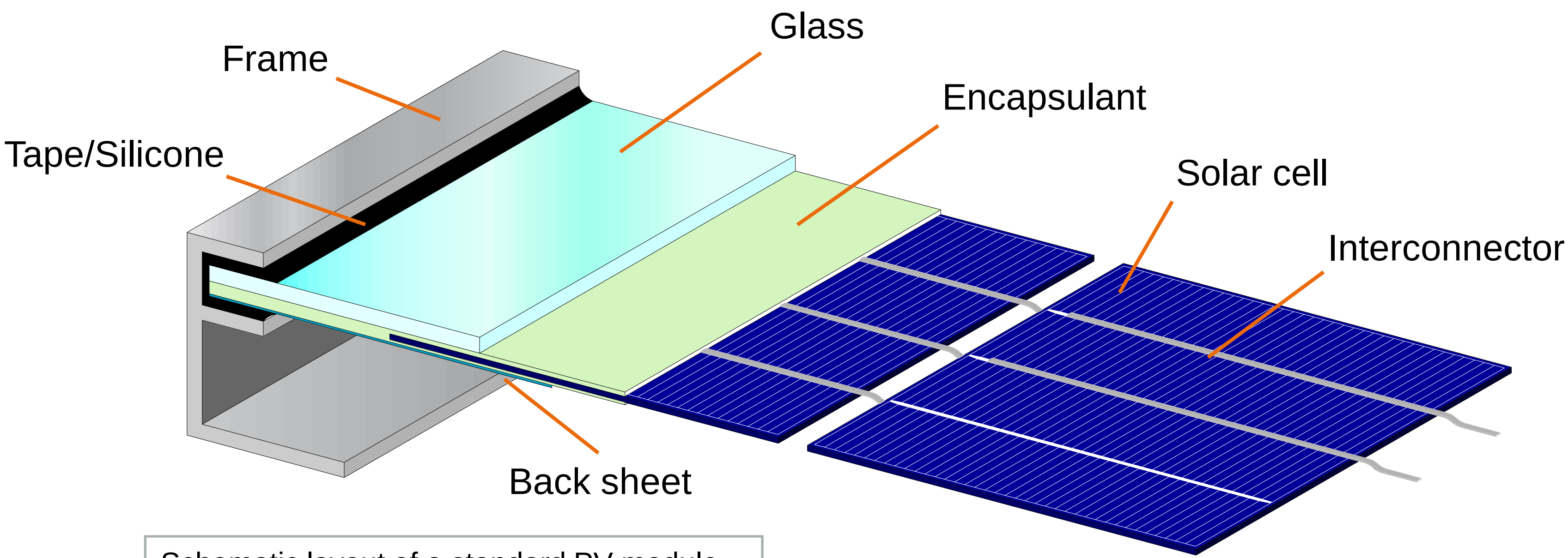
Agenda

- Introduction – stress in PV modules
- Experimental Approach
- Results and Discussion
- Conclusions and Outlook

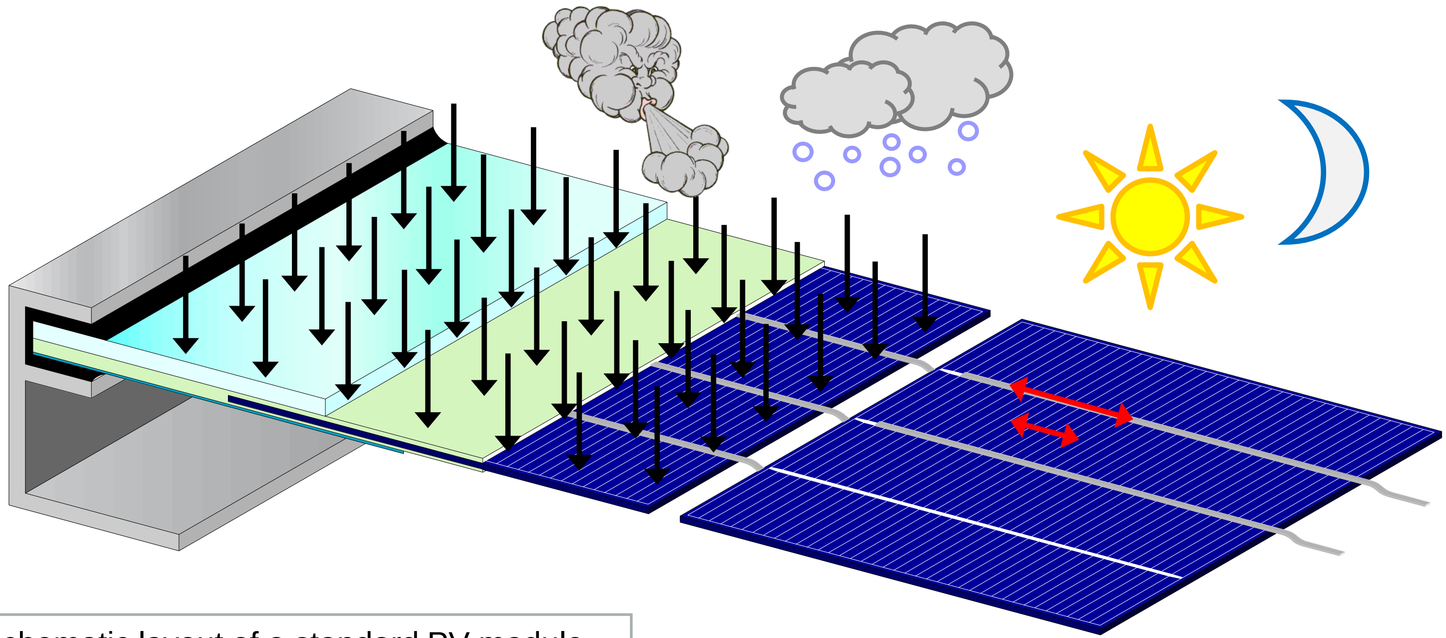
Introduction
Setup of PV modules



Schematic layout of a standard PV module

Introduction
Setup of PV modules

- Loads on PV modules can cause defects
  - Temperature changes
  - Mechanical Loading (Transport, Wind, Snow, etc.)



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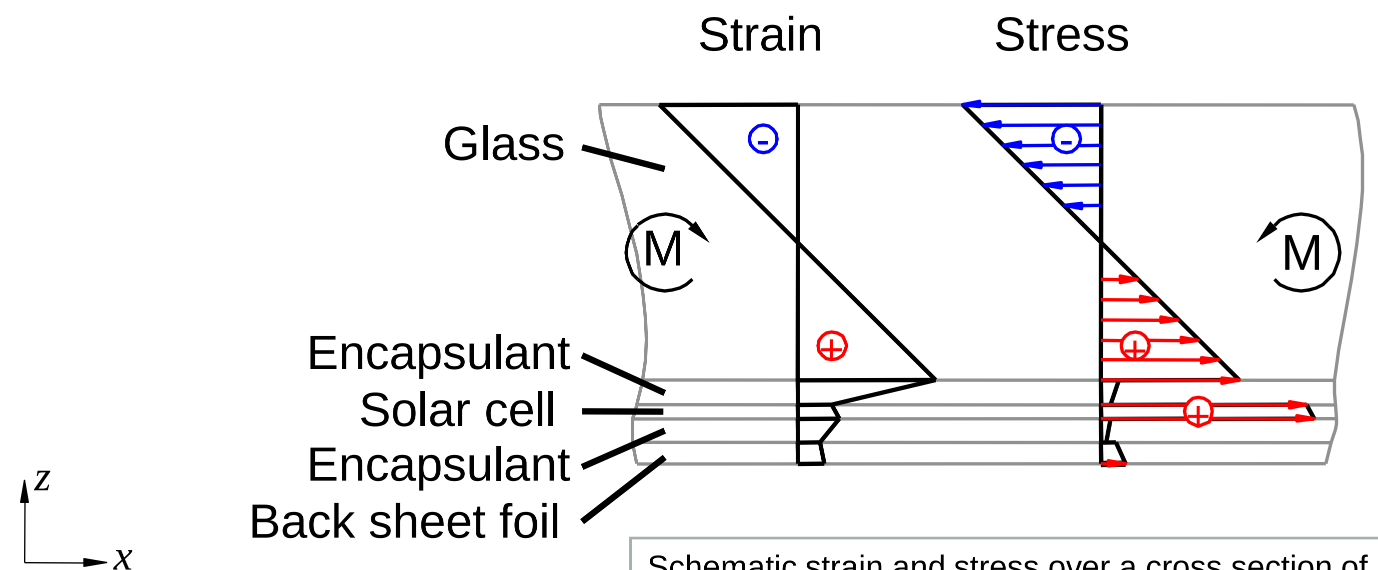
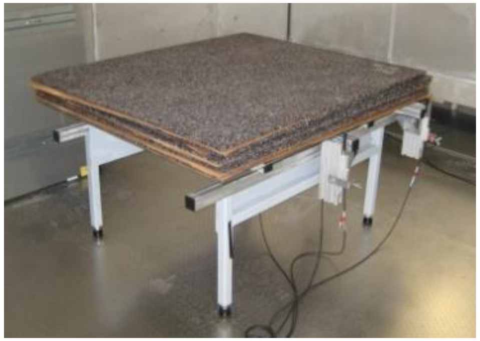


Schematic strain and stress over a cross section of a PV module

Introduction
Mechanical load test (MLT)

- MLT during module certification process
- Uniform area load on horizontally mounted PV module
  - Wind load (2400 Pa)
  - Snow load (5400 Pa)
- State of the art in mechanical load testing
  - Approximation of area load through several single loads
  - Apply defined weights (rubber mats, sand bags)
  - Air pressure



Standard IEC 61215 (crystalline PV modules), IEC 61646 (Thin film PV modules)

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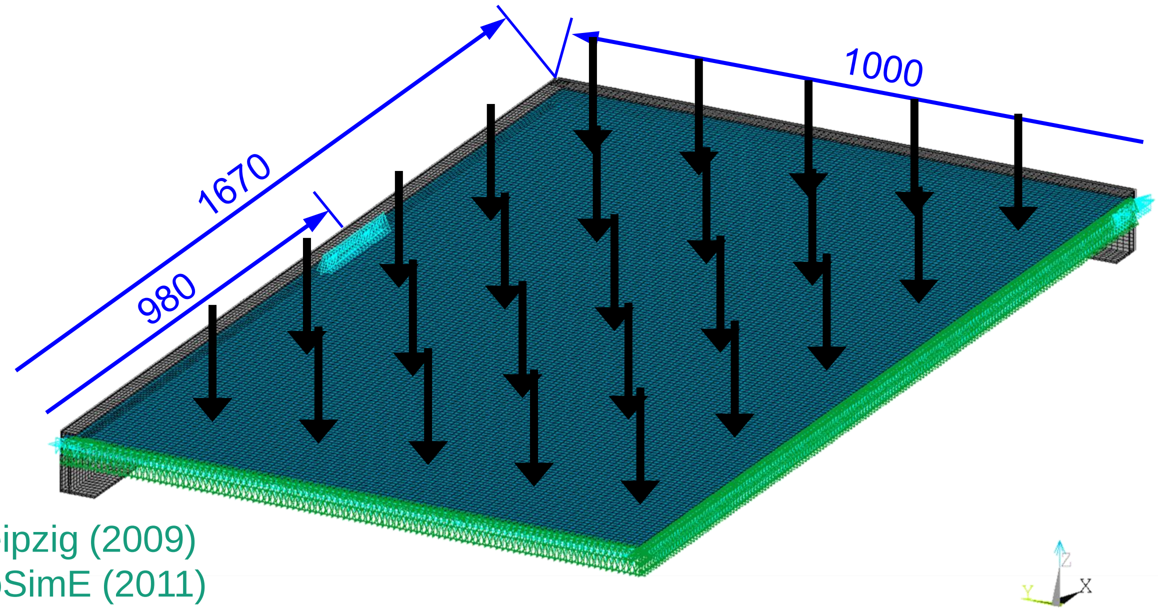
Introduction
Simulation of PV modules

- Finite element analysis (FEA) of PV module with all relevant materials and layers
- Mechanical properties from literature and experiments (tension test, DMA, dilatometer etc.)
- Simplifications:
  - Symmetry

Scheme of used finite element modell



M. Pander, Masterarbeit, HTWK Leipzig (2009)
M. Pander *et al.*, Proceedings EuroSimE (2011)
S. Dietrich *et al.*, Proceedings SPIE Optics+Photonics (2010)

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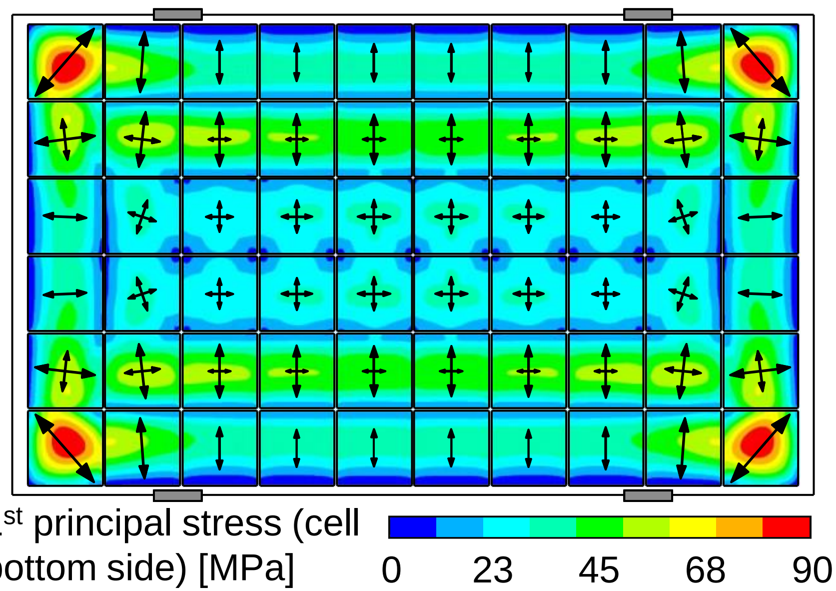
Introduction

Cracks in encapsulated solar cells

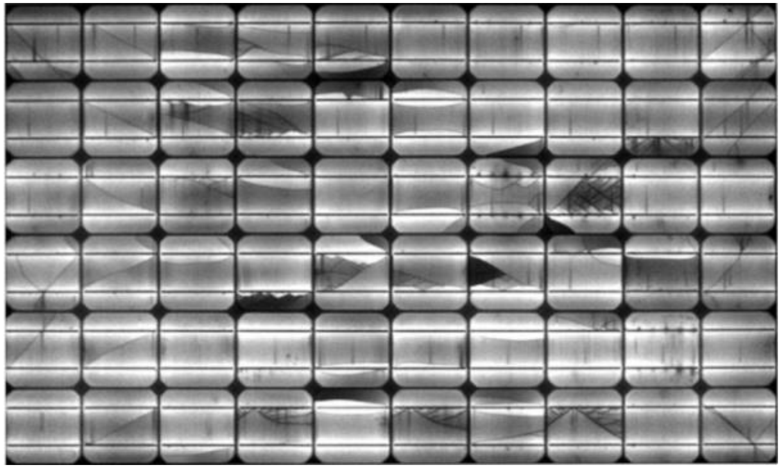
- Simulation uniform area load (5.4 kPa) on standard PV module

→ Inhomogeneous stress distribution + stress directions

→ Varying percentage of cracks with different crack directions



Standard PV module under area load (5.4 kPa)



EL image of a PV-Module after MLT (5.4 kPa)
T. Potthoff *et al.*, Workshop PV-Modultechnik, TÜV Rheinland (2008)

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Introduction
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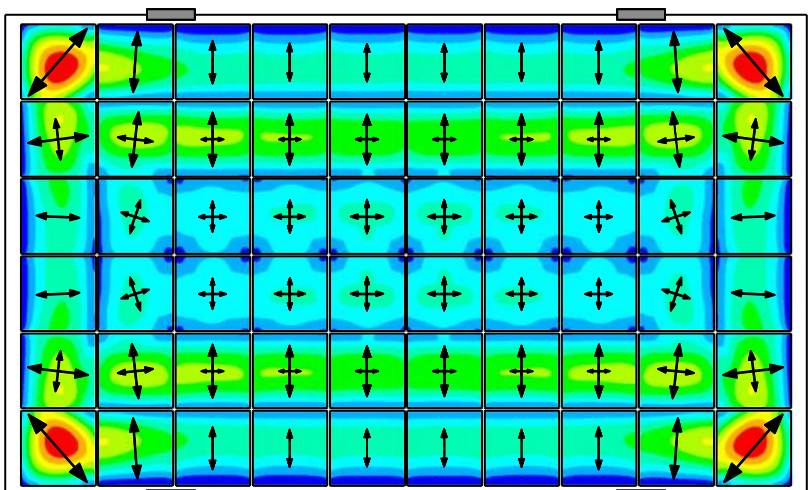

1st principal stress (cell bottom side) [MPa]

Standard PV module under area load (5.4 kPa)

59,3	37,0	37,0	40,7	25,9	40,7	33,3	51,9	33,3	63,0
11,1	49,1	43,1	44,4	44,4	40,7	44,4	43,1	51,9	22,2
22,2	29,6	48,2	37,0	33,3	51,9	25,9	37,0	33,3	25,9
33,3	25,9	40,7	33,3	51,9	33,3	44,4	33,3	37,0	40,8
44,4	49,1	40,7	25,9	59,3	40,7	70,4	66,7	49,1	29,7
51,9	33,3	40,7	55,6	40,7	37,0	22,2	44,4	44,4	63,0

Analysis of 27 PV modules after MLT (5.4 kPa): Percentage of solar cells with a least 1 crack [%]

S. Kajari-Schröder, *et al.*; Proc. 27th EU PVSEC, (2012)

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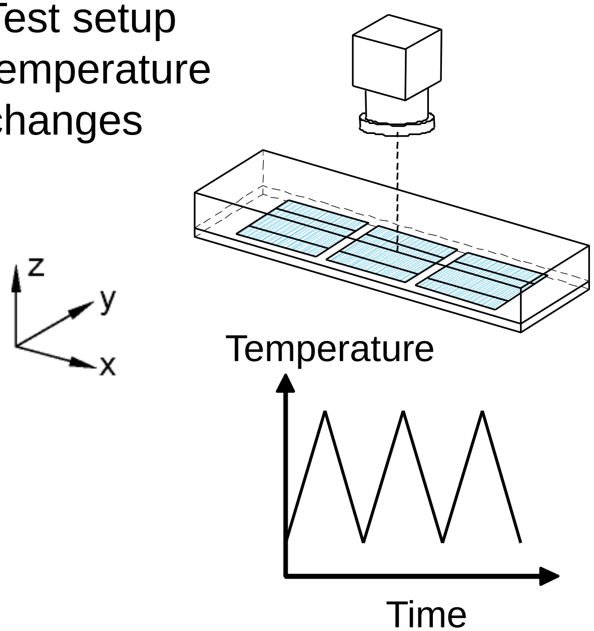
Experimental approach

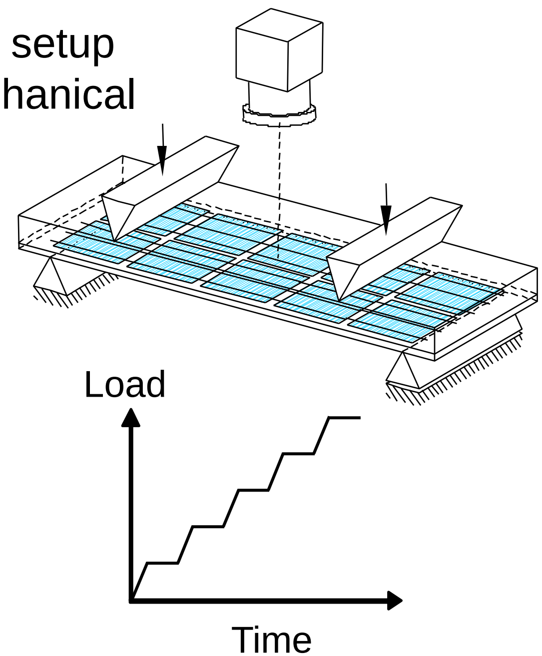
Experimental Approach

- Investigation of cracks under well-known boundary conditions
- Separate investigation of mechanical load and temperature changes on adapted test specimens

Test setup temperature changes



Test setup mechanical load



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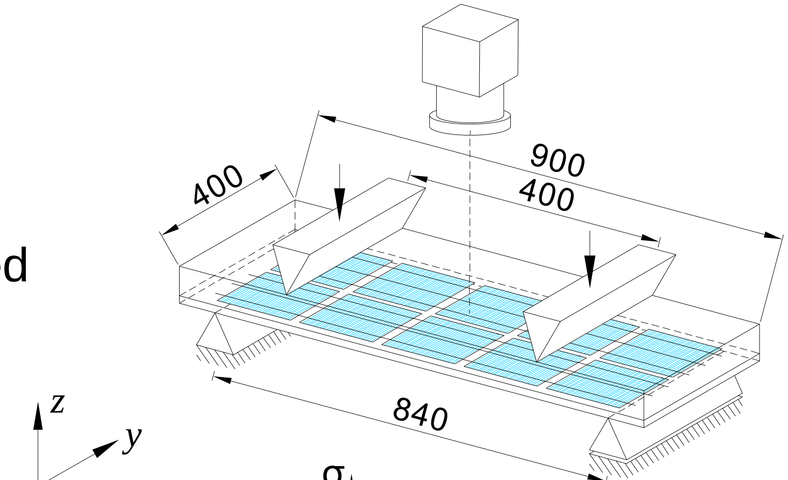
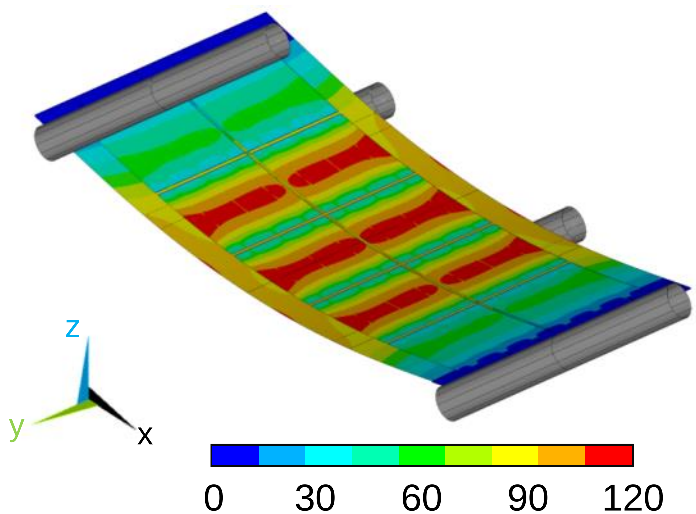
Experimental Approach

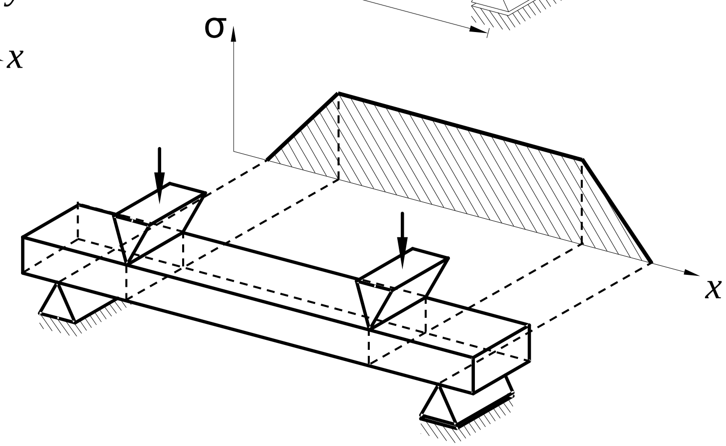
Test setup for mechanical loading

- 4-point-bending to induce uniaxial bending and to inspect cells during testing → stress direction is considered
- EL analysis at each load step





1st principal stress on glass bottom side at a load of 1000 N [MPa]



Scheme of stress distribution at bottom side of a monolithic beam

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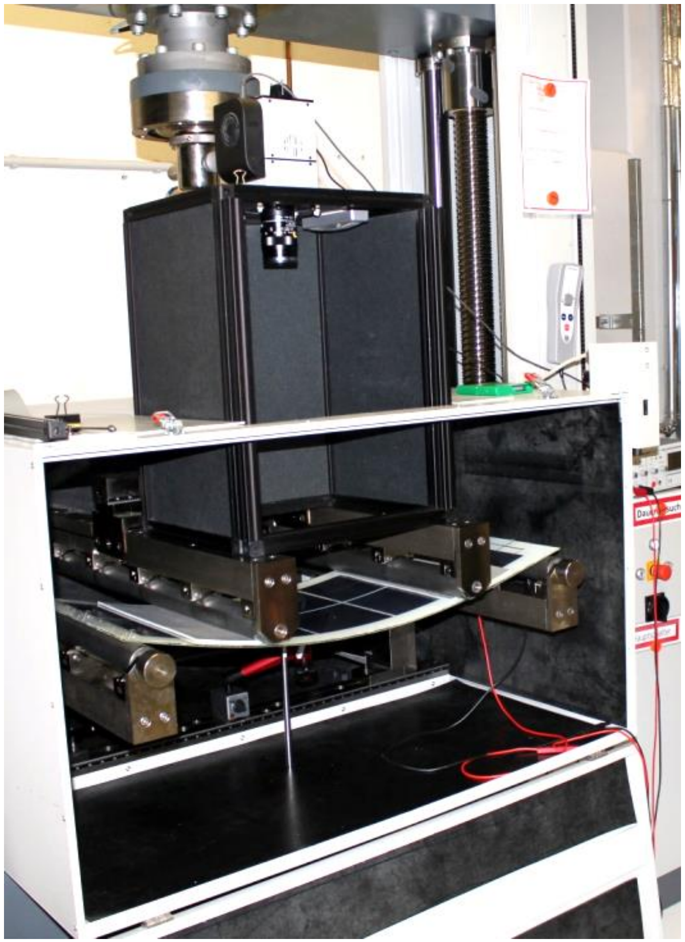
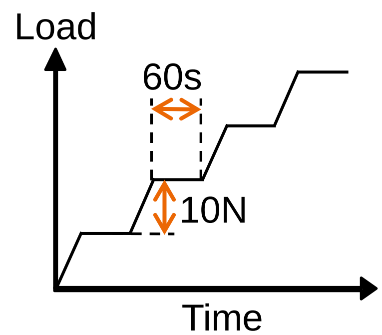
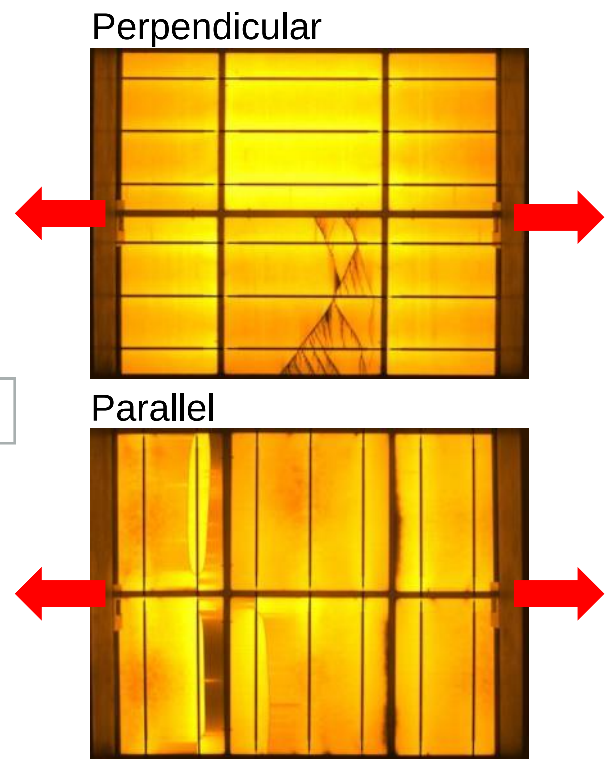
Experimental Approach
Test setup and test procedure for mechanical loading



Test setup for mechanical loading on universal testing machine Zwick Z400



Scheme of test procedure

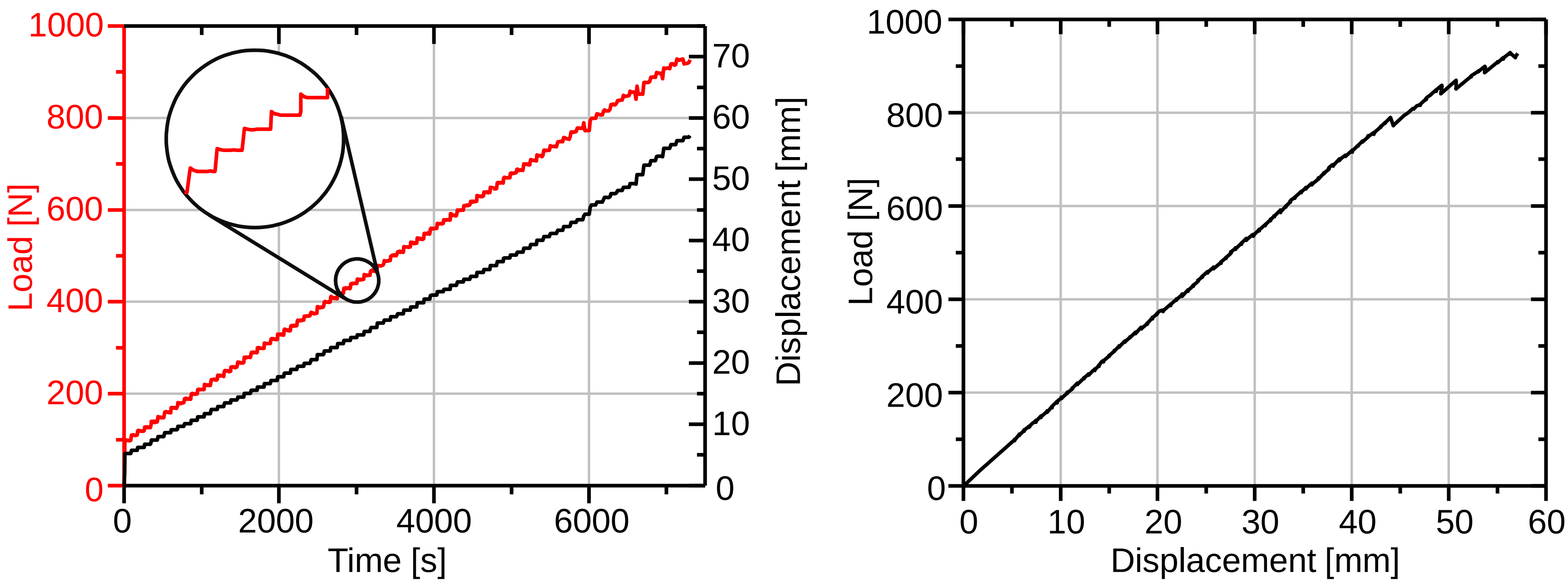


EL image during mechanical loading ca. 6.0 V; 3.0 A; 60 s

Experimental Approach

Test procedure for mechanical loading

- Measurement of load-time dependency and load-displacement dependency



Representative results of a mechanical load test

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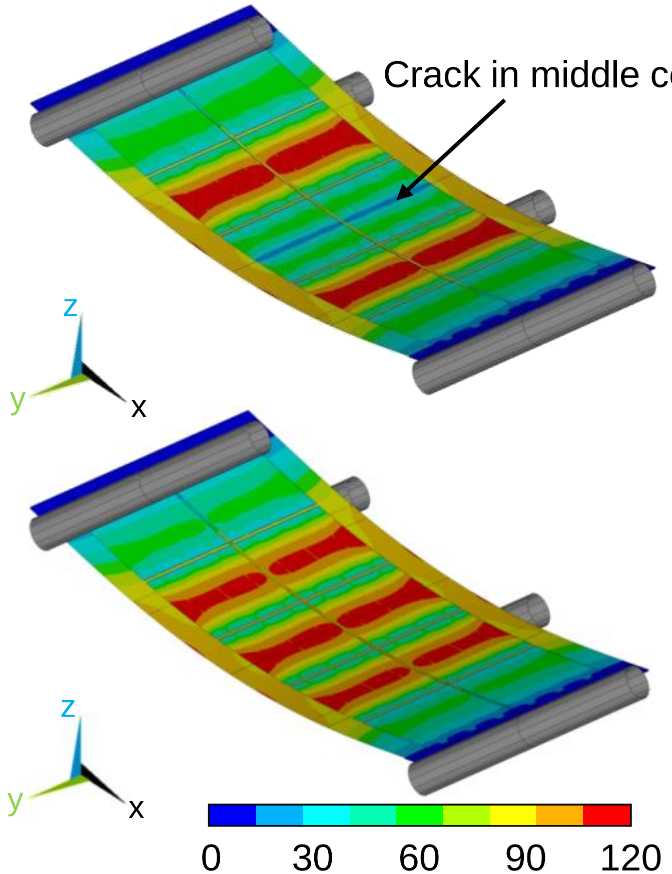
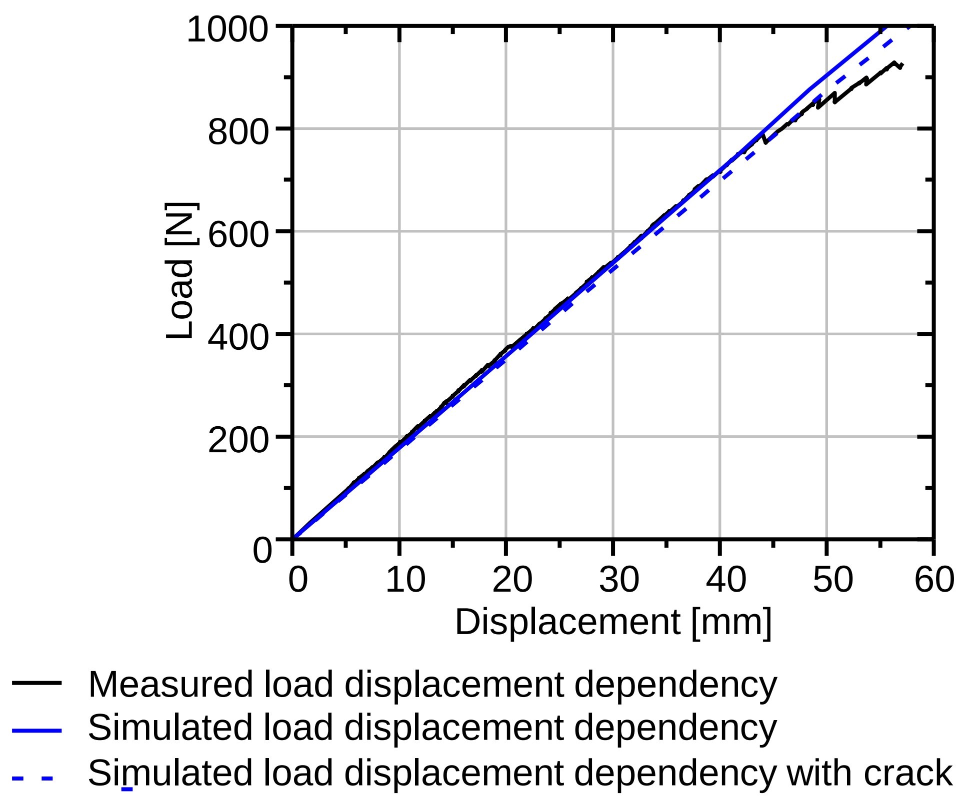
Experimental Approach
Evaluation

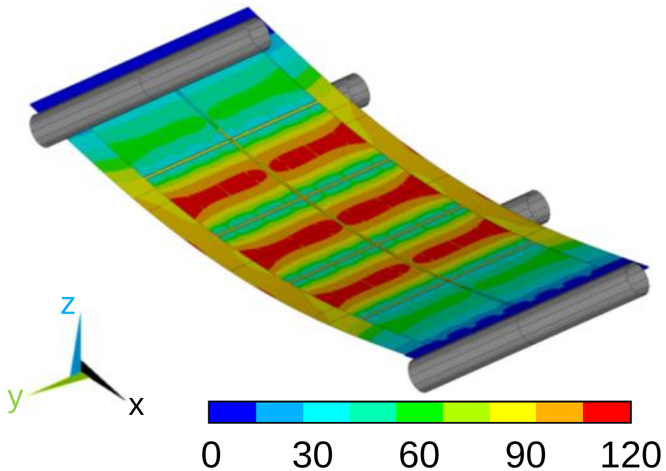


1st principal stress on cell bottom side at a load of 1000 N [MPa]

- Comparison with simulation results

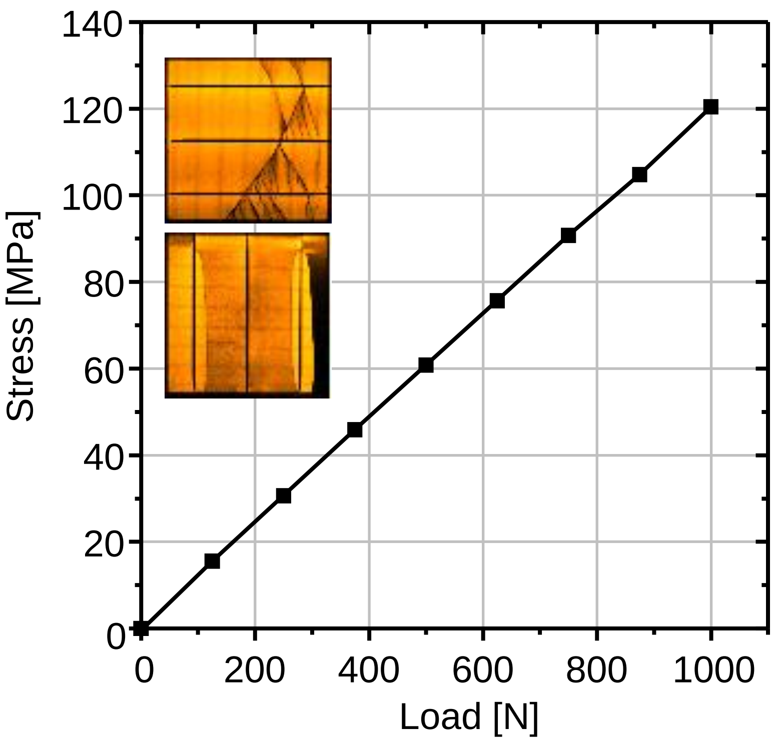


Experimental Approach
Evaluation



1st principal stress on cell bottom side at a load of 1000 N [MPa]

- Evaluation of fracture stress



Maximum stress in silicon (bottom side)

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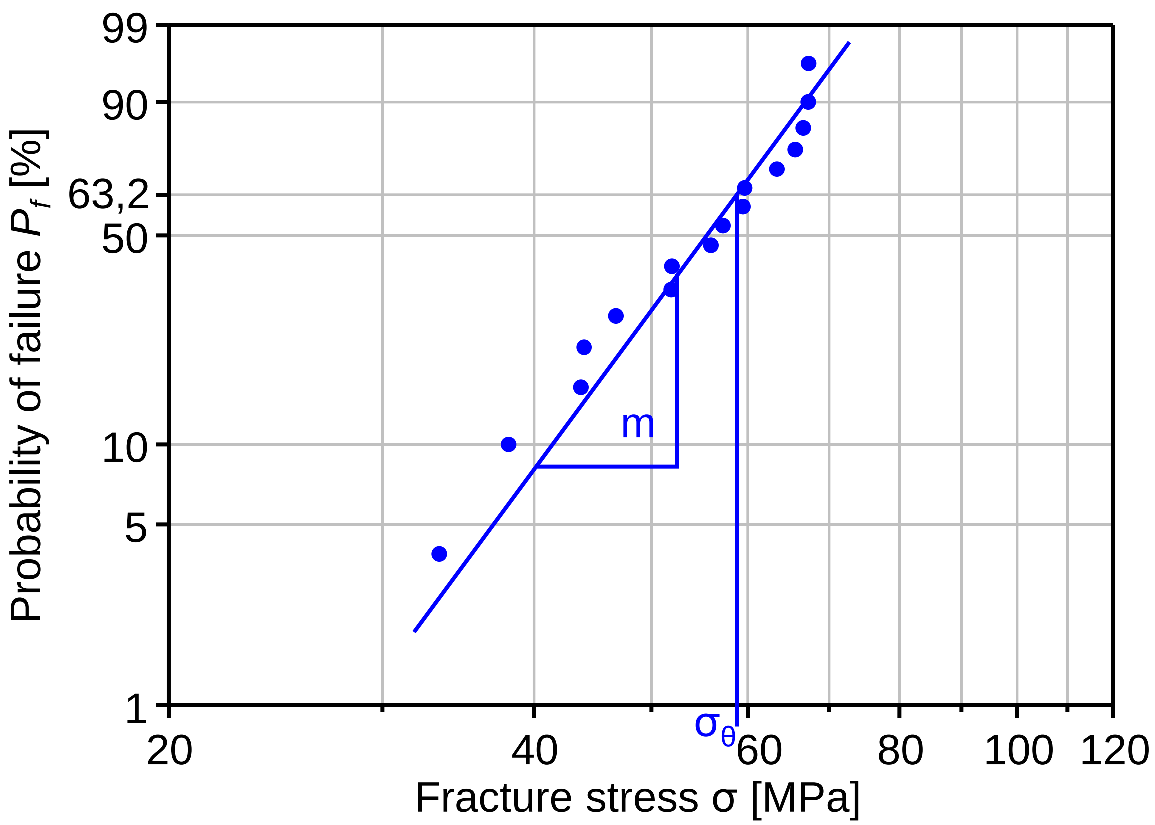
Experimental Approach
Evaluation

- Statistical evaluation of crack occurrences
- Implementation of Weibull distribution

$$P_f(\sigma) = 1 - e^{-\left(\frac{\sigma}{\sigma_\theta}\right)^m}$$

- Determination of characteristic stress σ_θ and Weibull modulus m

→ „In-laminate strength“



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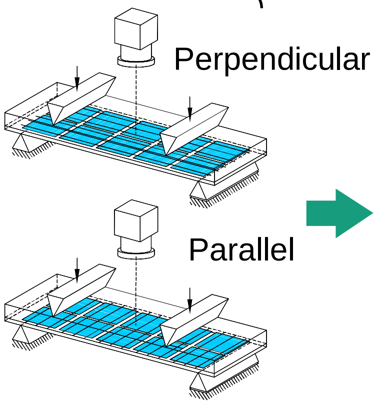
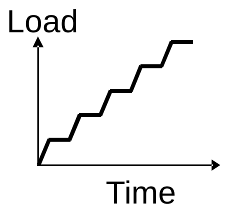
Experimental Approach

Test setup

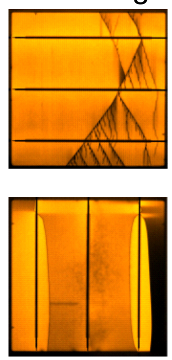


Test procedure

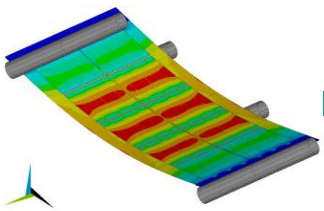


Evaluation

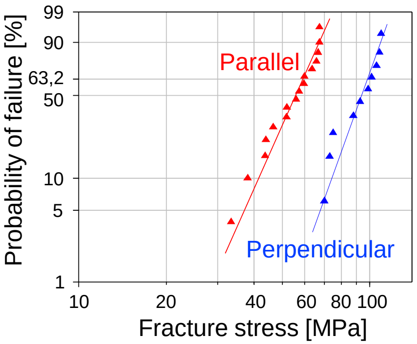
Crack origin



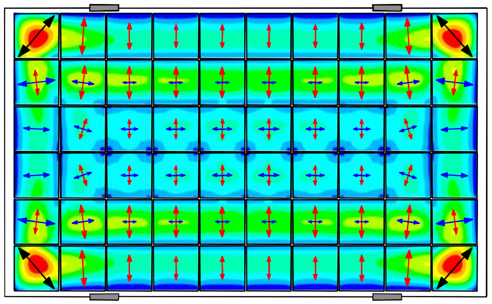
Fracture stress



Statistics (Weibull)



Stress in cells from finite element simulation



Cracks perpendicular to busbars

<0,1	<0,1	<0,1	<0,1	
<0,1	<0,1	<0,1	<0,1	1,9
<0,1	<0,1	<0,1	<0,1	0,1

Cracks parallel to busbars

5,4	5,8	11,9	69,4	
30,2	33,2	43,1	49,1	9,4
2,8	2,2	1,6	1,0	<0,1

Probability of failure [%]

	69,4	11,9	5,8	5,4	5,4	5,8	11,9	69,4	
11,2	49,1	43,1	33,2	30,2	30,2	33,2	43,1	49,1	11,2
0,2	1,1	1,6	2,2	2,8	2,8	2,2	1,6	1,1	0,2
0,2	1,1	1,6	2,2	2,8	2,8	2,2	1,6	1,1	0,2
11,2	49,1	43,1	33,2	30,2	30,2	33,2	43,1	49,1	11,2
	69,4	11,9	5,8	5,4	5,4	5,8	11,9	69,4	

Transformation to full-scale PV modules (Example multi-crystalline cells under 5,4 kPa)

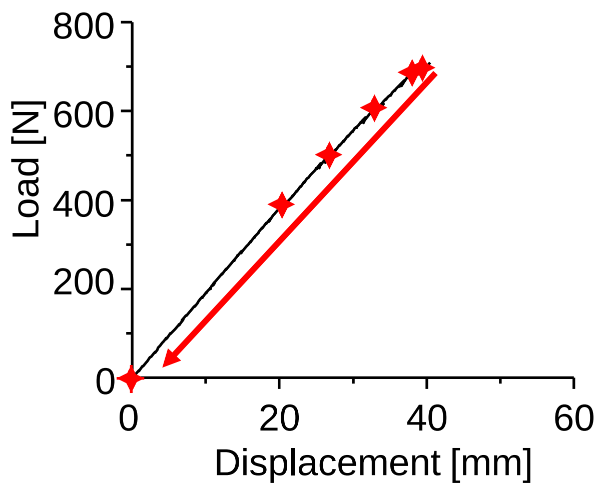
M. Sander *et al.*; Solar Energy Materials & Solar Cells *111* *(2013)*

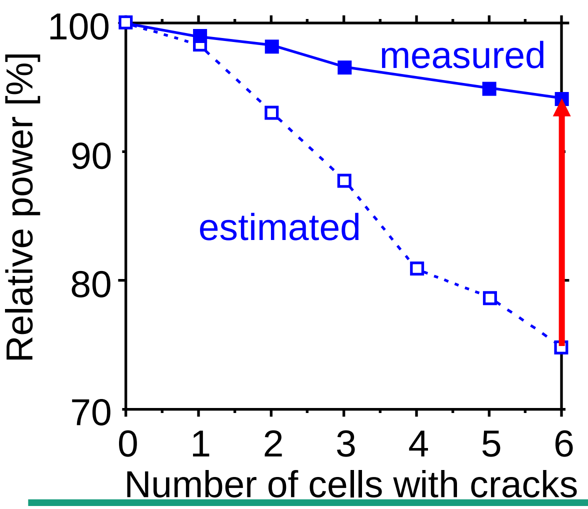
Results and Discussion

Comparison of different cell types

Results and Discussion

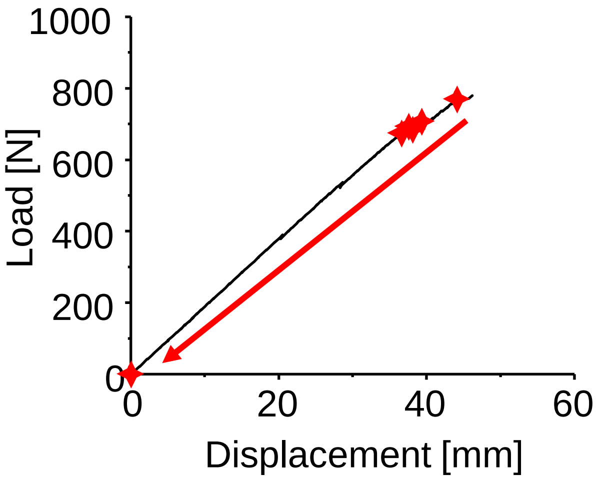
Mechanical loading parallel to busbars

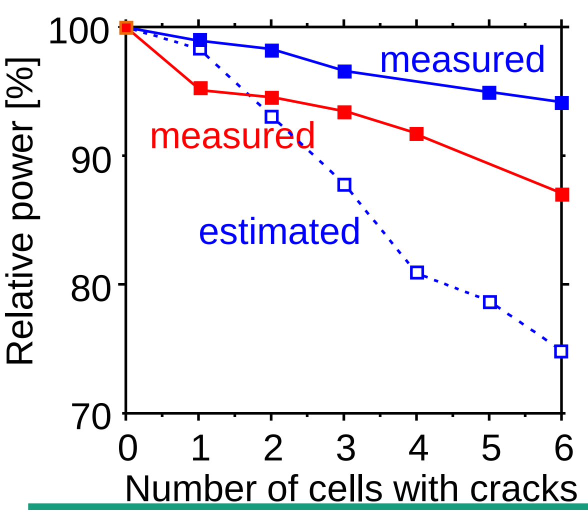


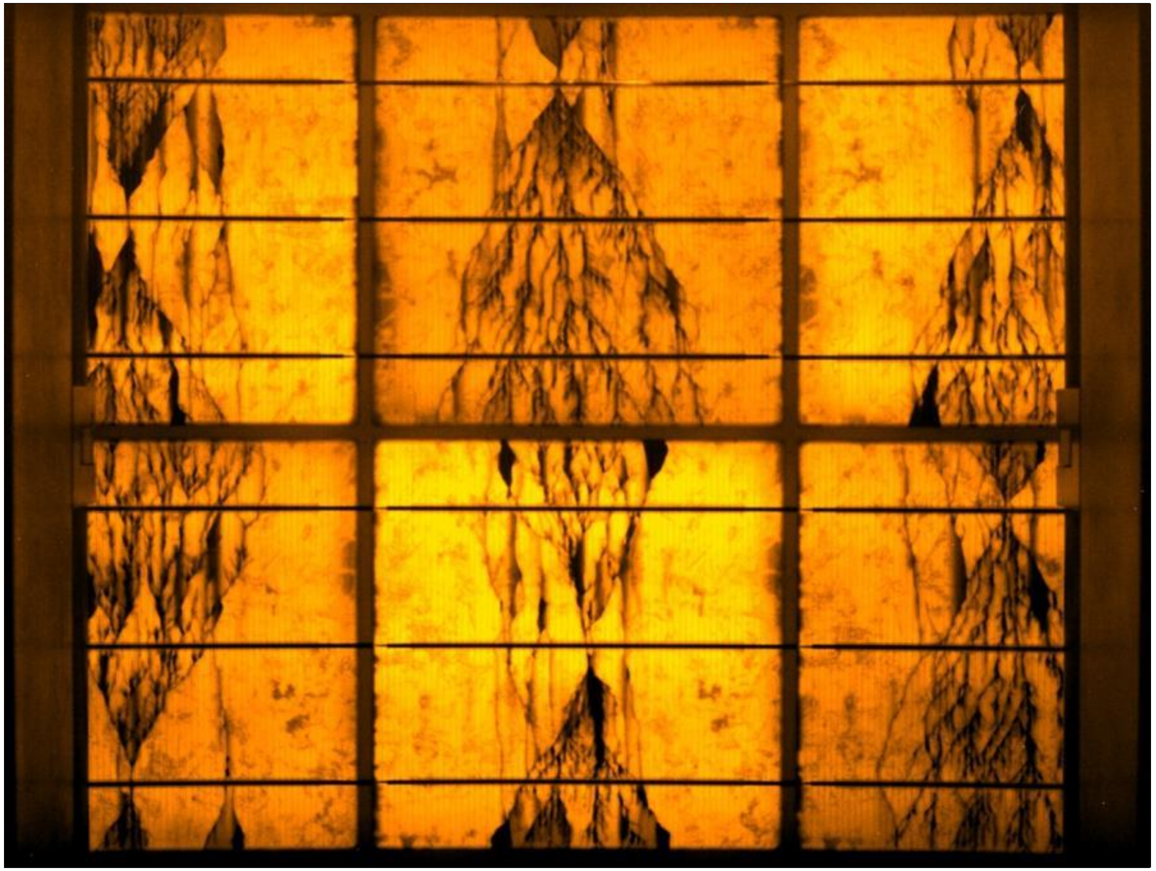


EL image of test specimen: Multi-crystalline, parallel

Results and Discussion
Mechanical loading perpendicular to busbars







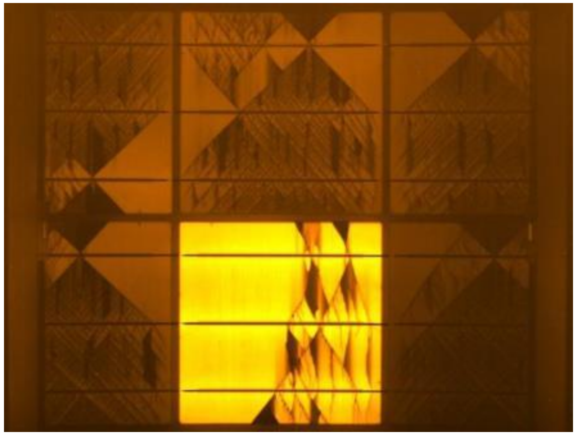
EL image of test specimen: Multi-crystalline, perpendicular

Results and Discussion

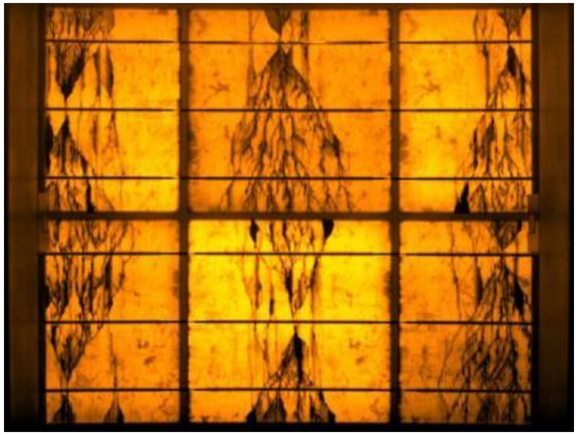
Mechanical loading: Comparison of different cell types

- Different crack appearance between mono-crystalline and multi-crystalline cells
- Predominant 45° crack angle in mono-crystalline cells → <110> direction

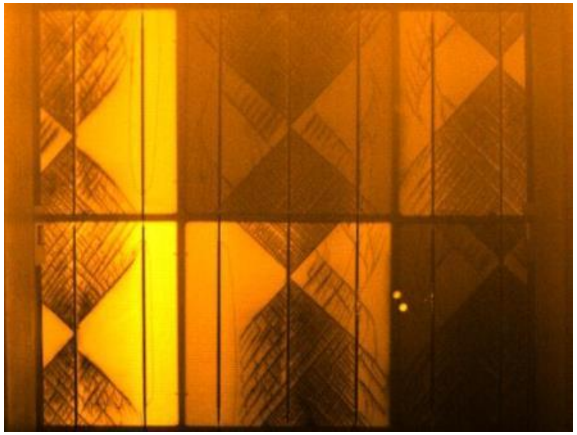
  D. Clarke, Semiconductors and Semimetals, 37 (1992)



Mono-crystalline, perpendicular



Multi-crystalline, perpendicular



Mono-crystalline, parallel

Multi-crystalline, parallel

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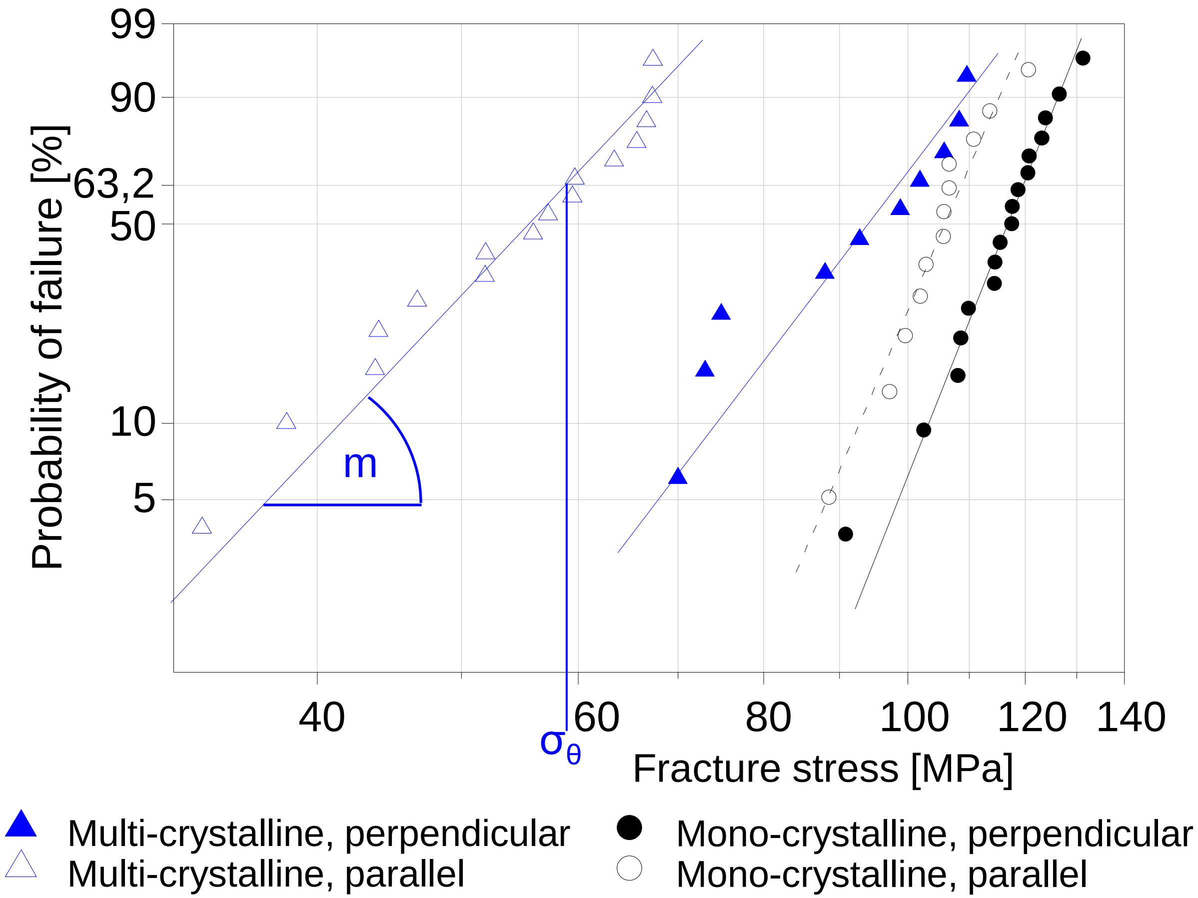
Results and Discussion

Mechanical loading: Comparison of different cell types

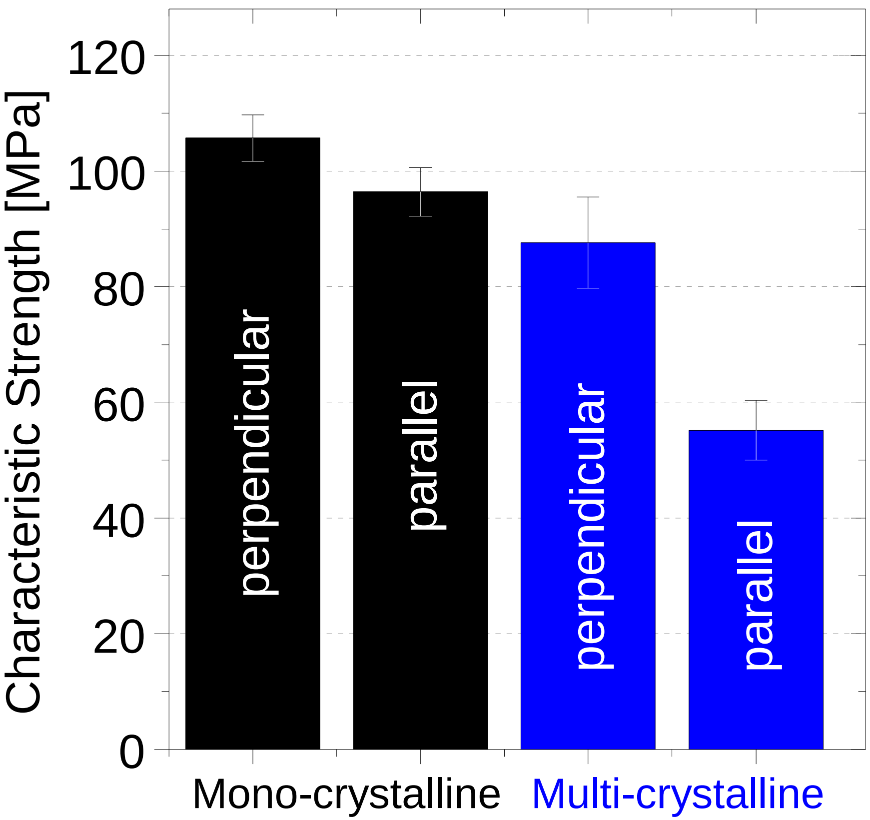
- Weibull evaluation of individual crack occurrences
- Determination of characteristic strength σ_θ and scattering m



Results and Discussion

Mechanical loading: Comparison of different cell types

- Comparison of different batches by their characteristic strength σ_θ
- Mono-crystalline cells show highest fracture strength
  R. de Donno, Master thesis (2011)
  M. Paggi *et al.*, Composite Structures 95 (2013)
- Difference in fracture strength between cracks parallel and perpendicular to the busbars → influence of the soldered interconnector
  S. Dietrich *et al.*, Proceedings SPIE Optics+ Photonics, (2013)



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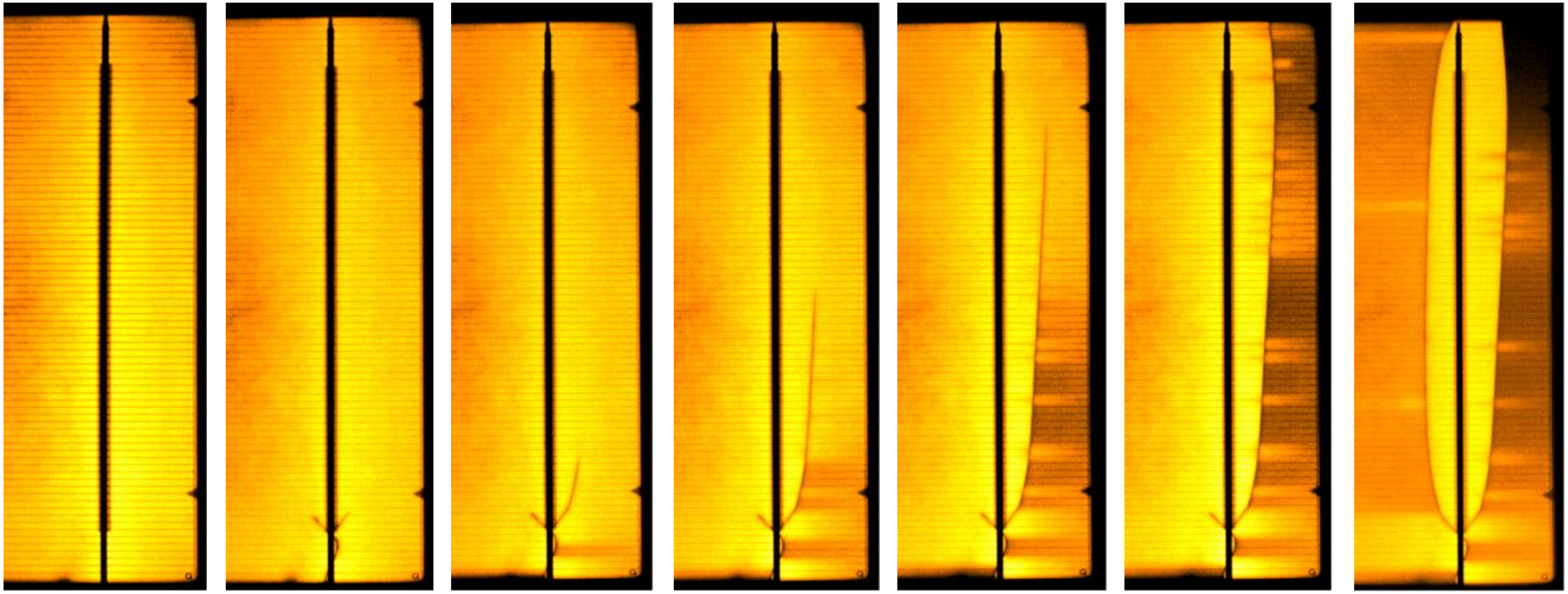
Results and Discussion

Mechanical loading: Influence of existing cracks

- Influence of existing cracks at a macroscopic scale

Soldered Laminated 100 N 110 N 120 N 130 N 200 N



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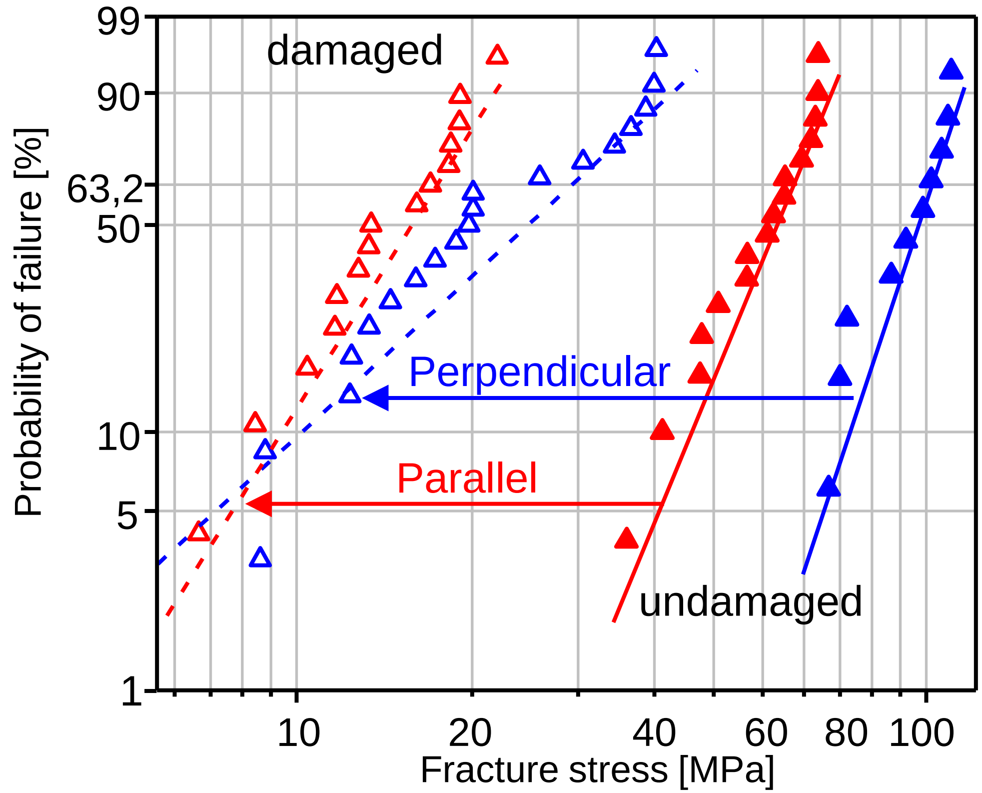
Results and Discussion

Mechanical loading: Influence of existing cracks

- Influence of existing cracks at a macroscopic scale
- Definition of separate classes for crack occurrences from existing cracks

→ Existing cracks reduce the fracture strength significantly

→ Should be avoided by any means

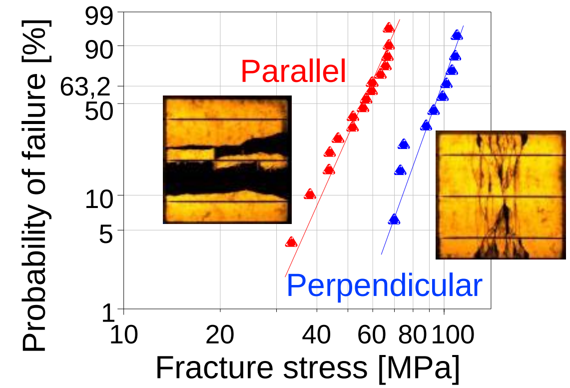


▲ Multikristallin, perpendicular
△ Multikristallin, perpendicular, damaged
▲ Multikristallin, parallel
△ Multikristallin, parallel, damaged

Results and Discussion

Transfer to full-scale PV modules

Example: Multi-crystalline cells



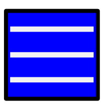
In-laminate strength testing

Strength parameters for loading perpendicular and parallel to busbars

$\sigma_{\theta,x}=98{,}4\ MPa,\ m_x=8{,}0$

$\sigma_{\theta,y}=58{,}8\ MPa,\ m_y=6{,}4$

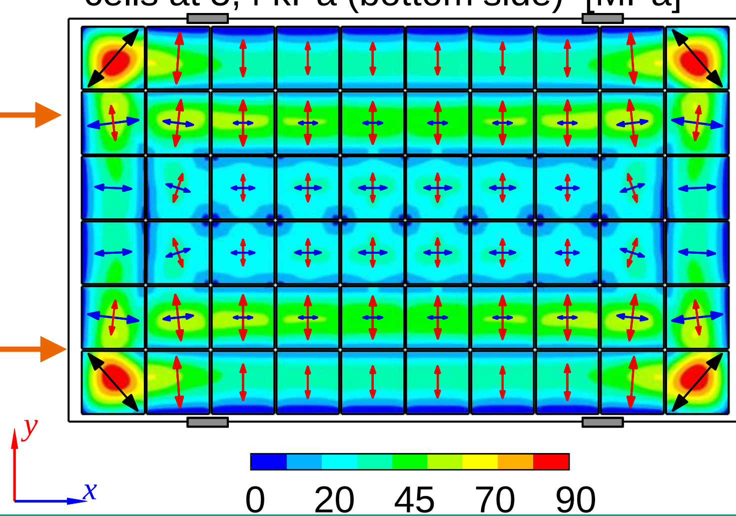
FE model of solar module



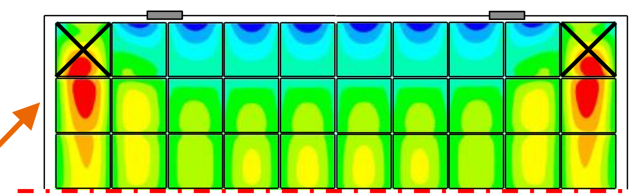
Loads and boundary conditions

5,4 kPa, 4 clamps

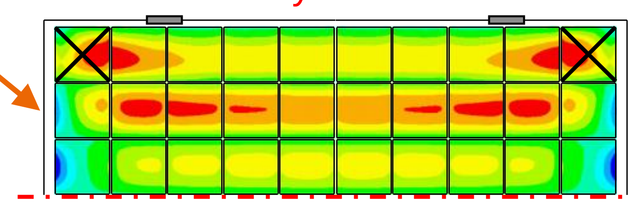
1st and 2nd principal stress in solar cells at 5,4 kPa (bottom side) [MPa]



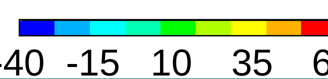
Stress in x direction



Stress in y direction



Stress [MPa]



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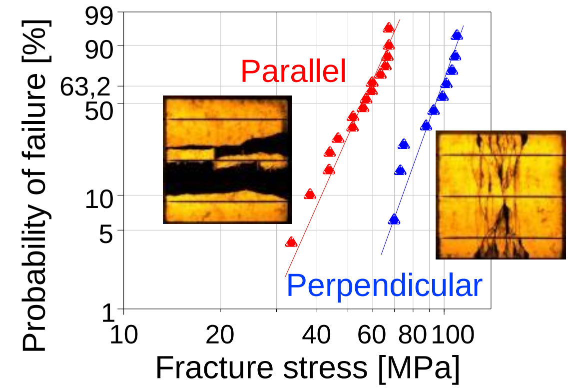
Results and Discussion

Transfer to full-scale PV modules

Example: Multi-crystalline cells



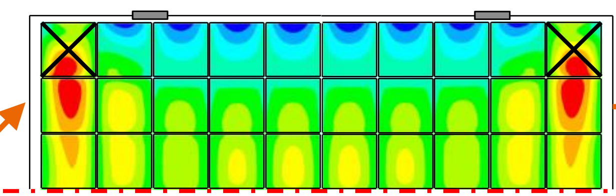
In-laminate strength testing

Strength parameters for loading perpendicular and parallel to busbars
$\sigma_{\theta,x}$=98,4 MPa, m_x=8,0
$\sigma_{\theta,y}$=58,8 MPa, m_y=6,4

Total probability of failure

$$1 - P_{f,Gesamt}(\sigma_x, \sigma_y) = (1 - P_{f,x}) \cdot (1 - P_{f,y})$$

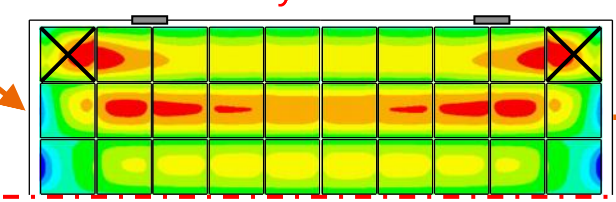
Stress in x direction



Cracks perpendicular to BB:

	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	
1,9	<0,1	0,0	<0,1	<0,1	<0,1	<0,1	0,0	<0,1	1,9
0,1	<0,1	0,0	<0,1	<0,1	<0,1	<0,1	0,0	<0,1	0,1

Stress in y direction



Cracks parallel to BB:

	69,4	11,9	5,8	5,4	5,4	5,8	11,9	69,4	
9,4	49,1	43,1	33,2	30,2	30,2	33,2	43,1	49,1	9,4
<0,1	1,0	1,6	2,2	2,8	2,8	2,2	1,6	1,0	<0,1

	69,4	11,9	5,8	5,4	5,4	5,8	11,9	69,4	
11,2	49,1	43,1	33,2	30,2	30,2	33,2	43,1	49,1	11,2
0,2	1,1	1,6	2,2	2,8	2,8	2,2	1,6	1,1	0,2
0,2	1,1	1,6	2,2	2,8	2,8	2,2	1,6	1,1	0,2
11,2	49,1	43,1	33,2	30,2	30,2	33,2	43,1	49,1	11,2
	69,4	11,9	5,8	5,4	5,4	5,8	11,9	69,4	

Stress [MPa] -40 -15 10 35 60

Probability of failure [%] 0 20 40 60 80 100

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Results and Discussion

Transfer to full-scale PV modules

Analysis of 27 PV modules after MLT (5,4 kPa): Percentage of cells with at least one crack [%]
S. Kajari-Schröder *et al.*; Solar Energy Materials & Solar Cells, 95 (2011)

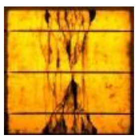
Total:

	69,4	11,9	5,8	5,4	5,4	5,8	11,9	69,4	
11,2	49,1	43,1	33,2	30,2	30,2	33,2	43,1	49,1	11,2
0,2	1,1	1,6	2,2	2,8	2,8	2,2	1,6	1,1	0,2

Total:

36,1	38,0	43,5	37,0	59,3
46,3	46,3	52,8	51,9	26,9
42,6	35,2	39,8	30,6	30,6

Cracks perpendicular to BB:

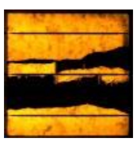


	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	
1,9	<0,1	0,0	<0,1	<0,1	<0,1	<0,1	0,0	<0,1	1,9
0,1	<0,1	0,0	<0,1	<0,1	<0,1	<0,1	0,0	<0,1	0,1

Cracks perpendicular to BB:

0	0	0	0	0
0	0	0	0	0,9
0	0	0	0	5,6

Cracks parallel to BB:



	69,4	11,9	5,8	5,4	5,4	5,8	11,9	69,4	
9,4	49,1	43,1	33,2	30,2	30,2	33,2	43,1	49,1	9,4
<0,1	1,0	1,6	2,2	2,8	2,8	2,2	1,6	1,0	<0,1

Cracks parallel to BB:

32,4	32,4	35,2	19,4	0
33,3	33,3	29,6	17,6	0,9
21,3	22,2	14,8	12,0	3,7

Dendritic:

2,8	1,9	1,9	0,9	4,6
10,2	6,5	5,6	9,3	9,3
10,2	4,6	8,3	3,7	11,1

45°:

0	19,4	3,7	14,8	48,2
1,9	1,9	6,5	15,7	10,2
0	0,9	2,8	6,5	0,9

Several directions:

0,9	2,8	2,8	1,9	5,6
0,9	3,7	10,2	9,3	4,6
11,1	6,5	13,9	5,6	8,3

Probability of failure [%]

0 20 40 60 80 100

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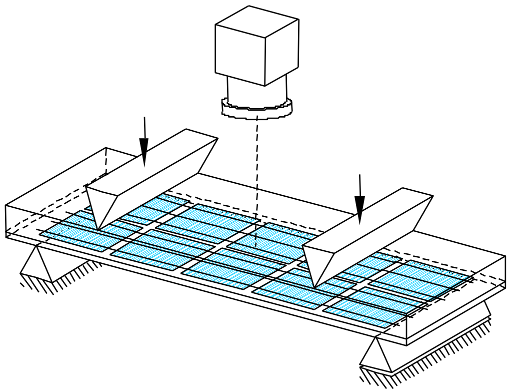
Conclusions and Outlook



- Experimental approach for investigation of cracks under well-known boundary conditions
  - Determination of “In-laminate strength”
  - Quick and efficient method
  - Opportunity for further fields of application
- Comparison of different influences by characteristic strength
  - Cell type (mono, multi, cell thickness, contact layout)
  - Manufacturing conditions (soldering conditions, different encapsulants)
- A probability of failure can be calculated for each cell in a PV module for a specific (complex) load situation → basis for reliability concept and optimization

Conclusions and Outlook

- "In-laminate strength" has been found to be very sensitive to changes
  - Influences of different soldering conditions and encapsulants
  - Decrease of fracture strength after thermal cycling
  - Increase of fracture strength after damp heat testing
- Outdoor exposure of test specimens for a certain period of time and correlation of fracture strength

→ Determination of acceleration factors

→ Insight into occurring mechanisms

Publication: Sander, M.; Influence of manufacturing processes and subsequent weathering on cell cracks in PV modules; EU PVSEC 2013, 4AV.5.30, to be published

Thanks for your Attention

martin.sander@csp.fraunhofer.de

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