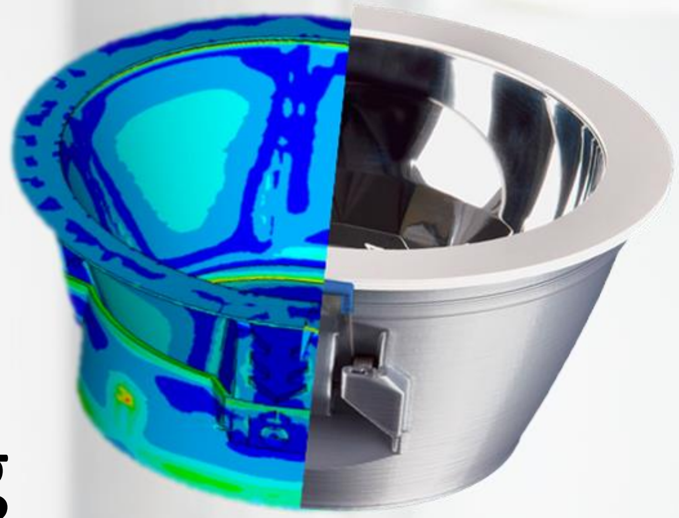


# Multi-physics modelling
-
# from virtual prototyping towards a digital twin

Roy Engelen | SASG meeting | June 4 2019

# Content

- Virtual Prototyping
  - Design Optimization
  - Thermal Management
- Multi-Physics
  - Thermal Structural example
  - Detailed model setup
- Towards a Digital Twin

# Virtual Prototyping

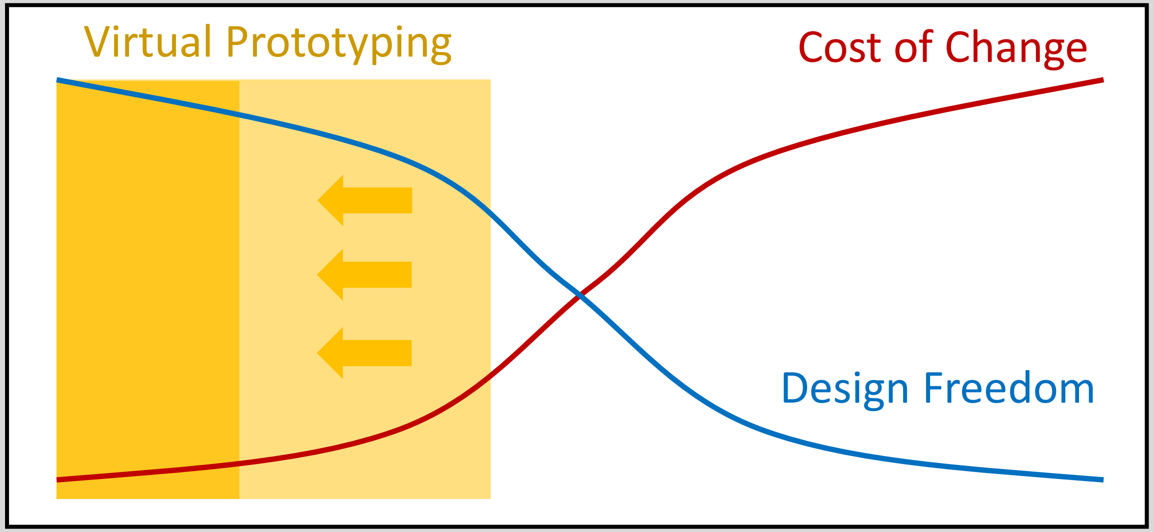
# Virtual Prototyping

**Virtual prototyping** is a method in the process of product development.

It involves using computer-aided design (CAD), computer-automated design (CAutoD) and computer-aided engineering (CAE) software to validate a design before committing to making a physical **prototype**.

The rationale for Virtual Prototyping is commonly:

- to reduce the amount of trail-and-error
- to avoid expensive changes in pre-production and onwards




**Concept | Design Cycles | Pre-Production | Mass Production | Customer Experience**



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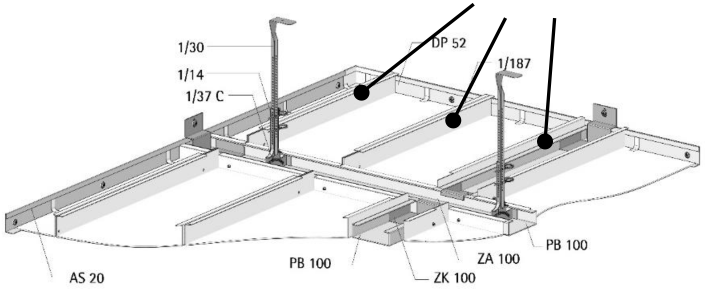
# Virtual Prototyping
## Design Optimization using Structural Mechanics

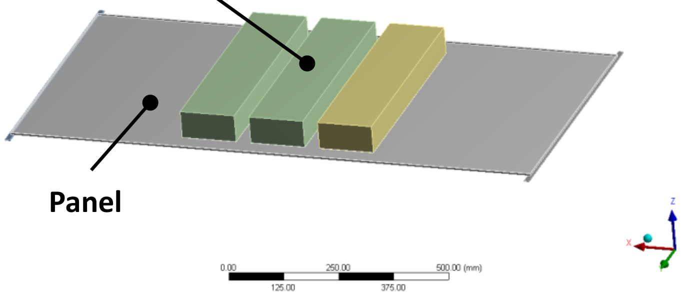
**Flexbend Luminaire**

**Reinforcement Bars**




**Bandraster ceiling support**

**Light Engine**

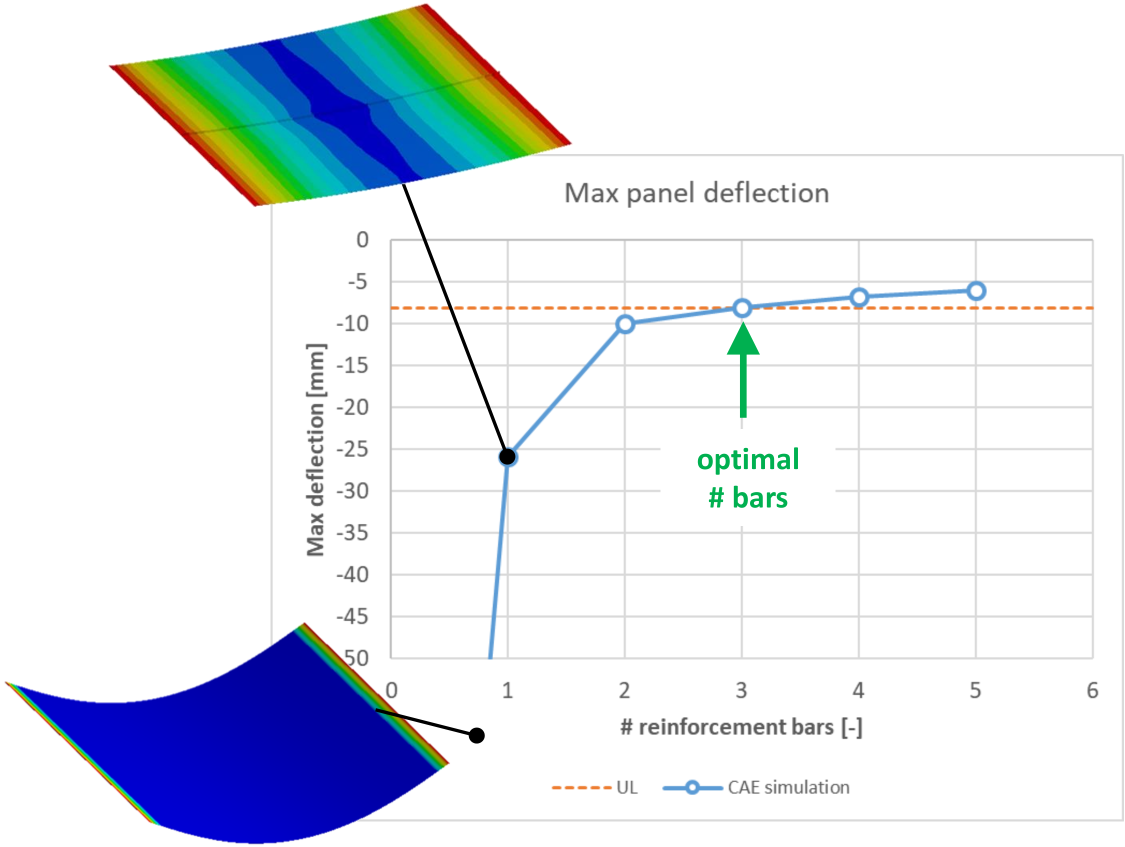


**Panel**

Calculate max panel deflection for Bandraster ceiling:

- Panel weight
- Light Engine weight

As function of the # of reinforcement bars



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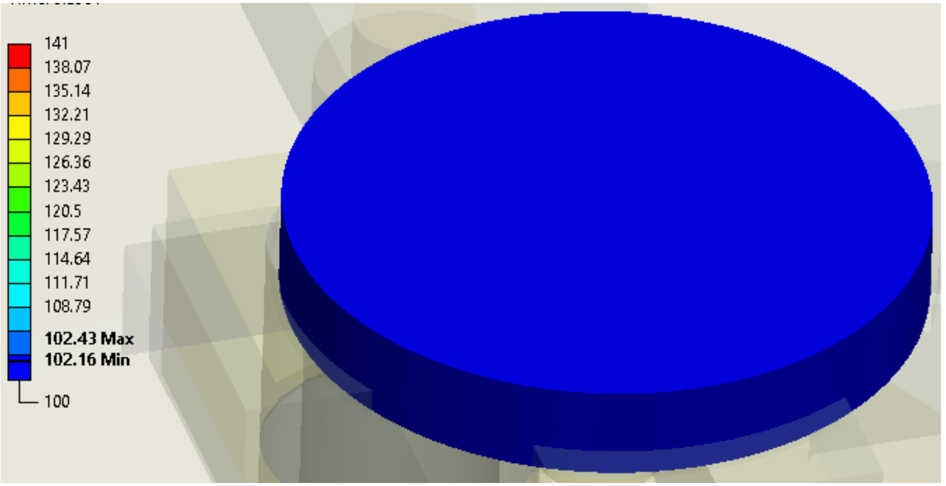
# Virtual Prototyping

## Thermal Management – impact of material choice

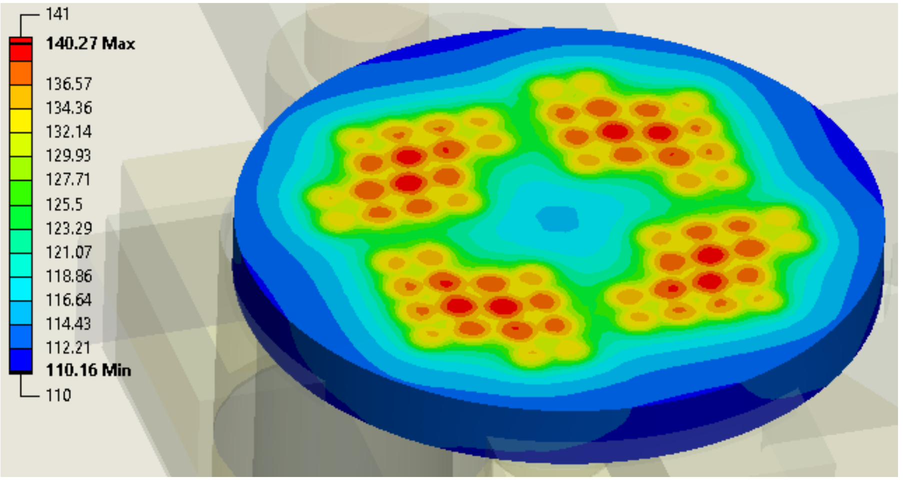
Flat optical mirror heats up when reflecting light from multiple sources

- Low vs high thermal conductivity
- Low vs high reflectivity
- Cooling via convection, less via conduction (frame)




**Mirror type A**

High (thermal) conductivity
Low reflectivity
No T gradient in mirror




**Mirror type B**

Low (thermal) conductivity
High reflectivity
High T gradient in mirror



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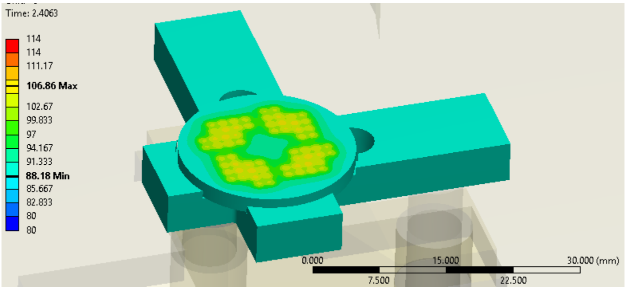
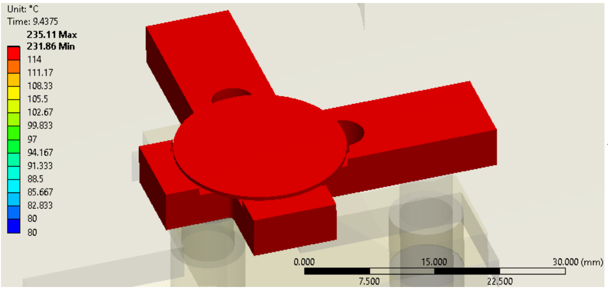
# Virtual Prototyping
## Thermal Management
## Optimum design

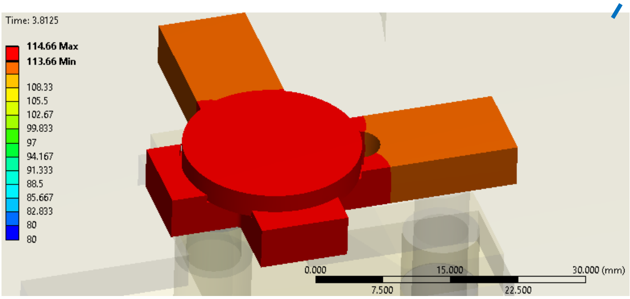
- Reflectivity is inversely related to the amount of heat generation in the mirror.
- Optimum Design is not achieved by changing the mirror material type only.
- Optimum Design achieved by material choice and additional convective cooling.



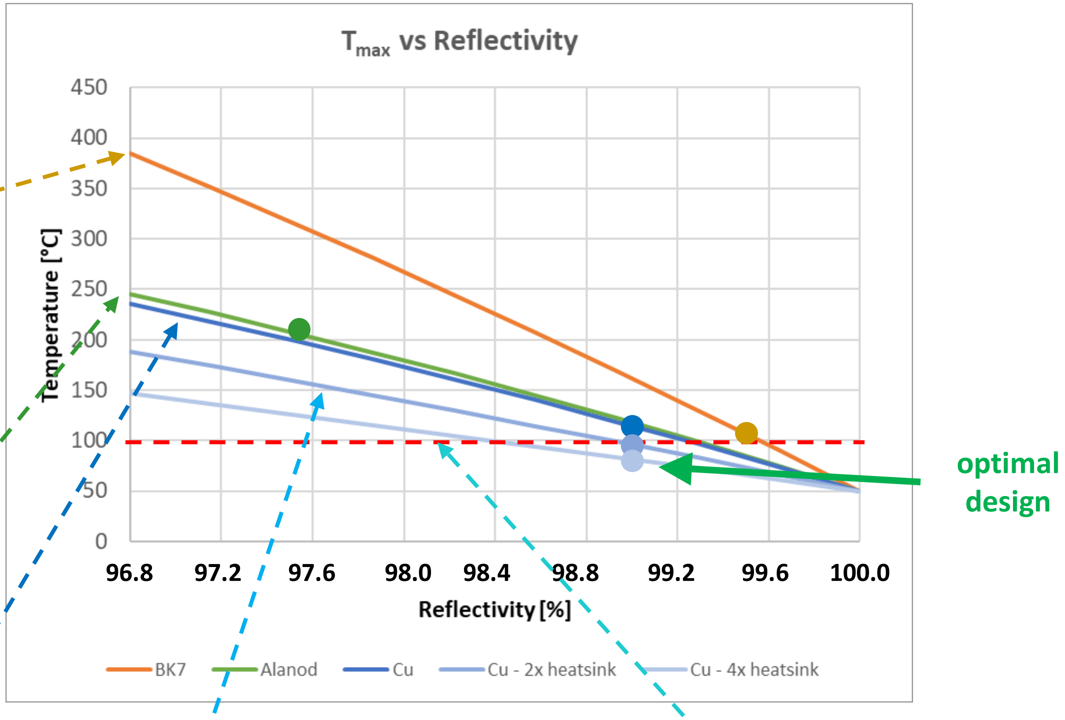

Type B @ 99.5% reflectivity

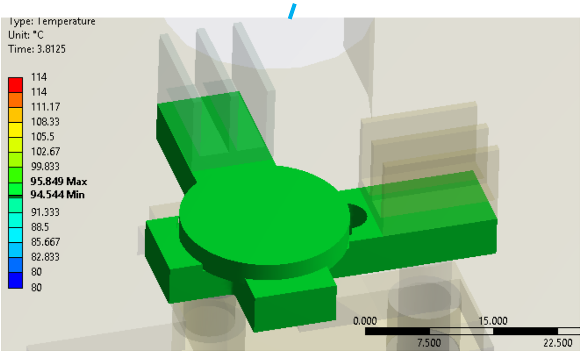



Type C @ 97% reflectivity

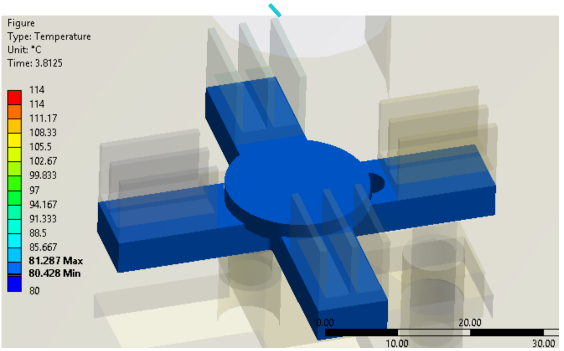



Type A @ 99% reflectivity




Type A + 2x heatsink @ 99% reflectivity




Type A + 4x heatsink @ 99% reflectivity



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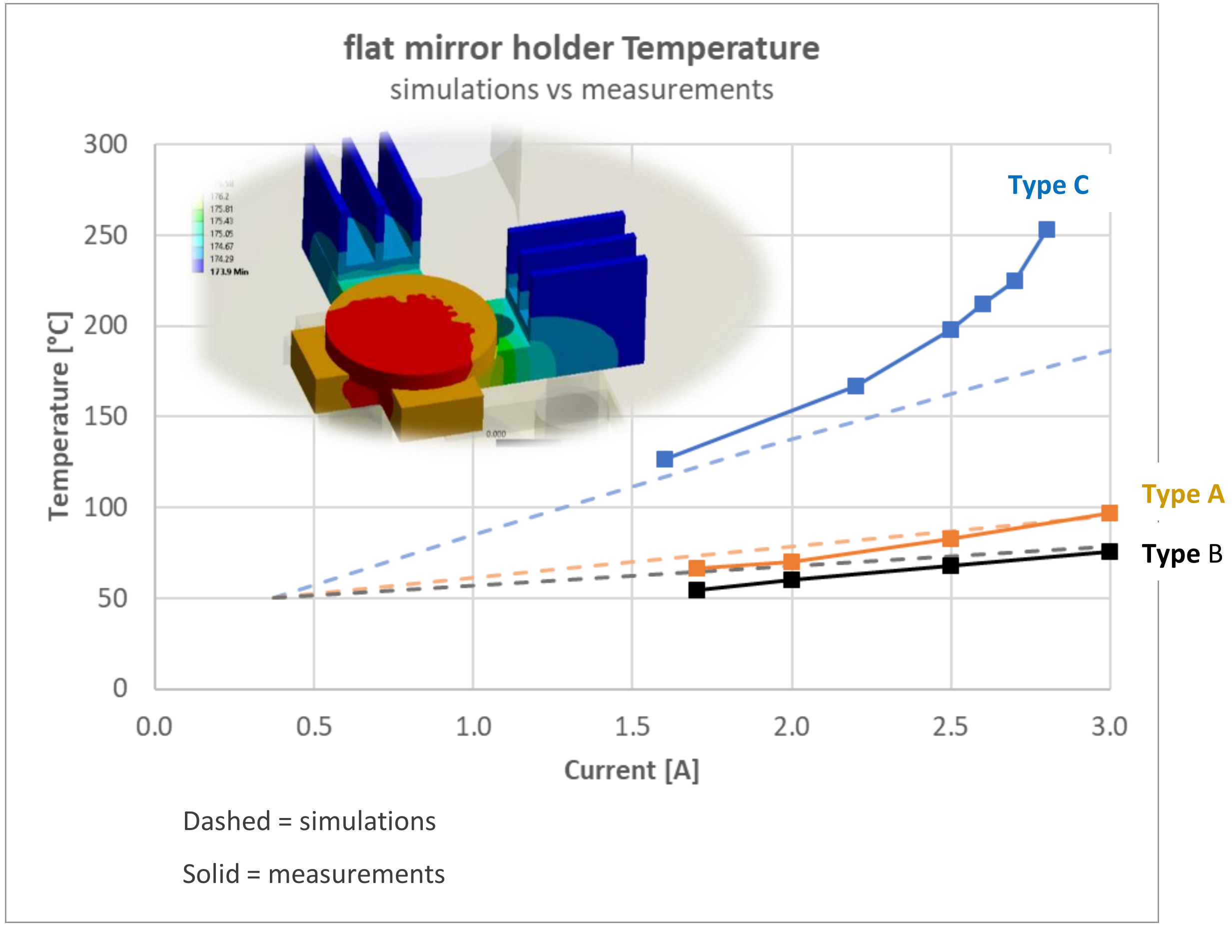
# Virtual Prototyping
## Thermal Management – model validation

- Temperature of Mirror Surface cannot be measured directly
- Temperature of Mirror Holder can be measured
- Good agreement between simulations and measurements for the various mirror types
- Slight difference in T for low current due to assumption of ambient temperature
- Larger difference at high T (Type C) due to mirror deterioration



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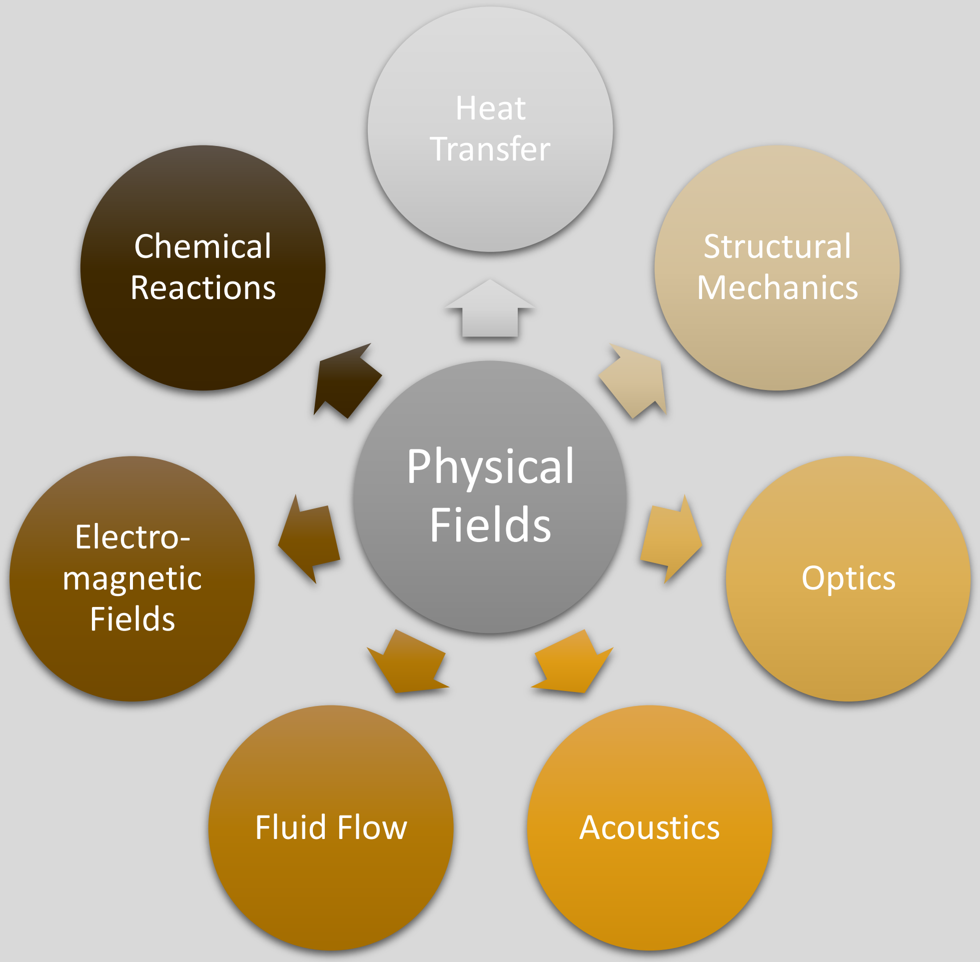
# Multi-Physics

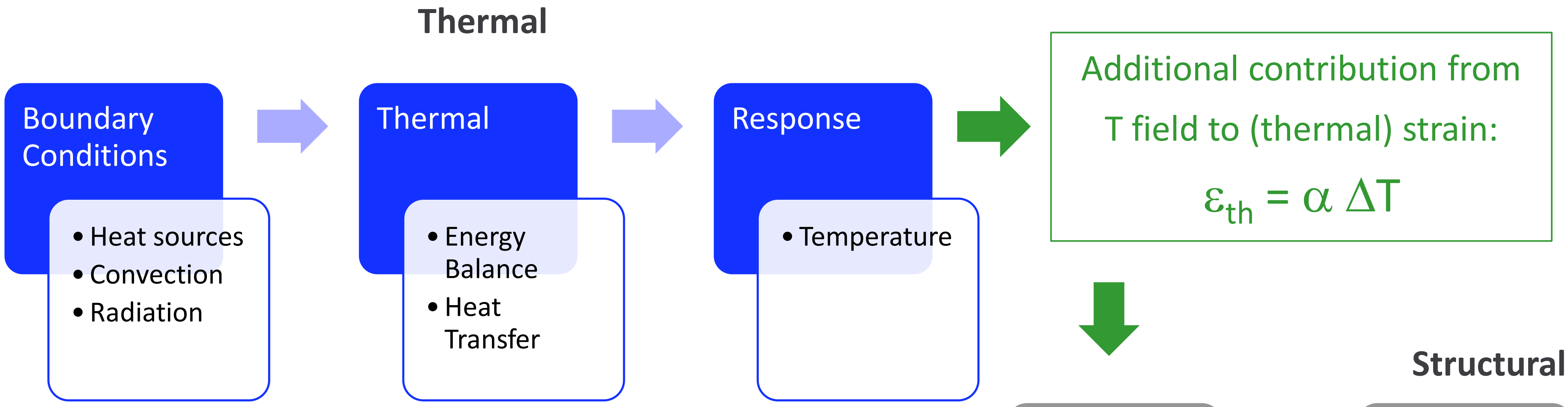
# Multi-physics

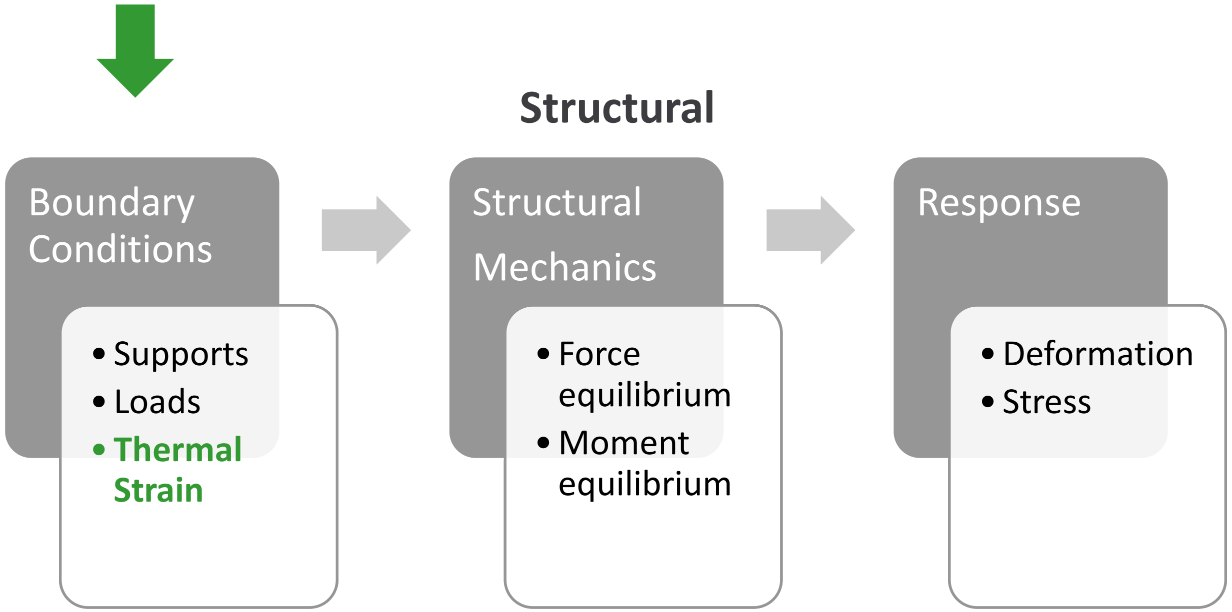
**Multi-physics** is defined as the **coupled processes or systems** involving more than one simultaneously occurring physical fields and the studies of and knowledge about these processes and systems.

... **Multi-physics** is a practice built on mathematics, physics, application, and numerical analysis.



# Types of physics coupling
## Uni-directional

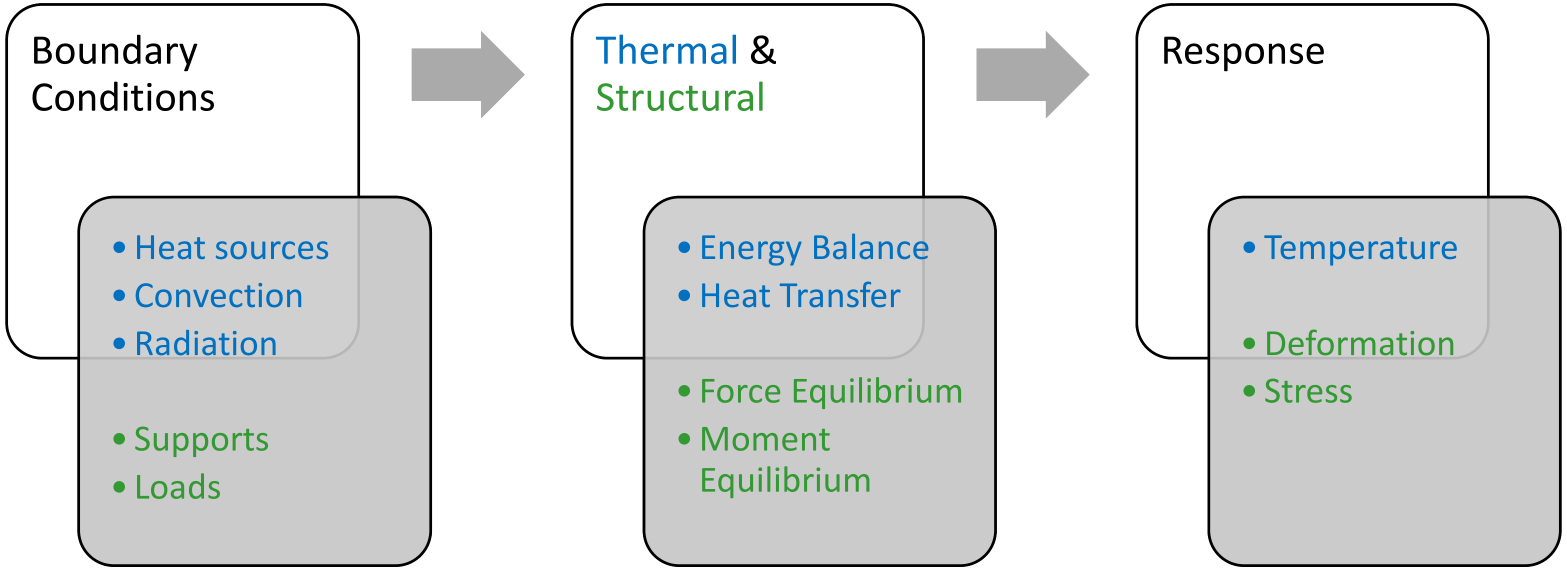



- Solve ***two separate sets*** of governing equations
- Thermal response converted to thermal strain (via expansion coefficient)
- Thermal ***response is used as input*** for structural analysis
- ***One-way coupling***: no impact of deformation on thermal response

# Types of physics coupling
## Bi-directional

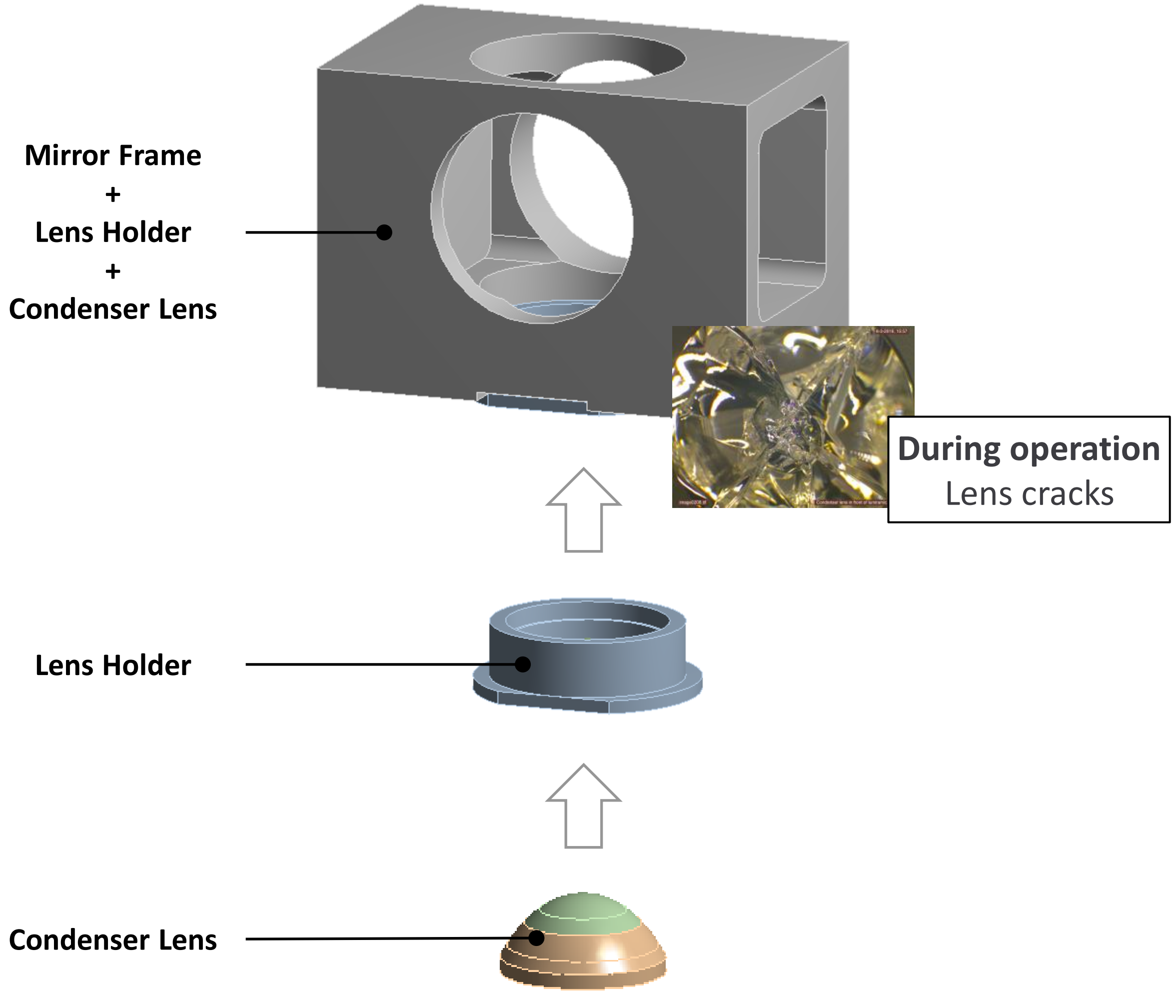
### Thermal & Structural




- Solve ***single set of combined governing equations*** simultaneously
- ***Bi-directional coupling***:
  - Temperature has impact on deformation response
  - Deformations have (possible) impact on thermal response

# Multi-physics
## Thermal-Structural example

- During operating conditions of the light source the Condenser Lens that has been mounted in the mirror frame cracks.
- By observation the cracks are believed to originate from the center of the lens, but this is not 100% sure.
- The lens is heated by the light bundle that passes through the center of the lens (see next slide).





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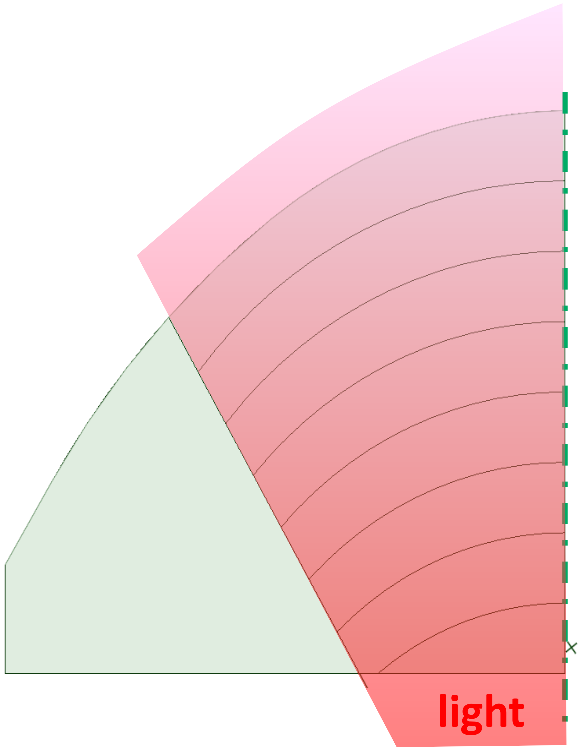
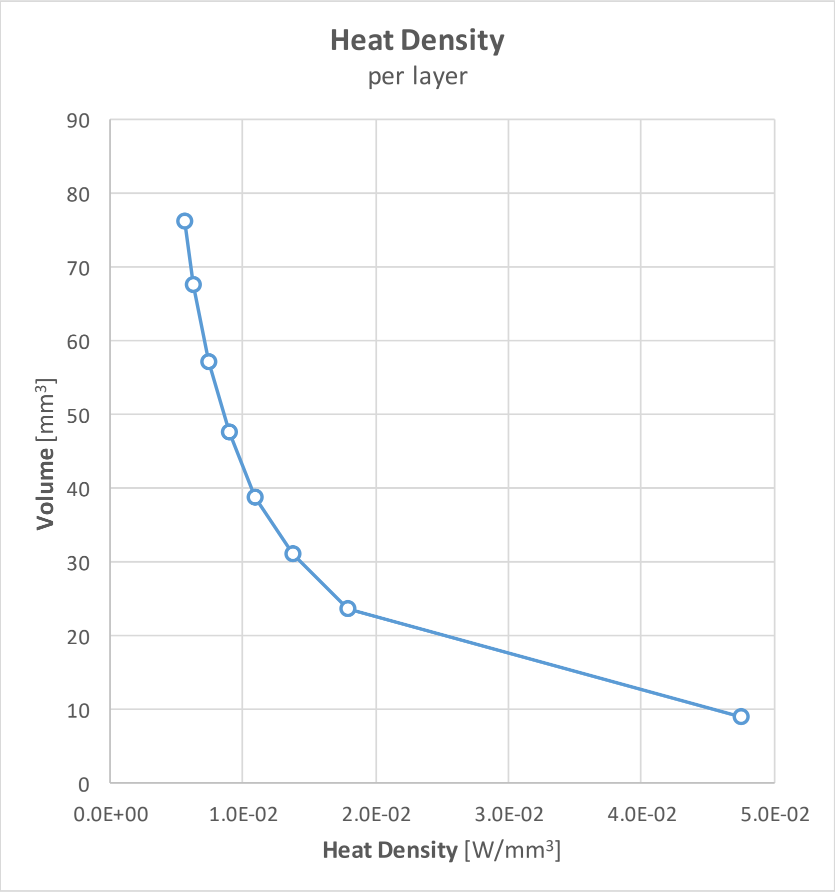
# Multi-physics

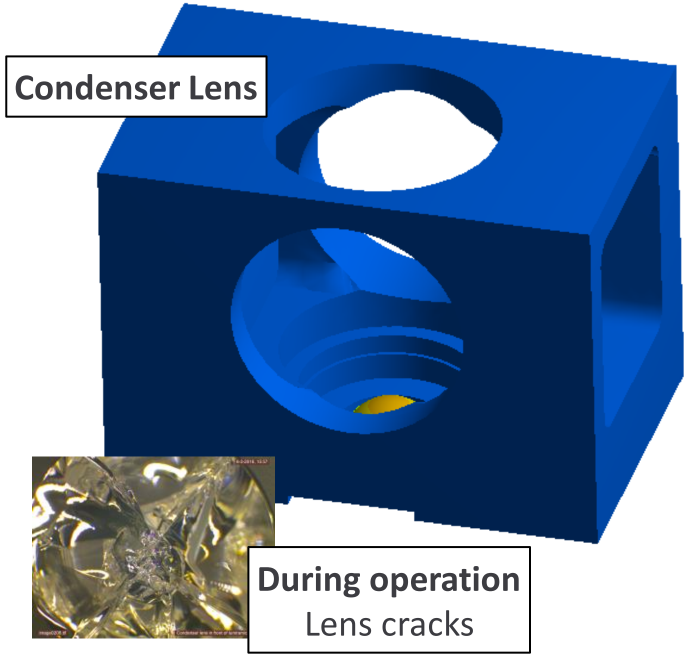
## Thermal-Structural example

- The light bundle travels through the red colored region
- In each curved section an equal amount of heat is generated
- The heat density increases towards the bottom (center) of the lens
- No heat is generated in the outer (rim) section of the lens

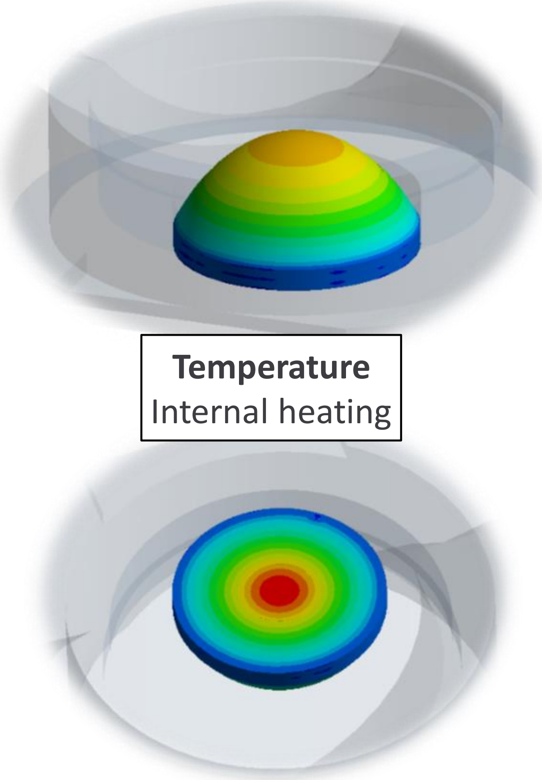


# Multi-physics
## Thermal-Structural example

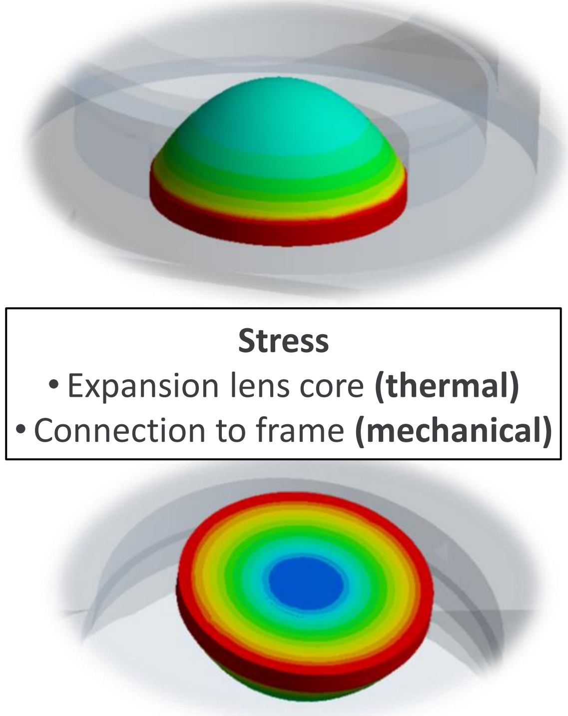



### THERMAL




- Thermal conduction only via outer rim (blue area)
- Additional cooling lowers the T but not the T gradient in the lens (crack risk remains)

### STRUCTURAL

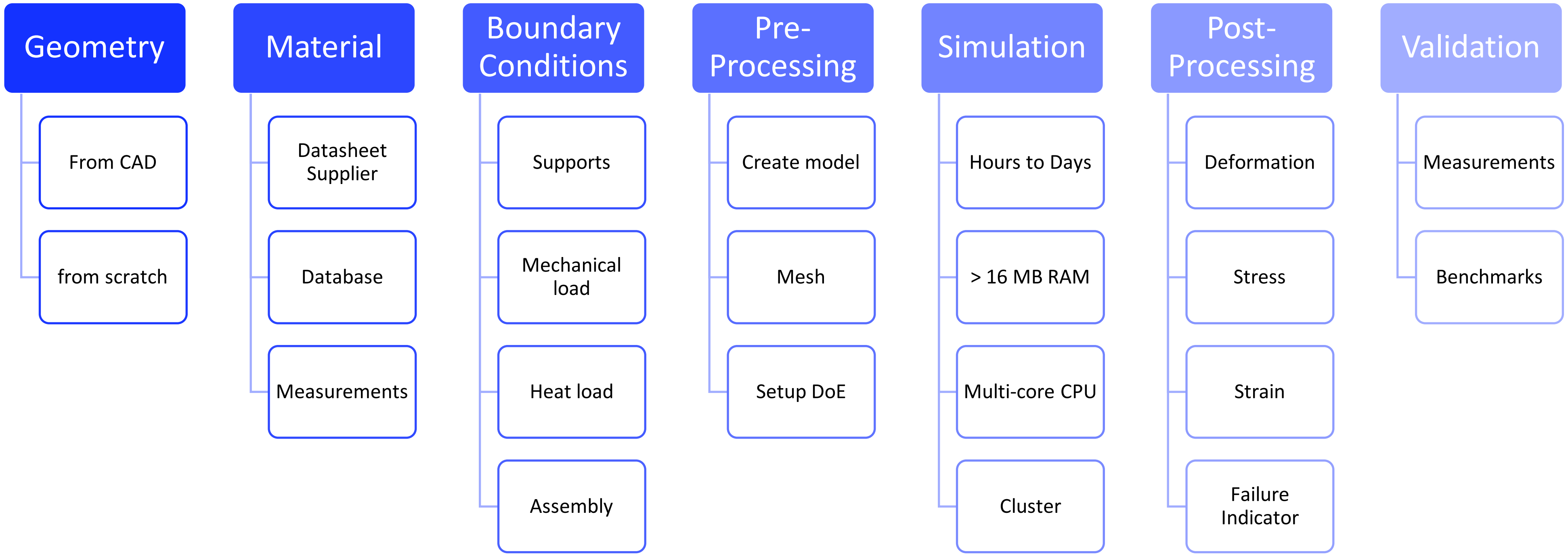



- Additional (mechanical) stress via Lens Holder / Lens connection
- DoE performed for lens holder material & lens holder connection (max stress below critical level)

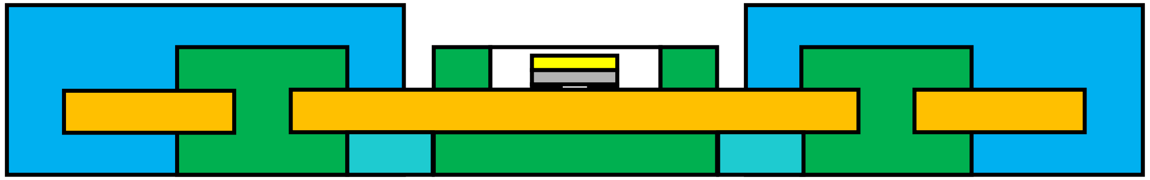
# Detailed model setup

# Model Setup

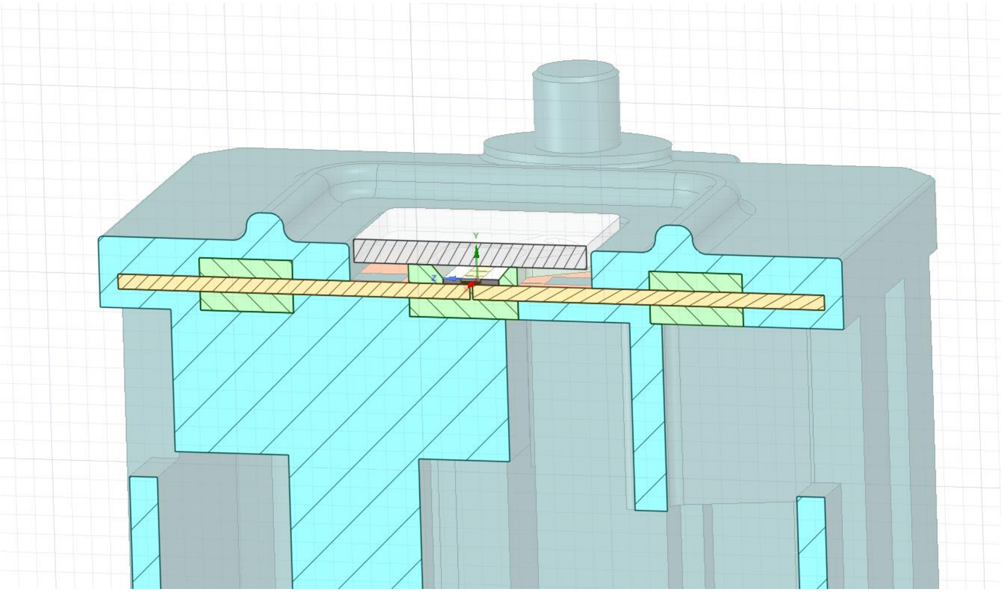
## WLP on Lead Frame

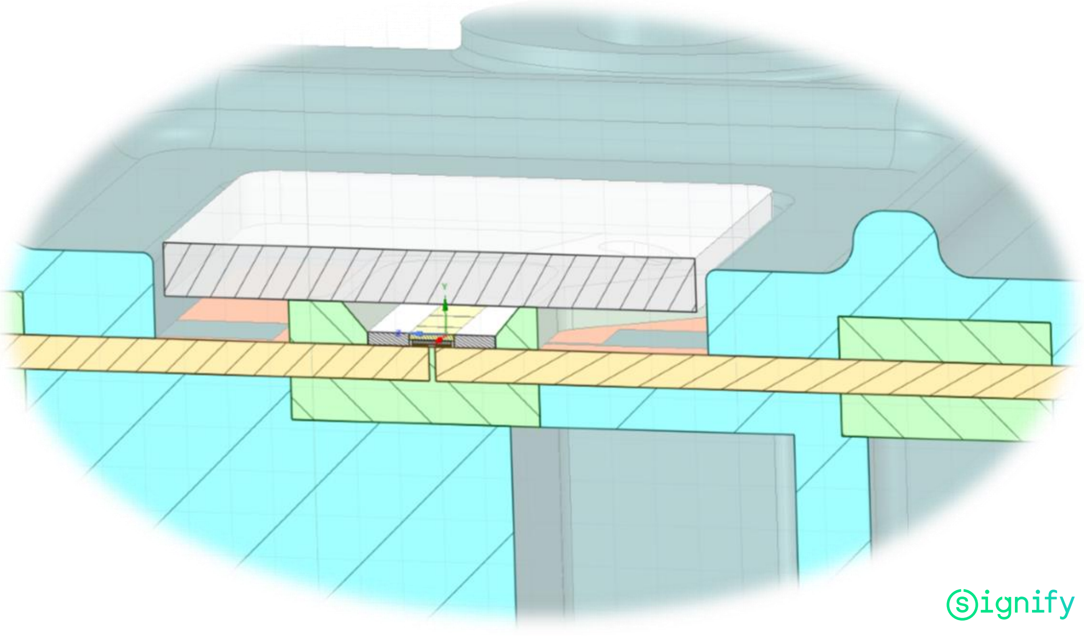


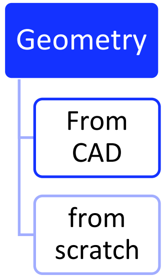
# Model Setup – Geometry
## WLP on Lead Frame



- 2D geometry created from scratch based on available CAD data
- 2D model geometry of Wafer Level Package (WLP) on Leadframe (LF, orange)
- Plastic Window (green, to connect and align LF parts)
- Overmould (blue) to define the optical window



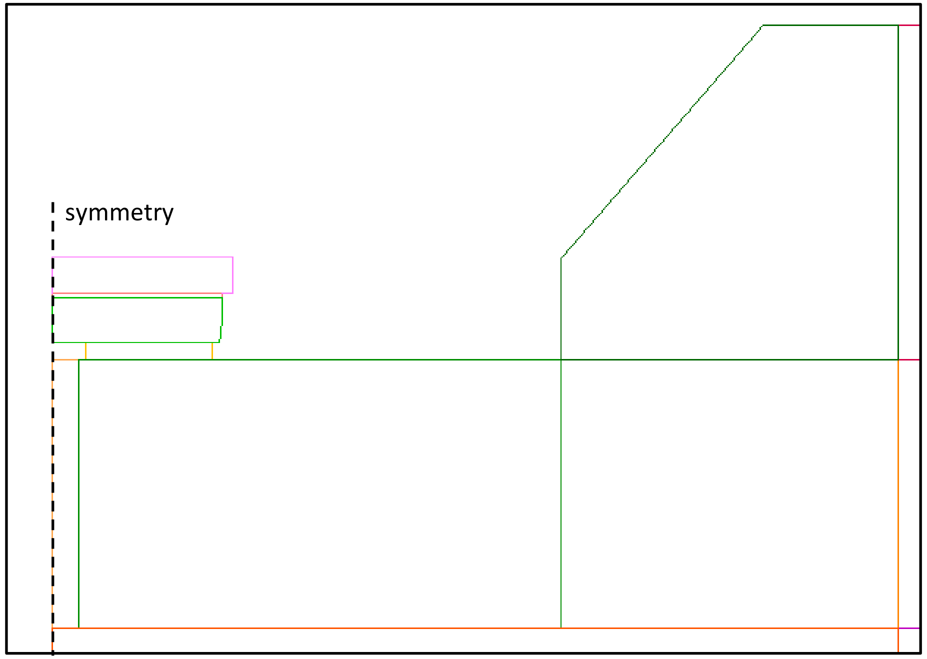





**Purpose**
Impact of WLP on LF substrate compared to standard Al-IMS L2 board

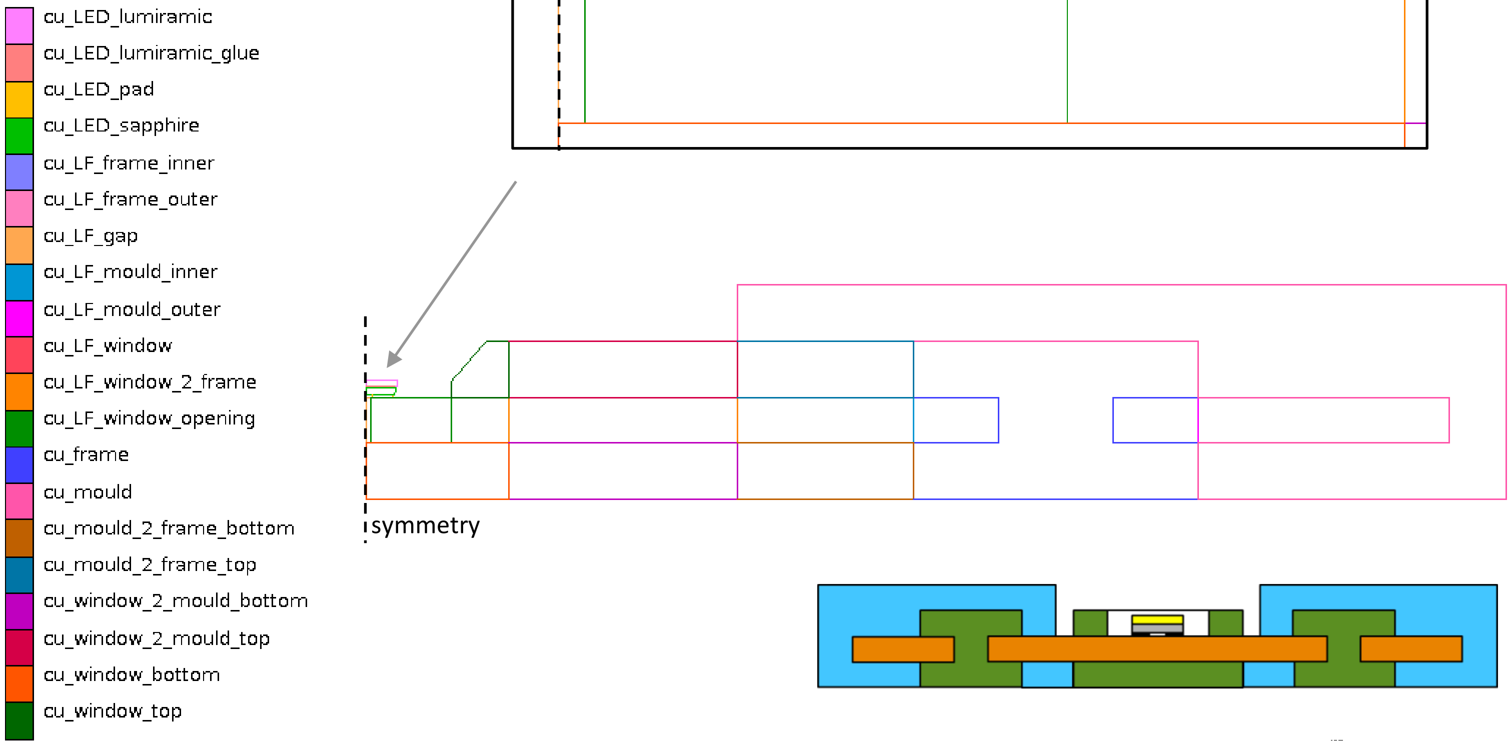
# Model Setup – Geometry
## WLP on Lead Frame






### 2D model geometry

- 2D parametric geometry
- Only half of the model is created (symmetry)



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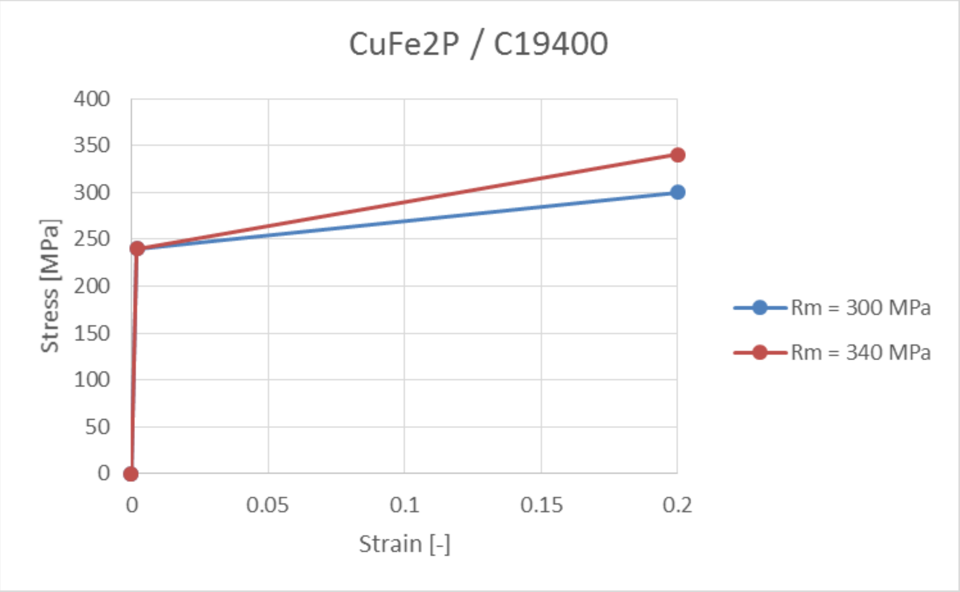
# Model Setup - Materials

## WLP on Lead Frame

Material
- Datasheet Supplier
- Database
- Measurements

| Property | Symbol | Value | Unit | Source |
|---|---|---|---|---|
| Young's Modulus | E | 123 | [GPa] | datasheet Wieland |
| Poisson's ratio | ν | 0.34 | [-] | datasheet Wieland |
| Coefficient of Thermal Expansion | CTE | 17.6 | [ppm / °C] | from 0 °C to 300 °C datasheet Wieland |
| Tensile Strength | $R_m$ | 300 - 340 | [MPa] | temper R300 / O60 datasheet Wieland |
| Yield Strength | $R_{p0.2}$ | ≤ 240 | [MPa] | temper R300 datasheet Wieland |
| Elongation | $A_{50mm}$ | ≥ 20 | [%] | temper R300 datasheet Wieland |
| Hardening modulus | h | 304 - 507 | [MPa] | calculated |




**LF material**

Mechanical properties

from supplier datasheet



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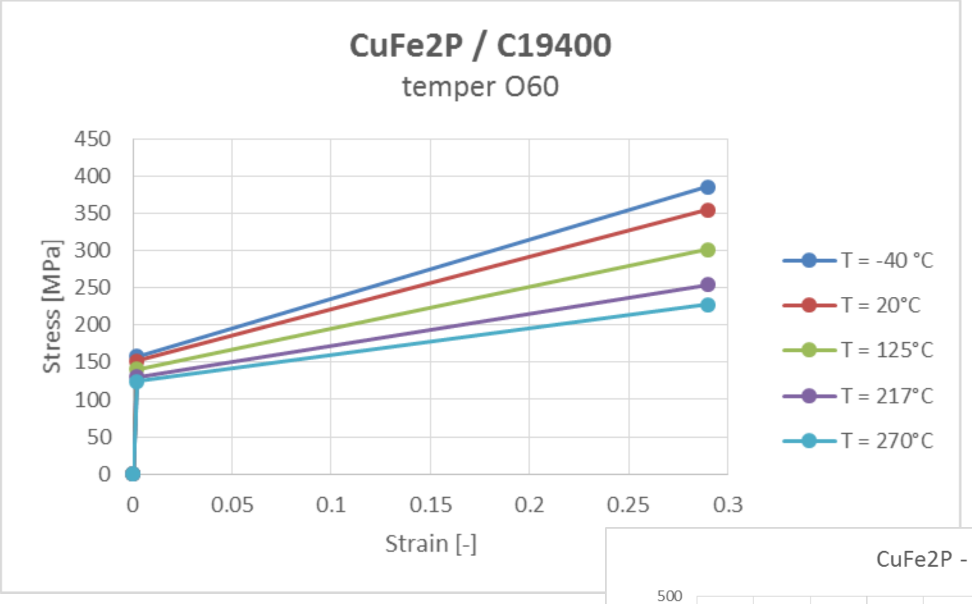
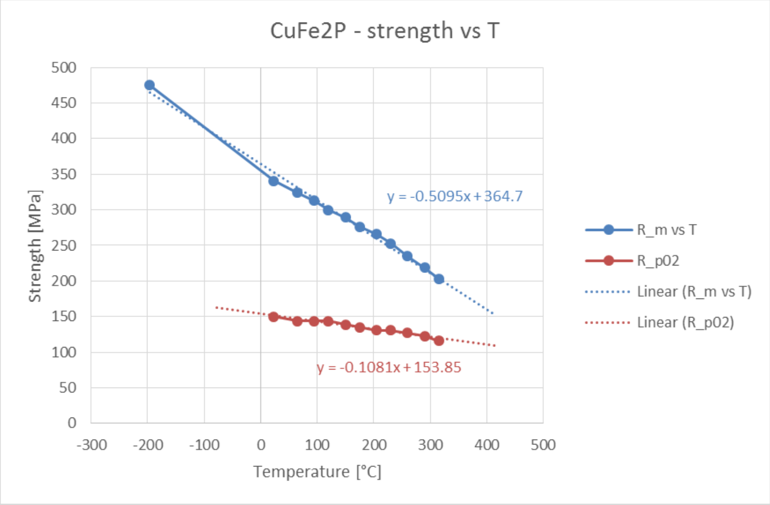
# Model Setup - Materials
## WLP on Lead Frame




Material
- Datasheet Supplier
- Database
- Measurements

**LF material**

T-dependent mechanical properties & strength

from Matweb database



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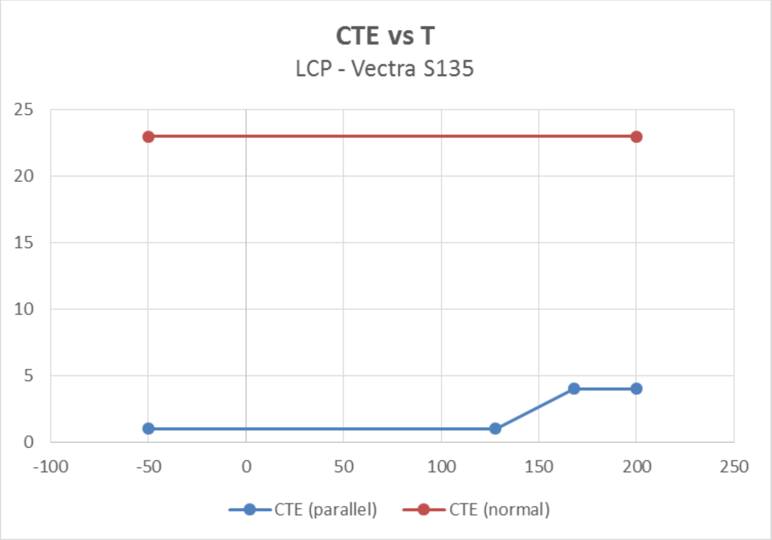
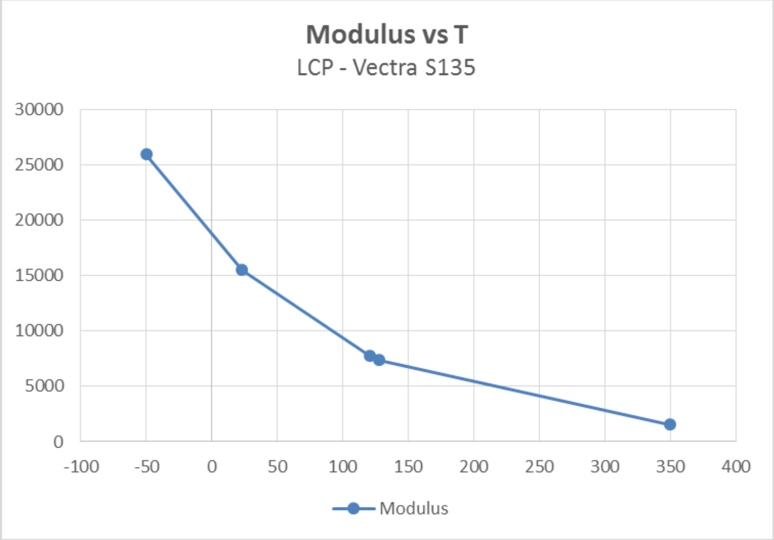
# Model Setup - Materials
## WLP on Lead Frame

Material
- Datasheet Supplier
- Database
- Measurements




| Temperature | CTE (parallel) | CTE (normal) | |
|---|---|---|---|
| -50 | 1 | 23 | |
| 88 | | | |
| 128 | 1 | | |
| 168 | 4 | | |
| 200 | 4 | 23 | |

| | Temperature | Modulus |
|---|---|---|
| | -50 | 25976 |
| | 23 | 15500 |
| HMT | 121 | 7750 |
| Tg | 128 | 7376 |
| Tmelt | 350 | 1534 |

**Plastic Frame**

T-dependent mechanical properties

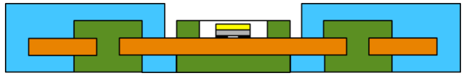
from DMA / TMA measurements



Signify

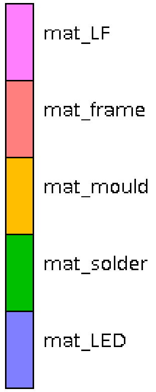
# Model Setup - Mesh
## WLP on Lead Frame

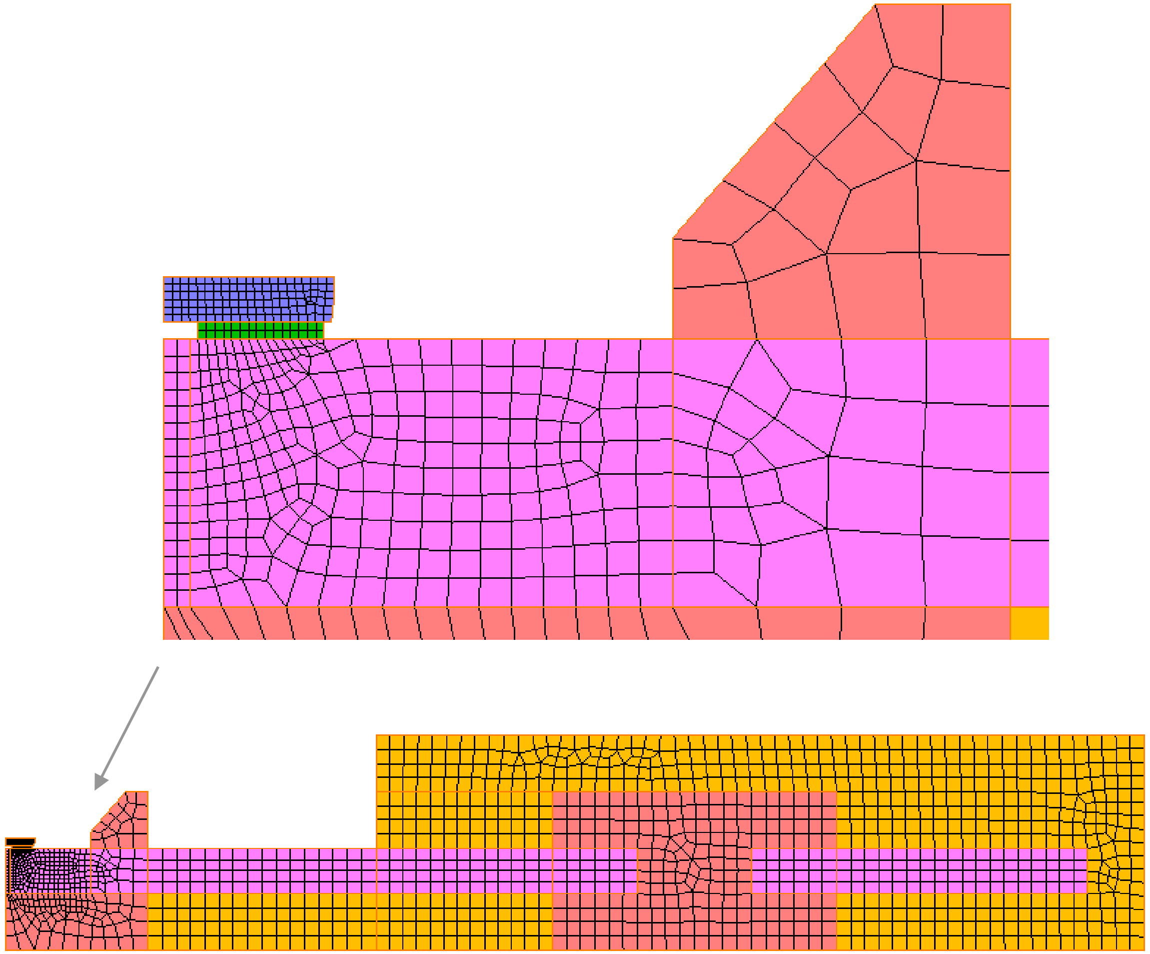




### 2D mesh

- Discretization of geometry into 2D elements (for numerical solution)
- Material assignment per region





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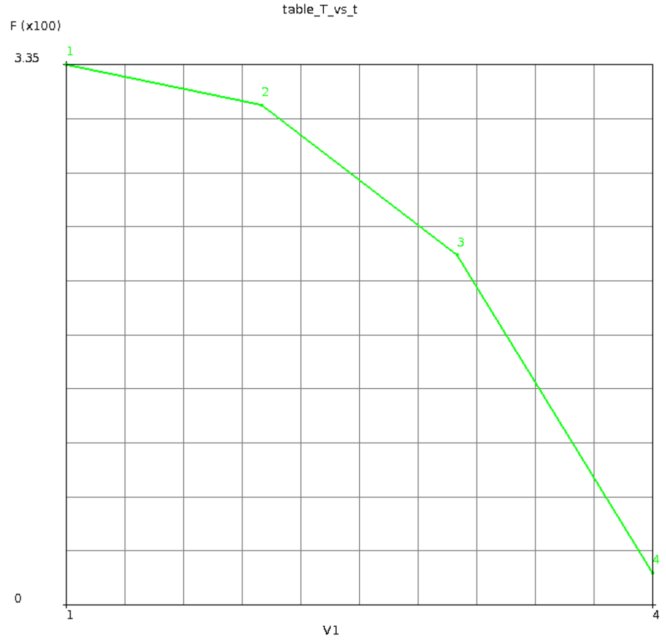
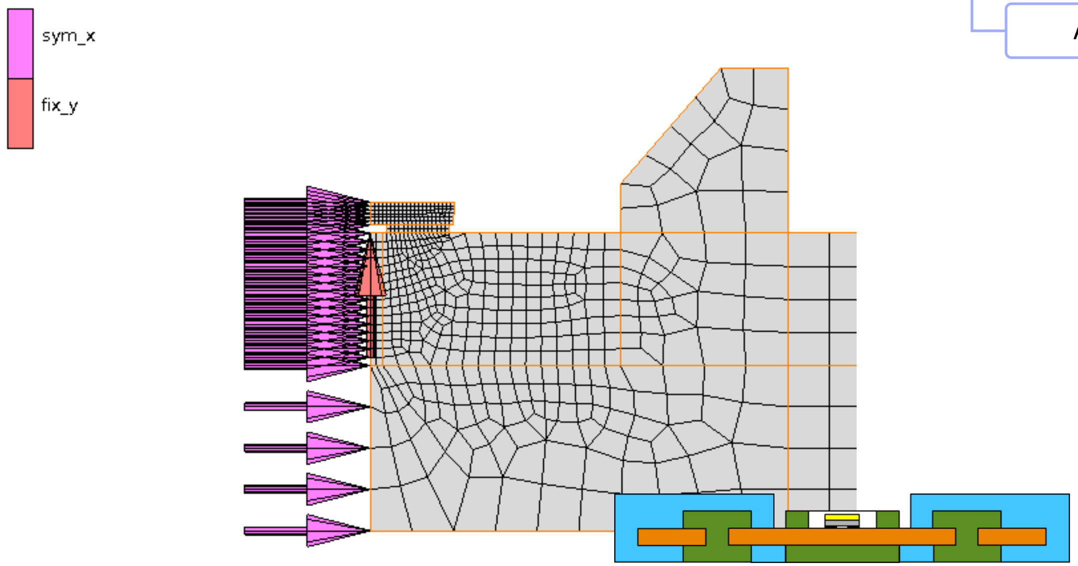
# Model Setup – Boundary Conditions
## WLP on Lead Frame






**Thermal BC**

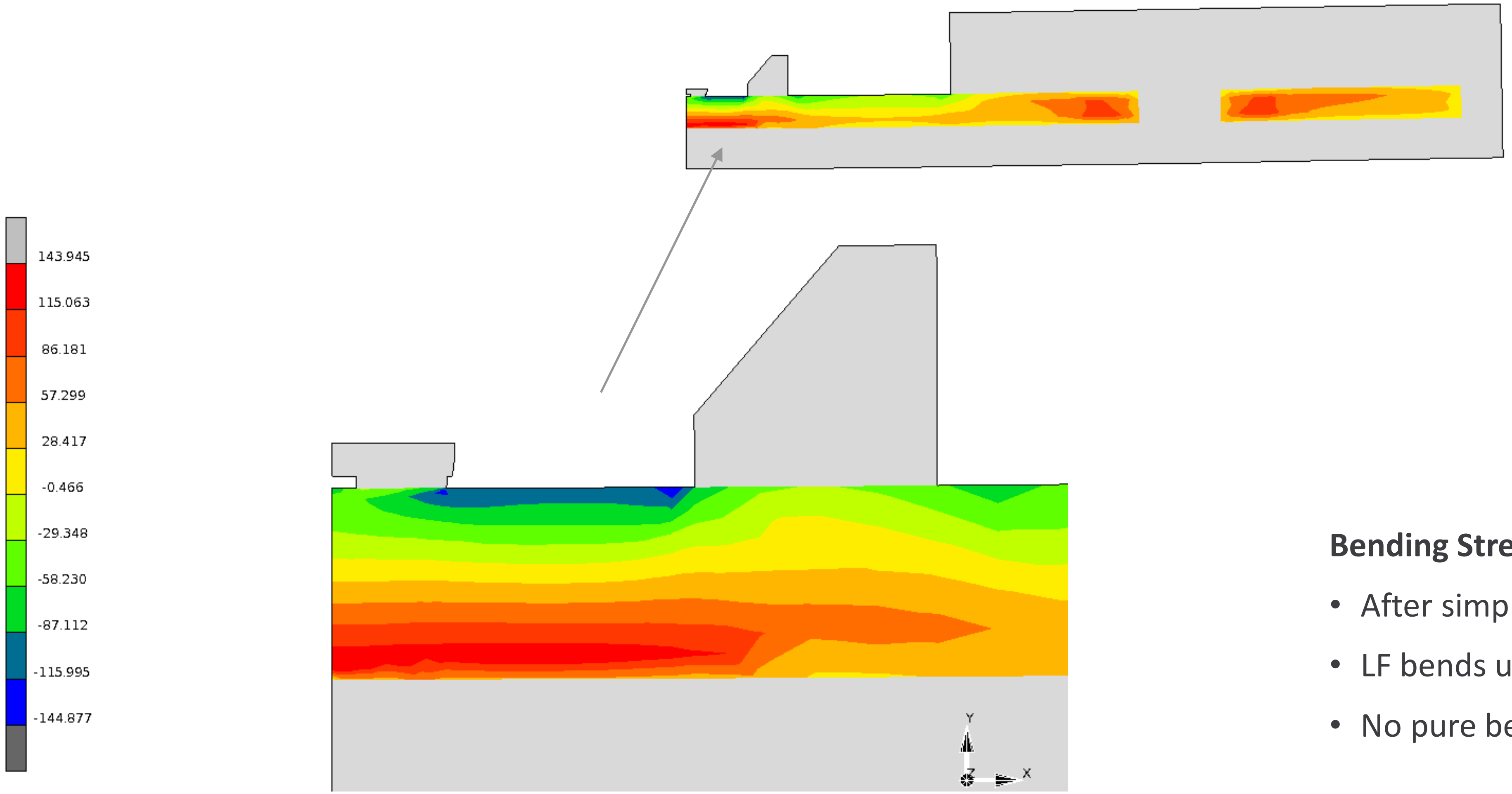
- Simple Cooldown from T solder, T frame, T overmould to RT
- Will be replaced by extended cooldown (incl. assy)

**Structural BC**

- Symmetry plane
- Fix z-coordinate at top LF
- Perfect adhesion between all materials

# Model Setup – Post-Processing
## WLP on Lead Frame

Post-Processing
- Deformation
- Stress
- Strain
- Failure Indicator




**Bending Stress in LF**

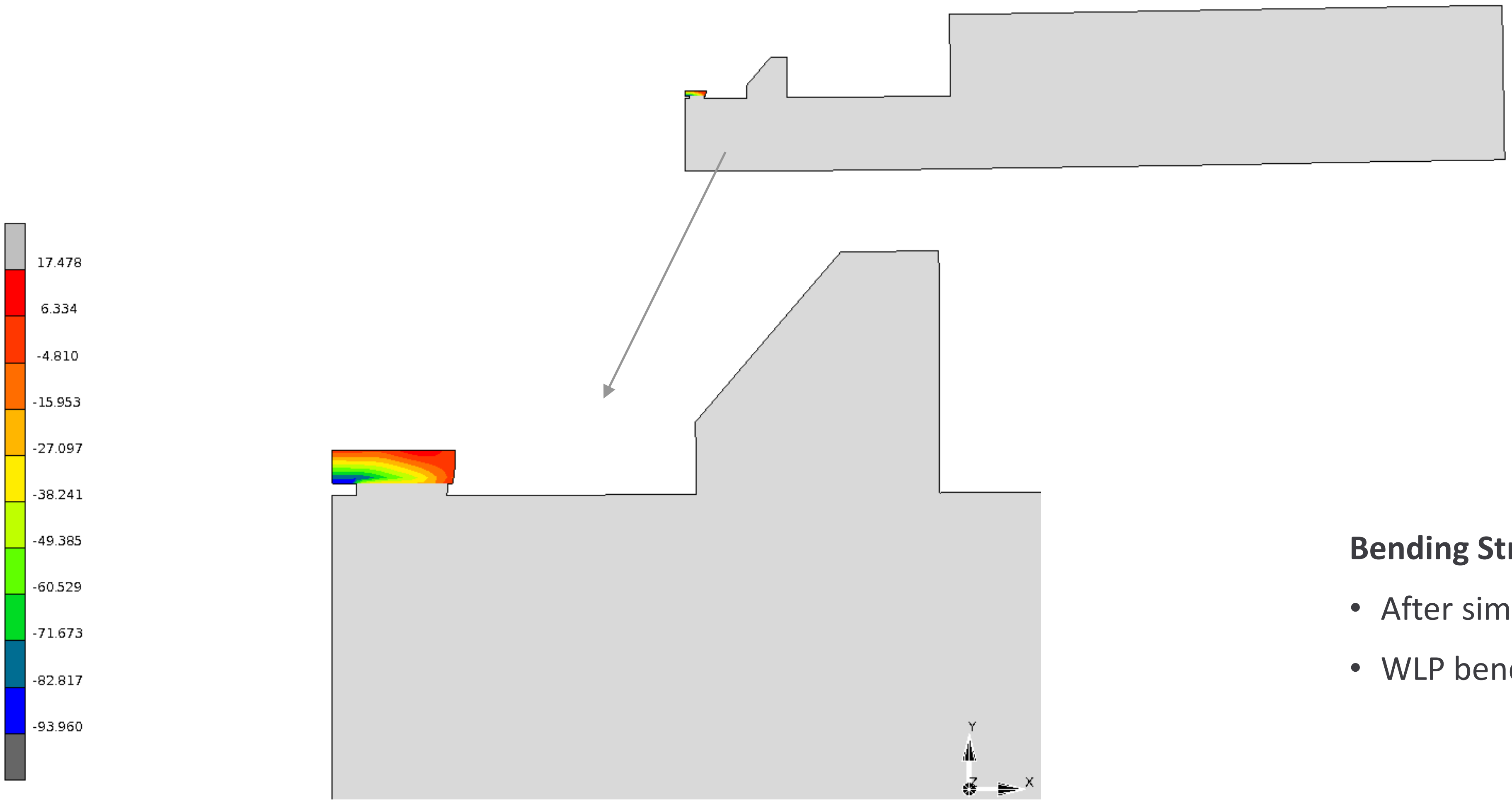
- After simple cooldown
- LF bends upwards (tensile at bottom)
- No pure bending at sides (frame)



Signify

# Model Setup – Post-Processing
## WLP on Lead Frame





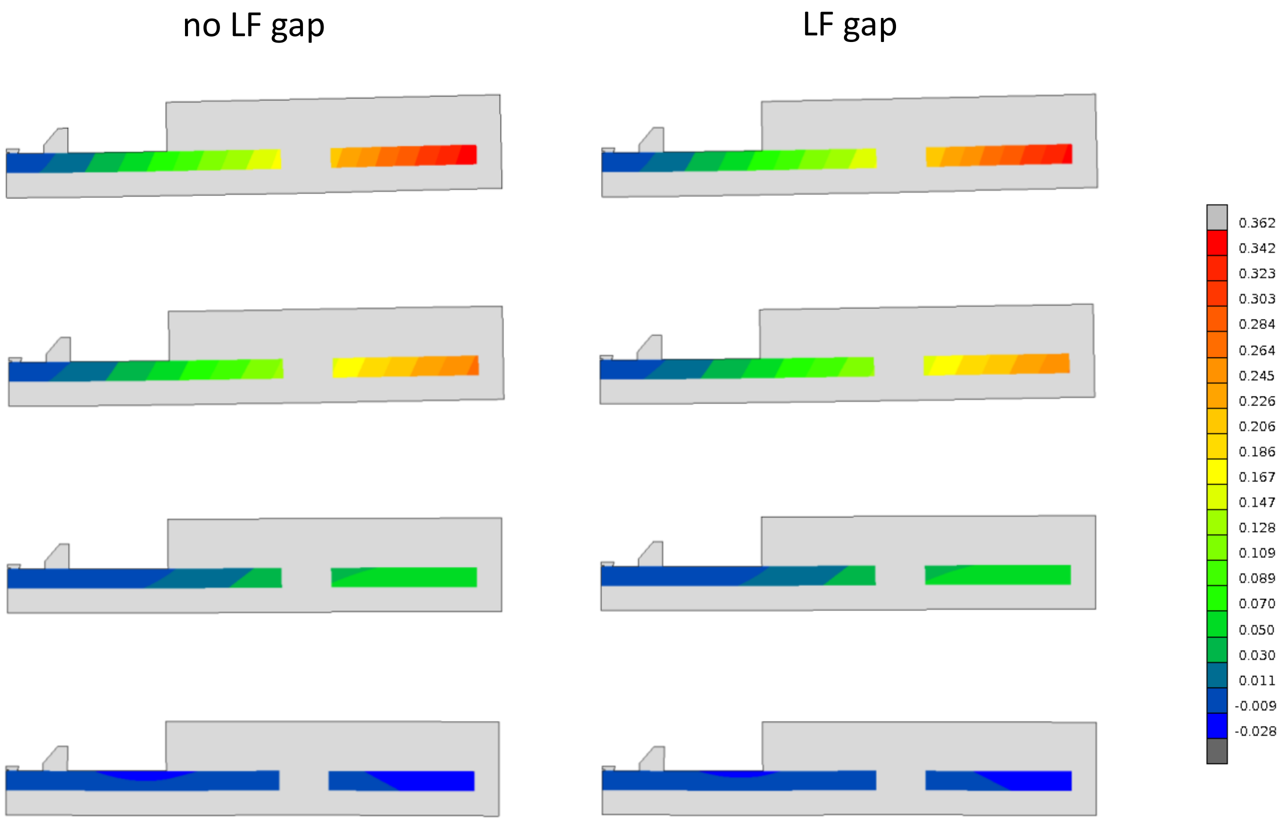

**Bending Stress in WLP**

- After simple cooldown
- WLP bends downwards (tensile at top)

Post-Processing
- Deformation
- Stress
- Strain
- Failure Indicator

# Model Setup – DoE
## WLP on Lead Frame

| CTE [ppm/°C] | E [GPa] | Frame |
|---|---|---|
| 1 | 15.5 | Type A ∥ |
| 6 | 13.8 | Type B ∥ |
| 18 | 13.8 | Type B ⊥ |
| 23 | 15.5 | Type A ⊥ |




**Vertical LF deformation**

- After simple cooldown
- Impact of modulus, CTE & orientation



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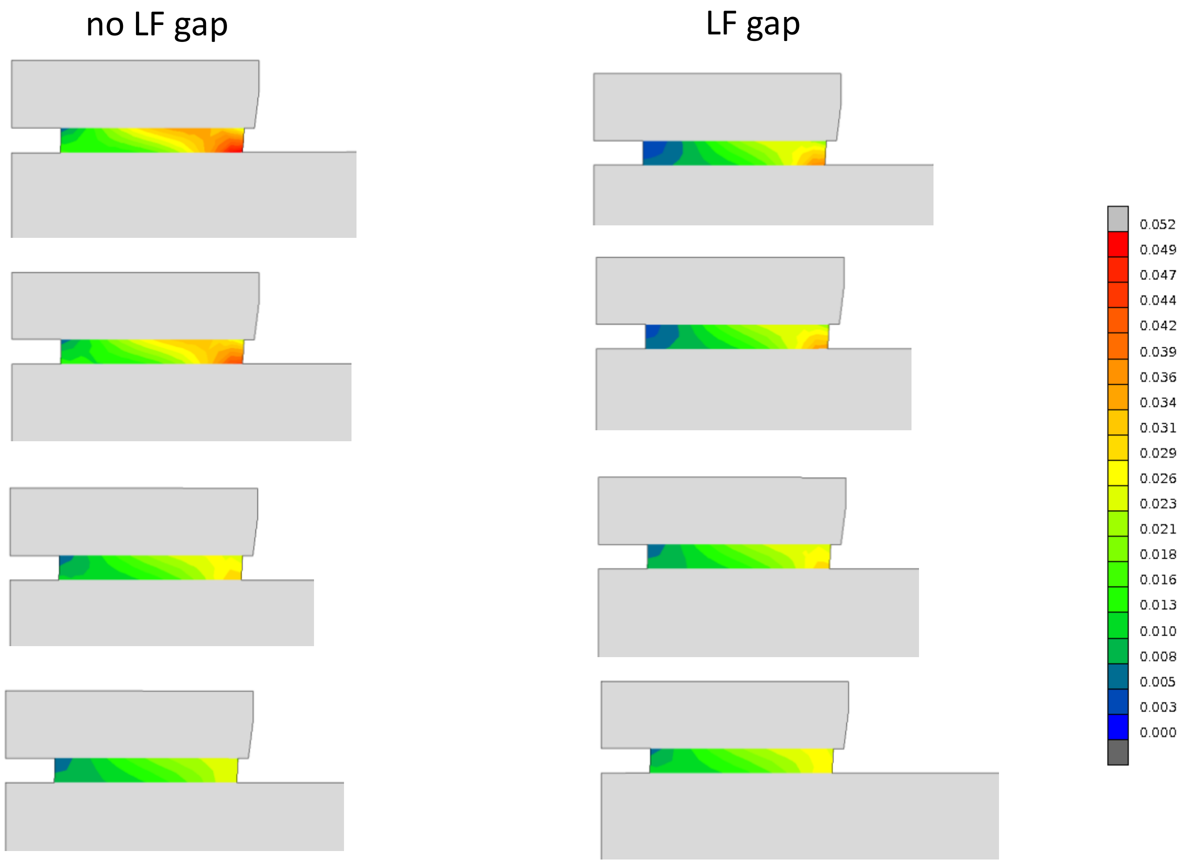
# Model Setup – DoE
## WLP on Lead Frame

Post-Processing
- Deformation
- Stress
- Strain
- Failure Indicator

| CTE [ppm/°C] | E [GPa] | LCP |
|---|---|---|
| 1 | 15.5 | Type A ∥ |
| 6 | 13.8 | Type B ∥ |
| 18 | 13.8 | Type B ⊥ |
| 23 | 15.5 | Type A ⊥ |




**Solder strain**

- After simple cooldown
- Impact of modulus, CTE & orientation



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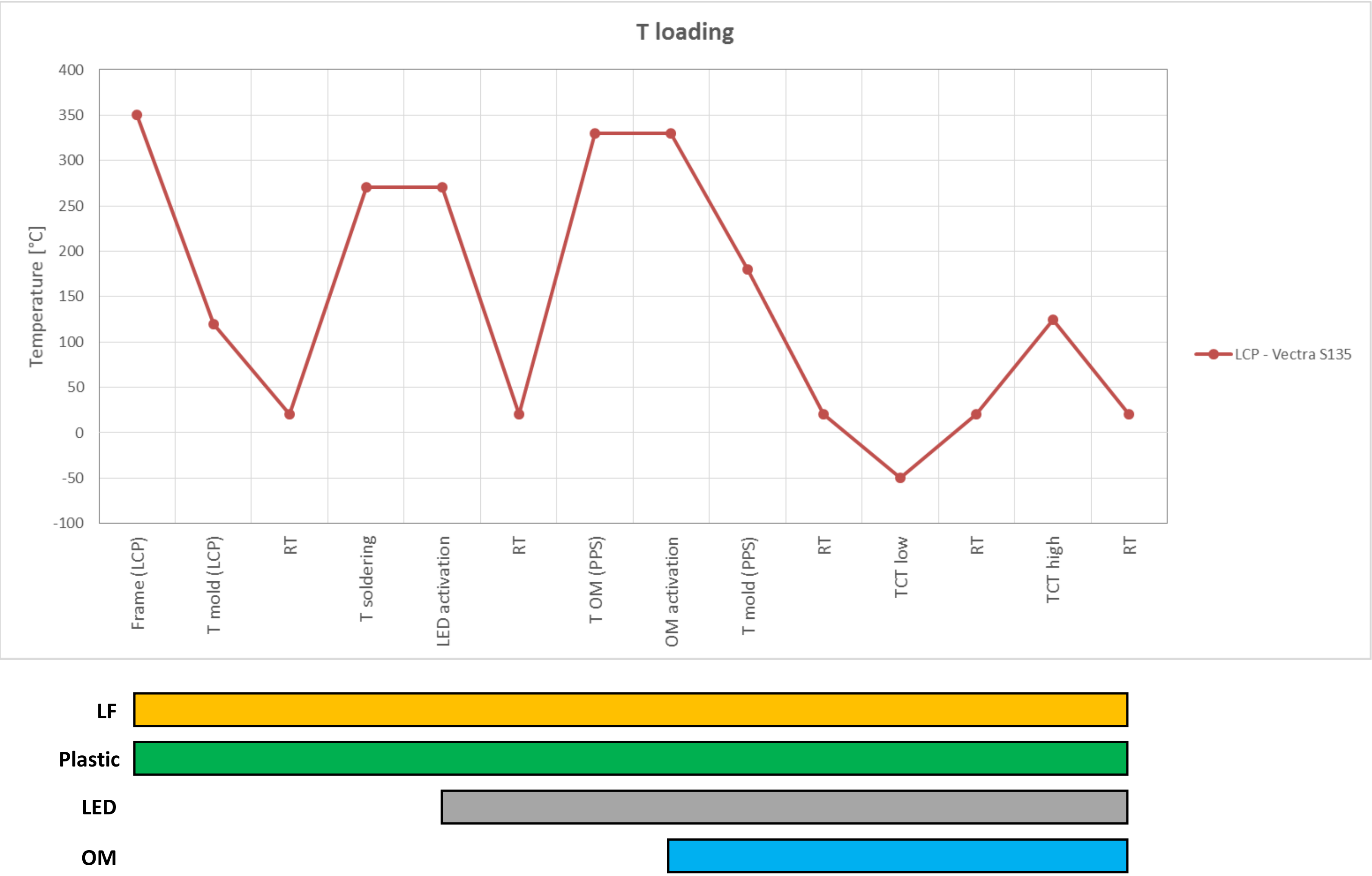
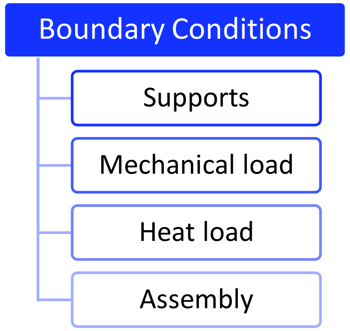
# Model Setup – Boundary Conditions (cont'd)

## WLP on Lead Frame



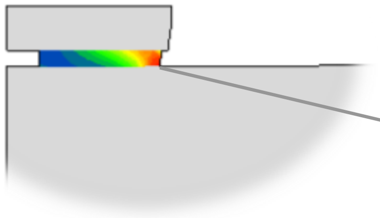

**Assy & operating conditions**

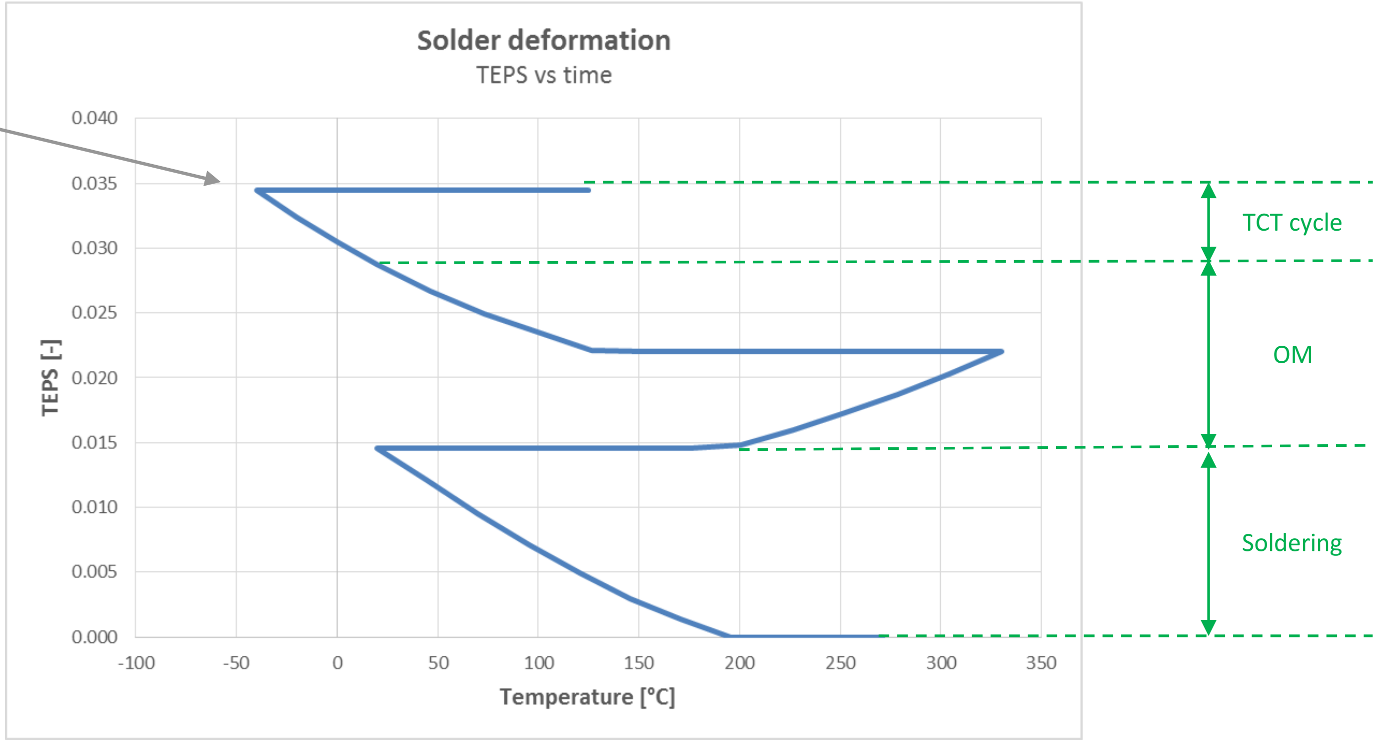
- Molding
- Soldering
- TCT (cycles)
- Assembly (part activation)

# Model Setup – failure indicator
## WLP on Lead Frame



The curve depicts the (max) total equivalent plastic as a function of the T during assembly & TCT.

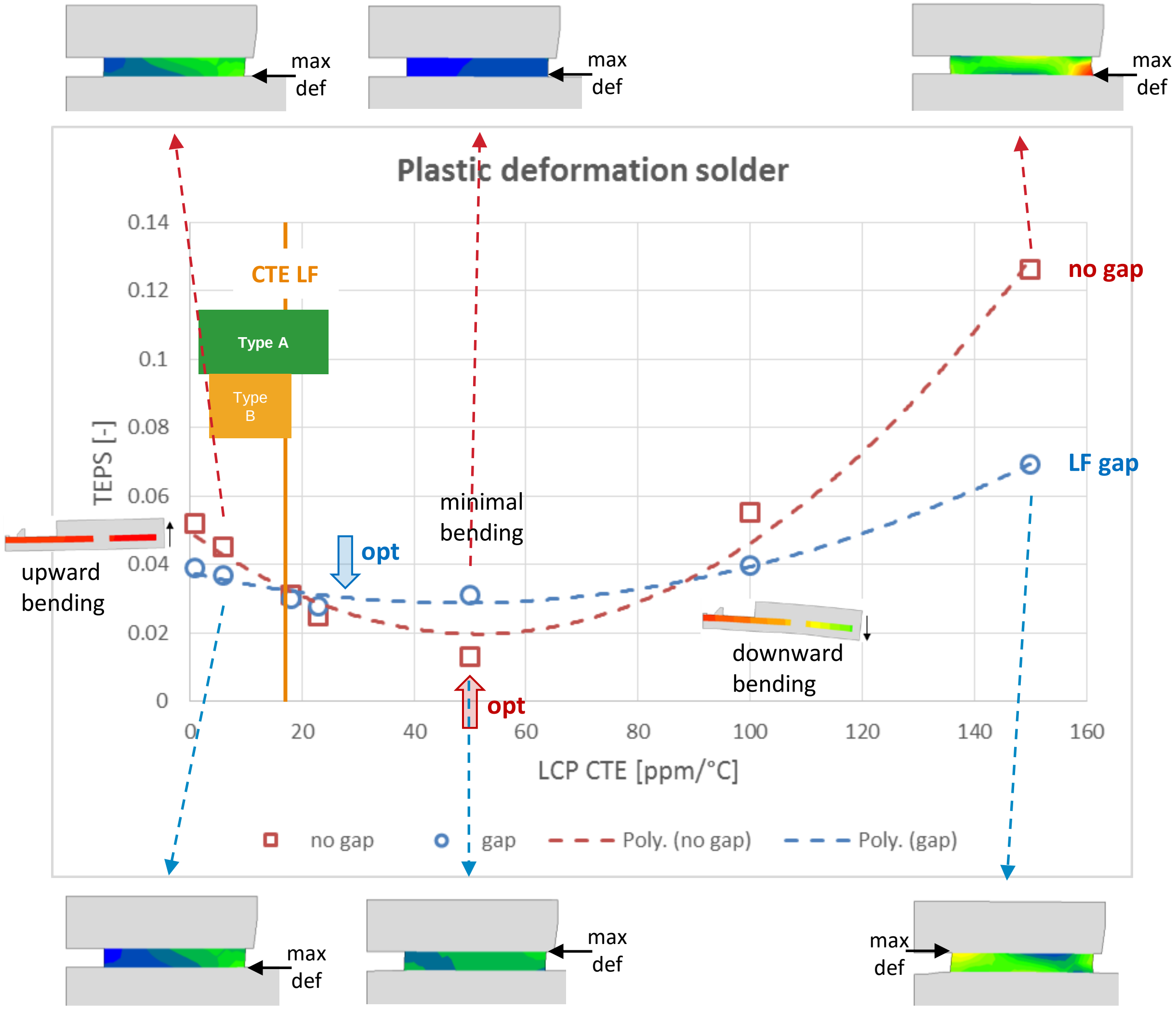


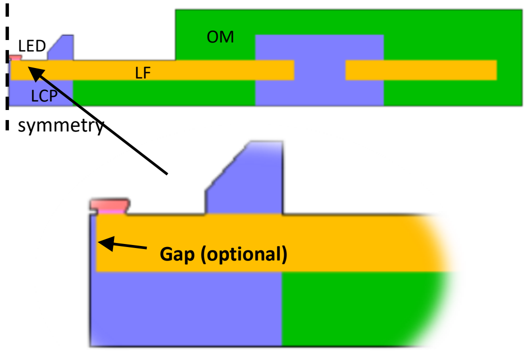



### Failure Indicator

- Solder strain
- Increase of strain during additional TCT cycles
- Used for solder lifetime predictions

# Model Setup – failure indicator DoE
## WLP on Lead Frame




Post-Processing
- Deformation
- Stress
- Strain
- Failure Indicator

**Failure Indicator DoE**

- Solder Strain as function of CTE plastic frame
- Optimal design depends on single-piece vs partitioned LF
- For current plastic and OM materials partitioned LF is optimal
- High CTE plastic frame can be beneficial for solder lifetime



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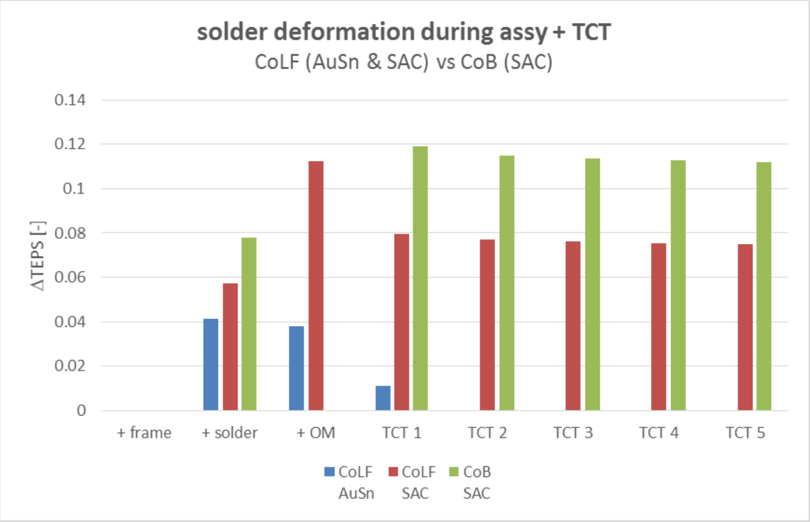
# Model Setup – failure indicators
## WLP on Lead Frame

**Solder deformation – LF vs IMS board**



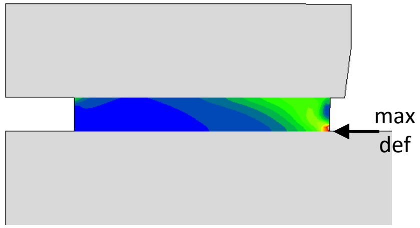

**CSP on LF (AuSn)**
lowest solder strain during assy + TCT

**CSP on LF (SAC)**
**compared to AuSn** high solder strain
**Compared to IMS board** high solder strain during OM, low solder strain during TCT

**CSP on Board (SAC)**
**compared to LF** lower solder strain during assy, higher solder strain during TCT

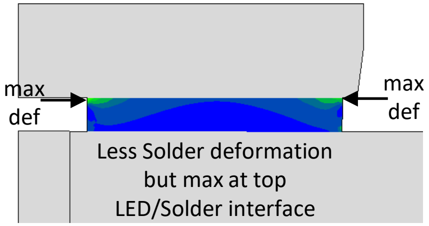
**Plastic to LF adhesion**

Solder has to compensate for CTE mismatch between LED/LF/LCP/OM




perfect adhesion

Solder has to compensate for CTE mismatch between LED/LF only

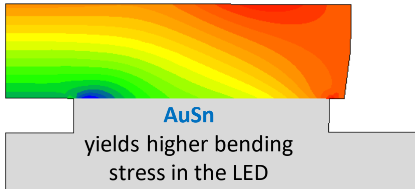



no adhesion

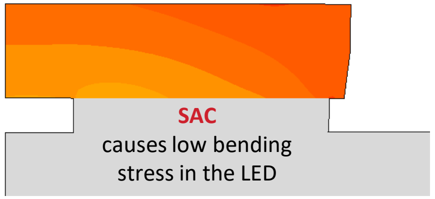
**Favorable**
No adhesion yields lower deformation levels in the solder.

**Unfavorable**
Only load-carrying capacity via the CSP solder pads -> very sensitive to external loads / deformation!

**LED stress vs solder type**




**4x SAC (tensile)**
**5x SAC (compressive)**




**AuSn** has higher modulus and higher yield strength compared to **SAC**

**Post-Processing**
- Deformation
- Stress
- Strain
- Failure Indicator



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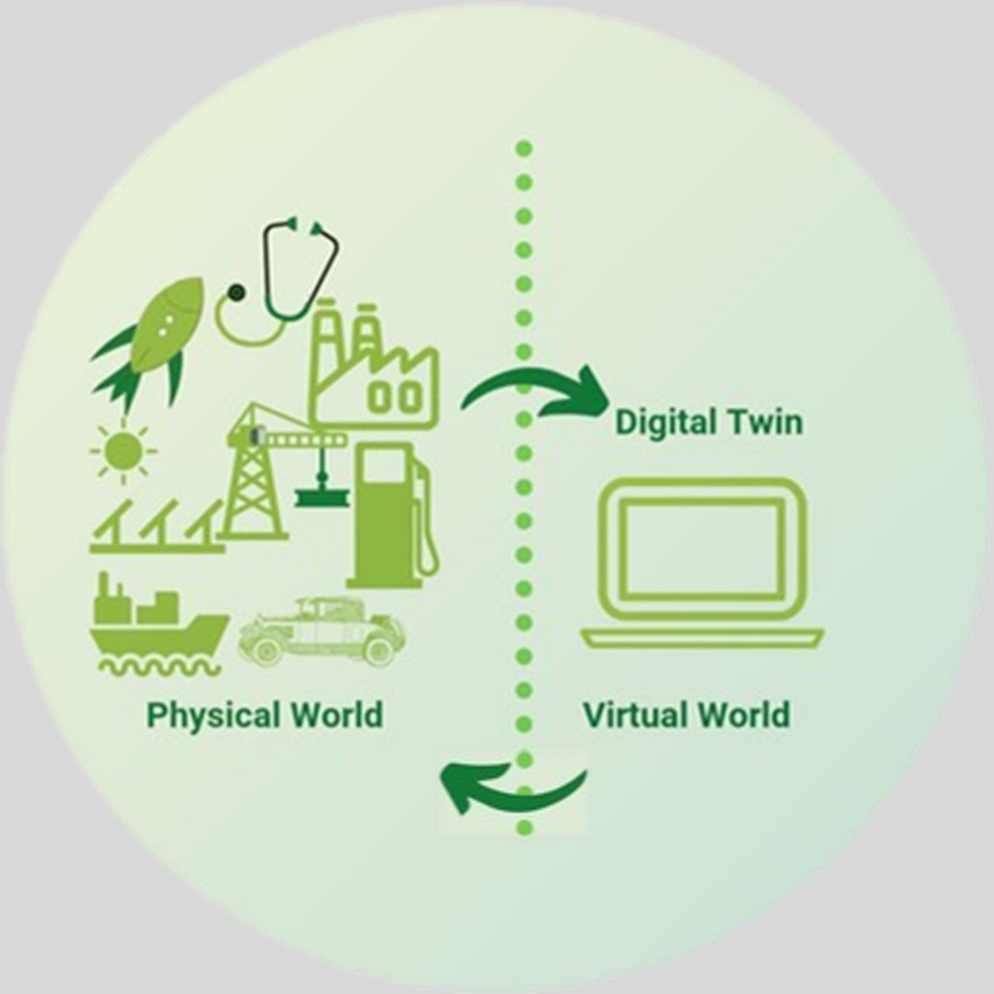
# Towards a Digital Twin

# Digital Twin

A **digital twin** is a virtual representation of a physical entity or system.

A digital twin is much more than a picture, blueprint or schematic: It is a dynamic, simulated view of a physical product that is **continuously updated** throughout the design, build and operation lifecycle, and exists in parallel to its corresponding physical object.

Digital twins can provide customer and equipment insights, improve quality and reliability, monitor performance, and mitigate downtime and increase availability.




[ESI 2019 symposium]



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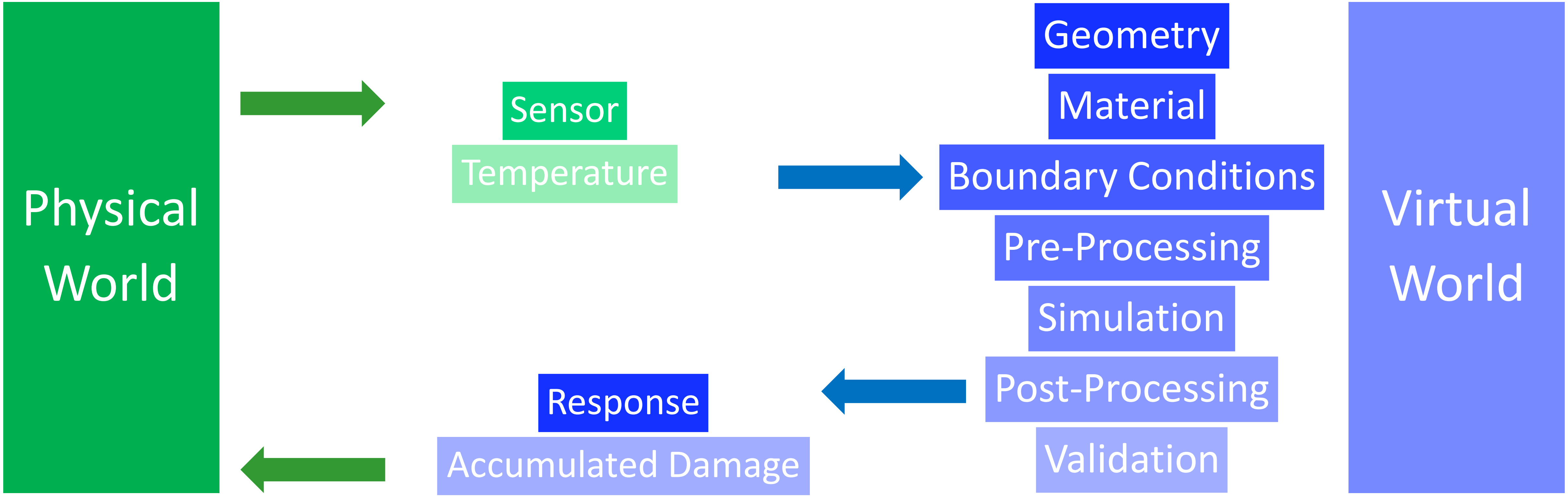
# Towards a Digital Twin
## Multi-physics simulations

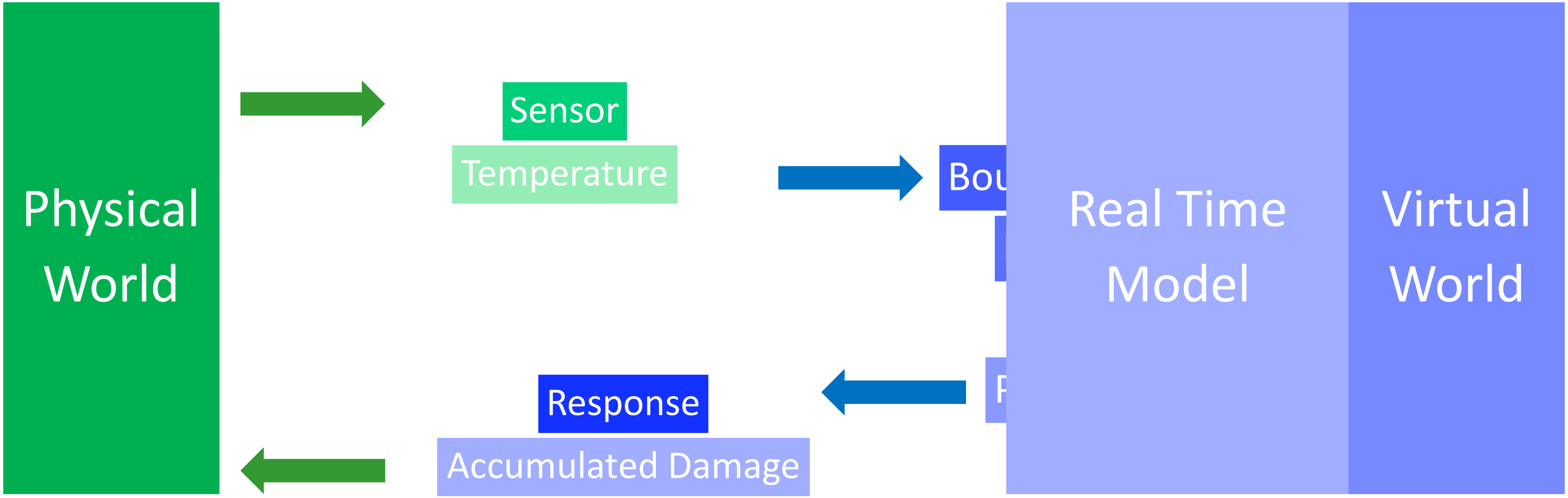


# Towards a Digital Twin

## Can multi-physics models be used in a Digital Twin?

- The creation of a physically based predictive model is a challenging task
- Coupling of the Physical World to the Virtual Model requires sensorial input
  *i.e. to read and apply realistic and real time loading conditions*
- Coupling of the Virtual Model to the Physical World requires validated critical damage parameter
  *the determination of the relevant failure indicator(s) is not straightforward*
- In order to allow for a real time coupling the simulation time needs to be reduced
  *typical simulation times vary from hours up to days depending on the model complexity*

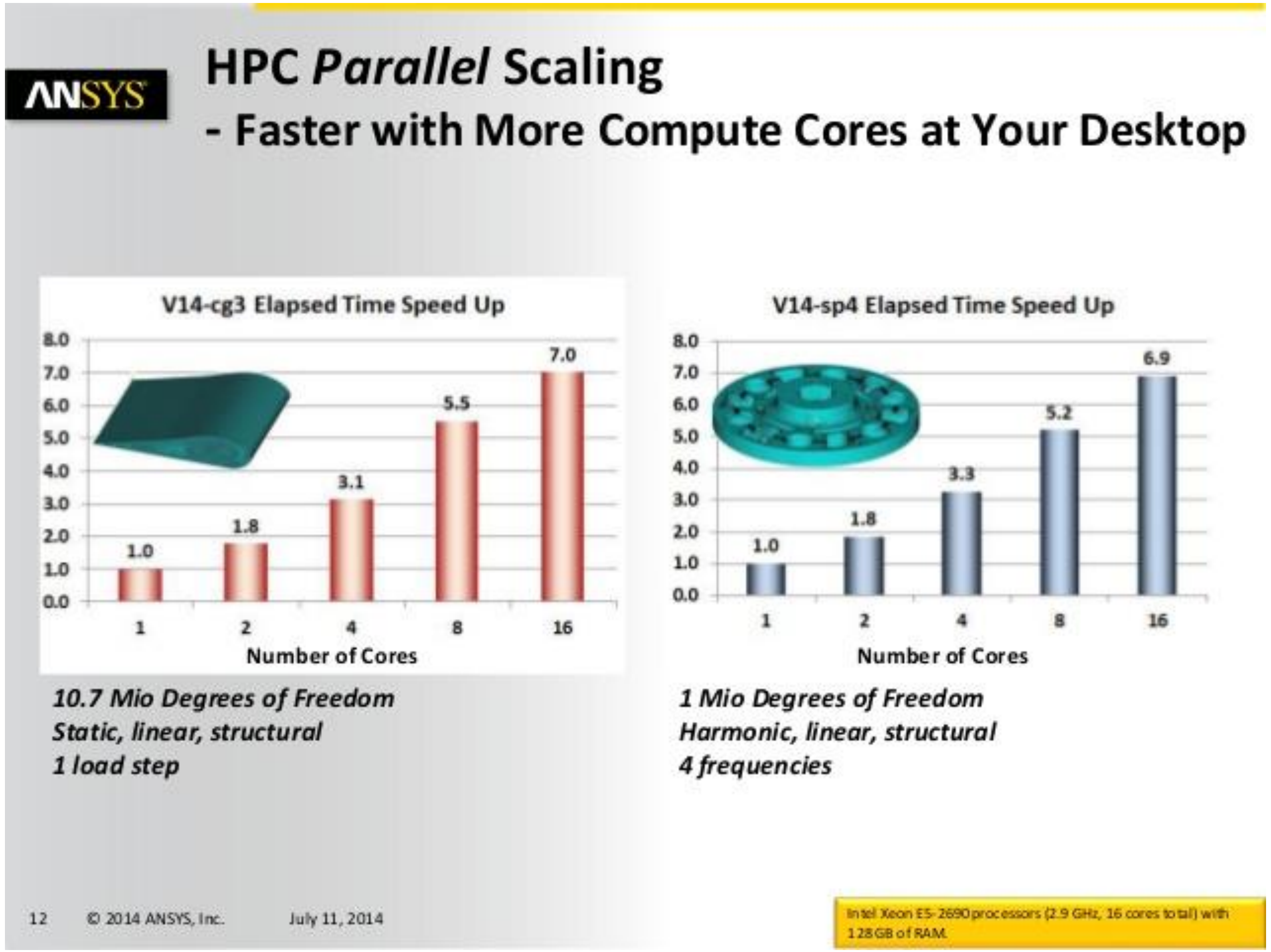
# Towards a Digital Twin
## Multi-physics simulations



# Towards a Digital Twin
## How to speed up simulation time?

**A. Parallel simulations on multiple cores**

- Requires additional hardware:
  - CPU cores
  - GPU cards
  - Infiniband network connection: low latency, high bandwidth
- Requires additional licenses
- Not limitless: gain in speed versus loss in additional I/O time
- HPC cloud solutions are available



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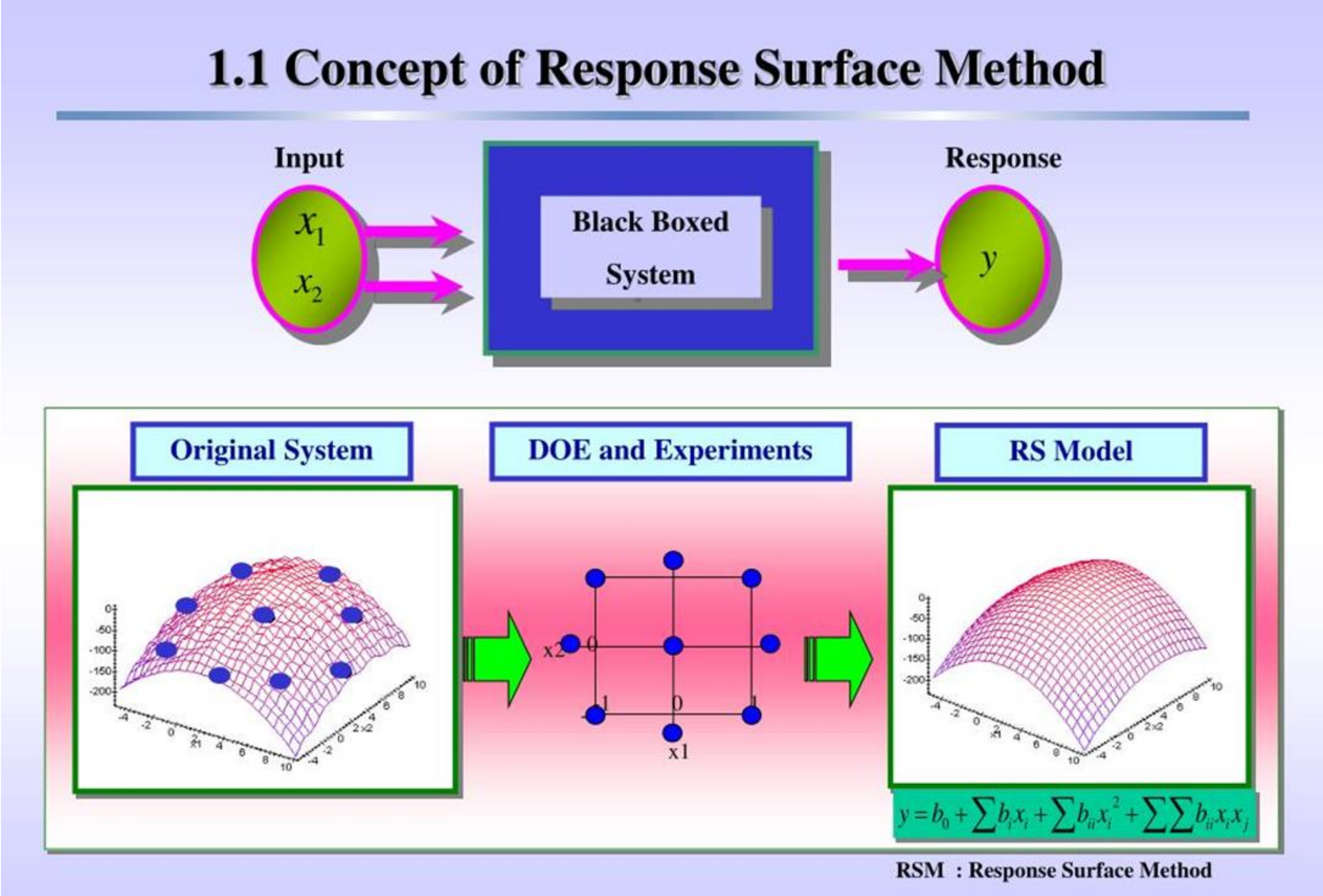
# Towards a Digital Twin
## How to speed up simulation time?

### B. Response Surface Model

- Use multi-physics model as black box
  - Define relevant inputs (e.g. sensor data)
  - Define required levels per input
  - Define relevant outputs (performance indicators)
- Perform a numerical DoE that covers the entire operating window (levels) of all inputs
- Derive mathematical expressions for the selected outputs (as function of the model inputs)
- Setup is computationally expensive:
  5 factors with 4 levels require 625 simulations
- Additional simulations and refitting of mathematical model is required if operating window changes, or if additional factors are required



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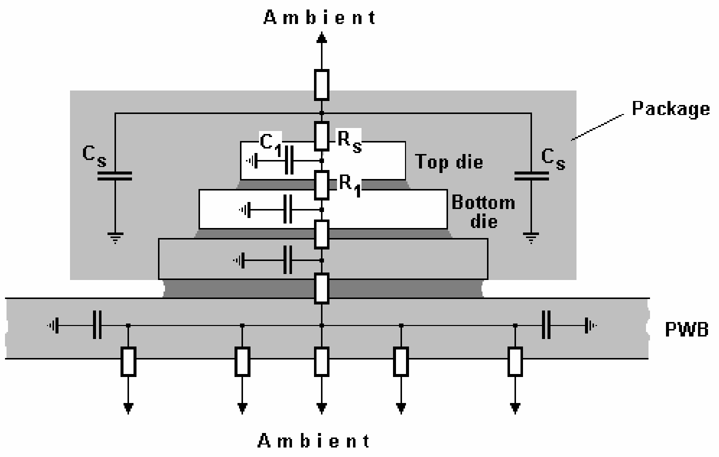
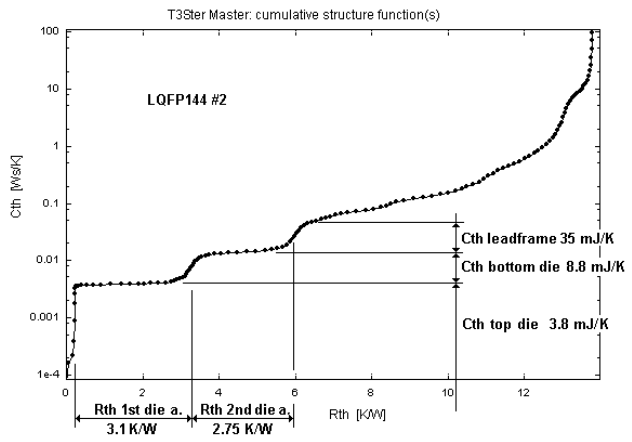
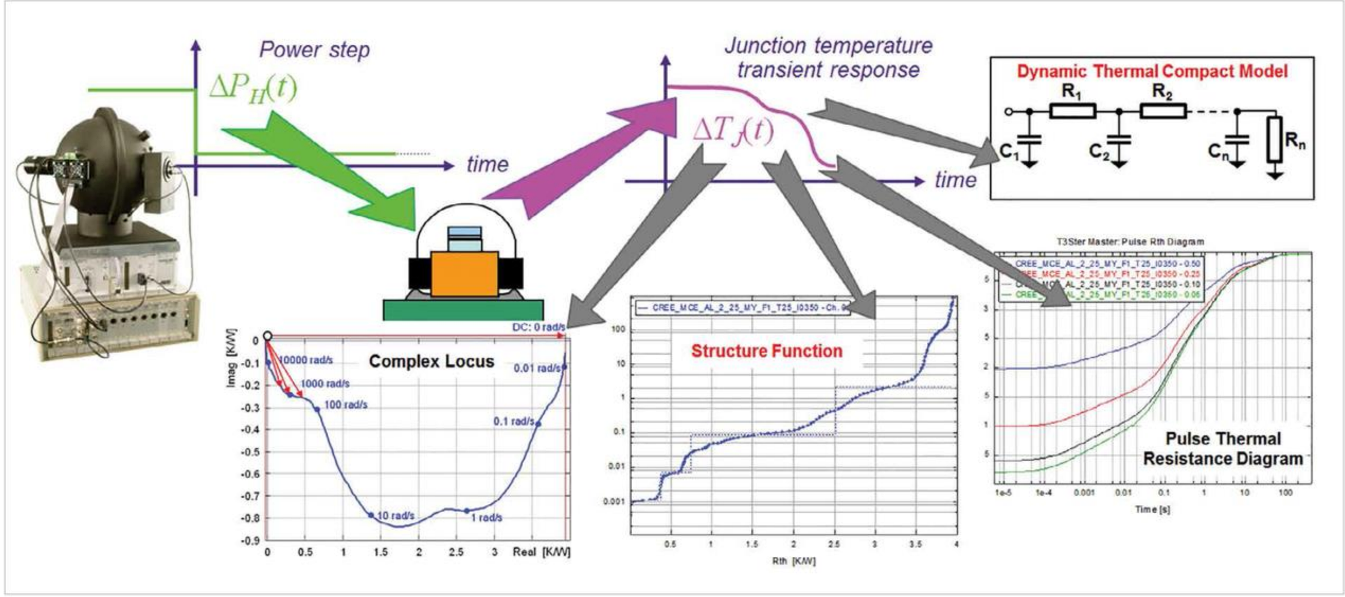
# Towards a Digital Twin
## How to speed up simulation time?

### C. Compact (thermal) models

- The thermal model can be represented as a one-dimensional resistor network
- Experimental setup (e.g. T3Ster Master) is available to determine these resistances with a thermal transient measurement
- Structure function (Resistance vs Capacity) shows the various resistances within the thermal flow
- Limitations:
  - Resulting model depends on chosen thermal boundary conditions (power step, convection, radiation, etc.)
  - Restricted to thermal simulations, structural simulations would require the construction of an ‘engineering model’ instead



# Towards a Digital Twin

## Can multi-physics models be used as a Digital Twin?

- The creation of a physically based predictive model is a challenging task
- Coupling of the Physical World to the Virtual Model requires sensorial input
  *i.e. to read and apply realistic and real time loading conditions*
- Coupling of the Virtual Model to the Physical World requires validated critical damage parameter
  *the determination of the relevant failure indicator(s) is not straightforward*
- In order to allow for a real time coupling the simulation time needs to be reduced
  *typical simulation times vary from hours up to days depending on the model complexity*
- Yes, as long as the multi-physics model can be adequately captured by a mathematical model (or a model with real time performance) and can be updated based on the sensorial inputs.
- In case of connected lighting one could e.g. think of lifetime predictions based on the real time monitoring of the luminaire state

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