COMPENSATING FOR THERMAL AND GRAVITATIONAL EFFECTS IN STRUCTURES AND ASSEMBLIES

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Acknowledgement

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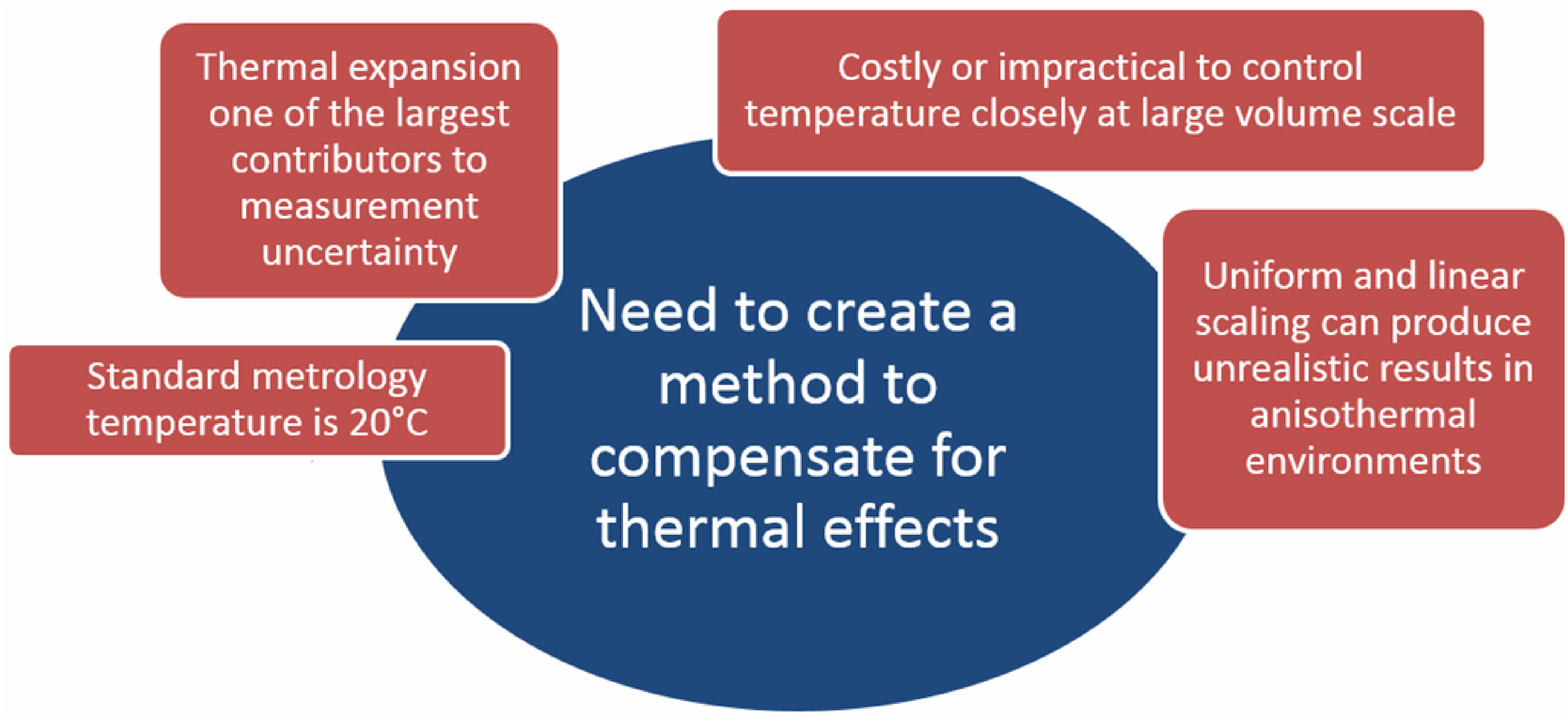
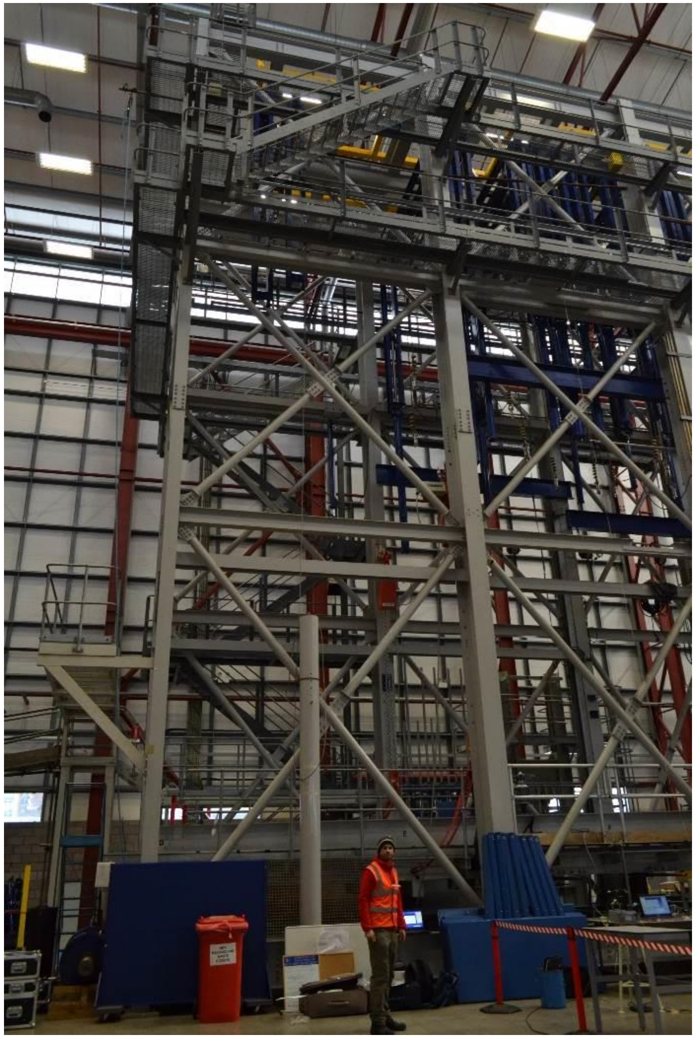
Problem

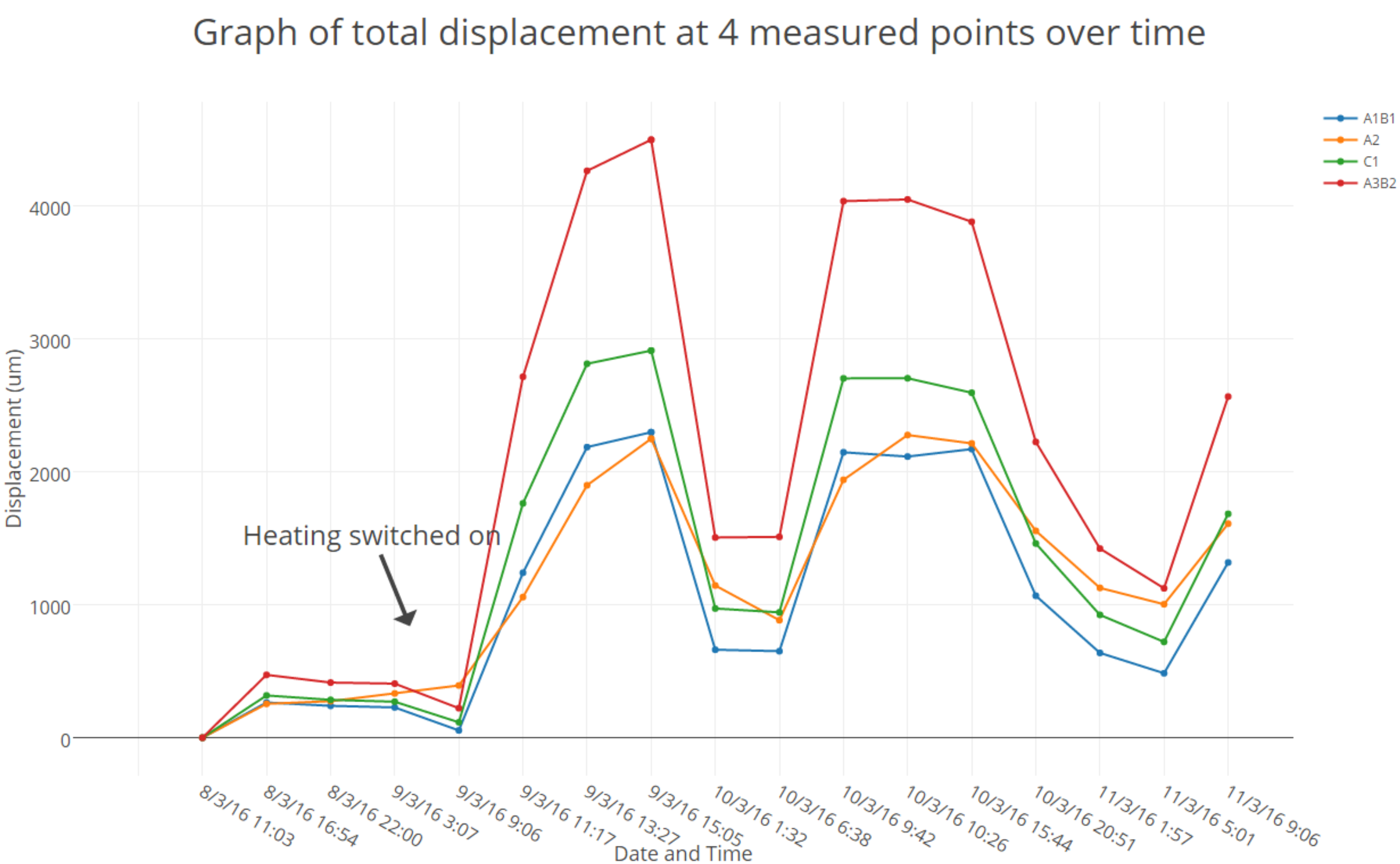

Thermal expansion one of the largest contributors to measurement uncertainty
Costly or impractical to control temperature closely at large volume scale
Standard metrology temperature is 20°C
Need to create a method to compensate for thermal effects
Uniform and linear scaling can produce unrealistic results in anisothermal environments

Measurement at Airbus (UK)



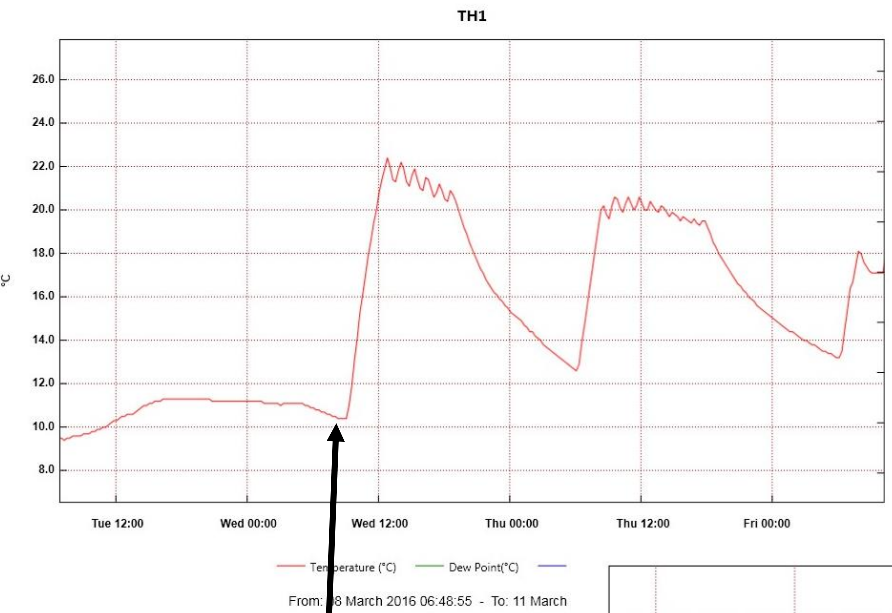
- Wing bending test rig at Airbus (UK)
- Dimensional measurements taken on structure with laser tracker
- Temperature monitored on the structure

Measurement at Airbus (UK)



- Laser tracker measurement
- 4 measured points on structure
- Additional 7 reflectors measured
- Repeated at regular time intervals throughout the day

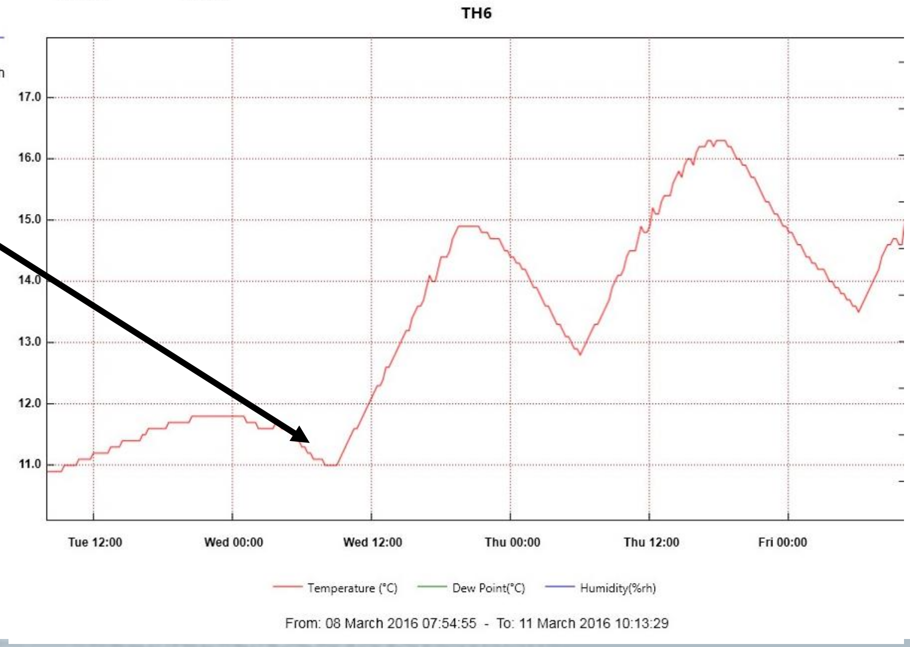
Measurement at Airbus (UK)



Temperature at the top

- Temperature monitored around volume
- 10 WiFi ambient temperature and humidity data loggers
- 10 wireless data loggers

Heating switched on



Temperature at bottom

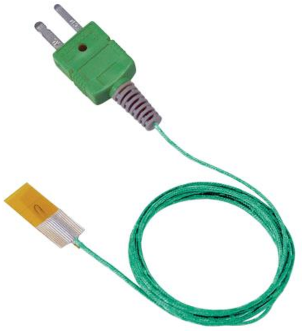
In a solution ...

Would like to be able to know:

- “true” geometry exactly
- if subsequent operations will work
- what remedial action is required

Measurement

Temperature:



- component
- environment

- thermocouples
- thermal imaging

Measurement

National Instruments 8-Slot Data Acquisition Chassis

National Instruments 16-channel Thermocouple Module

13 Type T and 18 Type K Thermocouple Sensors (±0.5ºC)

9 Omega Wireless Temperature Transmitters (18 thermocouple channels)

- Laser tracker
- Invasive temperature sensors

SpatialAnalyzer

NATIONAL INSTRUMENTS LabVIEW

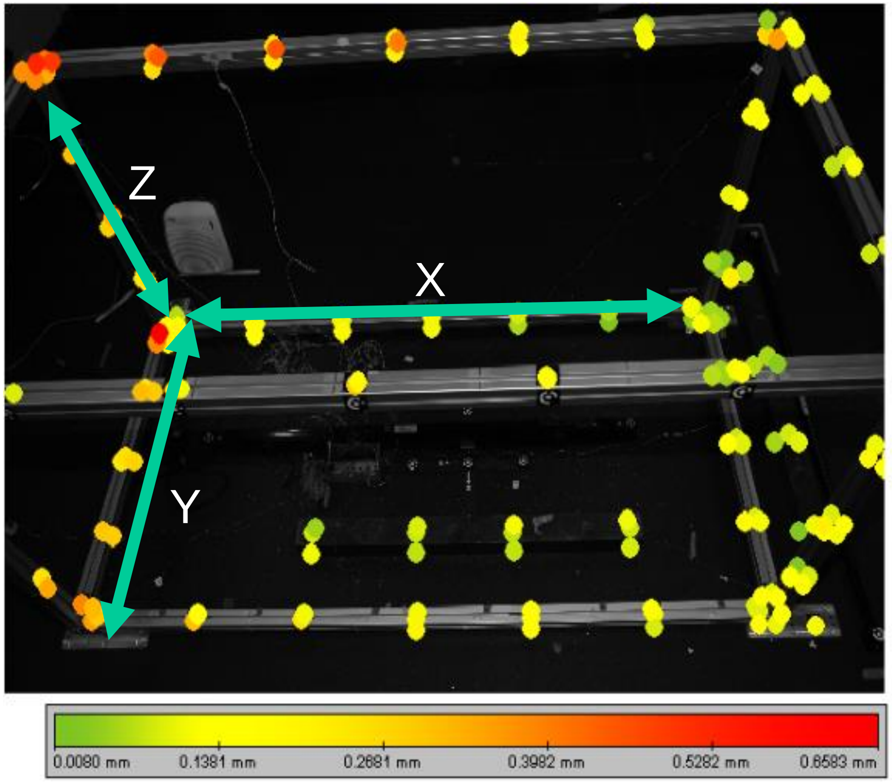
Measurement

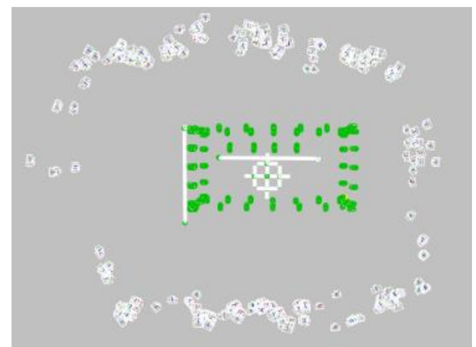
Position:

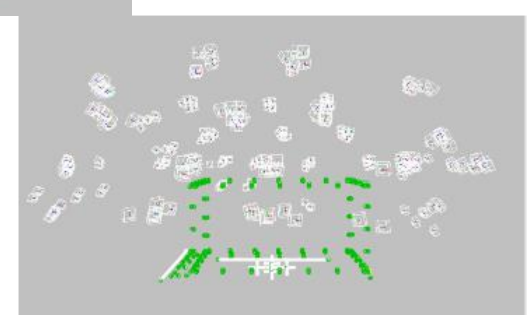
- points on component

- photogrammetry
- laser tracking

Photogrammetry



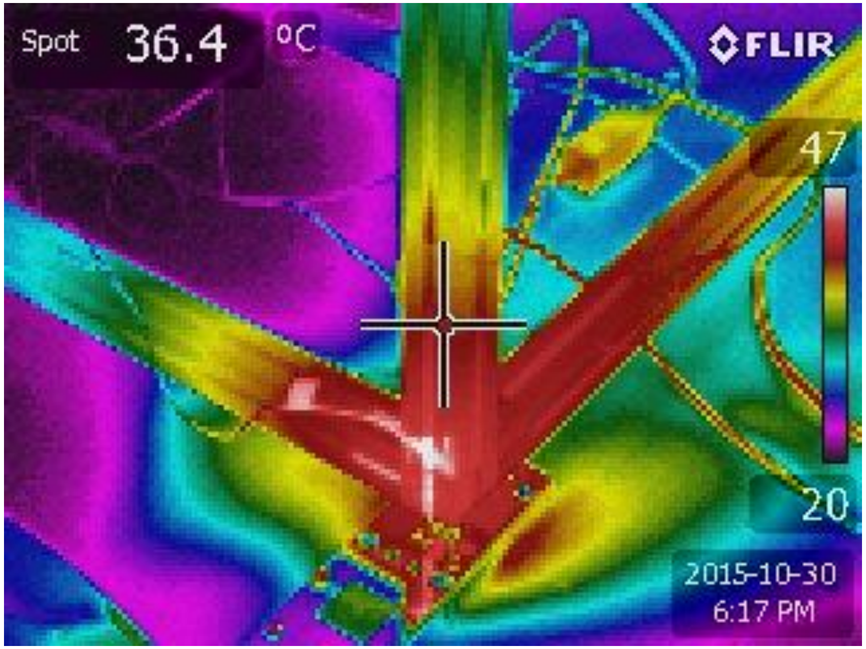




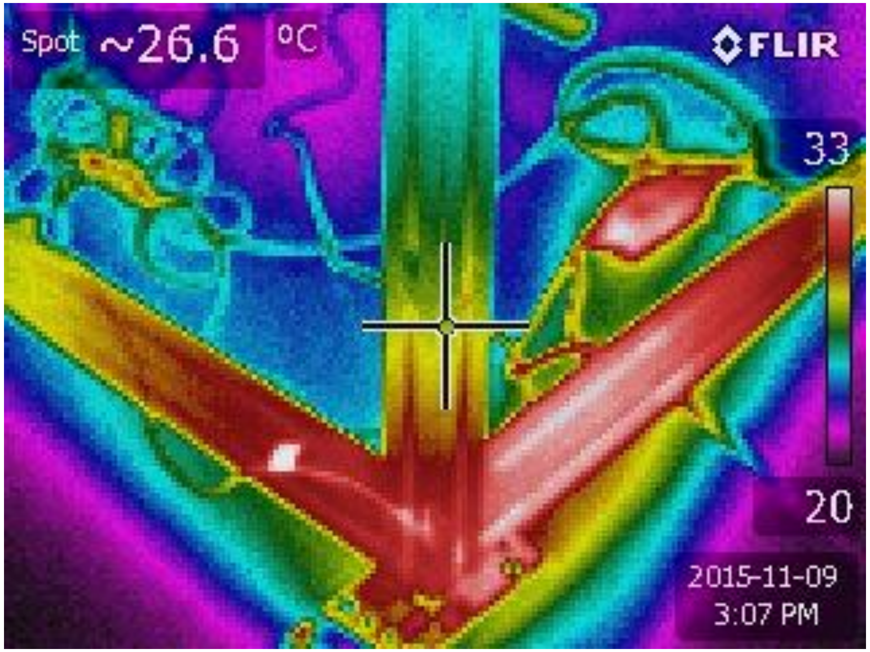
- Example photograph captured during photogrammetry overlayed with target total deformation
- Measurement uncertainty of points: 13-40 µm

Thermal imaging

- used qualitatively to plan sensor positions
- also used quantitatively to validate finite element thermal analysis

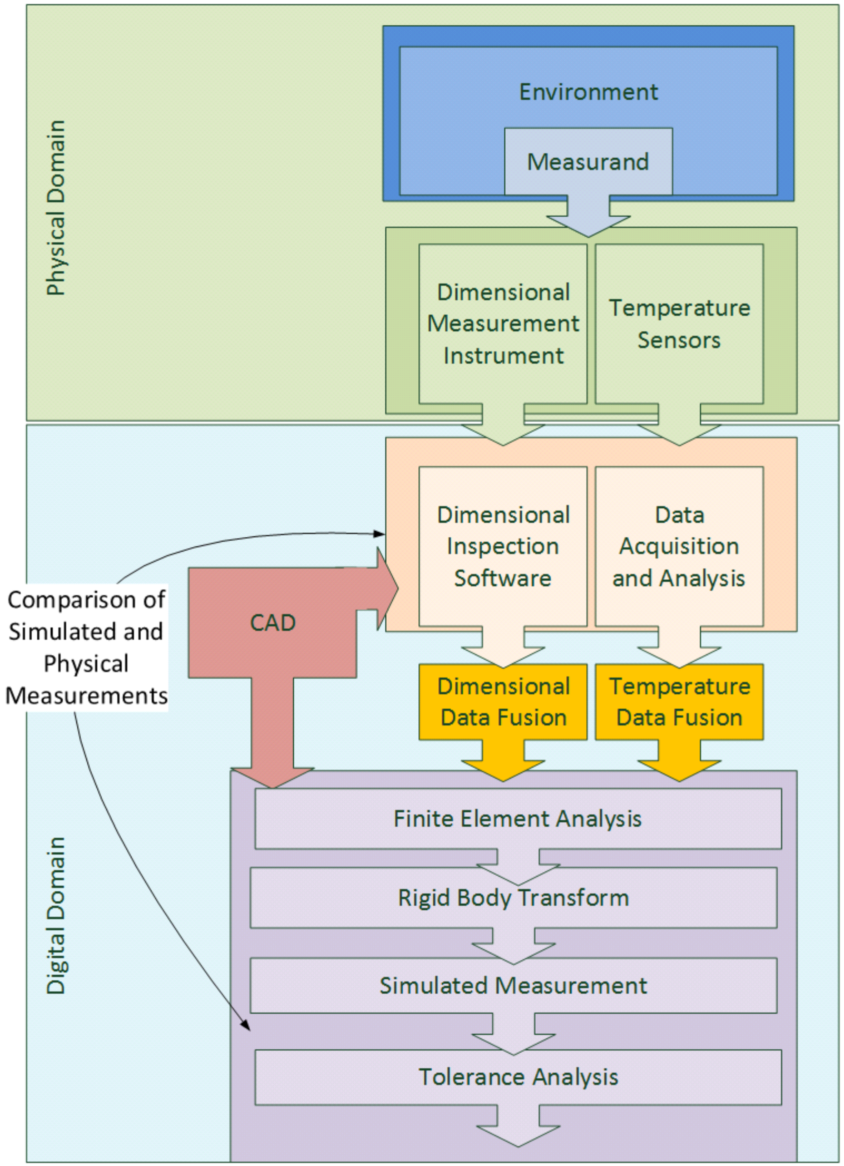


Heater setting 2, position 1

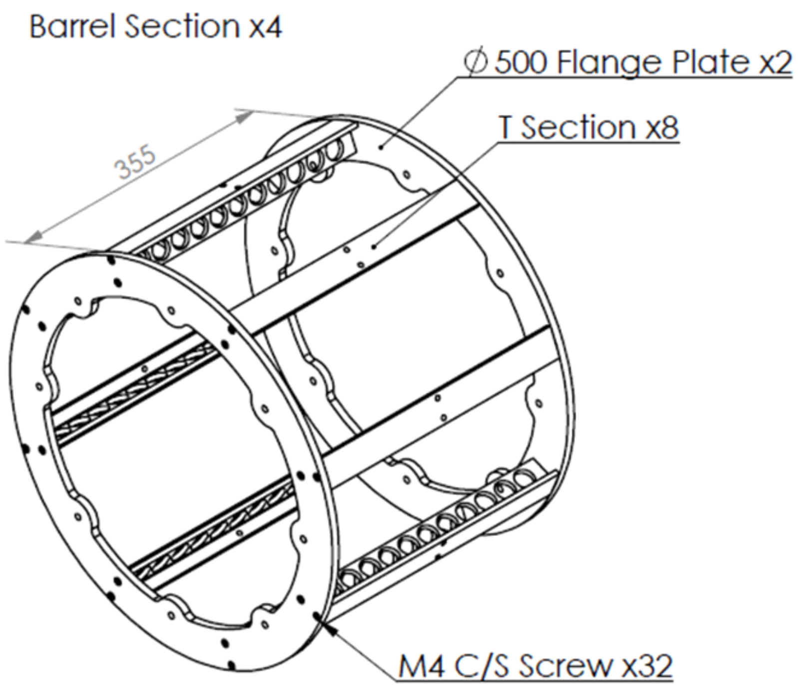


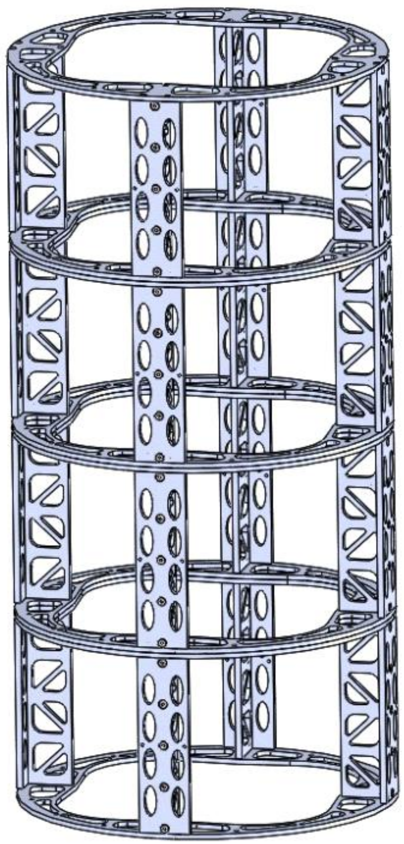
Heater setting 1, position 2

Hybrid approach



Test component / assembly

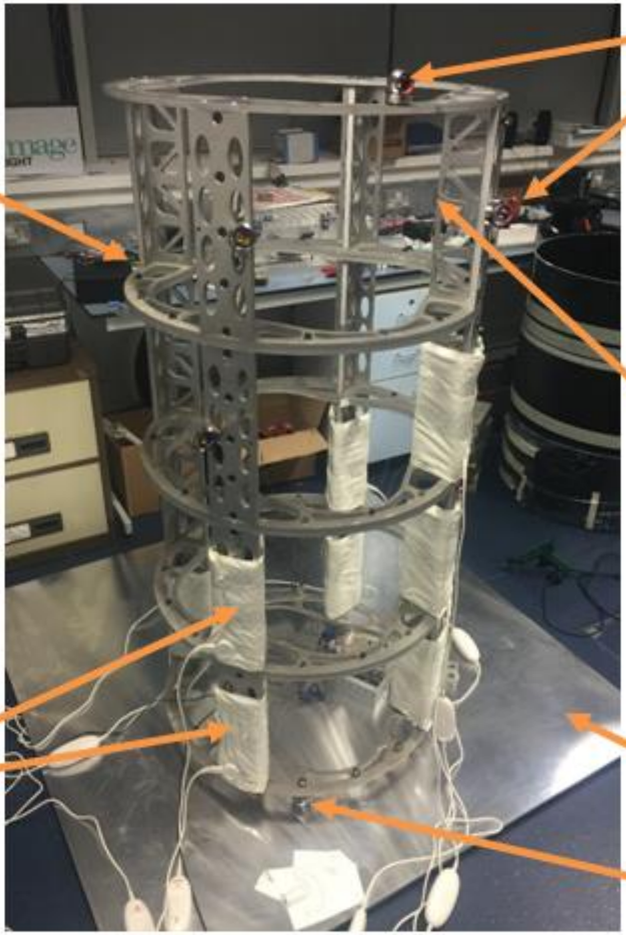




Experimental set-up

Structure assembled using 4 barrel sections

SMR targets to measure surface and hole positons



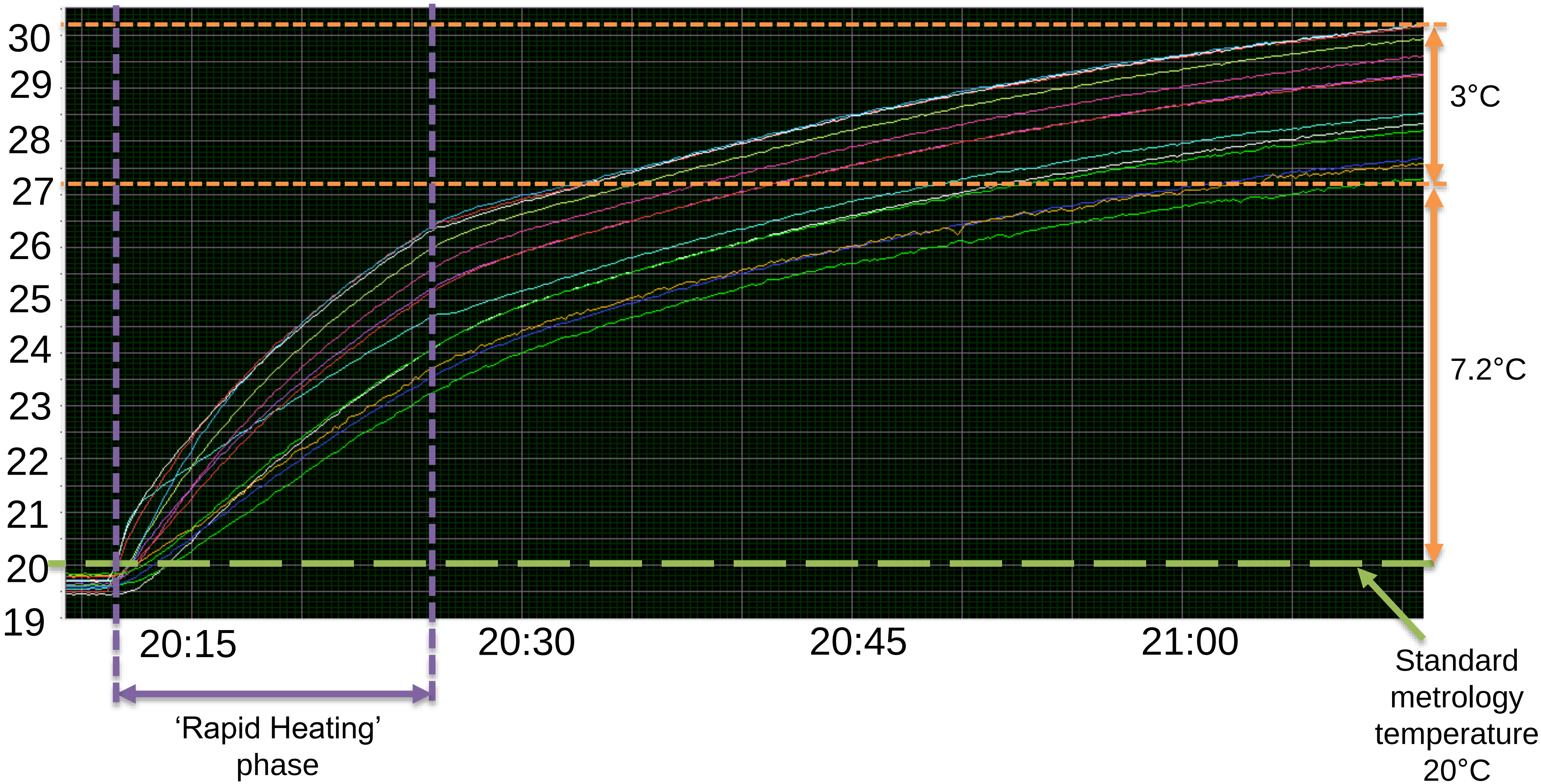
13 thermocouples to measure surface temperature

Heating pads X8

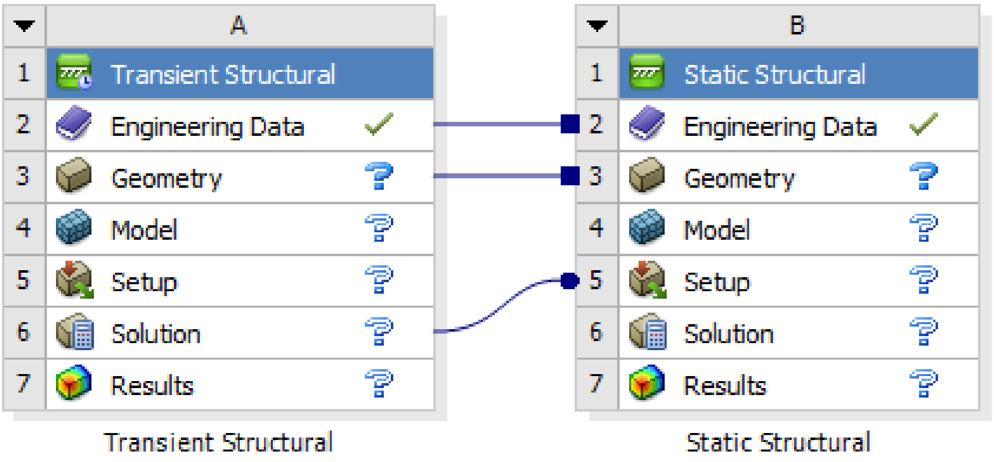
Aluminium tooling plate

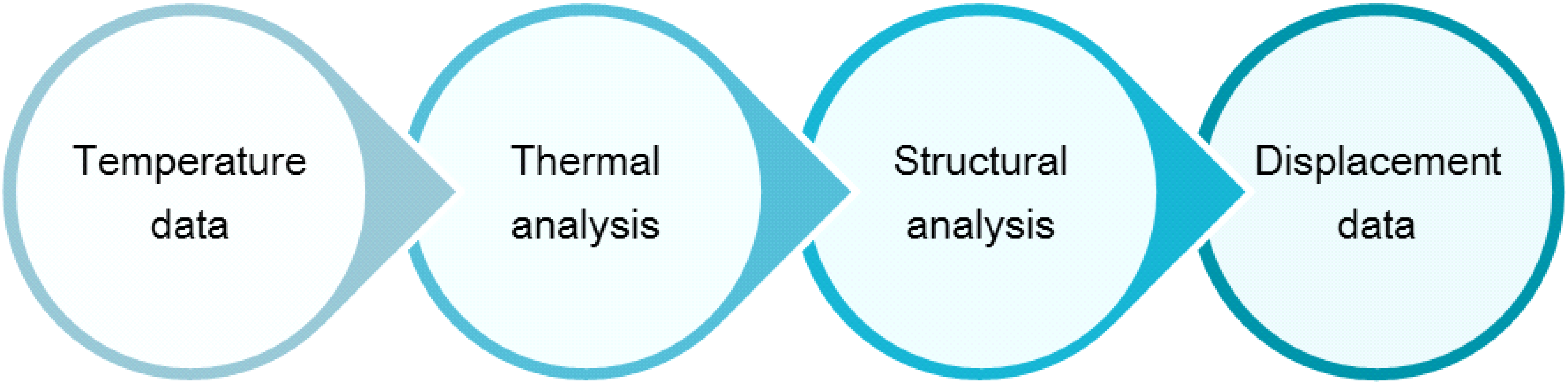
3-2-1 constraint using 3 tooling balls

Heating profile



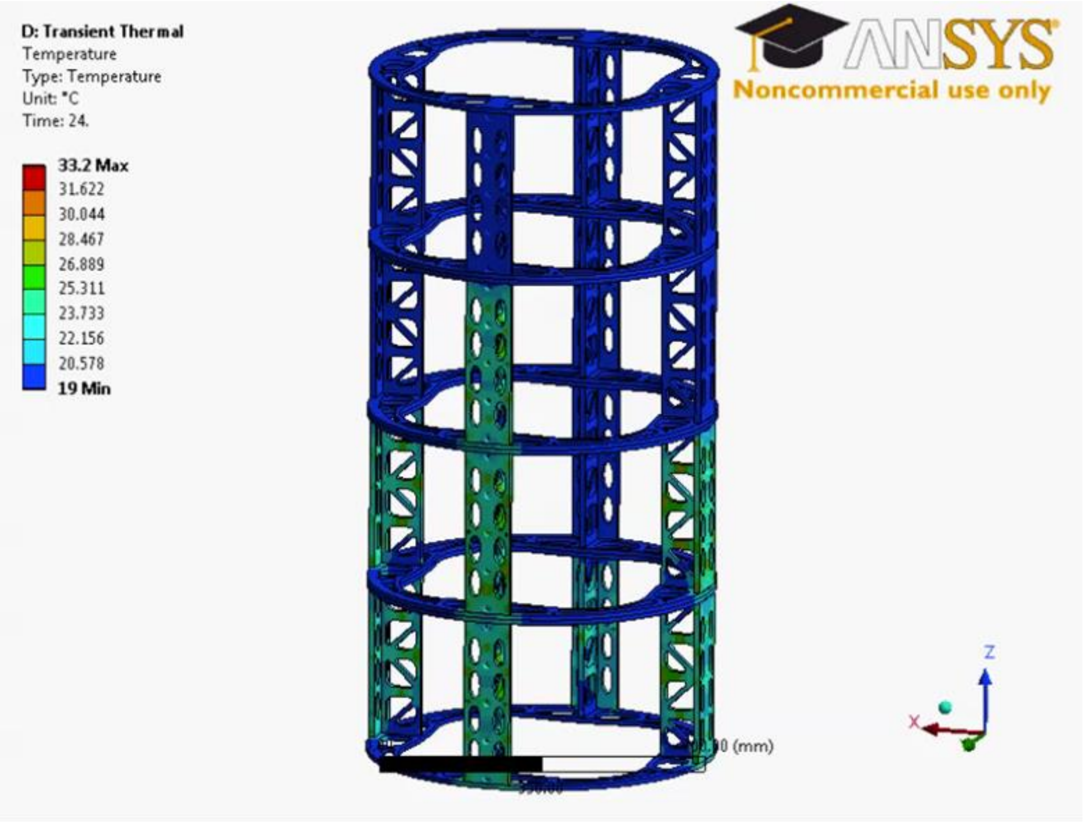
Steps of finite element analysis



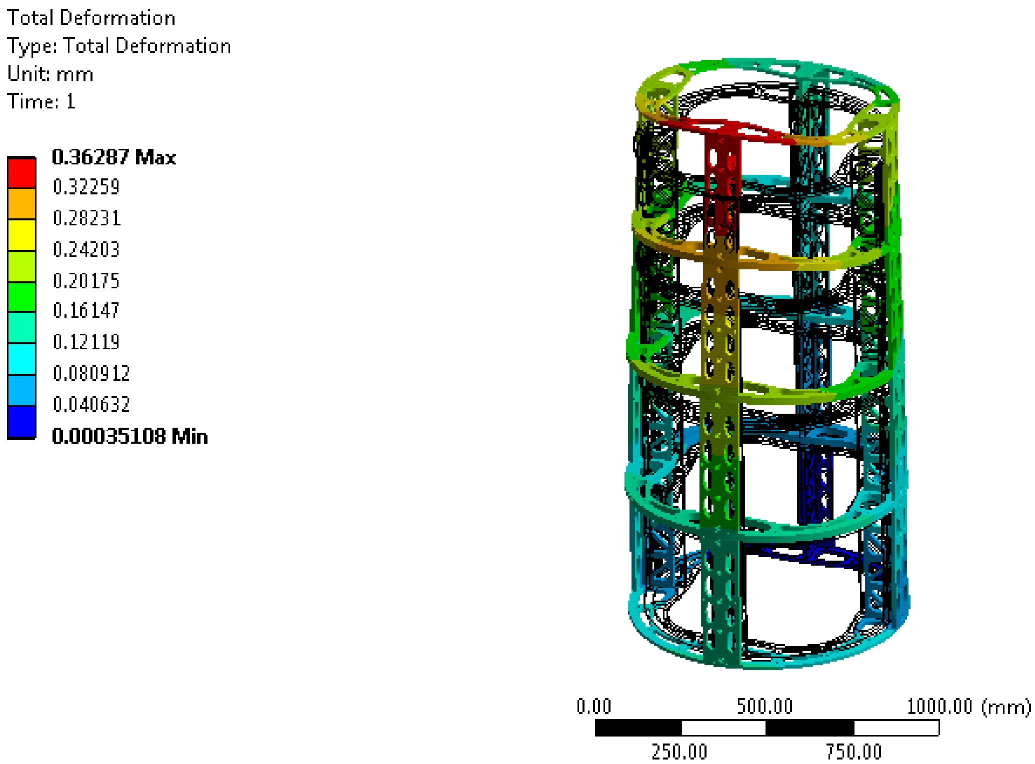


Transient thermal analysis

- Transient preferable as temperature does not stabilise
- Solution calculates temperature distribution at all nodes of model over time
- More time steps → more accurate prediction
- Temperature applied to nodes nearest the sensor position



Structural analysis



- Normal gravity applied
- Assumes structure is perfectly level
- Solution calculates displacement in X, Y and Z axes at all nodes of model
- Solution also calculates total displacement
- Support: movement in Z constrained, X and Y free

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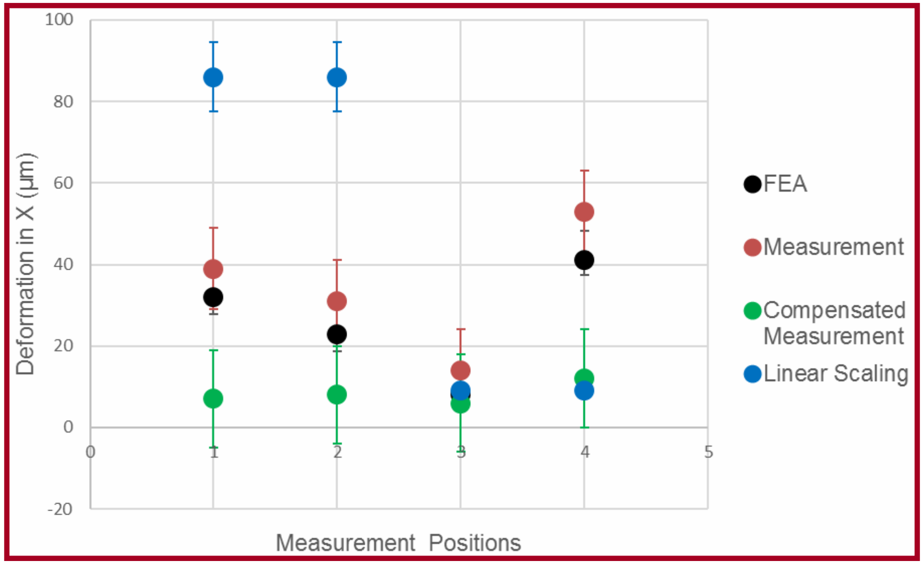
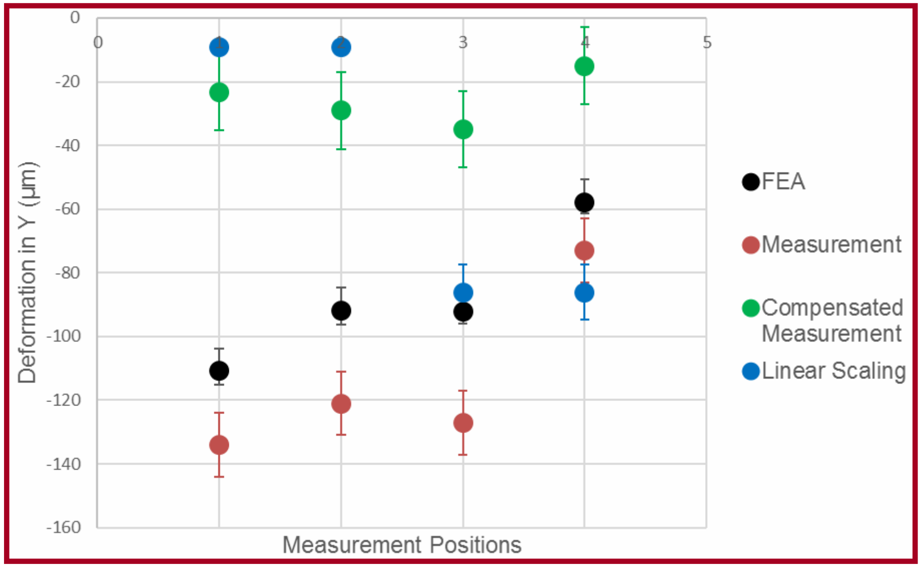
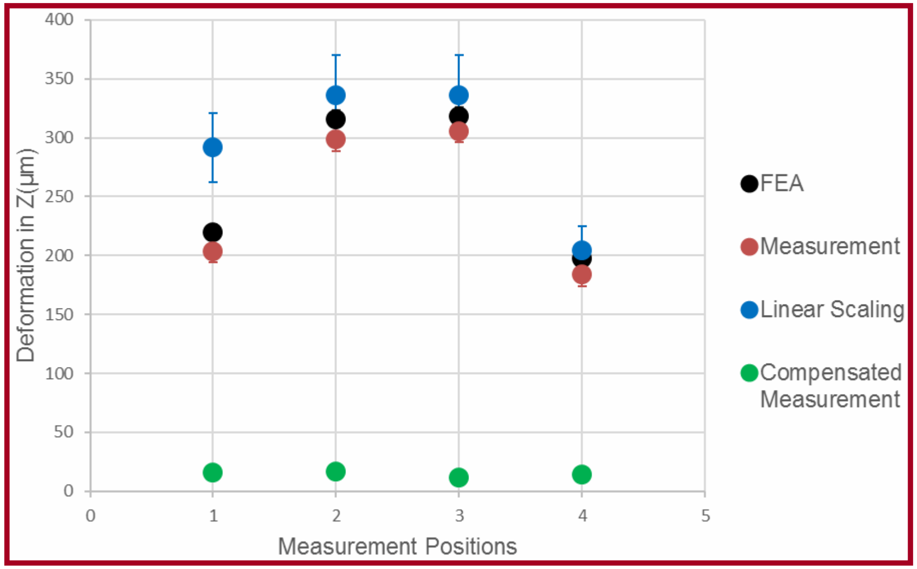
Deformations







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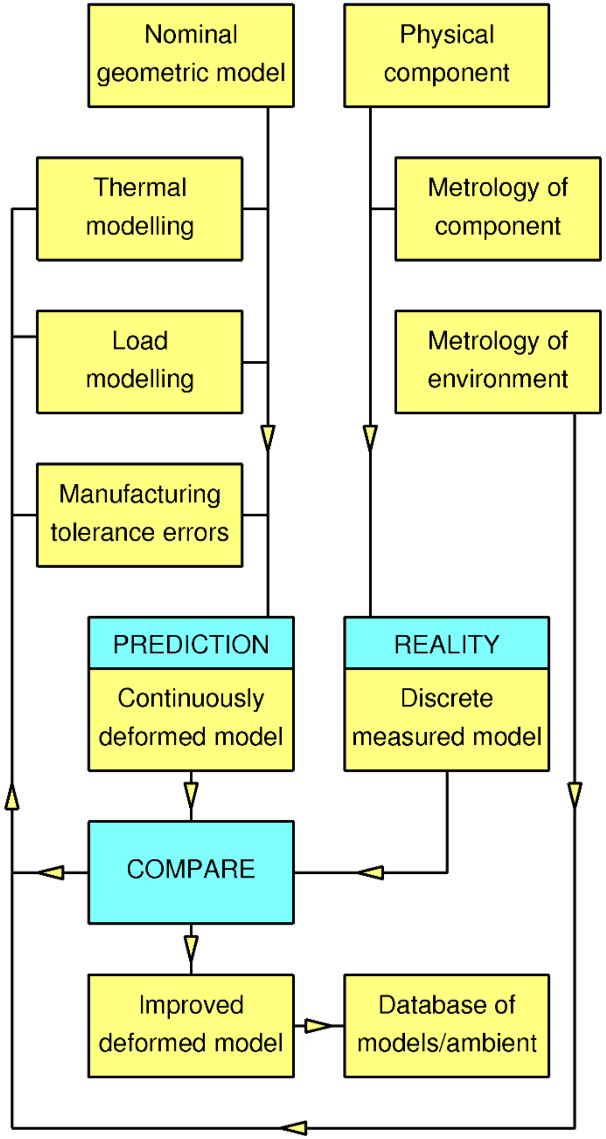
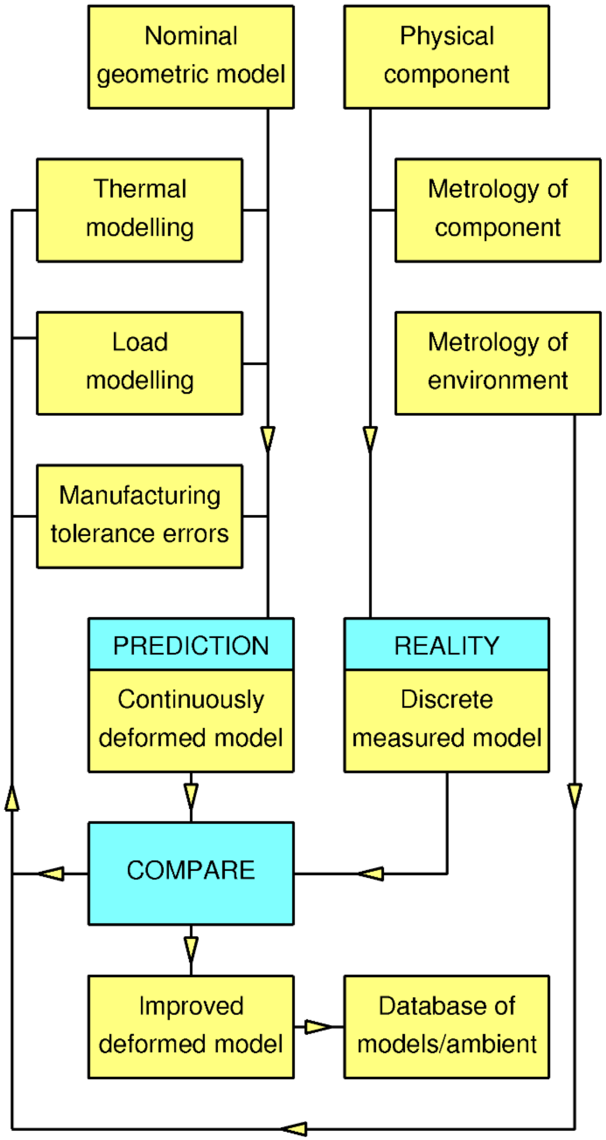
Hybrid approach

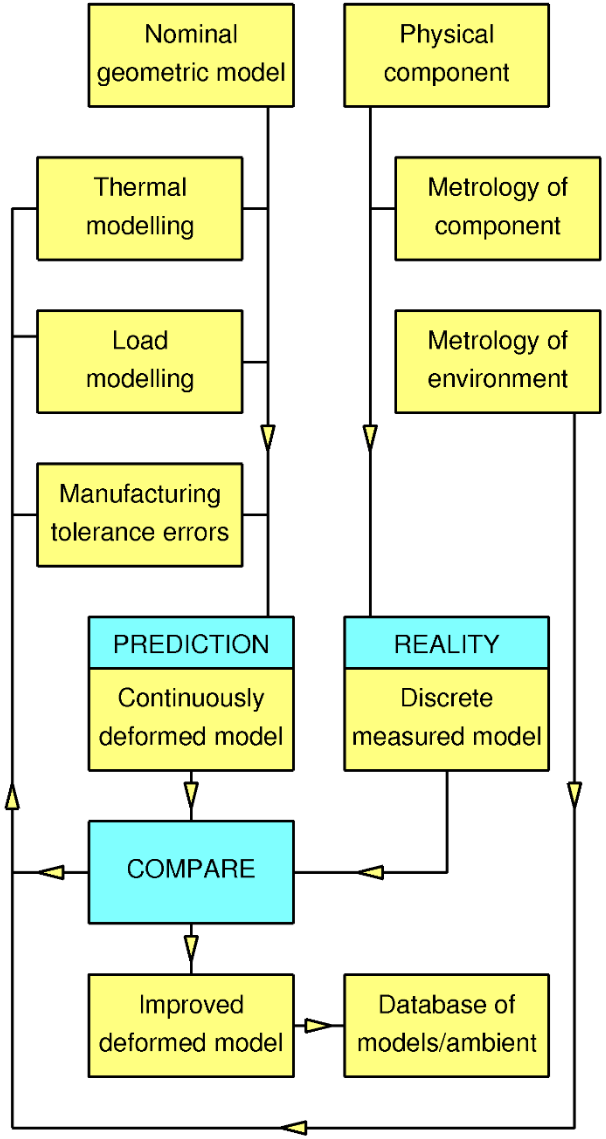


Hybrid approach



Two "models": geometric, physical

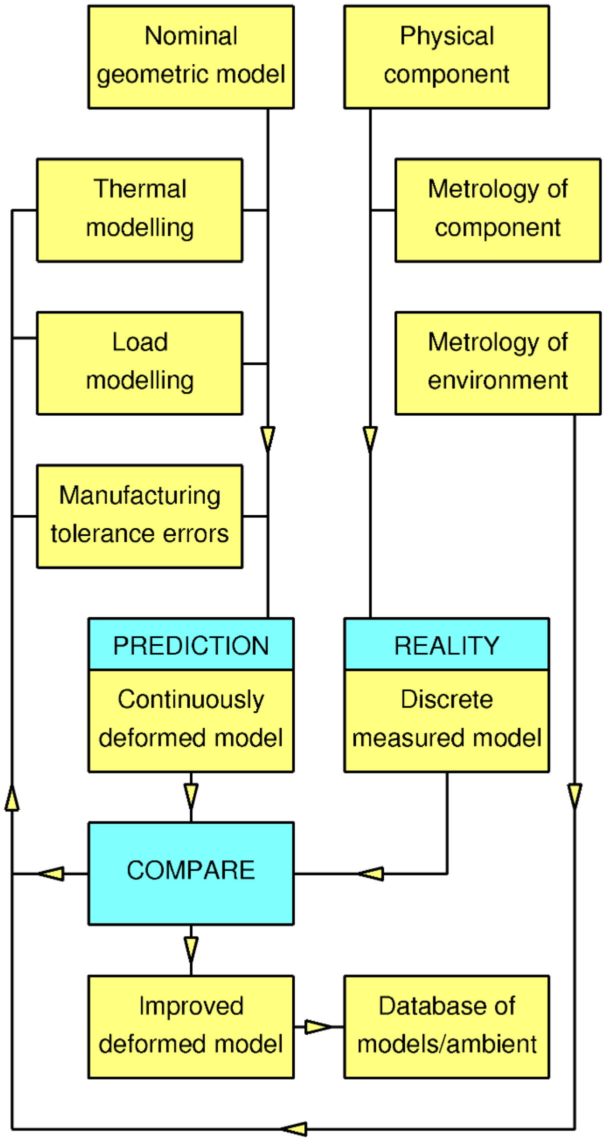
Hybrid approach



Two "models": geometric, physical

Physical: measure

Hybrid approach

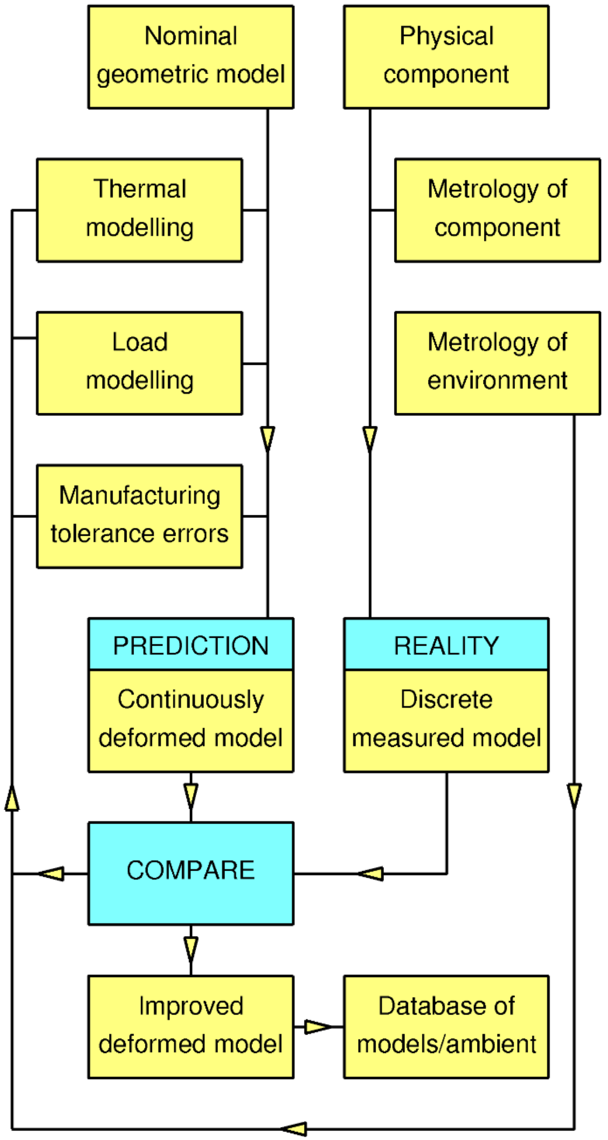


Two “models”: geometric, physical

Physical: measure

Geometric: FE analysis

Hybrid approach



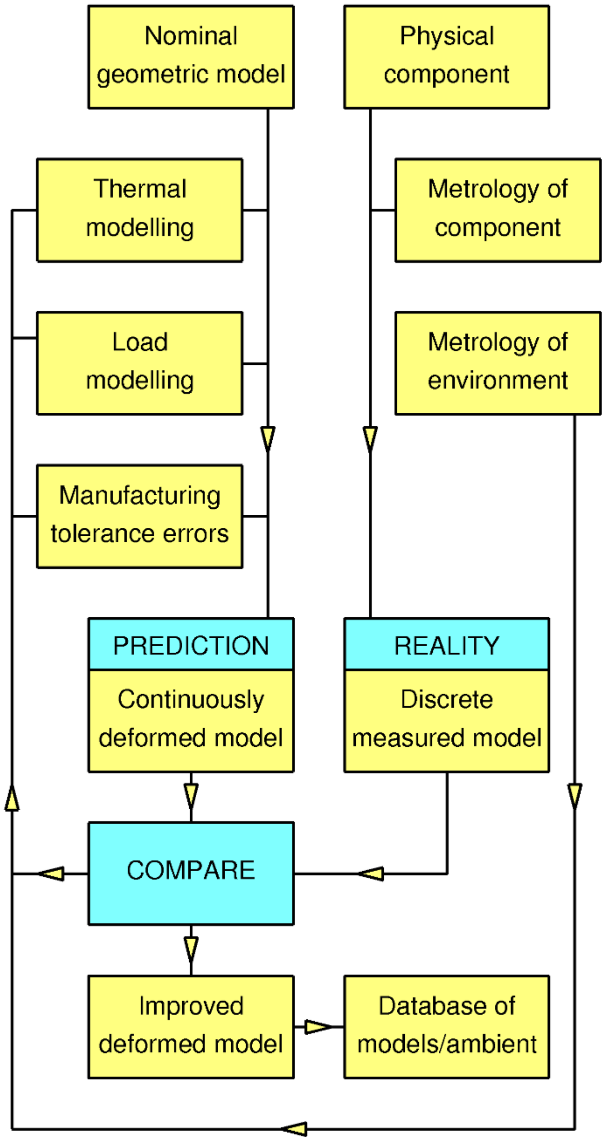
Two "models": geometric, physical

Physical: measure

Geometric: FE analysis

Prediction and reality

Hybrid approach



Two "models": geometric, physical

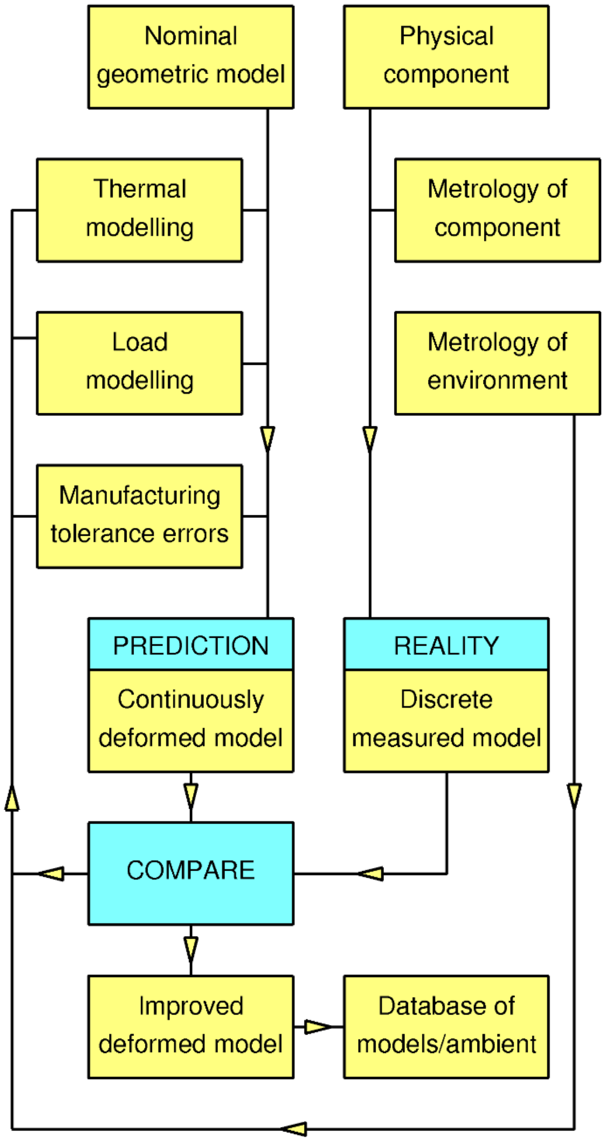
Physical: measure

Geometric: FE analysis

Prediction and reality

Comparison

Hybrid approach



Two "models": geometric, physical

Physical: measure

Geometric: FE analysis

Prediction and reality

Comparison

Improved model

Two models

Geometric/FE:

- point-based (nodes)
- large number of nodes

Measured:

- point-based
- small number of nodes

Two models

Geometric/FE:

- point-based (no
- large number of

Subject to errors due to assumptions in modelling and numerical effects in solving

Measured:

- point-based
- small number of nodes

Two models

Geometric/FE:

- point-based (no
- large number of

Subject to errors due to assumptions in modelling and numerical effects in solving

Measured:

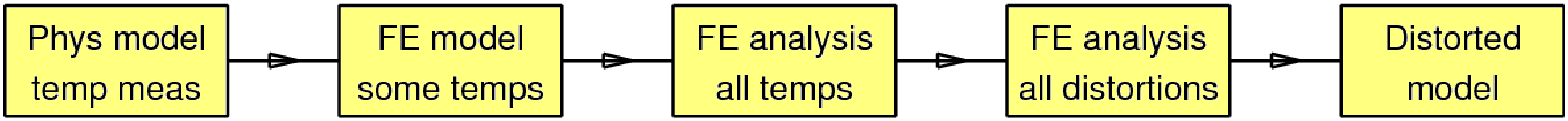
- point-based
- small number of

Best information about actual component (but subject to measuring errors)

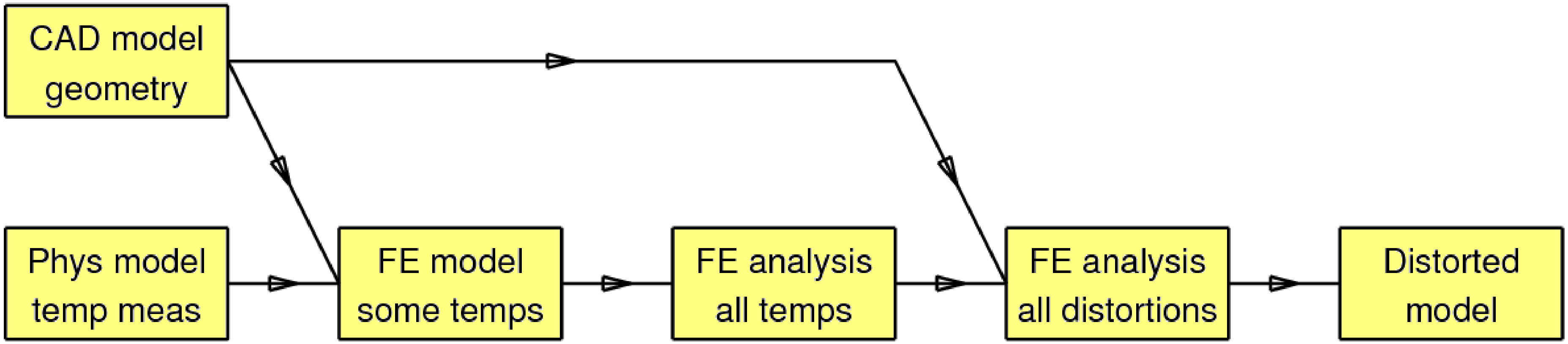
Avoiding thermal stage in FE analysis

Can the thermal analysis stage in the FE process be avoided?

FE analysis


Phys model
temp meas
FE model
some temps
FE analysis
all temps
FE analysis
all distortions
Distorted
model

FE analysis


CAD model
geometry
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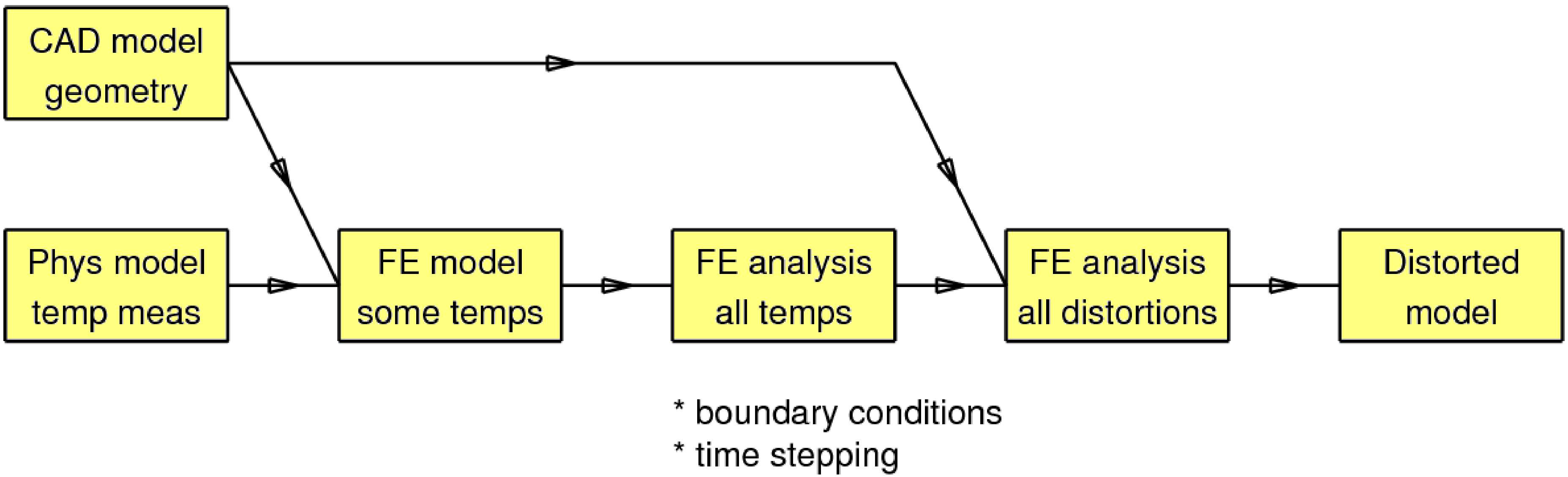
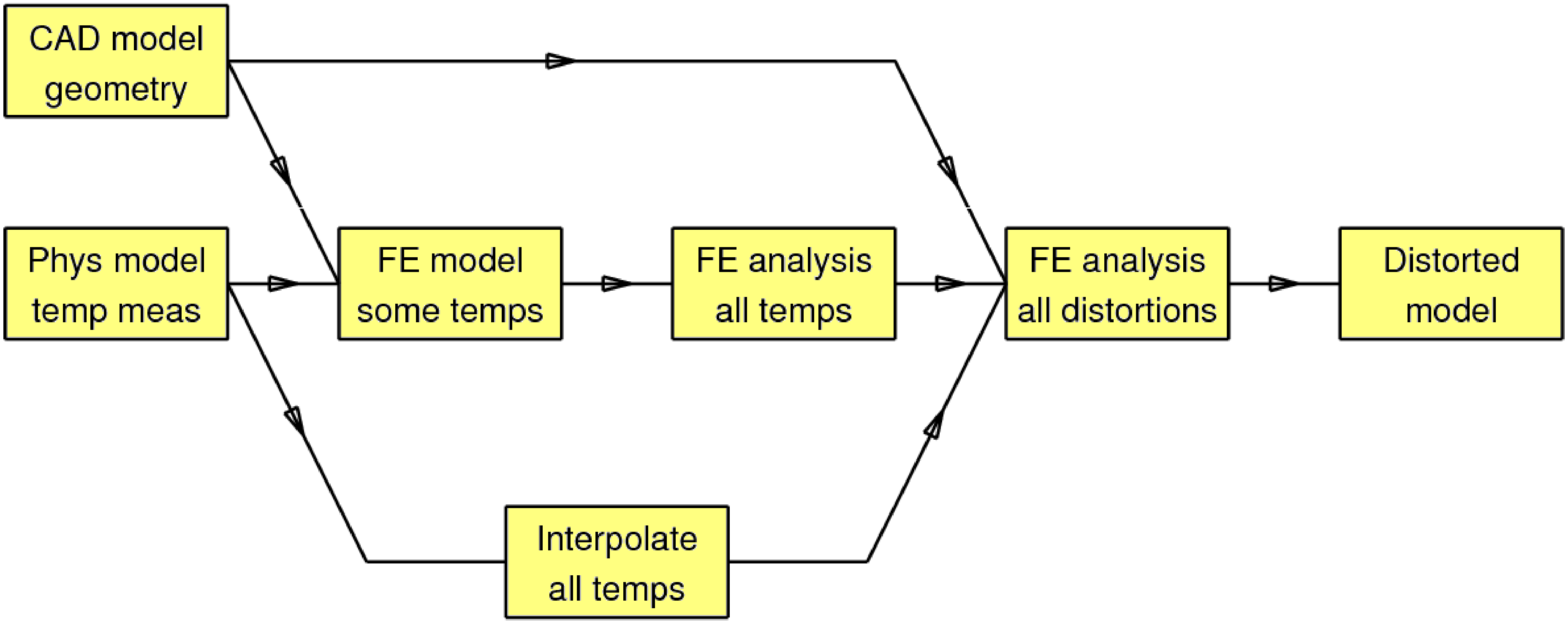
FE analysis


CAD model
geometry
Phys model
temp meas
FE model
some temps
FE analysis
all temps
FE analysis
all distortions
Distorted
model
* boundary conditions
* time stepping

FE analysis

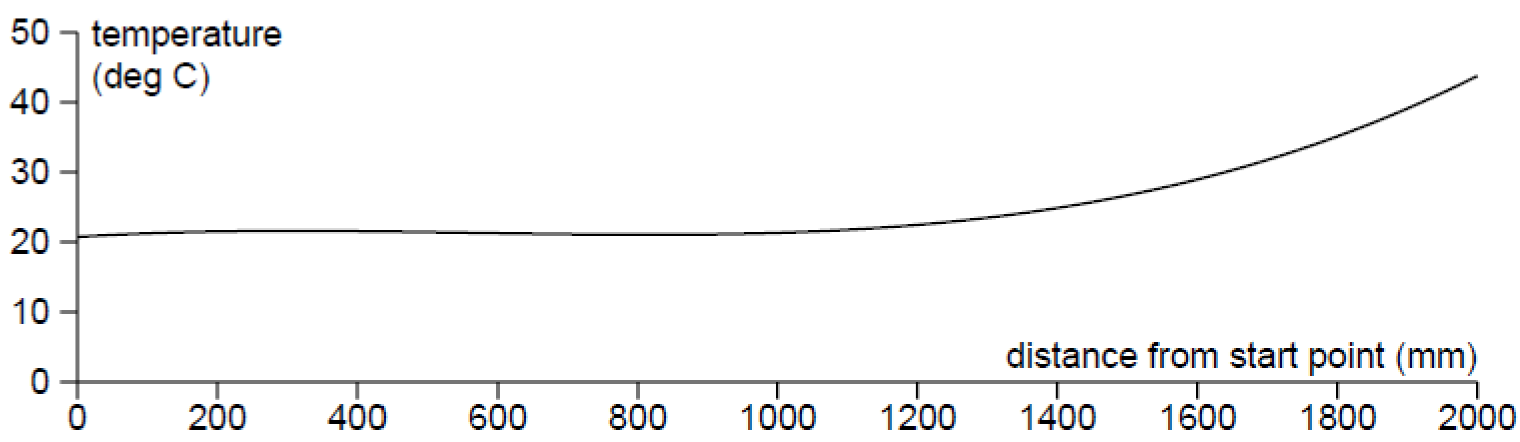

CAD model geometry
Phys model temp meas
FE model some temps
FE analysis all temps
FE analysis all distortions
Distorted model
Interpolate all temps

Temperature interpolation

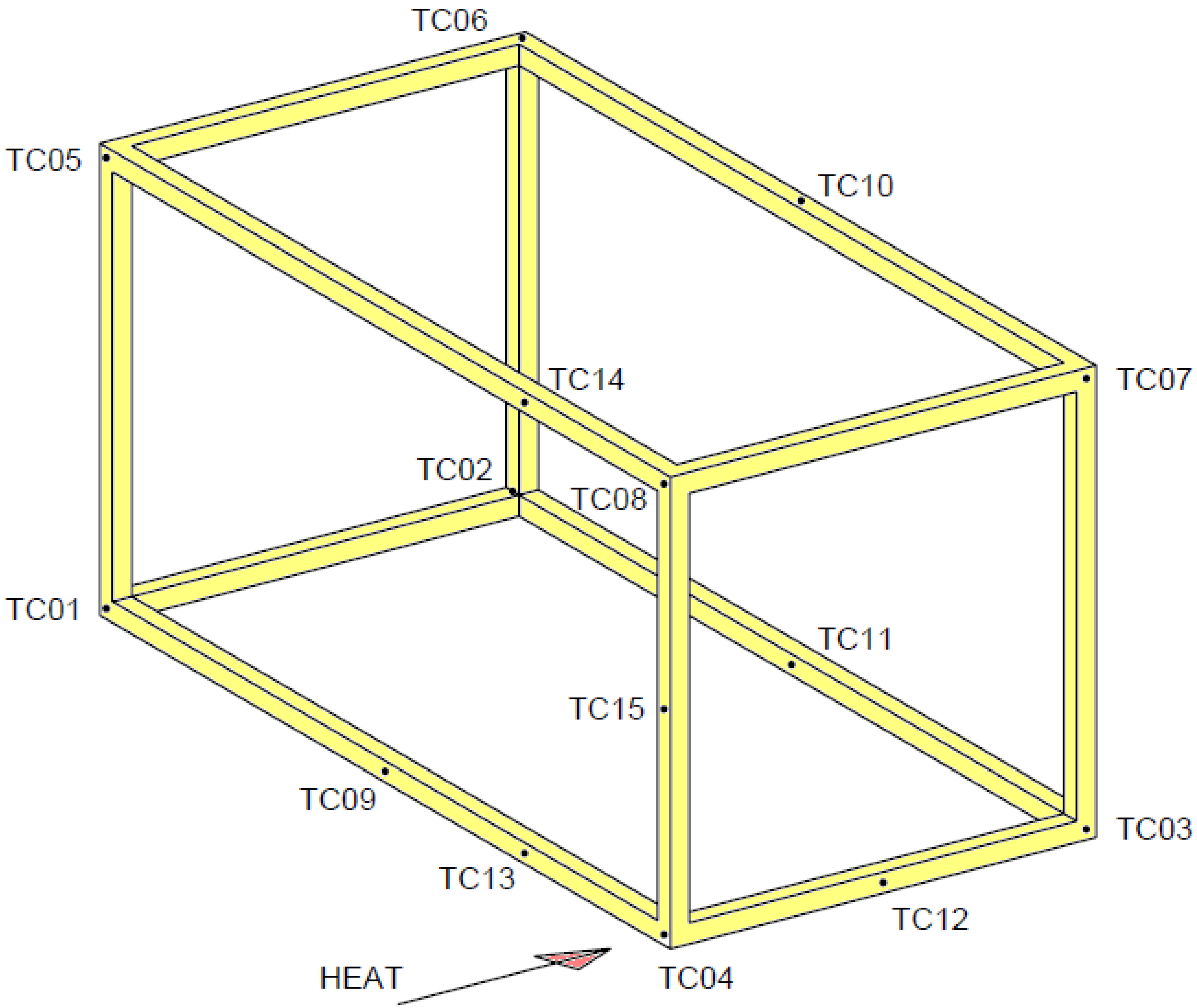
- regard temperature measurement points as forming “edges” in the body
- interpolate along each edge
- interpolate away from edges

Temperature interpolation example

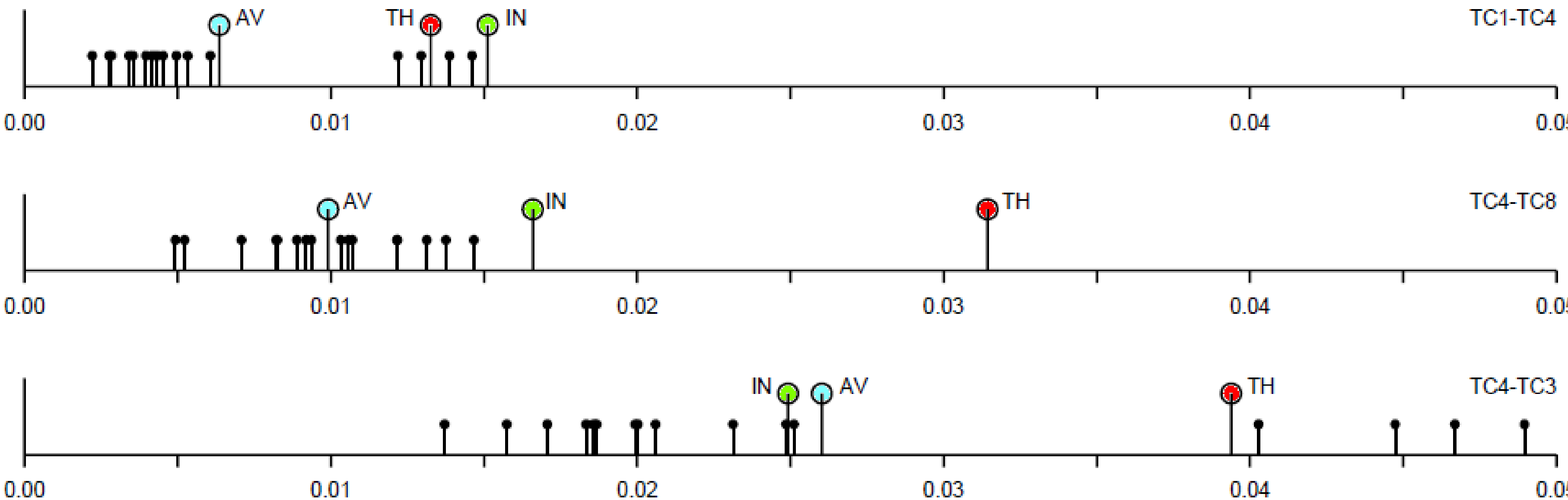
point	x (mm)	y (mm)	z (mm)	θ (°C)
tc01	39.0	56.4	1046.4	20.73
tc09	1039.0	56.4	1046.4	21.31
tc13	1516.55	56.4	1046.4	26.23
tc04	2039.0	56.4	1046.4	43.78



Frame example



Frame example



percentage change

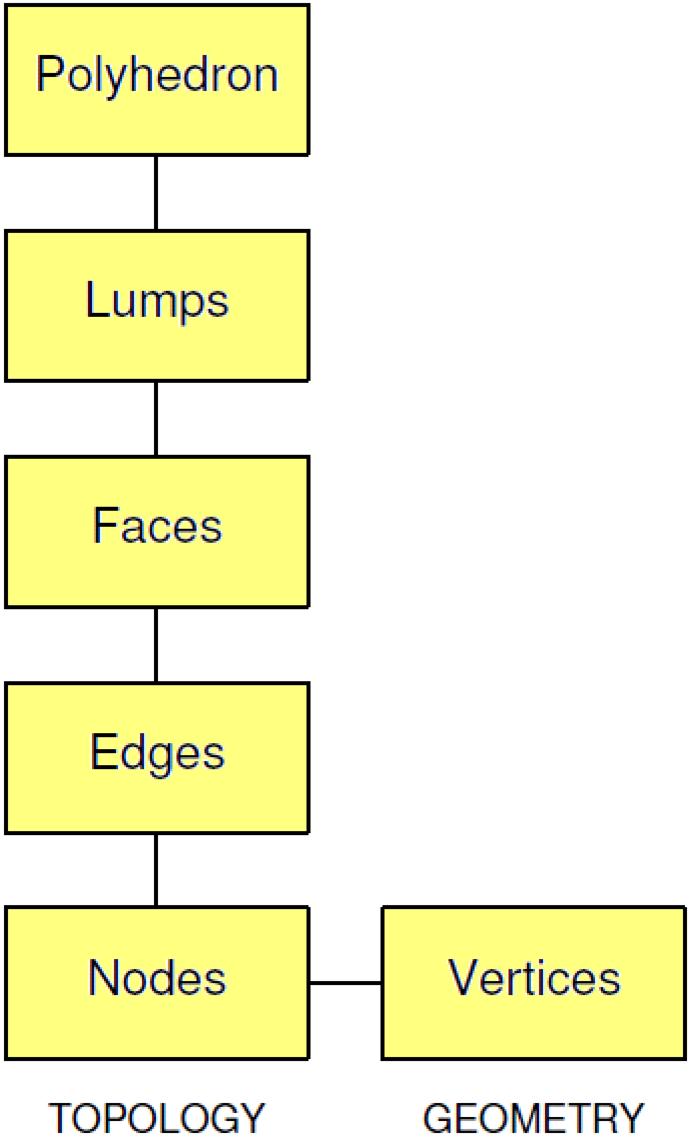
Improving FE results

Improving FE results on the basis of measurement results

Strategy

- establish a rigid-body transform at each of the measured points
- interpolate these transforms over the whole body
- for any point, transform its FE result by the interpolated transform

Polyhedron: data structure



- transform defined at each node
- interpolate across each item of the structure

Interpolation over polyhedron

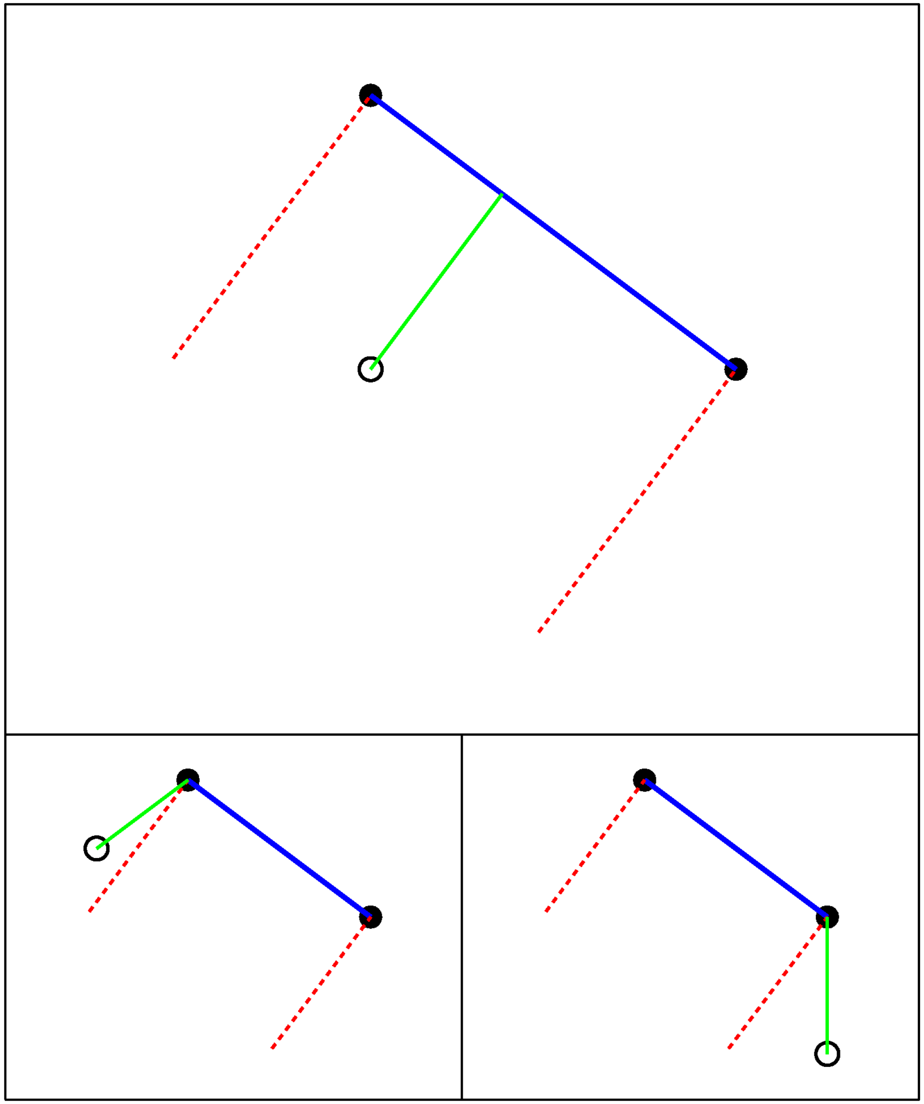
$$\mathrm{S}(\mathbf{r}) = \sum_{V \text{ in } L} \mathrm{wlump}(V, \mathbf{r}, L)\, \mathrm{S}(V)$$

Sum over vertices

Weighting function

Transform at a vertex

Distance functions: point-to-edge example



Weighting functions

Weights

$$\mathrm{wnode}(V, \mathbf{r}, N) = \begin{cases} 1 & \text{if } V \in N \text{ and } ||\mathbf{r} - V|| = 0 \\ 0 & \text{if } V \in N \text{ and } ||\mathbf{r} - V|| \neq 0 \\ 0 & \text{if } V \notin N \end{cases}$$

$$\mathrm{wedge}(V, \mathbf{r}, E) = \begin{cases} \dfrac{\sum_{N \in E} \mathrm{wnode}(V, N, \mathrm{proj}(\mathbf{r}, N))/\mathrm{dist}(\mathbf{r}, N)}{\sum_{N \in E} 1/\mathrm{dist}(\mathbf{r}, N)} & \text{if } V \in E \\ 0 & \text{if } V \notin E \end{cases}$$

$$\mathrm{wface}(V, \mathbf{r}, F) = \begin{cases} \dfrac{\sum_{E \in F} \mathrm{wedge}(V, E, \mathrm{proj}(\mathbf{r}, E))/\mathrm{dist}(\mathbf{r}, E)}{\sum_{E \in F} 1/\mathrm{dist}(\mathbf{r}, E)} & \text{if } V \in F \\ 0 & \text{if } V \notin F \end{cases}$$

$$\mathrm{wlump}(V, \mathbf{r}, L) = \begin{cases} \dfrac{\sum_{F \in L} \mathrm{wface}(V, F, \mathrm{proj}(\mathbf{r}, F))/\mathrm{dist}(\mathbf{r}, F)}{\sum_{F \in L} 1/\mathrm{dist}(\mathbf{r}, F)} & \text{if } V \in L \\ 0 & \text{if } V \notin L \end{cases}$$

Weighting functions

Weights

$$\mathrm{wnode}(V,\mathbf{r},N)=\begin{cases}1 & \text{if } V\in N \text{ and } ||\mathbf{r}-V||=0\\ 0 & \text{if } V\in N \text{ and } ||\mathbf{r}-V||\neq 0\\ 0 & \text{if } V\notin N\end{cases}$$

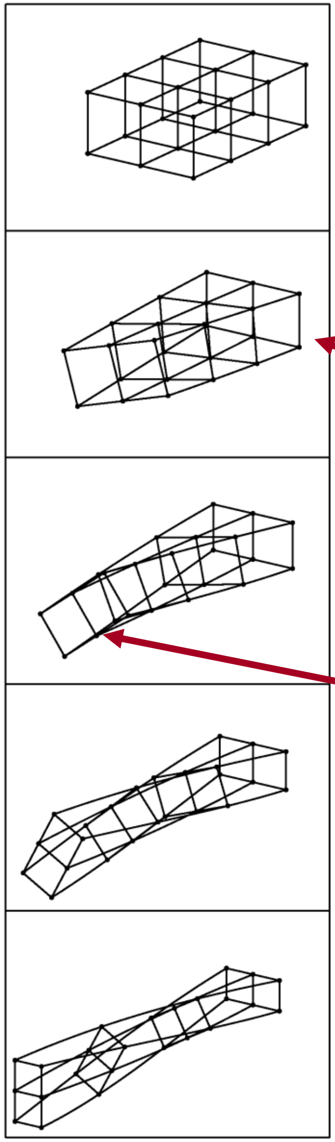
$\mathrm{wedge}(V,\mathbf{r},E)=$

$$\mathrm{wlump}(V,\mathbf{r},L)=\begin{cases}\dfrac{\sum\limits_{F\in L}\mathrm{wface}(V,F,\mathrm{proj}(\mathbf{r},F))/\mathrm{dist}(\mathbf{r},F)}{\sum\limits_{F\in L}1/\mathrm{dist}(\mathbf{r},F)} & \text{if } V\in L\\ 0 & \text{if } V\notin L\end{cases}$$

$\mathrm{wface}(V,\mathbf{r},F)=\Big\{\ \sum\limits_{E\in F}1/\mathrm{dist}(\mathbf{r},E)$ ... 0 if $V\notin F$

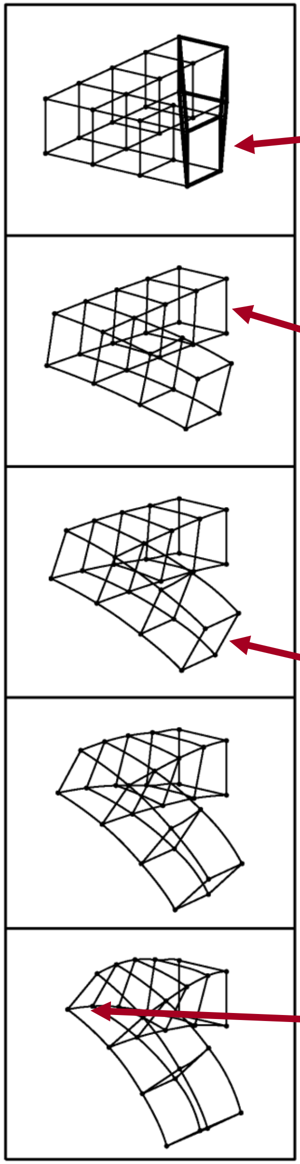
$$\mathrm{wlump}(V,\mathbf{r},L)=\begin{cases}\dfrac{\sum\limits_{F\in L}\mathrm{wface}(V,F,\mathrm{proj}(\mathbf{r},F))/\mathrm{dist}(\mathbf{r},F)}{\sum\limits_{F\in L}1/\mathrm{dist}(\mathbf{r},F)} & \text{if } V\in L\\ 0 & \text{if } V\notin L\end{cases}$$

Cuboid: twist and stretch



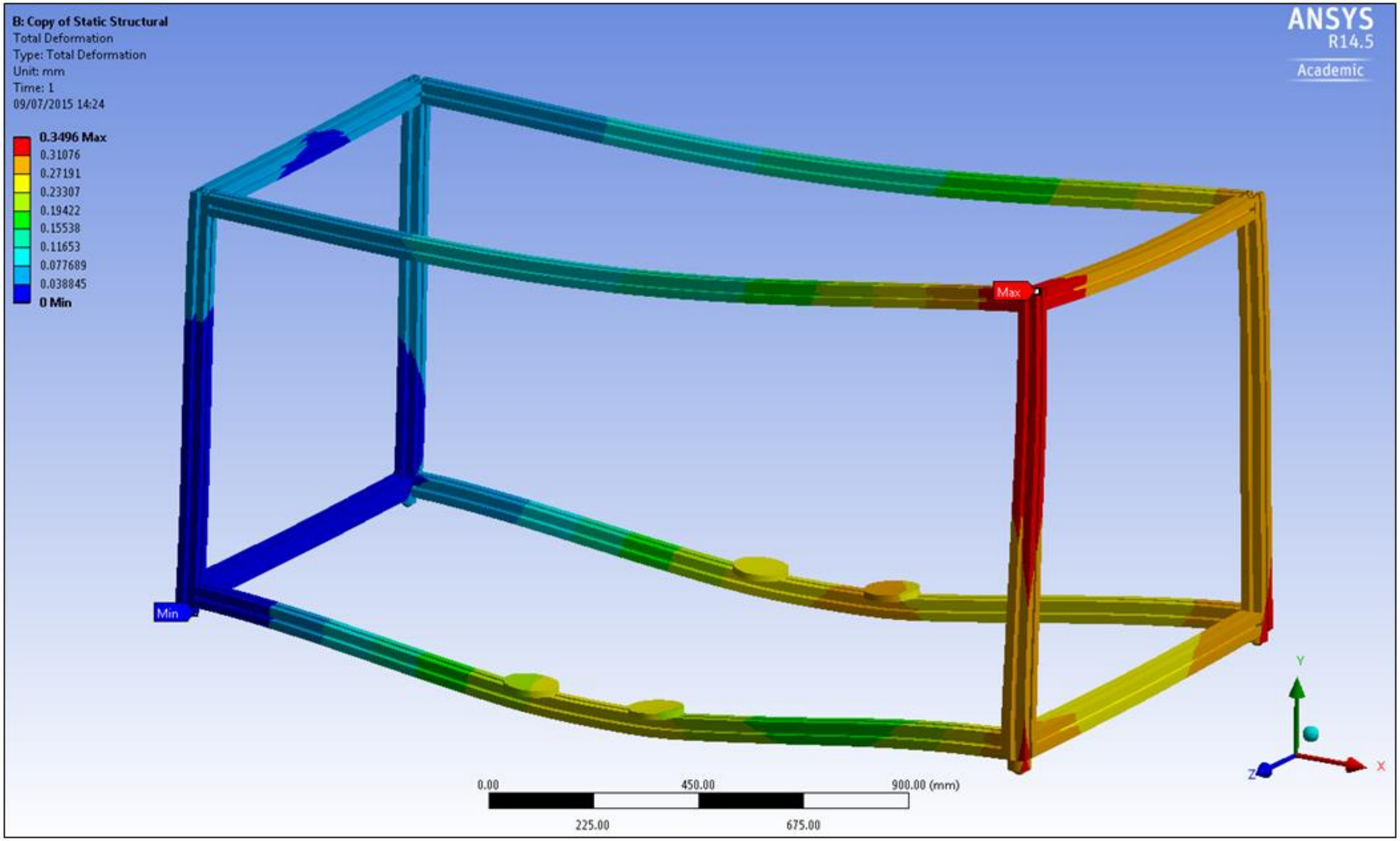
- cuboid is its own polyhedron
- back four nodes fixed
- front four nodes pulled forward and twisted

L-shaped block: twist

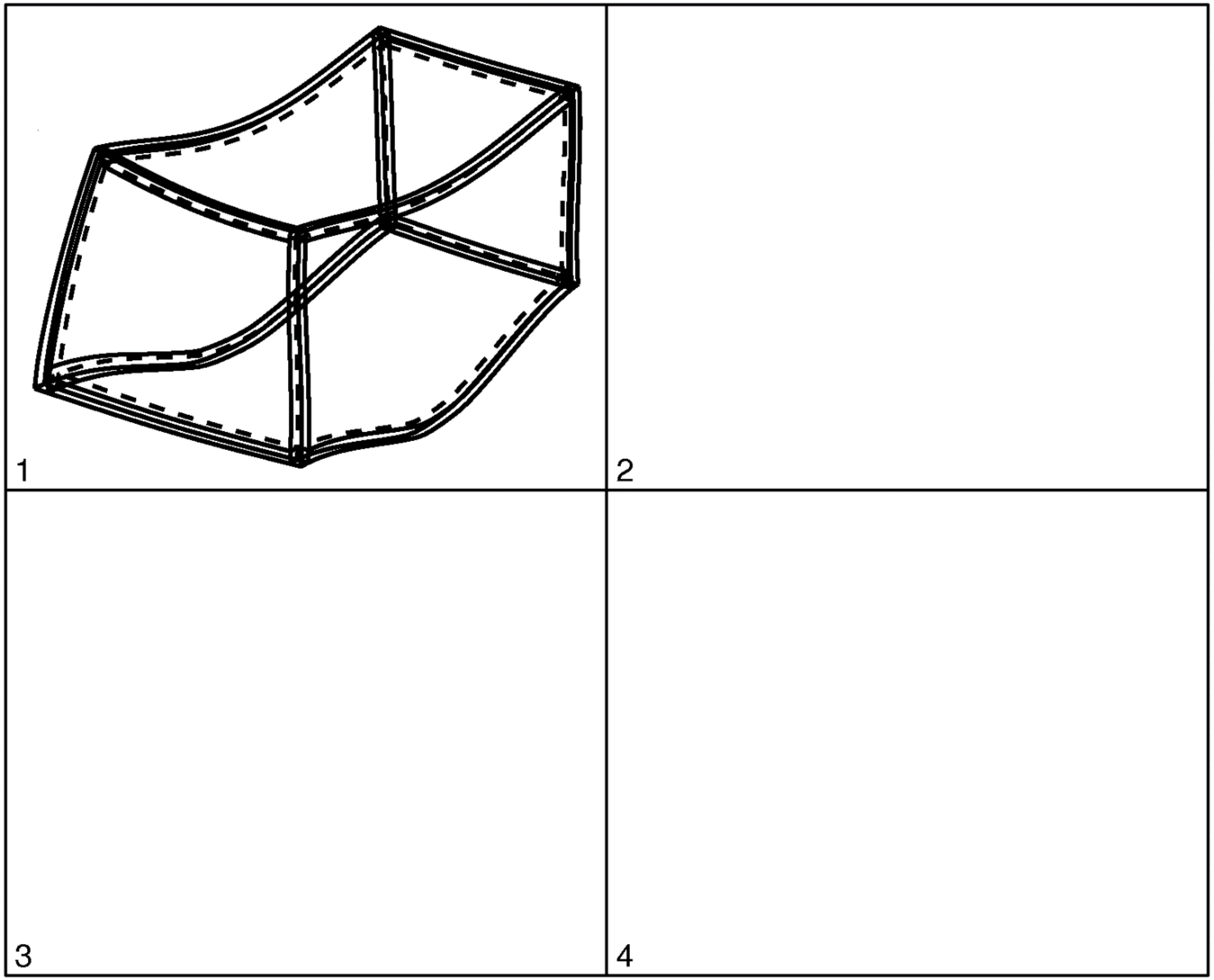


- polyhedron covers only part of block
- back four nodes fixed
- other four nodes twisted
- remaining nodes move smoothly

FE modelling

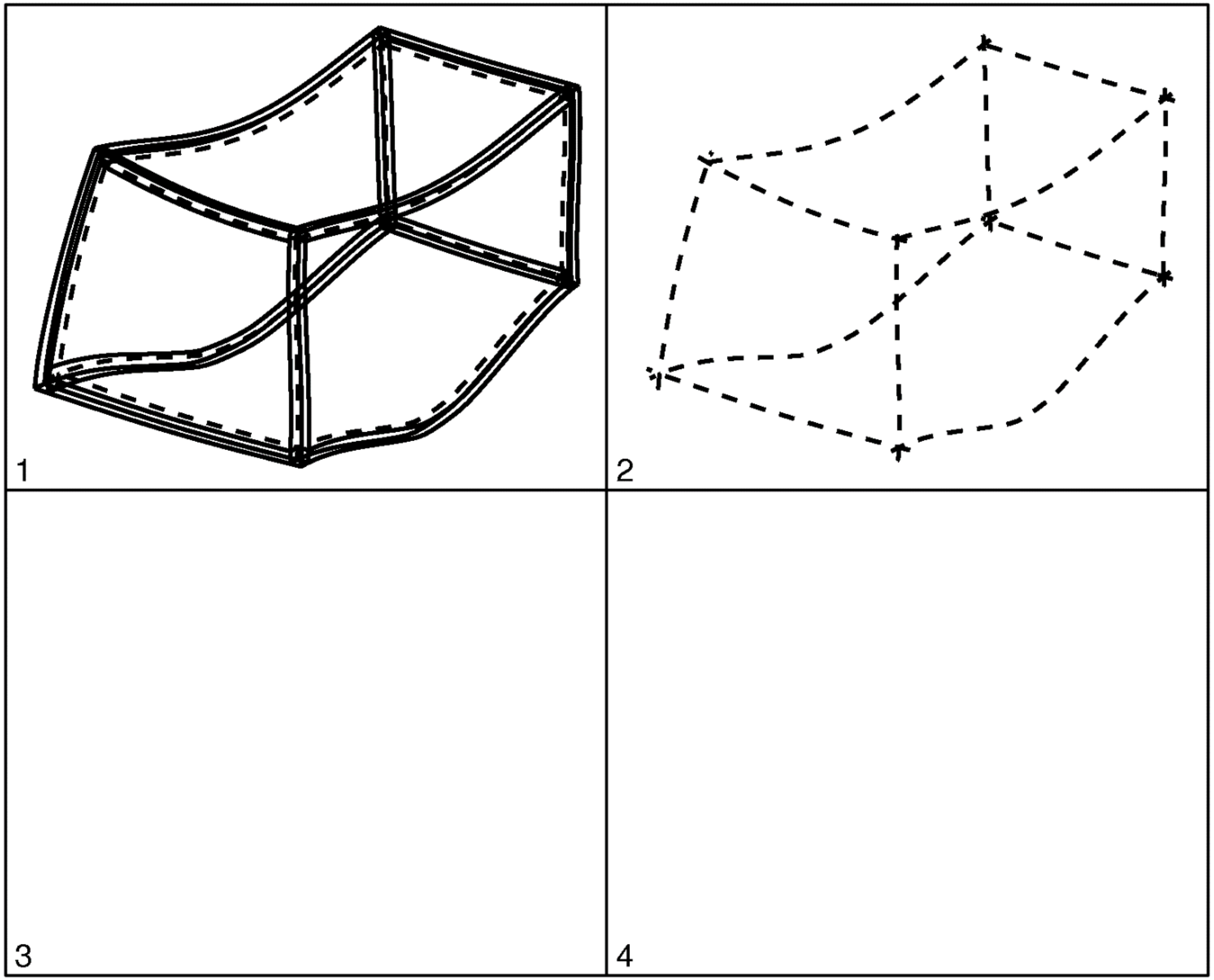


Comparison example



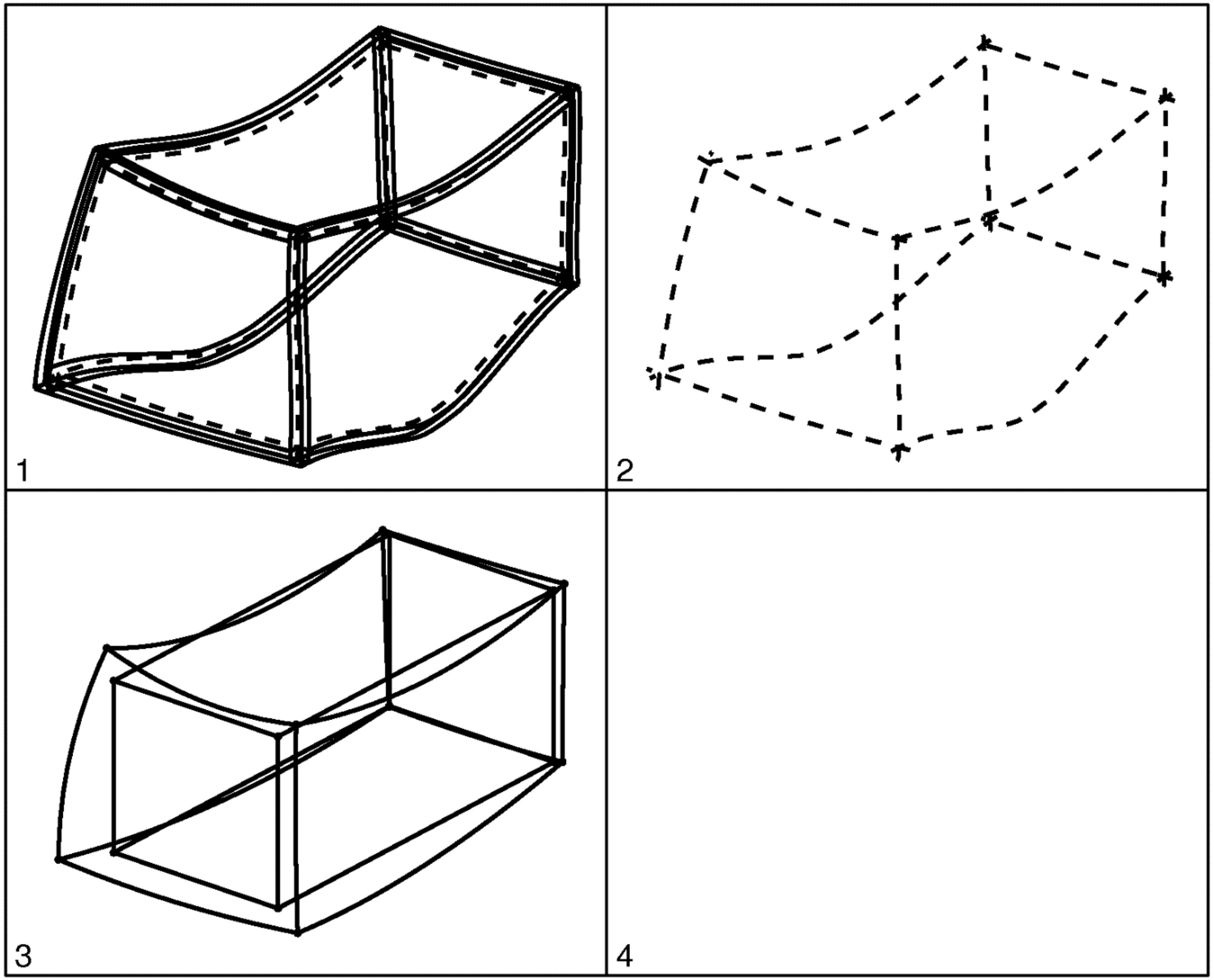
FEA model of deformation

Comparison example



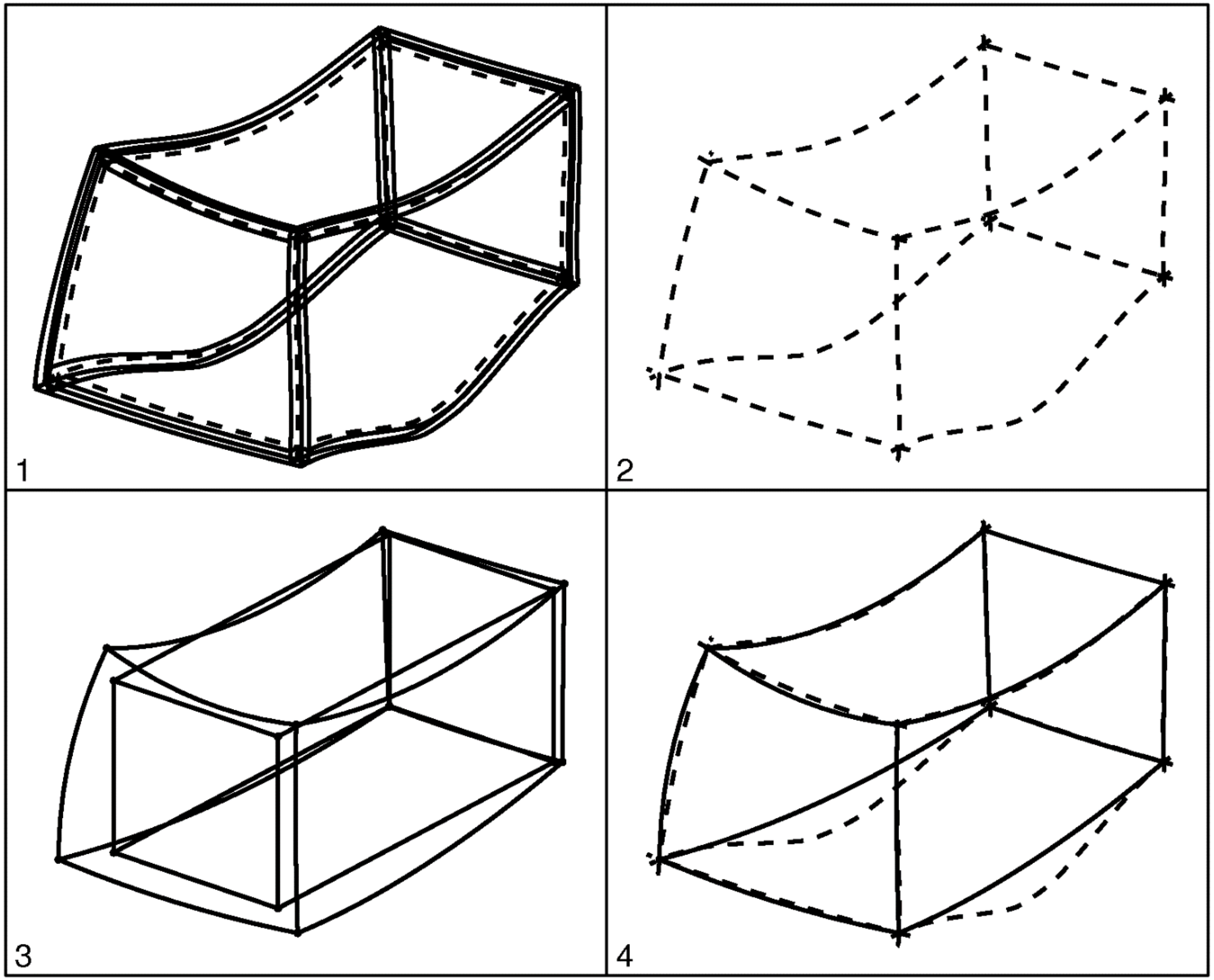
Extract inner cuboid

Comparison example



Compare with original

Comparison example



Interpolate transforms

Conclusions

- problem of thermal/gravitational effects when measuring
- hybrid approach: geometric model and physical component
- FE to predict distortions
- can replace explicit thermal analysis with interpolation
- can adjust FE results so that they agree with measured results