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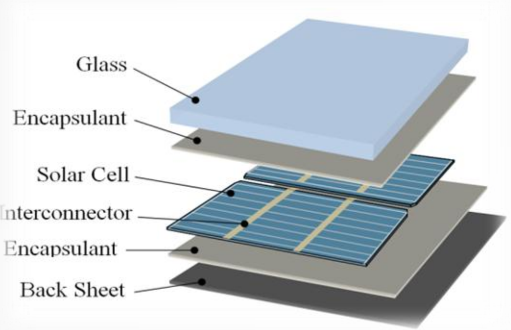
Failure analysis approach for poly-crystalline silicon in PV module four-line bending test



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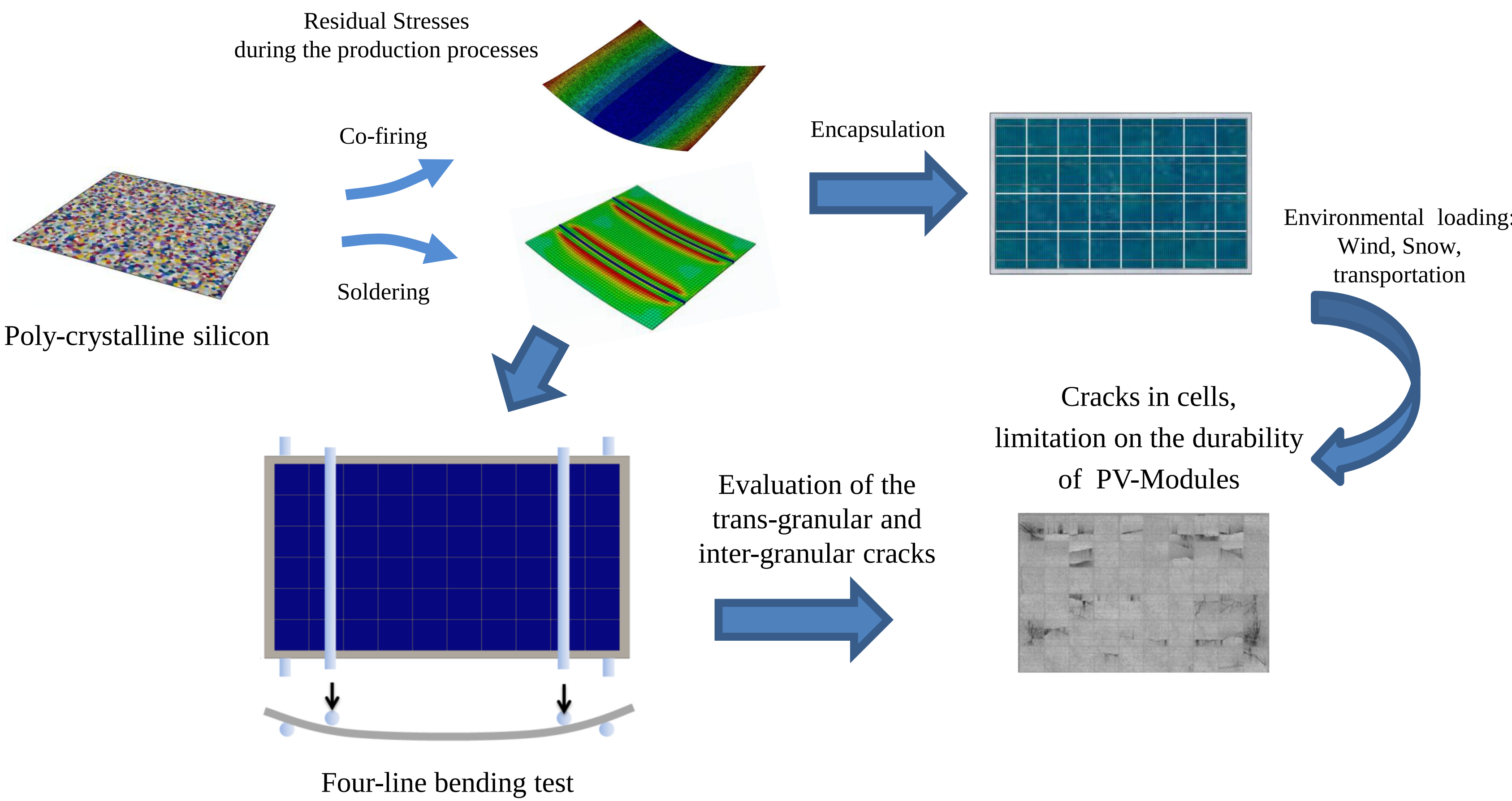
ISD, Hannover, 03.02.2015

Leibniz Universität Hannover

Contents

Introduction



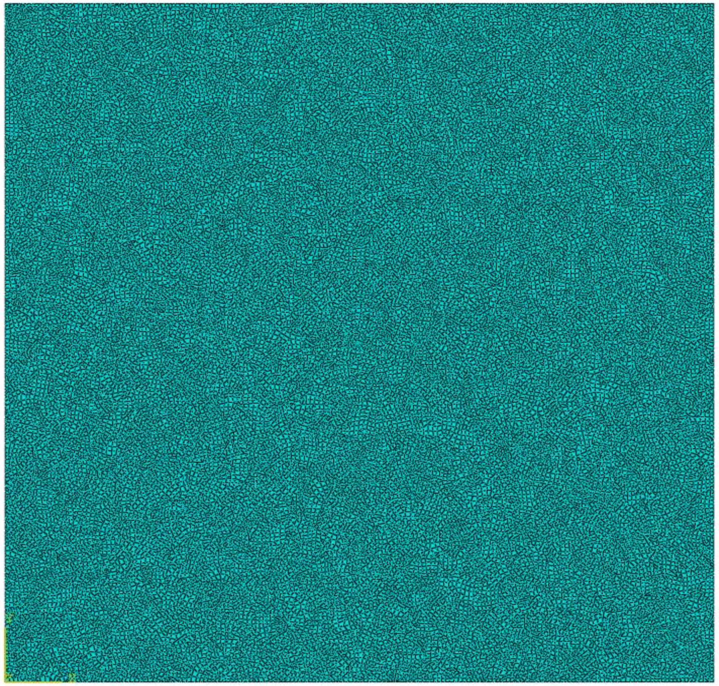
Contents

Geometrical description of poly-crystalline silicon

- Voronoi algorithm has been widely used to digitally generate the representative microstructure of poly-crystalline [Kumar et al. 1992, Mullen et al. 1997, …]
- Two modification algorithms applied to the Voronoi tessellation in order to avoid numerical problems (generation of distorted elements):

  I. Merging the centroids which are very close to each other(r_{min} =1.5 [mm])
  II. Removing very short edges after the Voronoi tessellation (L_{min} =0.15 [mm])

- Decomposition of the domain to N=3624 polygonal sub-domains, based on the experimental measurement of the centroids of the grains.



N=3624

1.36% of elements are distorted → Convergence problem in simulation

Contents

Contents

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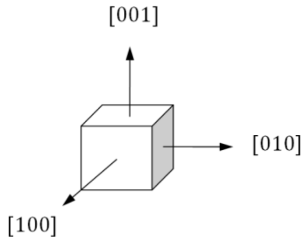
- The matrix of elastic moduli of silicon with the lattice direction of [001], [010] and [100] defined as the reference directions (in local COS):

$$\boldsymbol{C}_{si} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix}$$

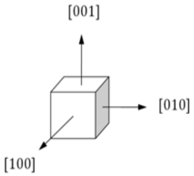
$$C_{11} = 164.8\ [GPa]$$

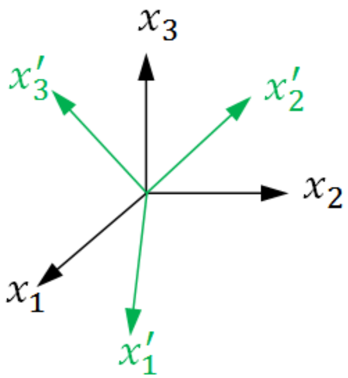
$$C_{12} = 63.5\ [GPa]$$

$$C_{44} = 79\ [GPa]$$



- Definition of the direction cosines' matrix for the new COS





$$Q_{ij} = \cos\,(x'_j, x_i) \quad i,j = 1,2,3$$

	x_1	x_2	x_3
x'_1	Q_{11}	Q_{12}	Q_{13}
x'_2	Q_{21}	Q_{22}	Q_{23}
x'_3	Q_{31}	Q_{32}	Q_{33}

Anisotropy of the silicon crystals

- Construction of the fourth order elasticity tensor $\mathbb{C}$ based on the matrix of elasticity moduli $\boldsymbol{C}$ in the reference lattice direction

$$\boldsymbol{C} = \begin{bmatrix} \mathbb{C}_{1111} & \mathbb{C}_{1122} & \mathbb{C}_{1133} & \mathbb{C}_{1123} & \mathbb{C}_{1131} & \mathbb{C}_{1112} \\ \mathbb{C}_{2211} & \mathbb{C}_{2222} & \mathbb{C}_{2233} & \mathbb{C}_{2223} & \mathbb{C}_{2231} & \mathbb{C}_{2212} \\ \mathbb{C}_{3311} & \mathbb{C}_{3322} & \mathbb{C}_{3333} & \mathbb{C}_{3323} & \mathbb{C}_{3331} & \mathbb{C}_{3312} \\ \mathbb{C}_{2311} & \mathbb{C}_{2322} & \mathbb{C}_{2333} & \mathbb{C}_{2323} & \mathbb{C}_{2331} & \mathbb{C}_{2312} \\ \mathbb{C}_{3111} & \mathbb{C}_{3122} & \mathbb{C}_{3133} & \mathbb{C}_{3123} & \mathbb{C}_{3131} & \mathbb{C}_{3112} \\ \mathbb{C}_{1211} & \mathbb{C}_{1222} & \mathbb{C}_{1233} & \mathbb{C}_{1223} & \mathbb{C}_{1231} & \mathbb{C}_{1212} \end{bmatrix}$$

where

$$\sigma_{ij} = \mathbb{C}_{ijkl} : \varepsilon_{kl}$$

$$i, j, k, l = 1,2,3$$

- Transformation of $\mathbb{C}$ (fourth order elasticity tensor) and subsequently $\boldsymbol{C}$ (matrix of elasticity moduli) from its local COS to the global COS

$$\mathbb{C}'_{ijkl} = (Q_{pi} Q_{qj} Q_{rk} Q_{sl}) \mathbb{C}_{pqrs} \qquad \begin{cases} i, j, k, l = 1,2,3 \\ p, q, r, s = 1,2,3 \end{cases}$$

$\mathbb{C}$ → Local COS

$\mathbb{C}'$ → Global COS

- Obtain the values of Young's modulus and Poisson's ratio in each arbitrary direction

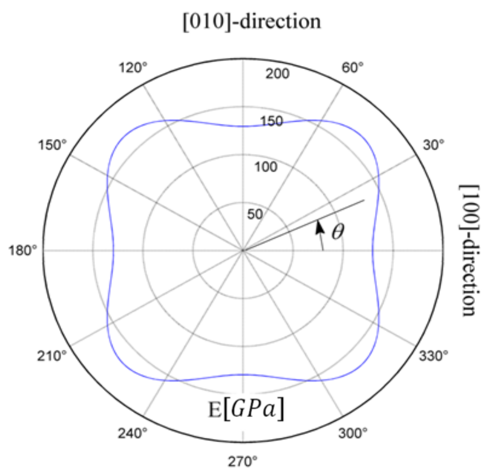
$$\begin{cases} E_i = \dfrac{\tau_i}{\gamma_i} = \dfrac{1}{S_{ii}} \\ \nu_{ij} = -\dfrac{\gamma_j}{\gamma_i} = -\dfrac{S_{ij}}{S_{ii}} = -\dfrac{S_{ji}}{S_{ii}} \end{cases} \qquad i, j = 1,2,3$$

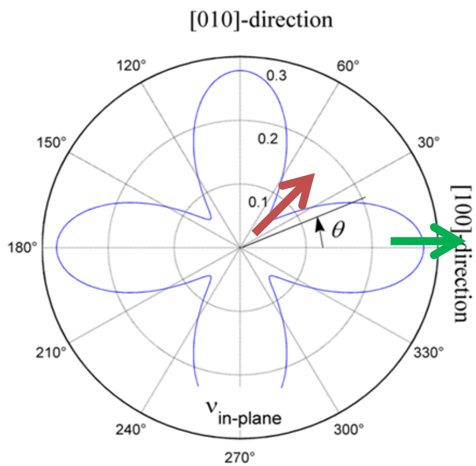
where

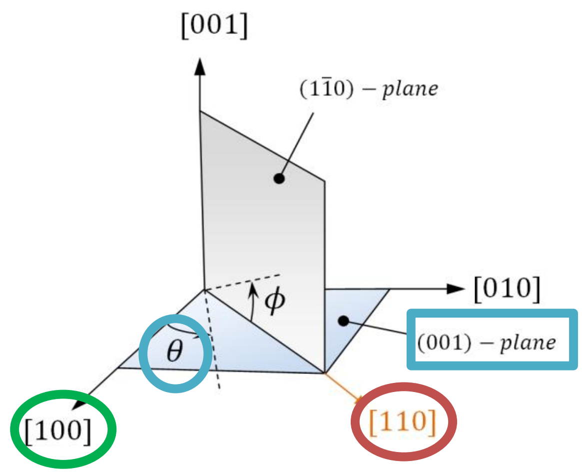
$$\boldsymbol{S} = \boldsymbol{C}^{-1}$$

Anisotropy of the silicon crystals

- Distribution of the Young's modulus and the Poisson's ratio in (001)-plane





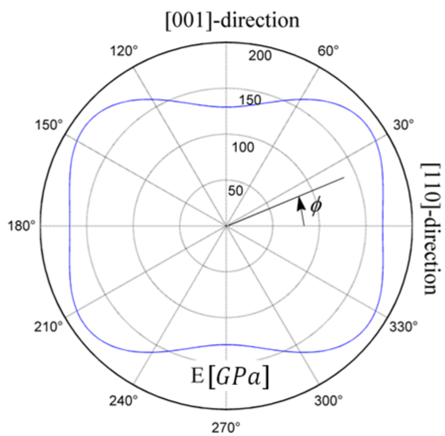


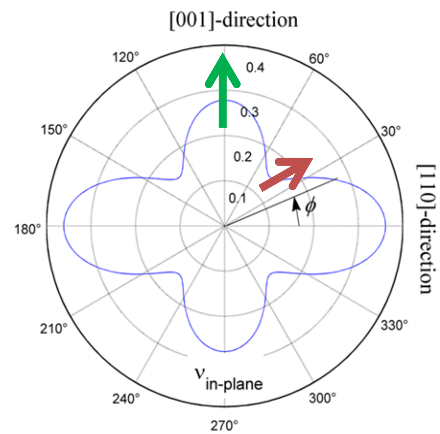
$$E_{min-001} = 129.5 \quad [GPa] \qquad \nu = 0.2781$$

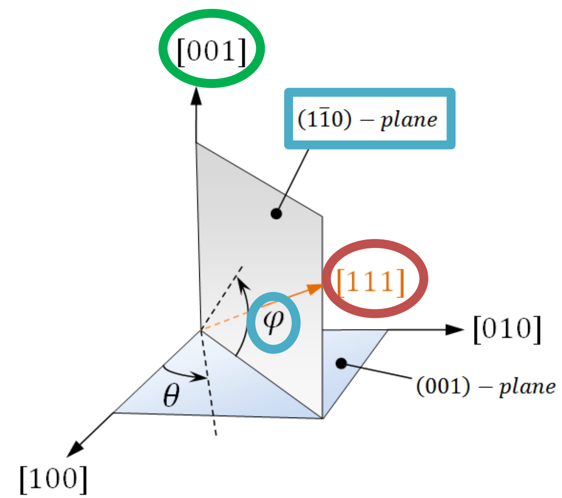
$$E_{max-001} = 168.0 \quad [GPa] \qquad \nu = 0.0633$$

Anisotropy of the silicon crystals

- Distribution of the Young’s modulus and the Poisson’s ratio in (1$\bar{1}$0)-plane







$$E_{min-001} = 129.5 \quad [GPa] \qquad \nu = 0.2781$$

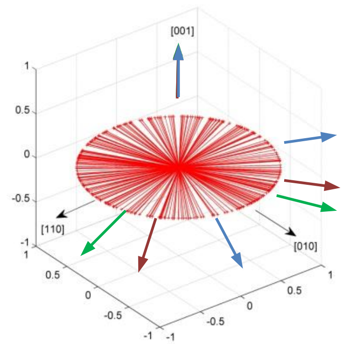
$$E_{max-1\bar{1}0} = 186.5\ [GPa] \qquad \nu = 0.1819$$

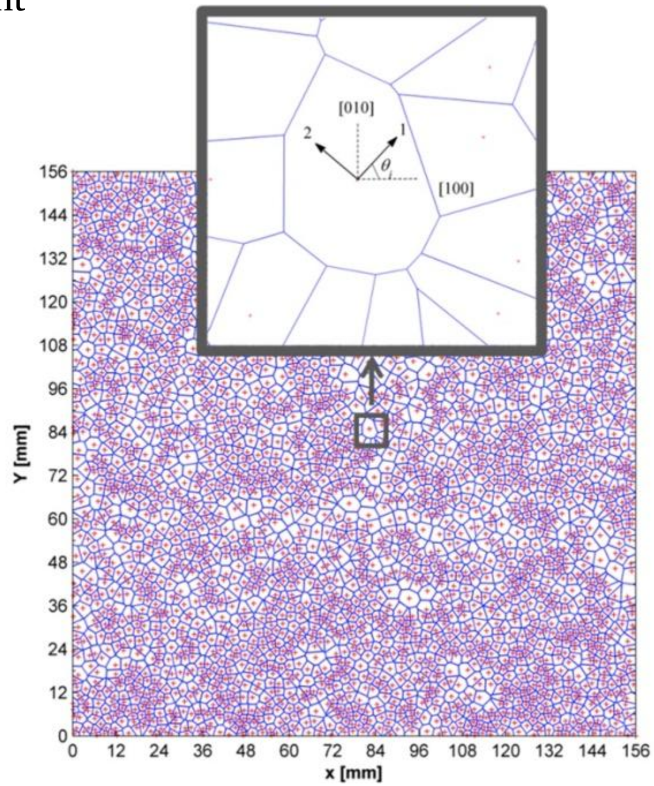
Contents

In-plane texturing pattern

- Crystallographic orientation for each grain is defined through the angle θ_i (One independent variable)

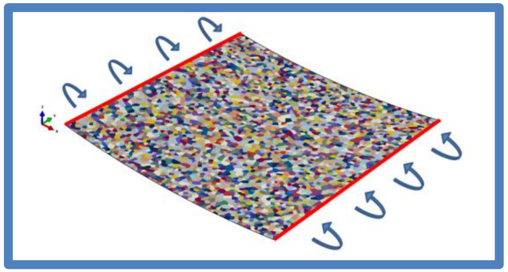
- Applying random orientation to each grain in the plane of (001)

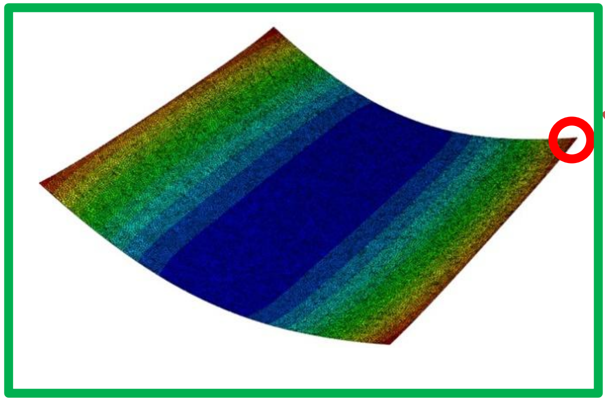


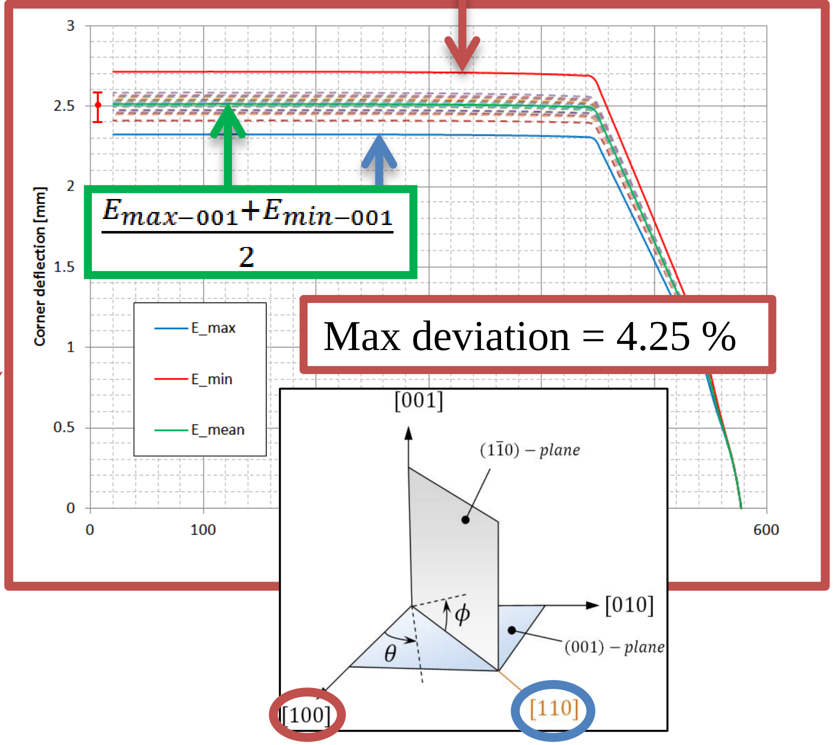


In-plane texturing pattern-An Application

- Performing the stability Analyses in two main steps:
  - Inserting a pair of distributed moments along two opposite sides of the wafer
  - Simulation of the Cooling down process through applying a uniform temperature field to the whole domain from 577° to 20°C



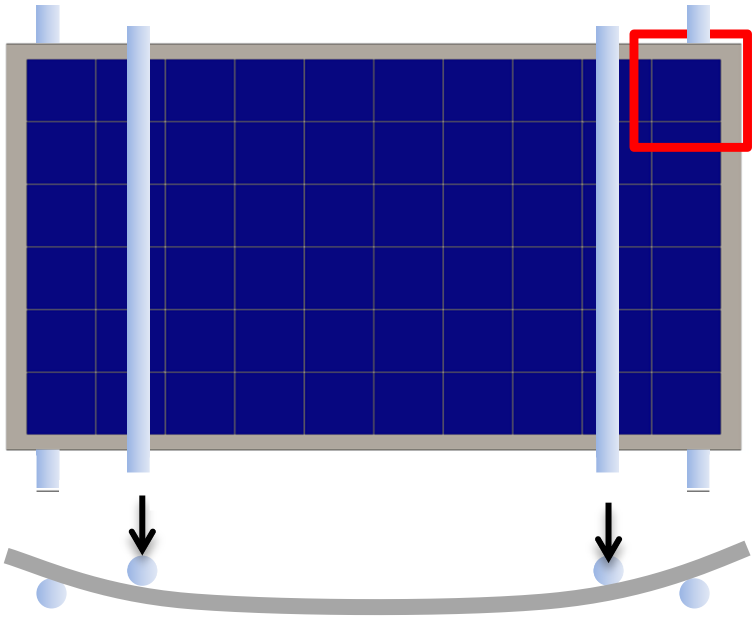


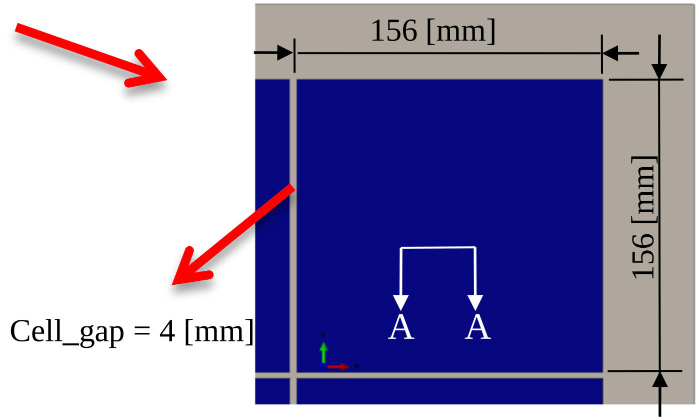


Contents

Contents

Geometrical and material description of the four-line bending test





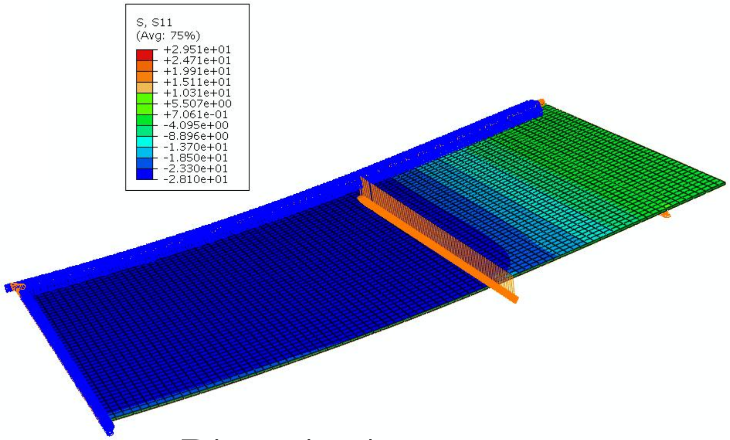
A-A cross section:

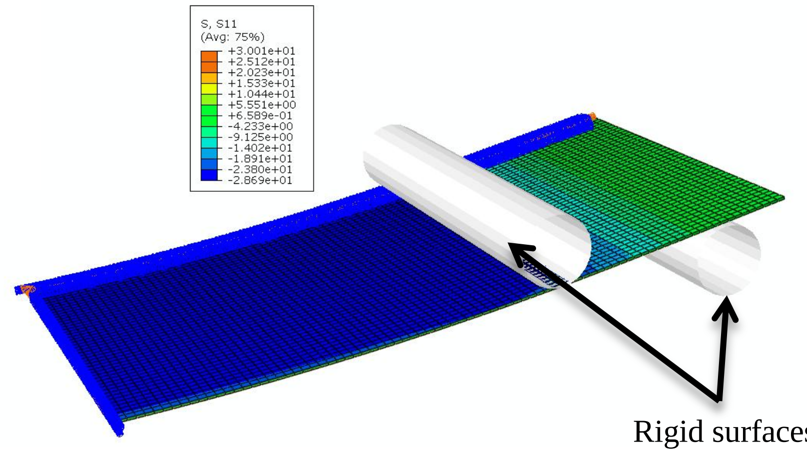
laminates
Backsheet
EVA_Bottom
Si
Al_Paste
EVA_Top
Glass

laminates	E [MPa]	ν
Backsheet	2584.5	0.271
EVA	7.9	.23
Si_homogen	161800	0.223
Al_Paste	3900	0.347
Glass	73000	0.23

Contents

Effect of contact on the structural behavior





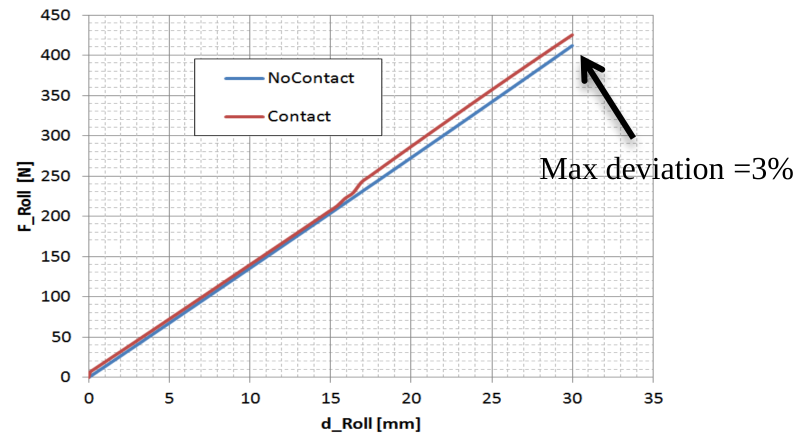
Discretization:

	Number of elements	Type of elements
Contact	4200	C3D20R
No contact	4200	C3D20R

Contact properties:

	Type
Tangential behavior	Frictional (0.1)
Normal behavior	Hard Contact

C3D20R: Quadratic 20 nodes solid elements



Contact does not have significant influence on the structural behavior of the PV-Module in four-line bending test

Contents

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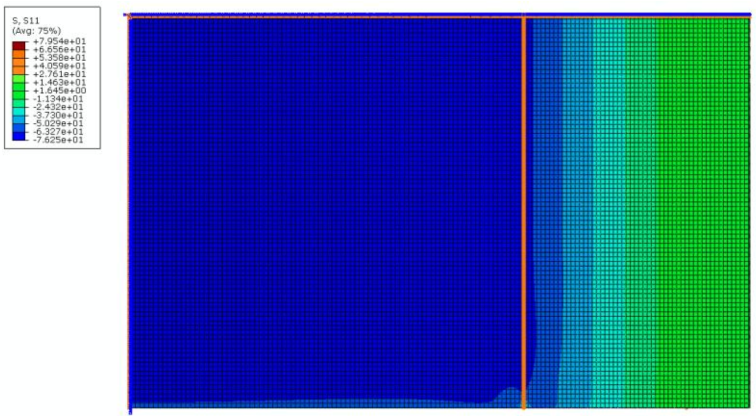
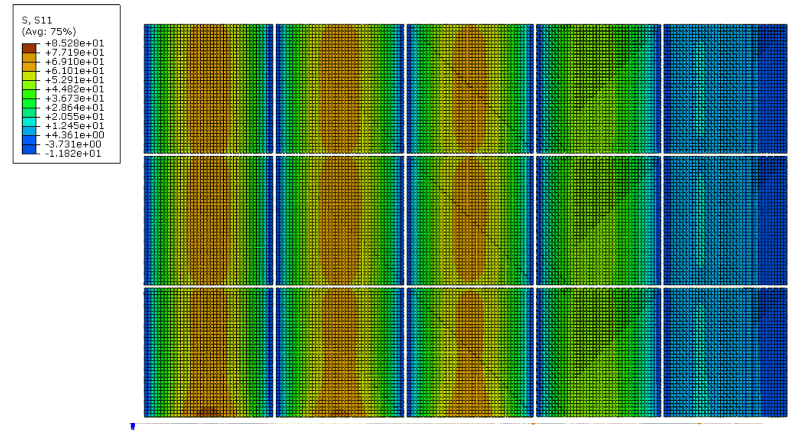
Effect of silicon layers on the structural behavior

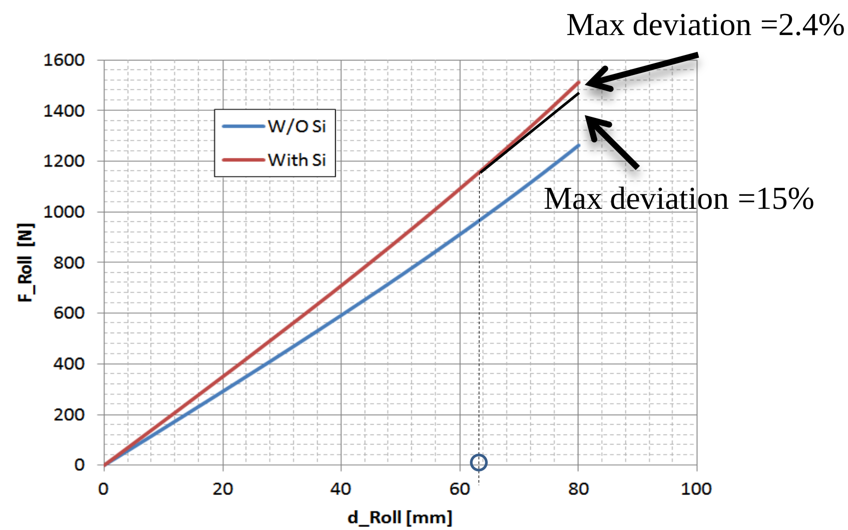




Discretization:

	Number of elements	Type of elements
W/O silicon	**34860**	**C3D20R**
With silicon	**170280**	**C3D20R**

We can neglect the material nonlinearities of silicon at the structural level and consider them just at the local analysis → By Performing local global analyses



Effect of silicon wafer can not be neglected in the structural behavior of the PV-Module

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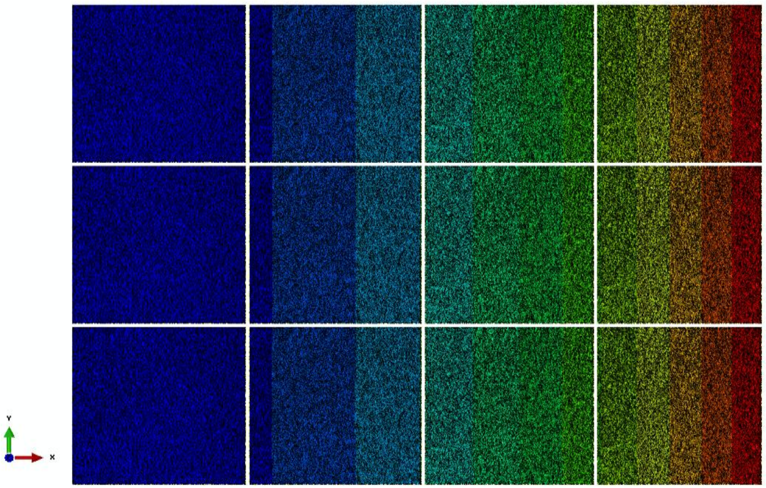
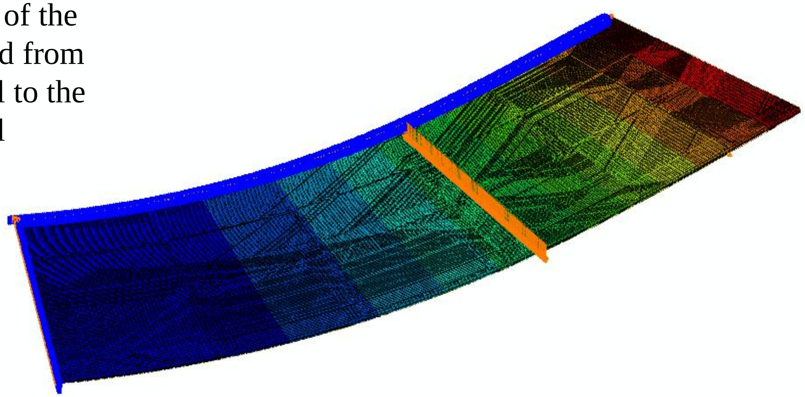
Contents

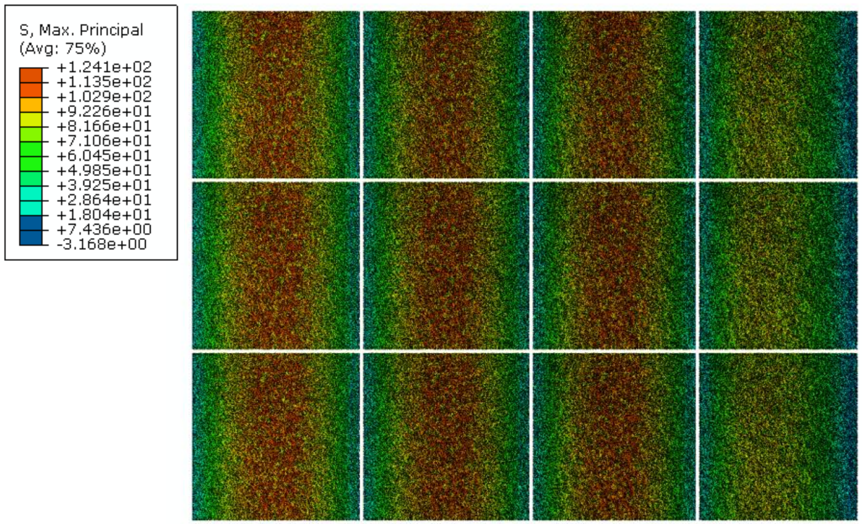


Transformation of the deformation field from the global model to the sub-model

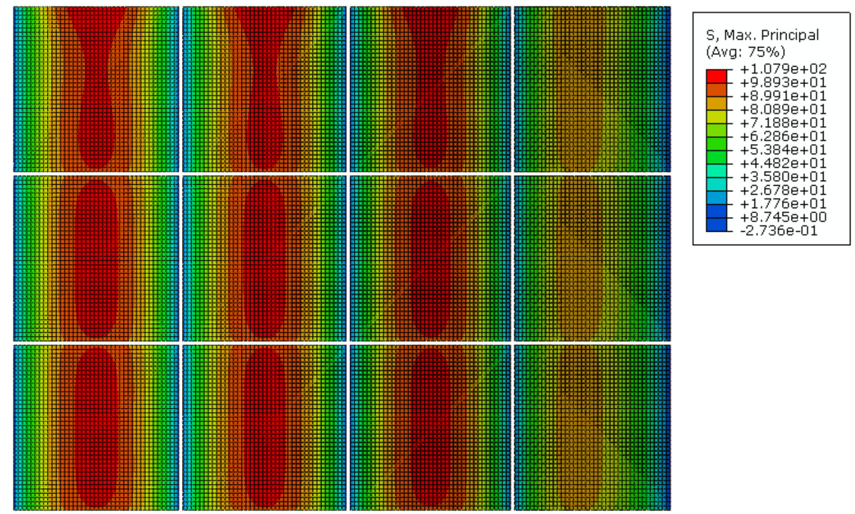


- Avoiding the propagation of the very fine mesh to the structural level (+)
- Possibility of investigating the effect of different grain distributions and orientations with less computational costs (+)
- With the one way sub-modeling method the strain field in the sub-model can not be redistributed (-) → Using encapsulated silicon wafer in the sub-model (Ongoing research)

Sub-modeling of the poly-crystalline silicon



Max. principal stress in sub-model



Max. principal stress in the global model

- ❑ Including the grain geometry and considering the anisotropy → 15% increase in the maximum principal stress in silicon layer

Contents

Contents

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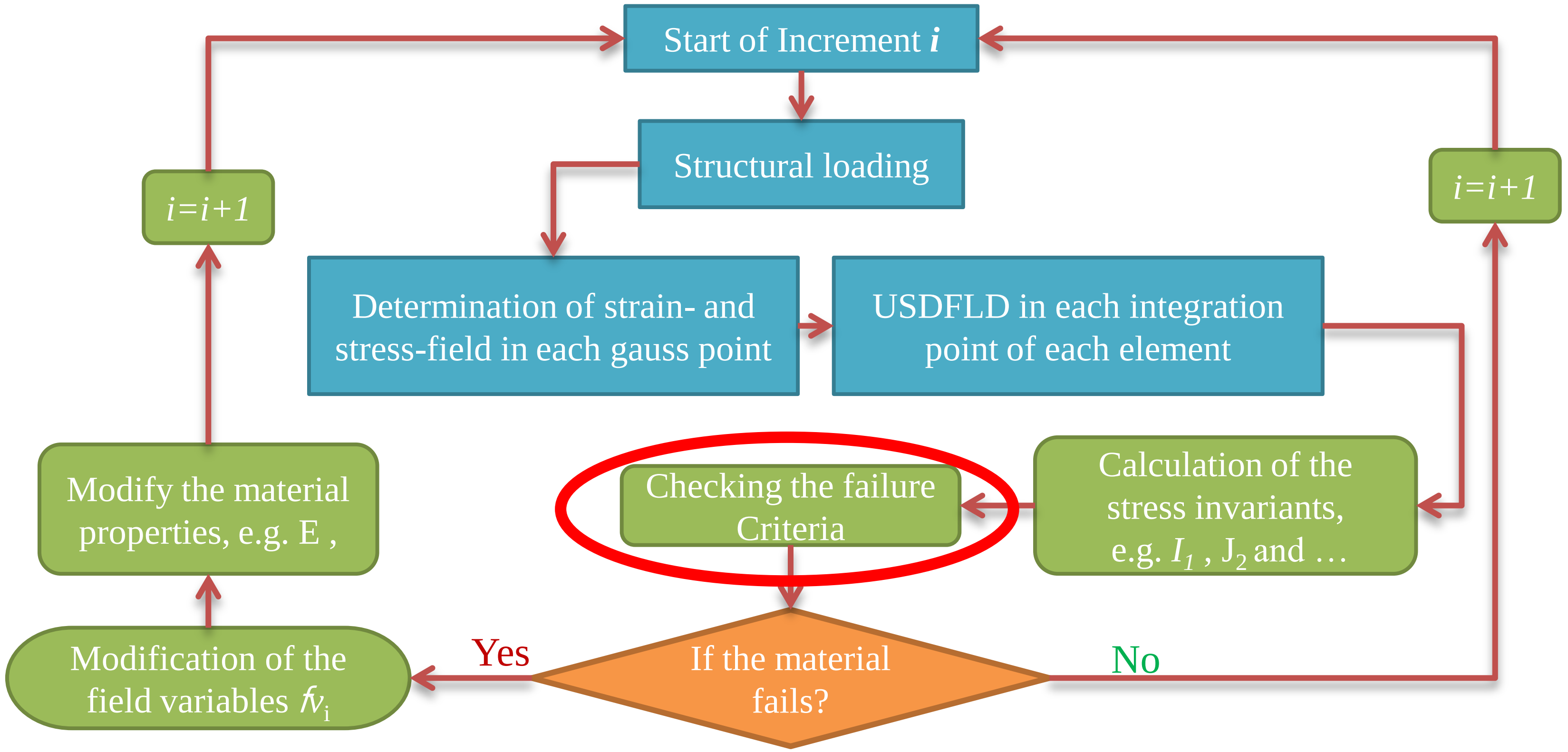
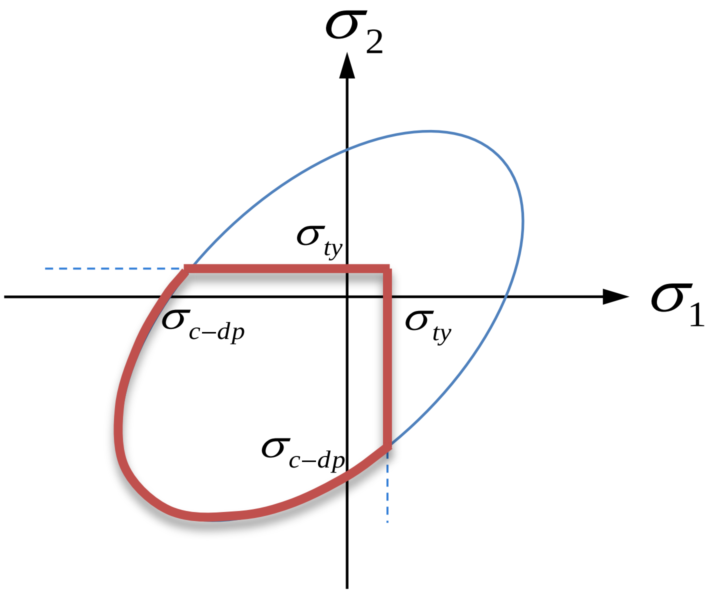
Introduction of USDFLD

- User subroutine USDFLD is used to model the complex material nonlinearity
- The subroutine has access to solution data , e.g. stresses, strains and …
- Material properties in ABAQUS/Standard can be defined as functions of field variables (fv_i)
- Subroutine USDFLD allows the user to define fv_i at every integration point of an element.
- The material properties can be a function of the solution data.



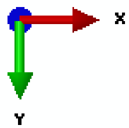
Failure criterion for silicon

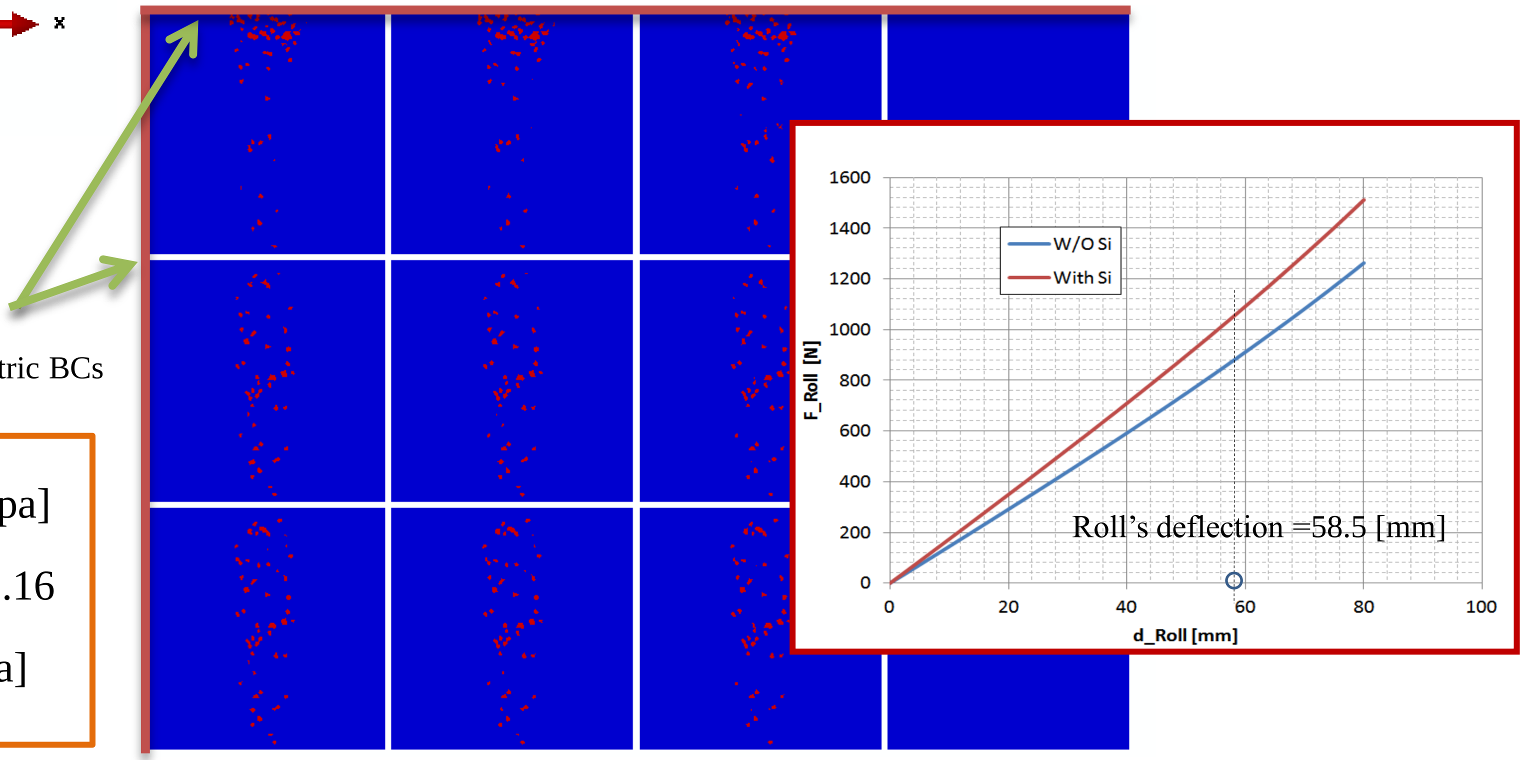
- Rankine criteria in tension
- Drucker-Prager criteria in compression
- Combination of Rankine and Drucker-Prager



Contents

Sub-modeling of the poly-crystalline silicon





Symmetric BCs

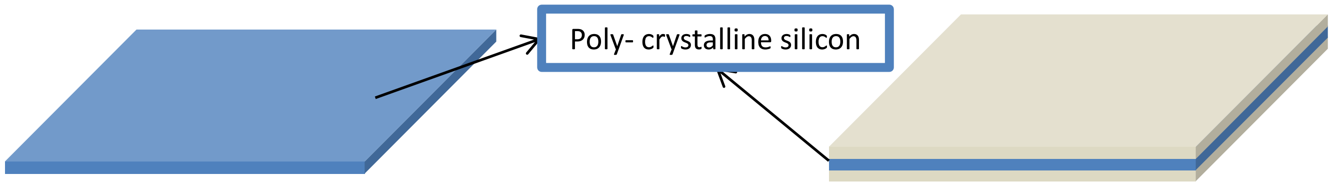
σ_{ucy}= 300. [Mpa]

$(\sigma_{bcy} / \sigma_{ucy})$= 1.16

σ_{ty}= 50 [Mpa]

Current sub-model:
No re-distribution of strain field in silicon is allowed

Proposed sub-model:
Poly-crystalline silicon is encapsulated in EVA layers
re-distribution of strain field in silicon is allowed



Contents

Conclusions

- The effect of grain orientations and distributions has been included in the structural analysis

- A failure criterion for poly-crystalline silicon has been proposed

- In order to avoid the fine meshing of the whole structure a sub-modeling approach has been applied using the silicon layer as sub-model

Ongoing research

- Effect of including the inter-connectors at the structural level on the failure behavior of the silicon is to be investigated

- The sub-modeling method using the encapsulated poly-crystalline silicon as sub-model is to be investigated

- The resulting residual stress field after the co-firing and soldering processes is to be taken into account

Acknowledgement

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Thanks for your attention!