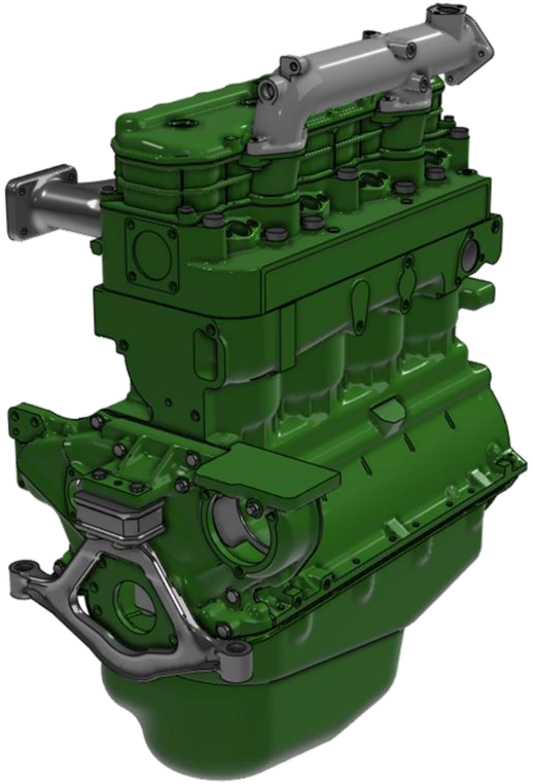
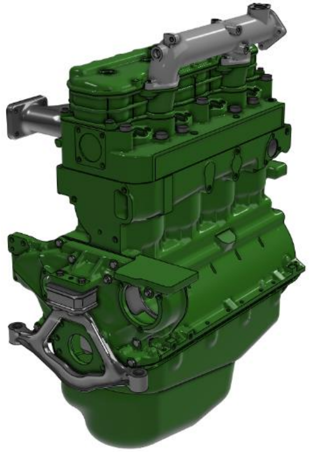
A large-scale implicit case study -
demonstrating some new features in LS-DYNA R13.0.0



Fredrik Bengzon, Thomas Borrvall, Anders Jonsson
DYNAmore Nordic AB, Ansys LST

Introduction

- New and extended functionality for LS-DYNA R13.0.0 implicit
  - Non-linear isotropic/kinematic hardening (*MAT_DAMAGE_3) w. temperature dependence
  - Gasket elements (*MAT_COHESIVE_GASKET and cohesive elements)
  - New enhanced assumed strain hexahedral element (*SECTION_SOLID, *ELFORM*=-18)
  - New functionality for bolt pre-tension (*INITIAL_STRESS_SECTION)
- applied to a large-scale implicit case study
  - 3.9E6 nodes,
  - 2.4E6 elements
- Also test existing features:
  - Contacts
  - New approach to load history management
  - Fatigue analysis (*MAT_ADD_FATIGUE and *FATIGUE)

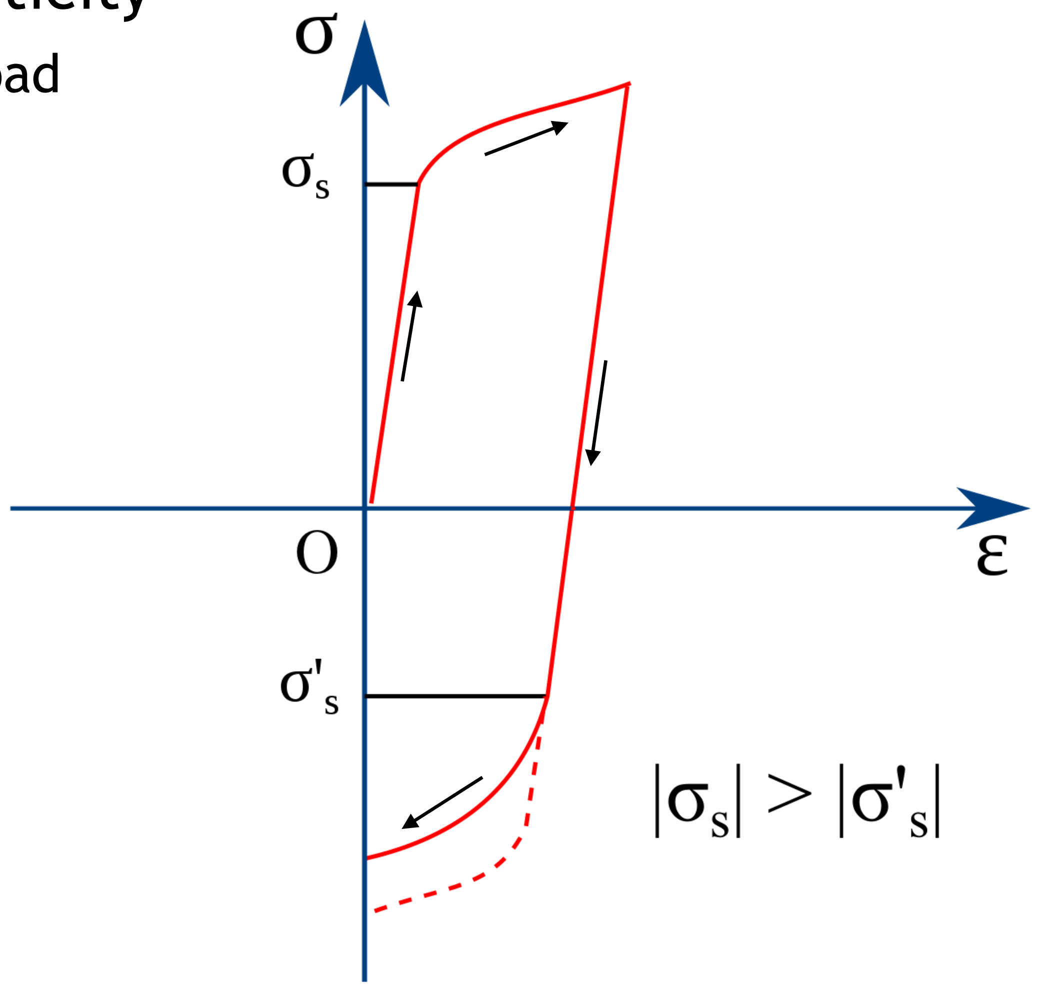


Non-linear isotropic/kinematic hardening material model

- *MAT_DAMAGE_3,(*MAT_153) for metals subjected to cyclic loading
  - From R13.0.0, extended to temperature dependent material parameters
  - Based on the works by Lemaitre/Dufailly/Chaboche
  - Often used in evaluations of cyclic plasticity, Low Cycle Fatigue and Thermo Mechanical Fatigue
  - Up to 10 back stress terms for kinematic hardening
  - Strain rate effects by Cowper-Symonds
  - Damage mechanics (driven by plastic strain) and failure
- Can capture many (but not all) observed behaviours related to cyclic loading
  - Bauschinger effect
  - Plastic shakedown
  - Ratcheting
  - Mean stress relaxation

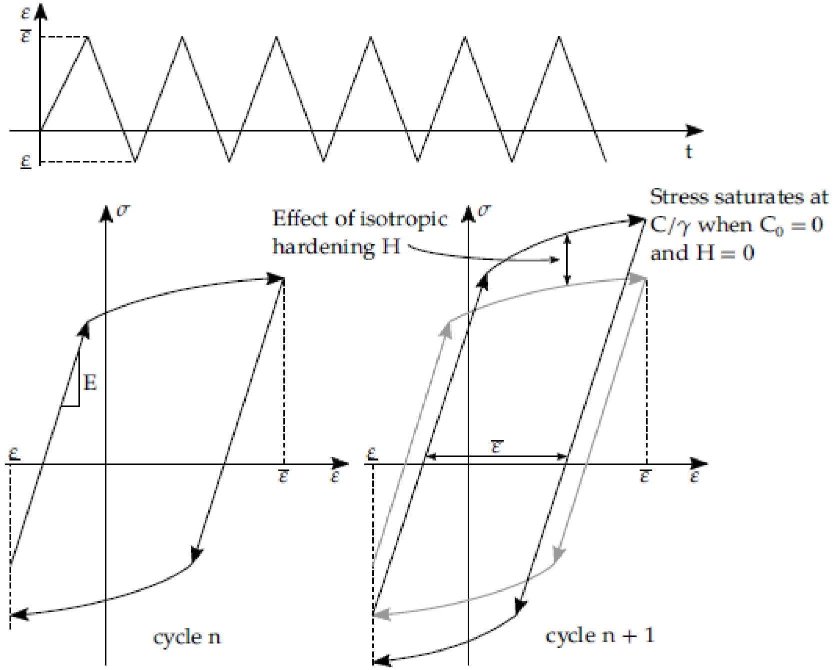
Non-linear isotropic/kinematic hardening material model

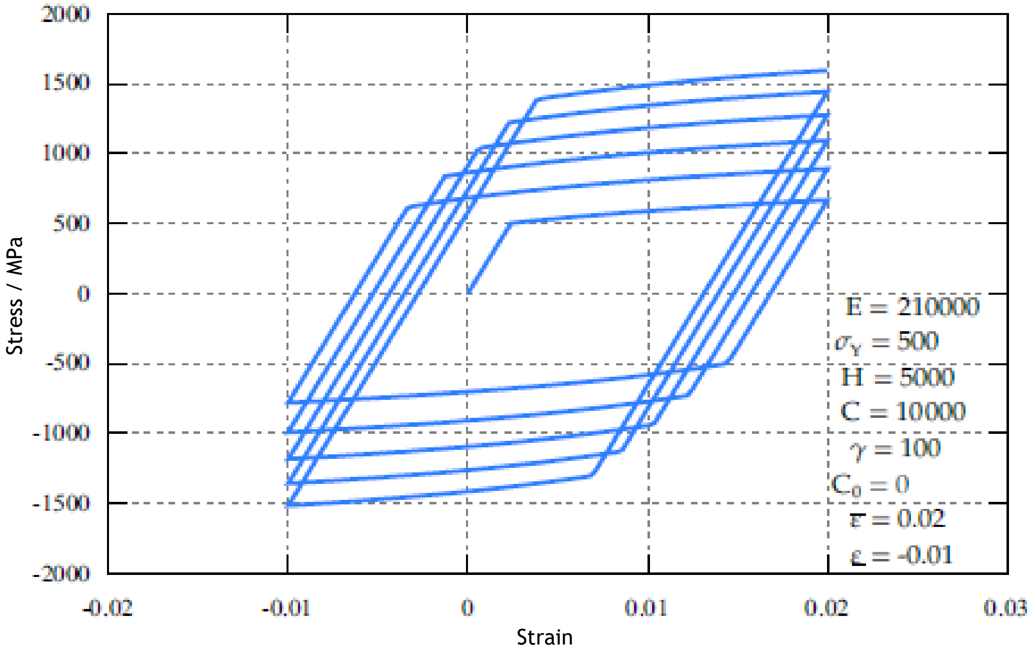
- *MAT_DAMAGE_3,(*MAT_153) for cyclic plasticity
  - **Bauschinger effect**: A reduced yield stress upon load reversal after initial plastic deformation
  - Plastic shakedown
  - Ratchetting
  - Mean stress relaxation



Non-linear isotropic/kinematic hardening material model

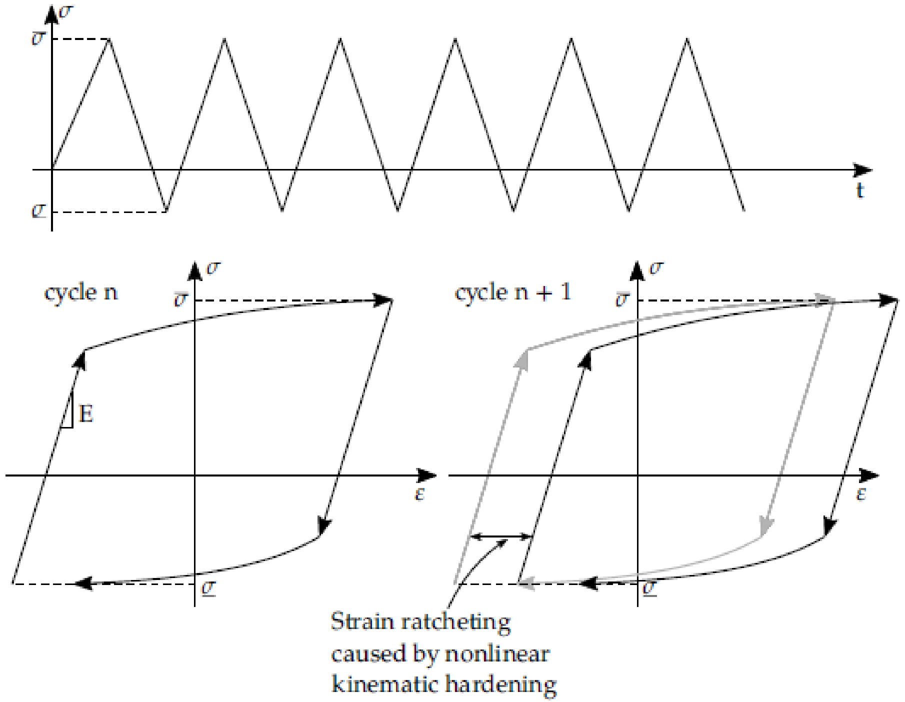
- *MAT_DAMAGE_3,(*MAT_153) for cyclic plasticity
  - **Plastic shakedown:** In a strain-controlled experiment, metals tends to harden towards a stabilized cycle
  - Ratchetting
  - Mean stress relaxation

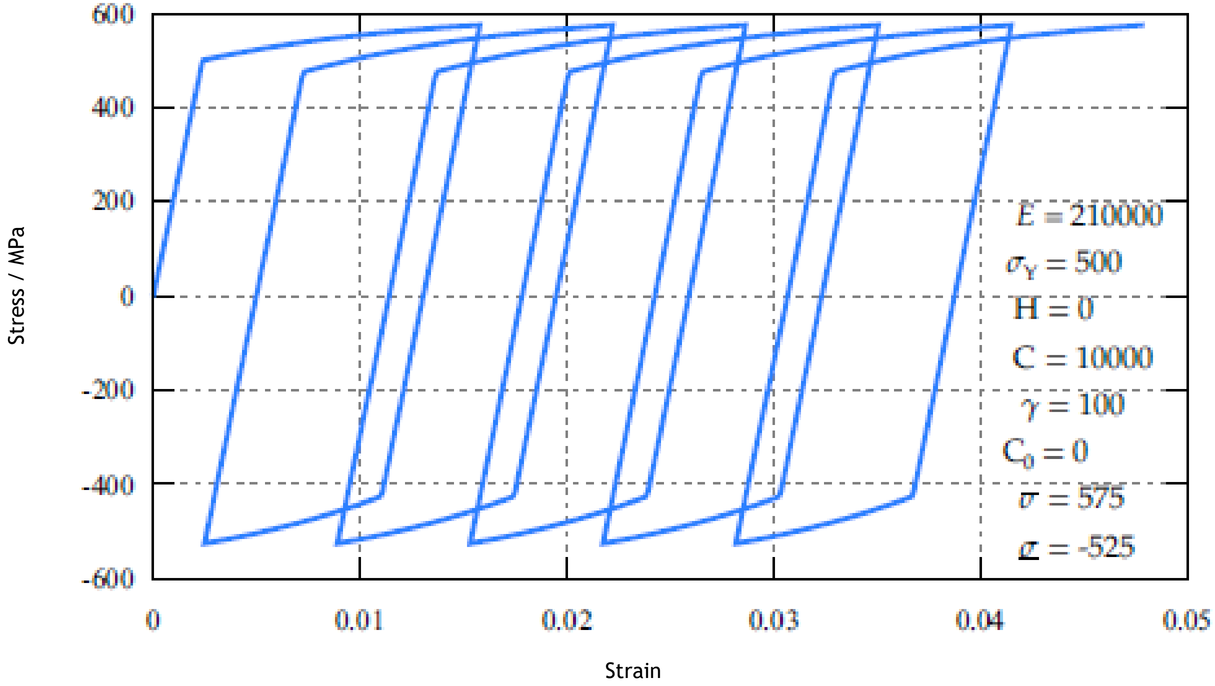




Non-linear isotropic/kinematic hardening material model

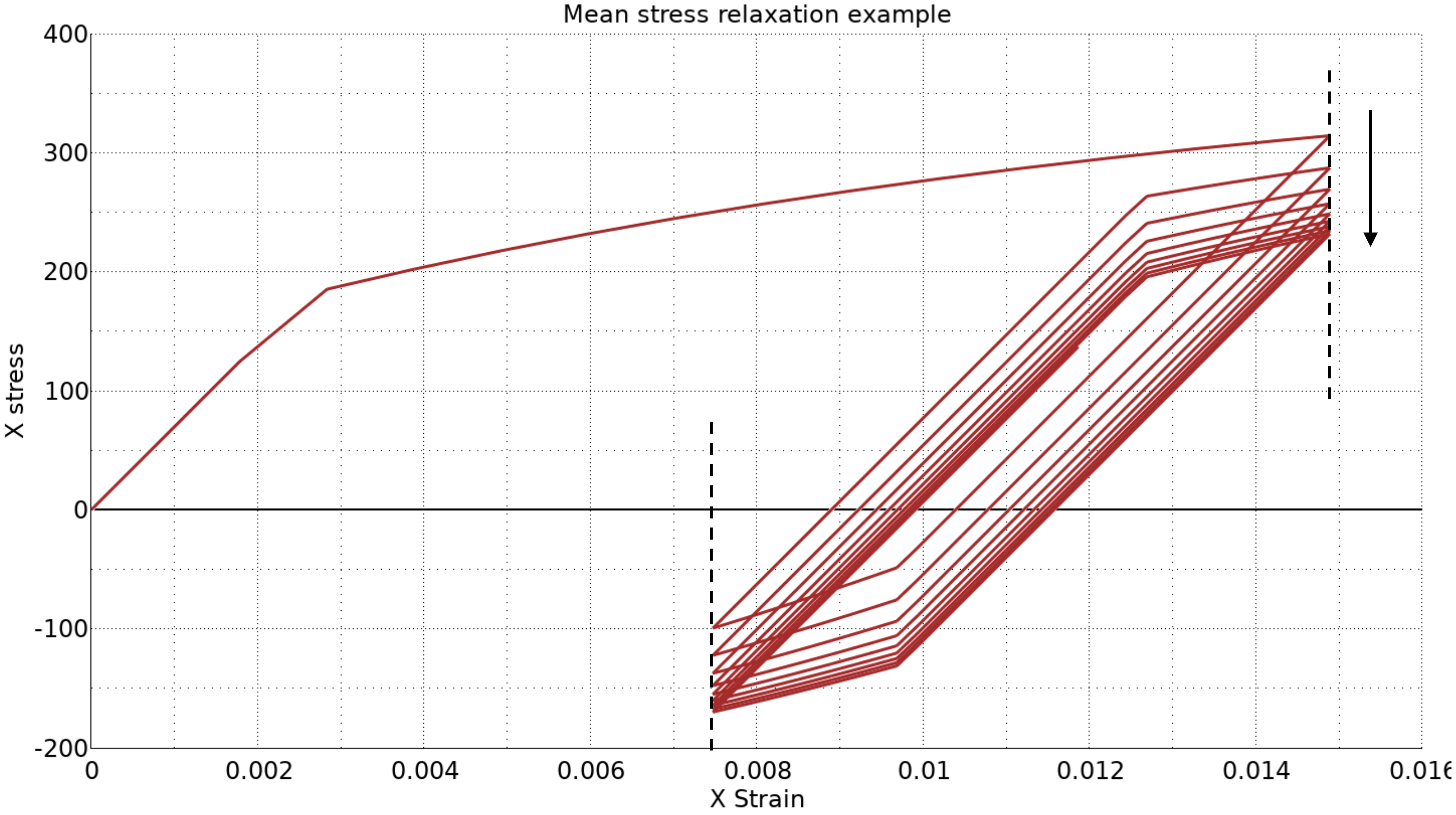
- *MAT_DAMAGE_3,(*MAT_153) for cyclic plasticity
  - **Ratchetting:** Unsymmetric cycles of stress between prescribed limits causes progressive “creep” or “ratchetting” in the direction of the mean stress
  - Mean stress relaxation





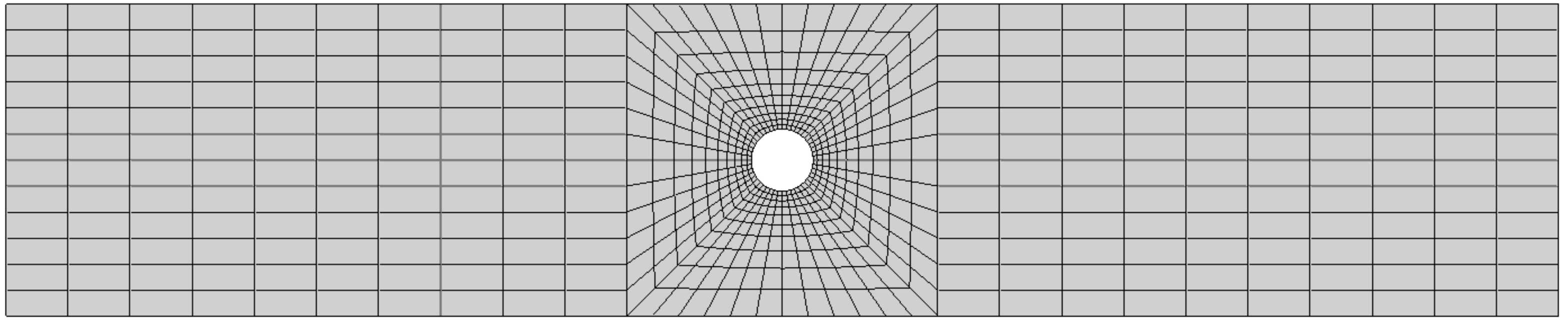
Non-linear isotropic/kinematic hardening material model

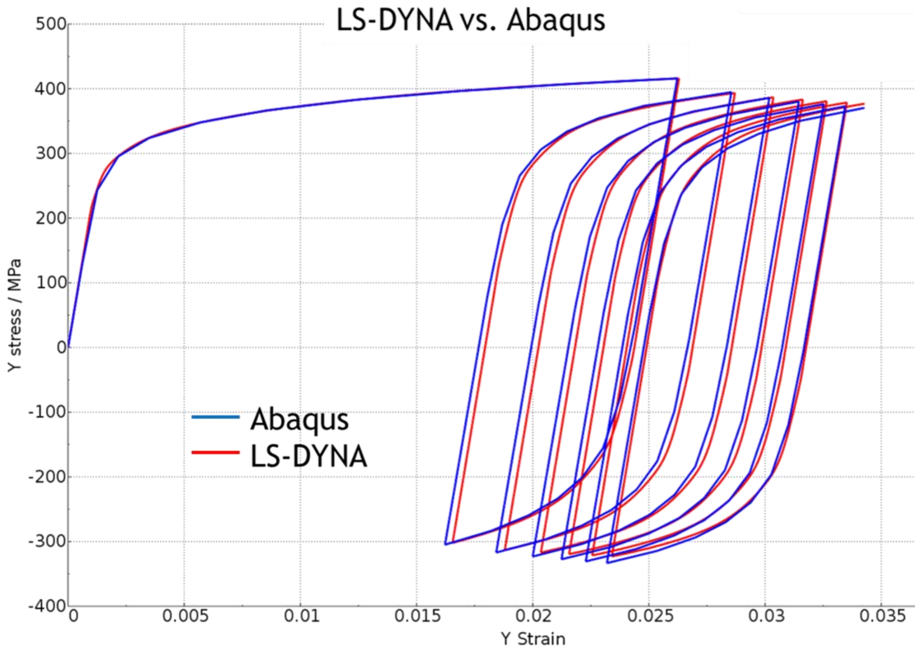
- *MAT_DAMAGE_3,(*MAT_153) for cyclic plasticity
  - **Mean stress relaxation:** In an unsymmetric strain-controlled test, the mean stress tends to zero.



Non-linear isotropic/kinematic hardening material model

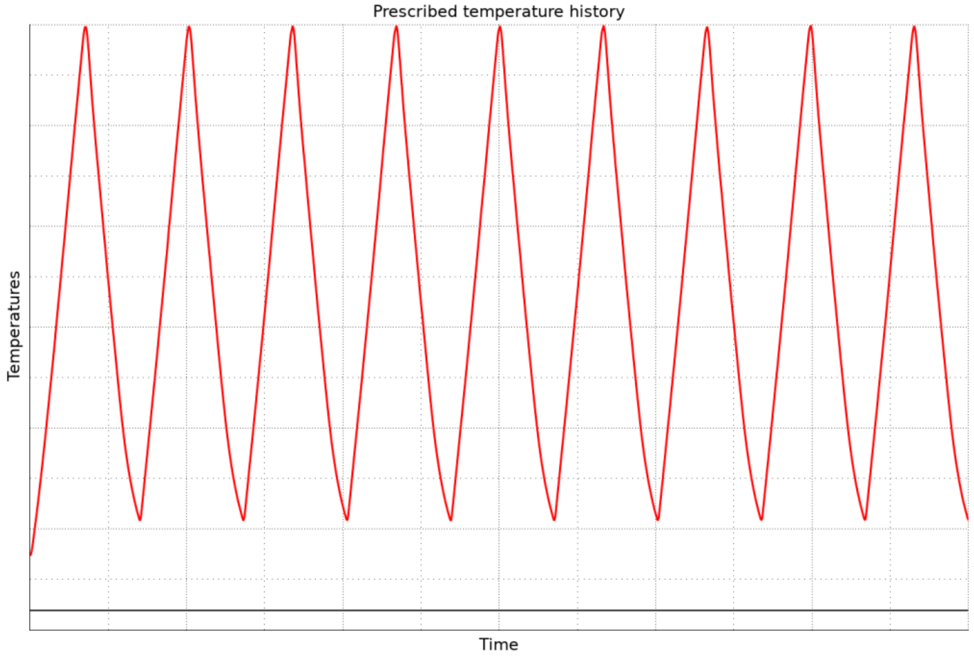
- *MAT_DAMAGE_3,(*MAT_153) for cyclic plasticity
  - Baushinger effect
  - Plastic shakedown
  - Ratchetting
  - Mean stress relaxation
  - **Combinations of the above**

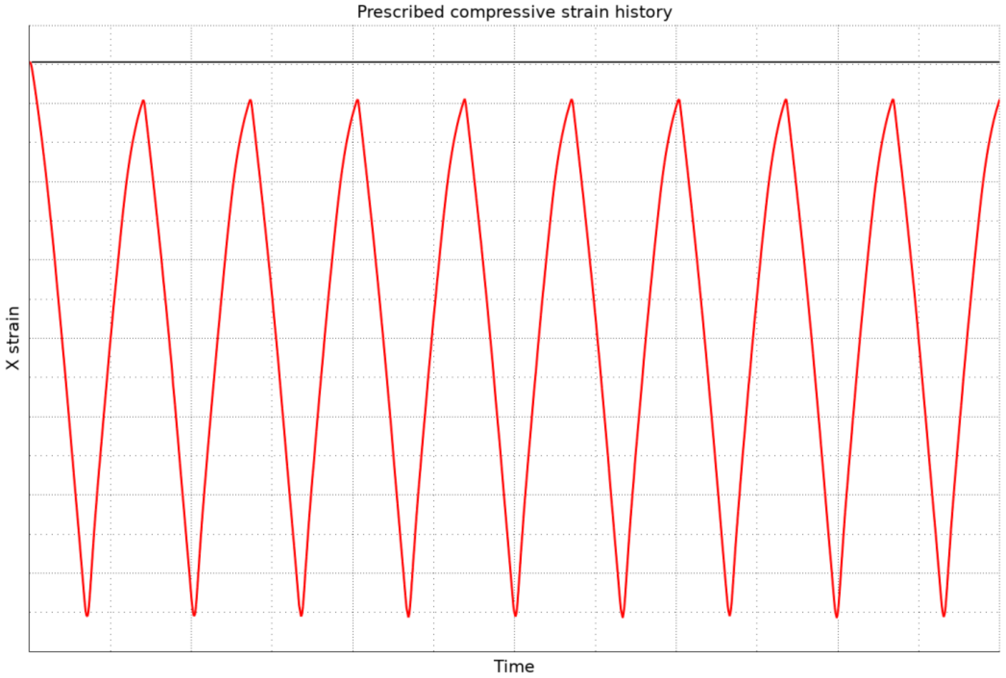




Non-linear isotropic/kinematic hardening material model

- With the introduction of temperature dependent material parameters, it is now also possible to apply to analyses of Thermo Mechanical Fatigue
- Thermal- and mechanical loading example
  - Prescribed temperature and strain history
  - “In-phase” loading: high temperature and high compressive strain at the same time





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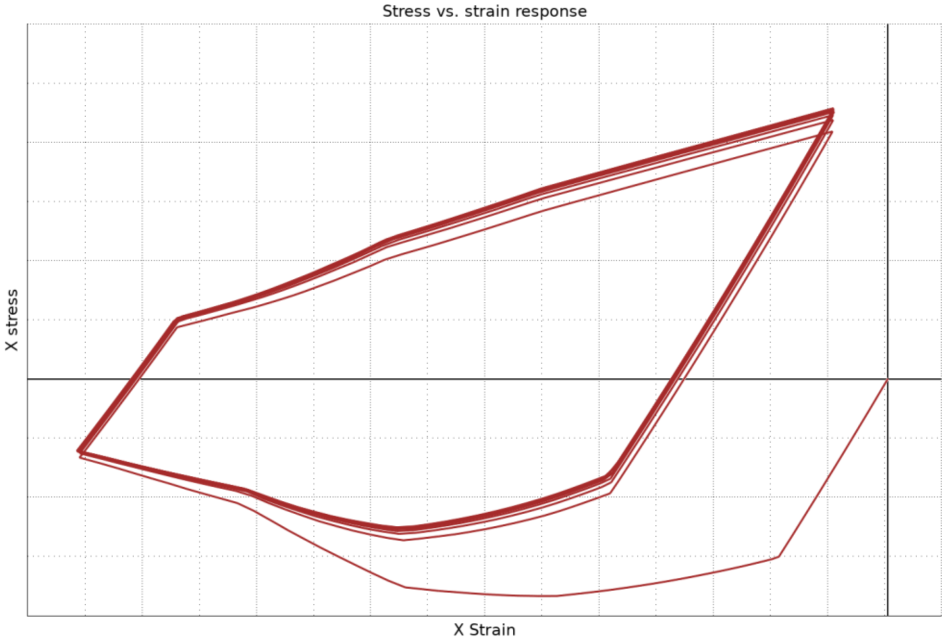
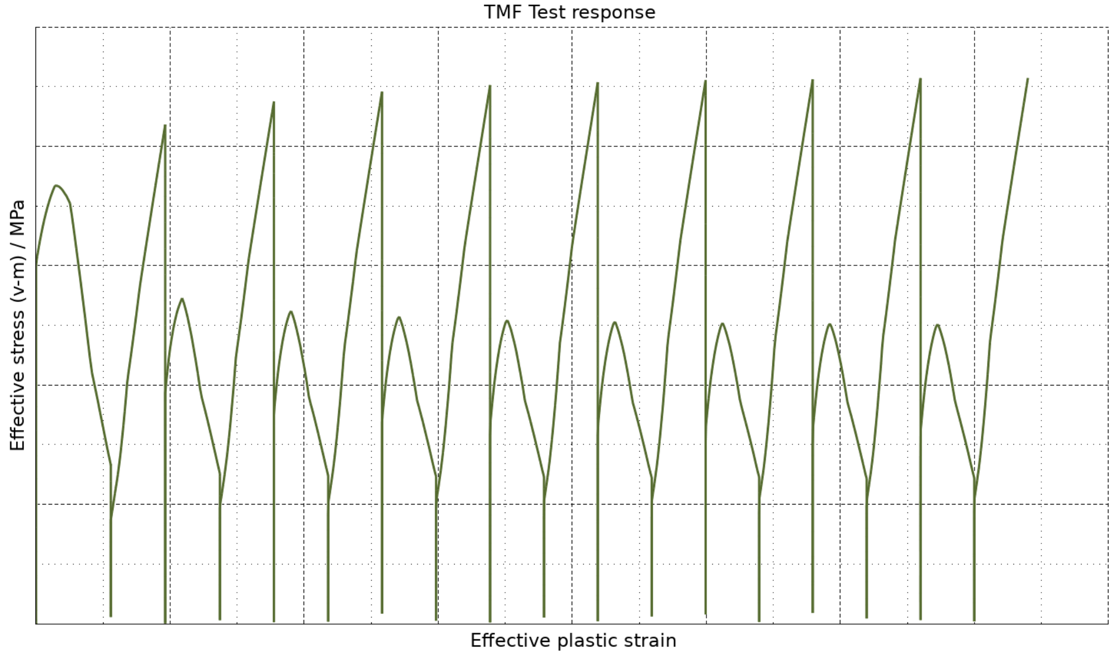




Non-linear isotropic/kinematic hardening material model

```
*MAT_DAMAGE_3_TITLE
SiMo as MAT_DAMAGE_3
$# 1    mid        rho        E        pr     sigy     hardi     beta     lcss
        500    7.85E-9     -501     -502
$# 2                                           src       srp
$# 3                                                            khflg
                                                                    2
$# 4  lckh      nkh
       530        4
```

load curve (or table ID for temperature dependence) defining isotropic hardening

E = -LCID for E vs. temp

pr = -LCID for ν vs. temp

strain rate effects can be included by the Cowper and Symonds model (scale yield stress)

khflg = 1 : direct input of hardening parameters
khflg = 2 : fit to half cycle
khflg = 3 : fit to stabilized cycle

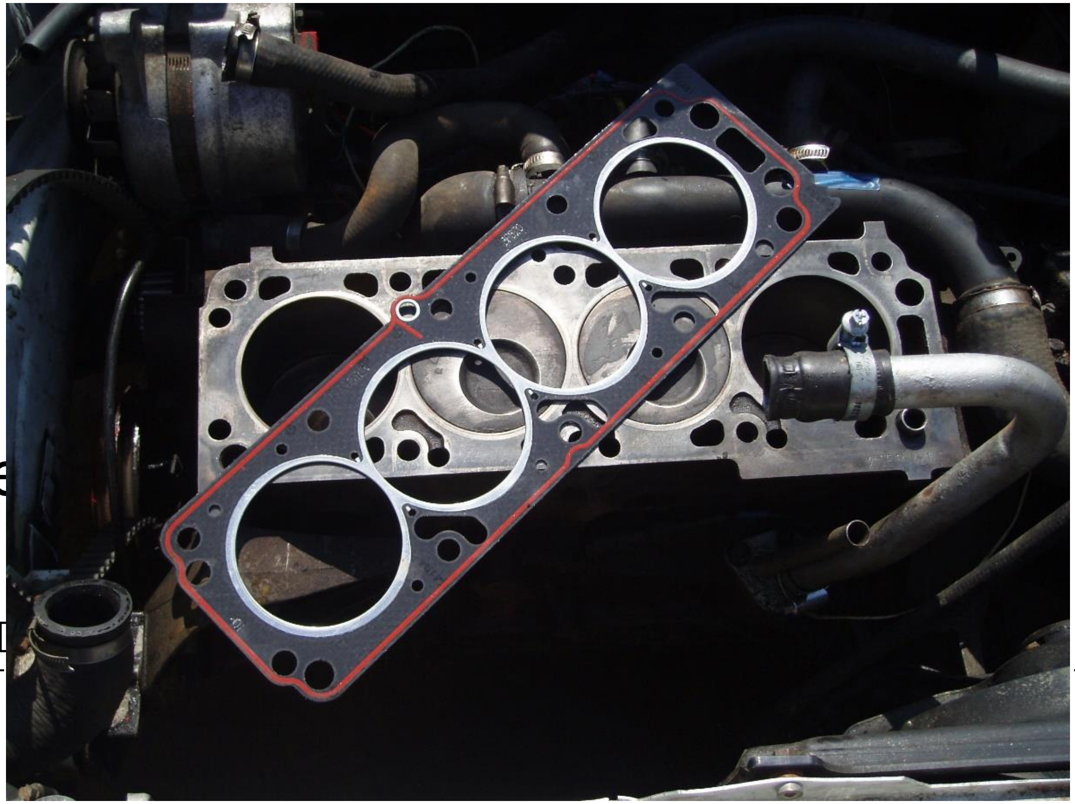
nkh = number of hardening parameters to fit

load curve (or table ID for temperature dependence) defining kinematic hardening

Note! Use `*MAT_ADD_THERMAL_EXPANSION` to include thermal expansion

Modelling gaskets

- Complicated components
  - High requirements on large deformations
  - Many tiny details
  - Incompressible materials, high contact pressure
- `*MAT_COHESIVE_GASKET` and cohesive ele
  - “High level” model for gaskets, from R13.0.0
  - Gasket thickness specified by *GASKETT* on *SECT

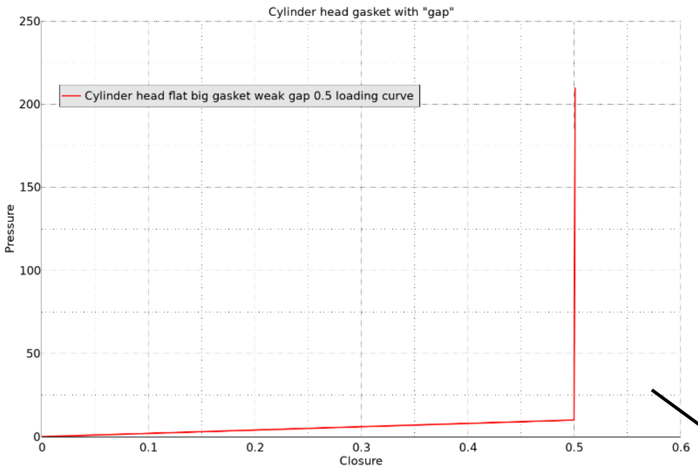


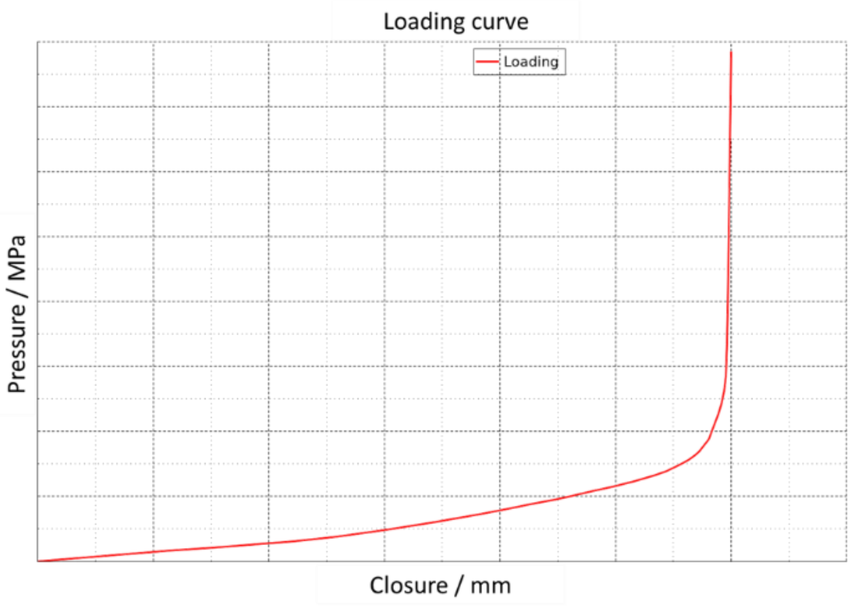
```
*SECTION_SOLID
$     secid    elform        aet
       2020        19                                                      1.5
```

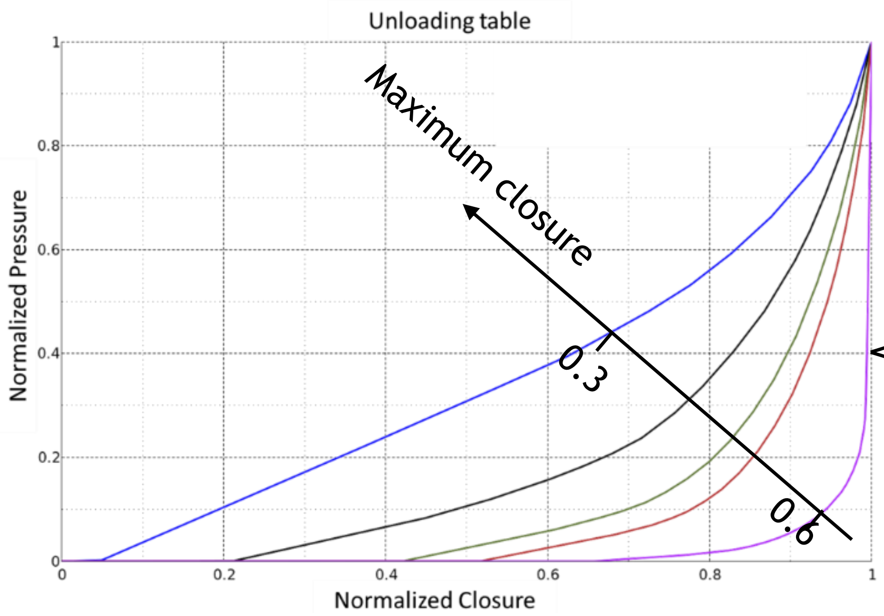
- Useful for evaluation of sealing performance
  - Contact pressure
  - Closure (opening)

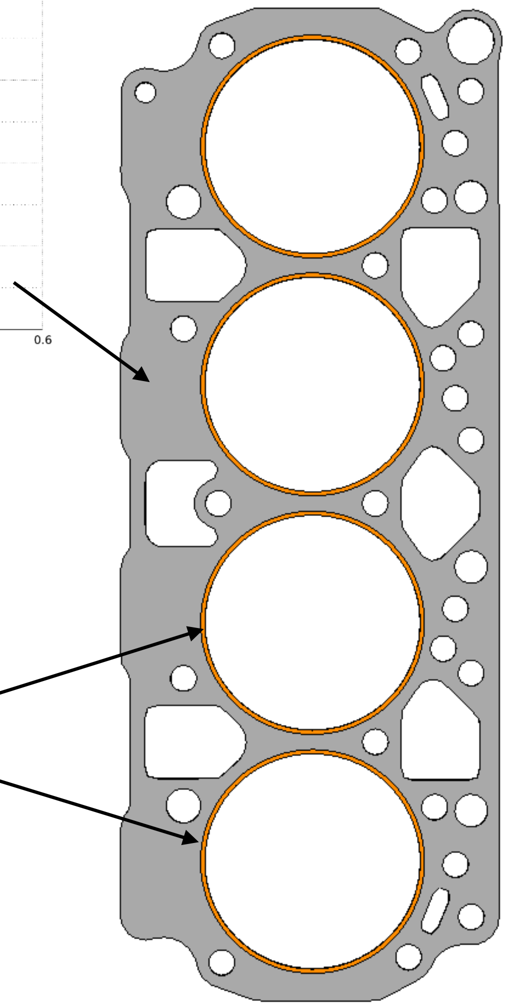
Modelling gaskets

- *MAT_COHESIVE_GASKET with cohesive
  - Pressure vs. closure curve for loading
  - Table of Normalized pressure vs. normalized cl
  - Model gaps by an initially very low stiffness



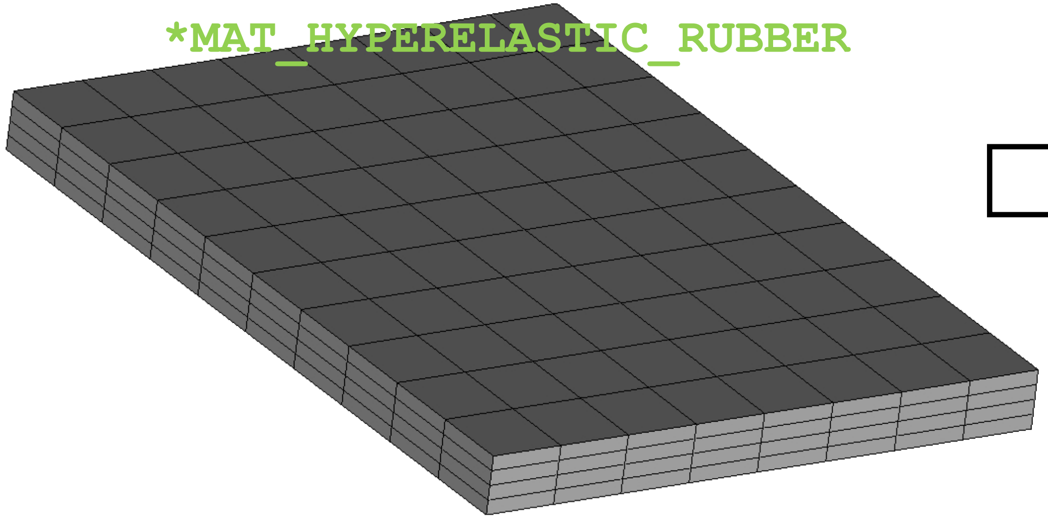




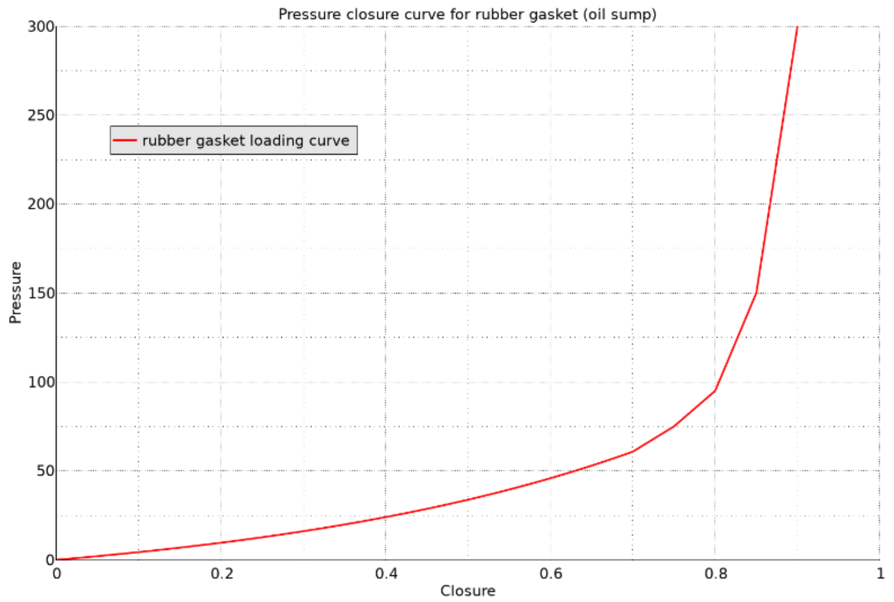


Modelling gaskets

- *MAT_COHESIVE_GASKET:
  - Pressure/closure curves either from testing, or provided by gasket supplier
  - Alternatively determine material parameters from a detailed local model
  - For example, compression of a rubber sealing



***MAT_COHESIVE_GASKET**

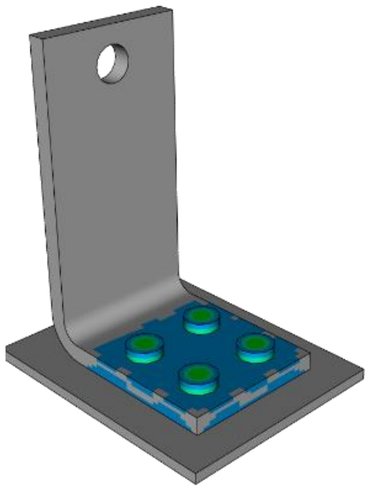


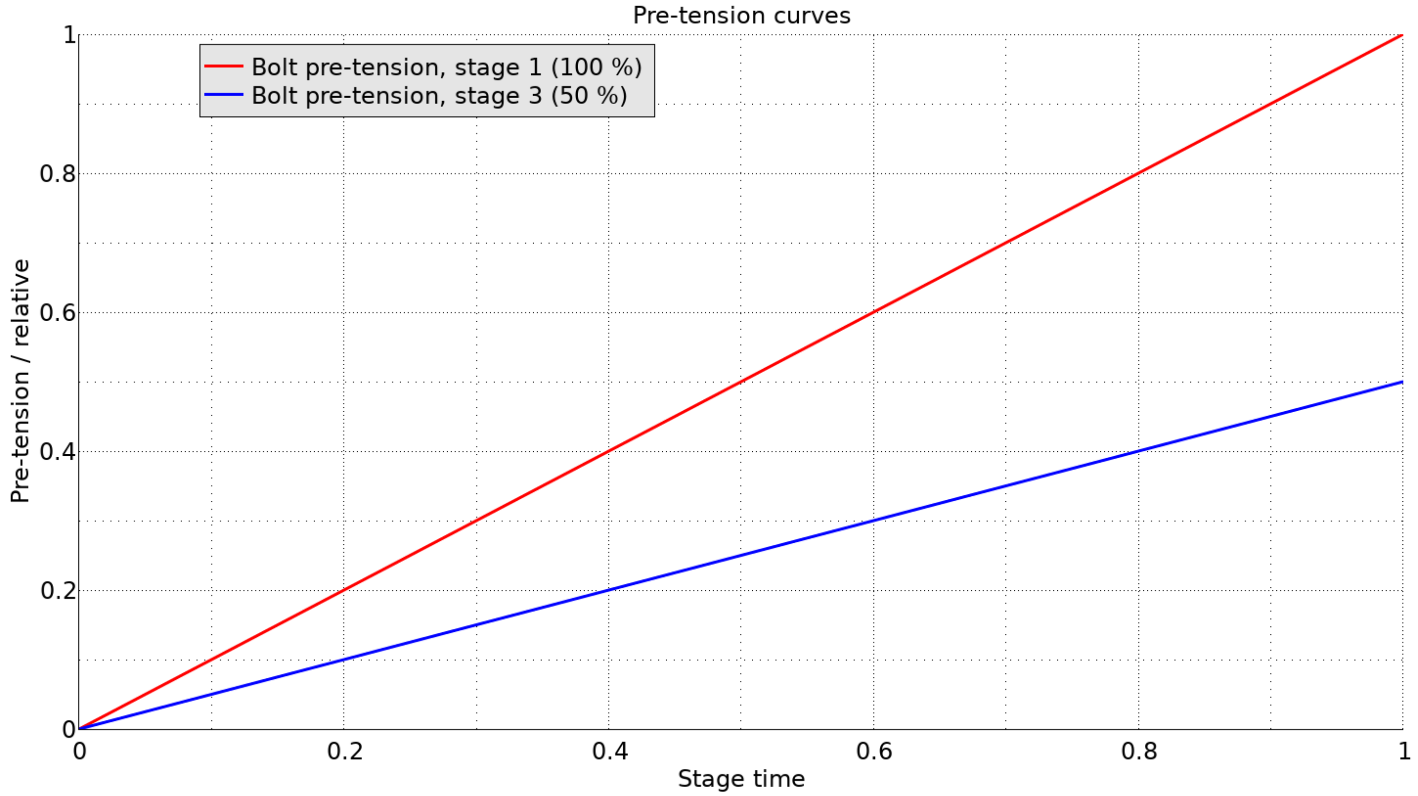
Load history management using *CASE and dynain.lsda

- An analysis consisting of a sequence of separate loadings or load steps can conveniently be divided into a sequence of LS-DYNA analyses
- Information is propagated via `dynain.lsda` - files from one load stage to the next
  - `*INTERFACE_SPRINGBACK_LSDYNA`, *FTYPE* = 3
  - Binary file containing deformed geometry, initial stresses, history variables, contact state from **Mortar contacts**, etc.
  - A bit similar to a restart file
  - Full flexibility to modify control cards settings, add parts etc. between stages
- The analyses are run automatically in a sequence
  - `*CASE` - functionality
  - Stage *n+1* starts with the final configuration of stage *n* as initial conditions

Reduction of bolt pre-tension

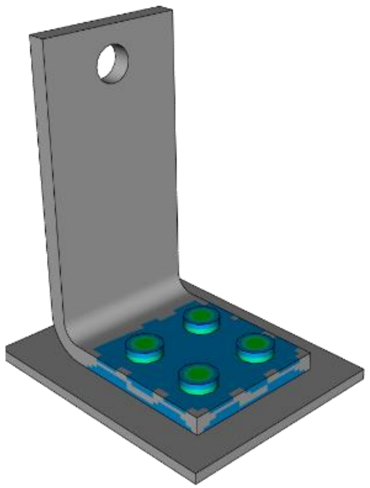
- Simulate loss of pre-tension, for example due to wear or creep
- Use `*CASE` and `dynain.lsda` for describing the stages
- Example:
  - Stage 1: Pre-tension, 100 %
  - Stage 2: Loading
  - Stage 3: Reduced pre-tension, 50 %

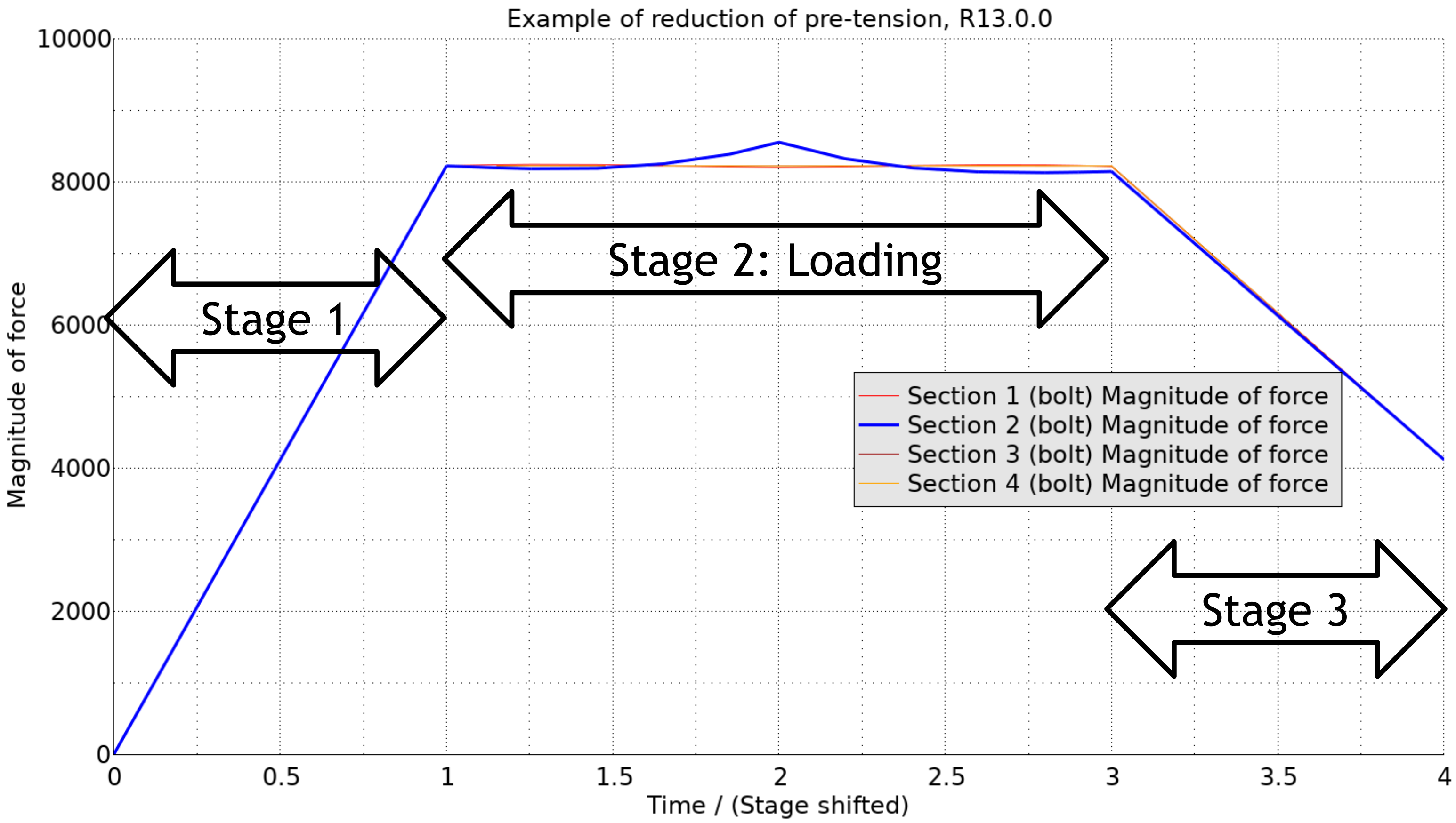




Reduction of bolt pre-tension

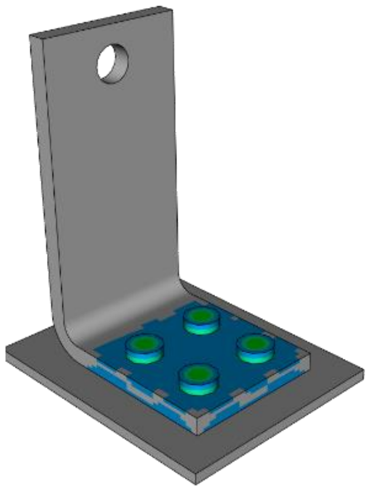
- Simulate loss of pre-tension, for example due to wear or creep
- Use `*CASE` and `dynain.lsda` for describing the stages
- Results: Bolt forces in R13.0.0

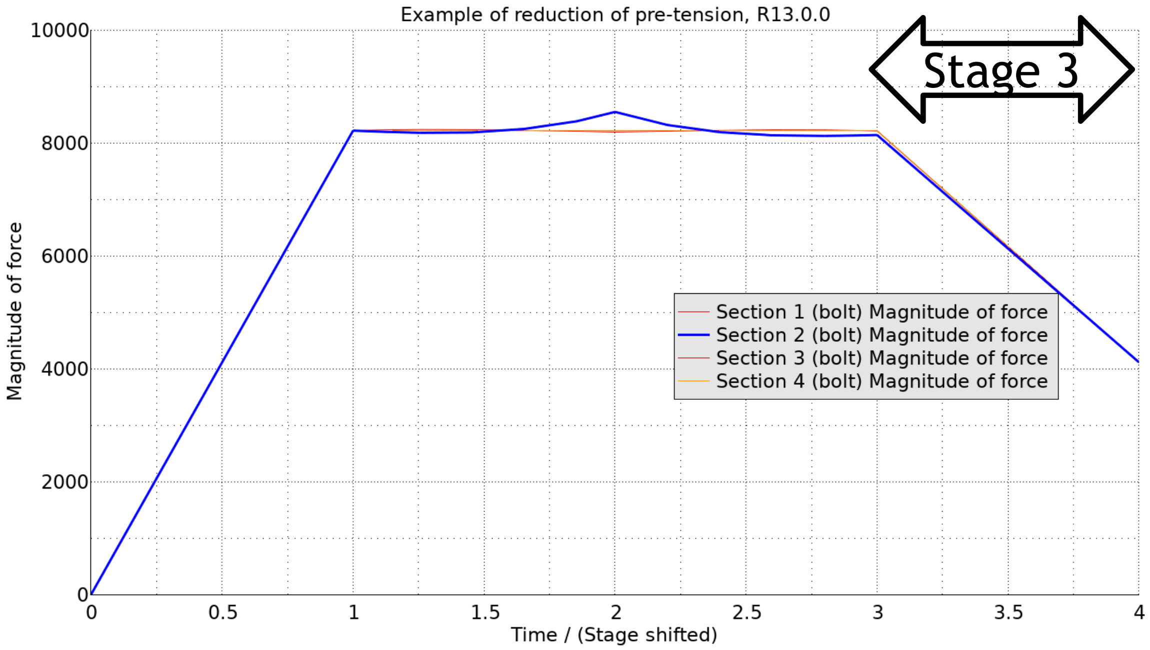




Reduction of bolt pre-tension

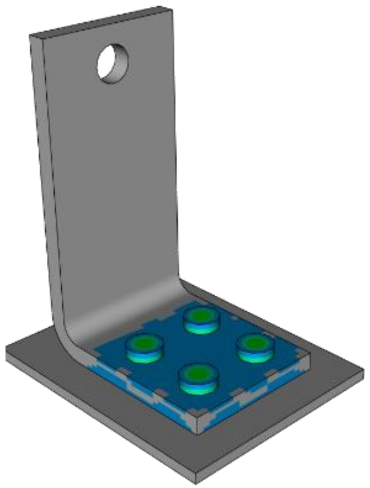
- Simulate loss of pre-tension, for example due to wear or creep
- Use `*CASE` and `dynain.lsda` for describing the stages
- Results: Bolt forces in R13.0.0
  - In stage 3, LS-DYNA detects existing pre-tension, and ramps the stresses from the initial value to the target

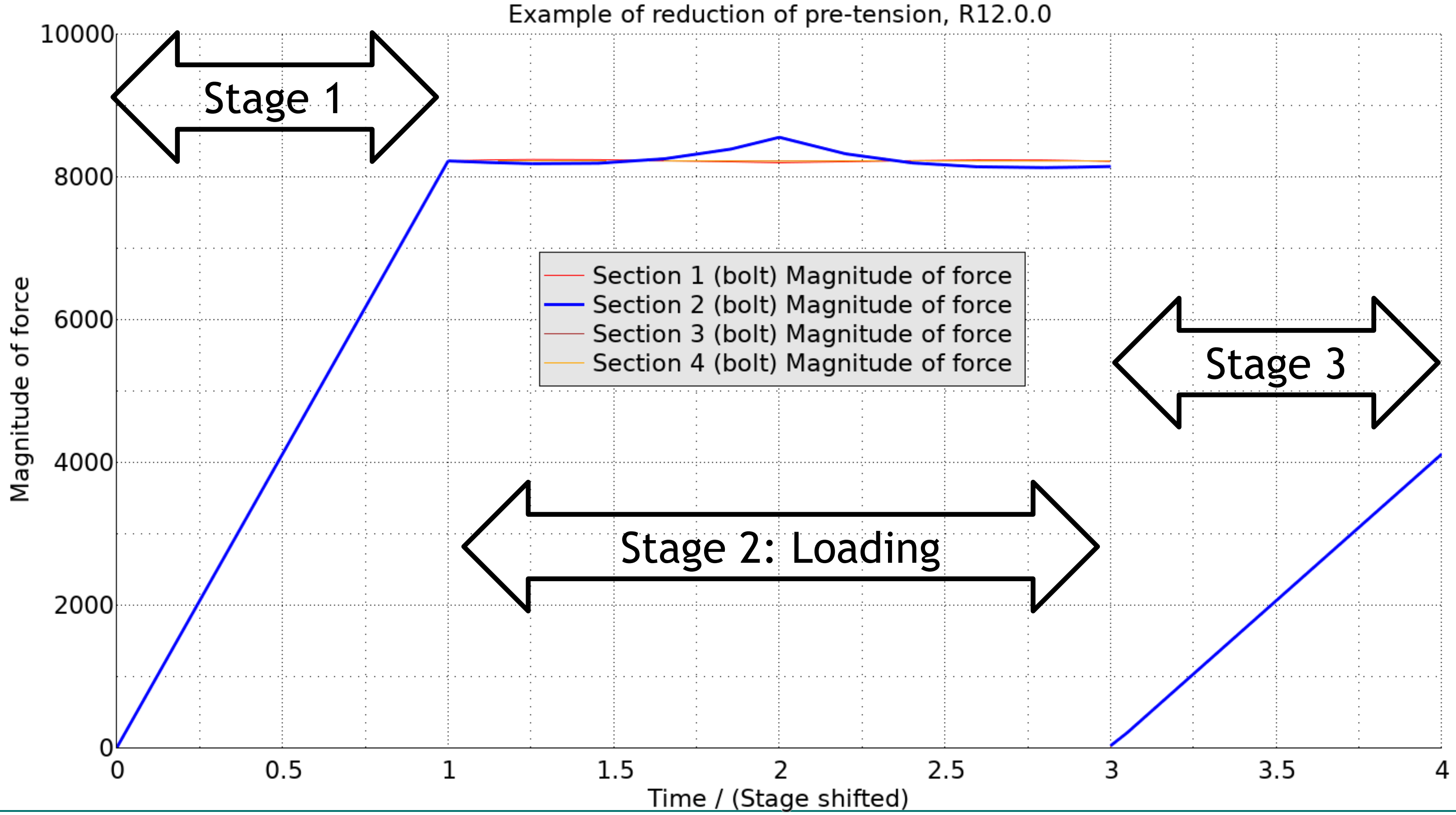




Reduction of bolt pre-tension

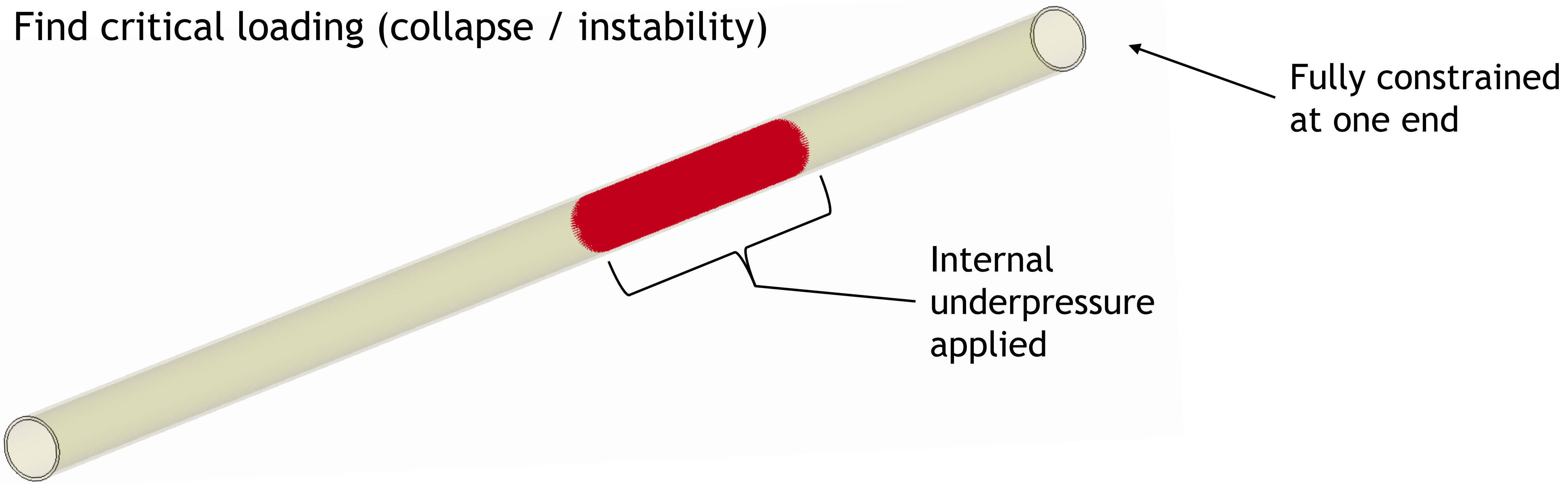
- Simulate loss of pre-tension, for example due to wear or creep
- Use `*CASE` and `dynain.lsda` for describing the stages
- Results: Bolt forces in R12.0.0
  - Pre-tension follows the curve “blindly”





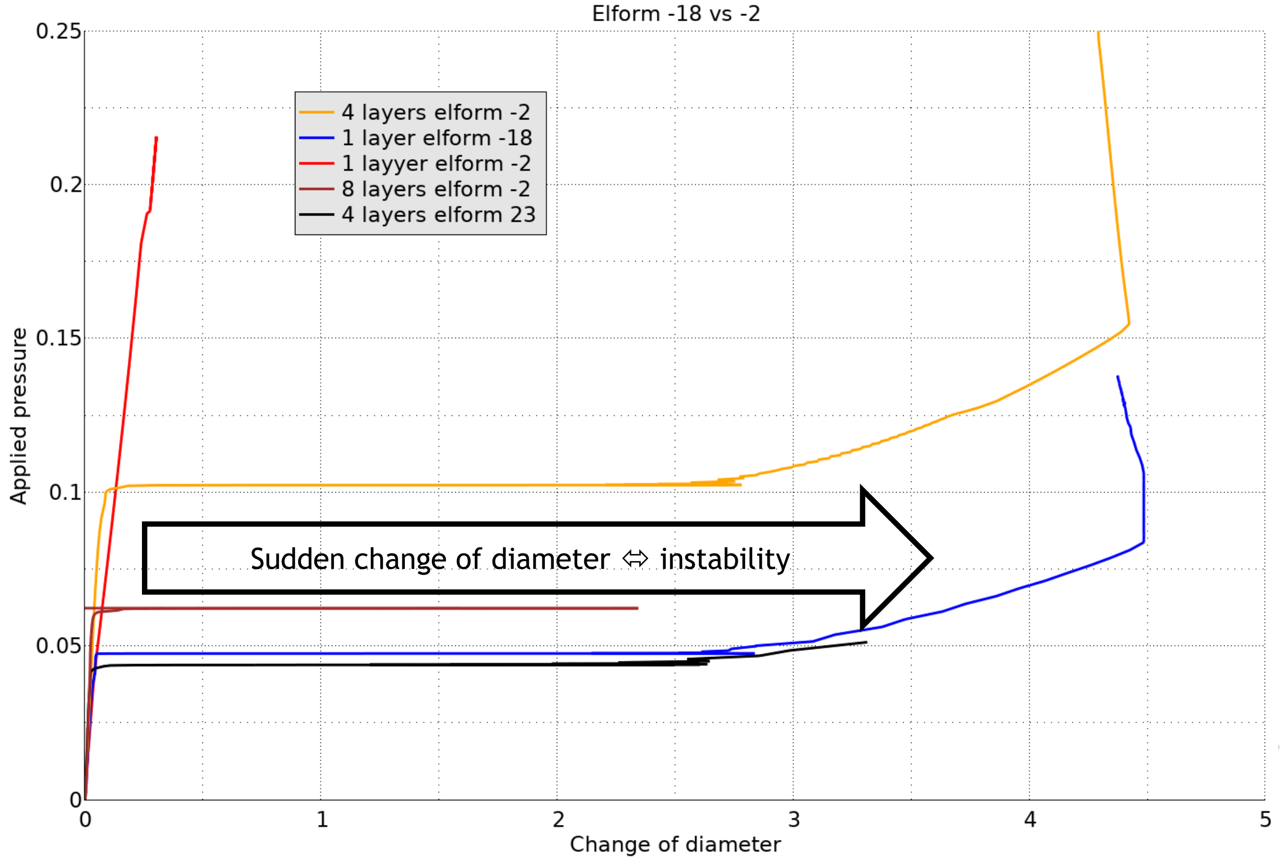
New enhanced assumed strain hexahedral element

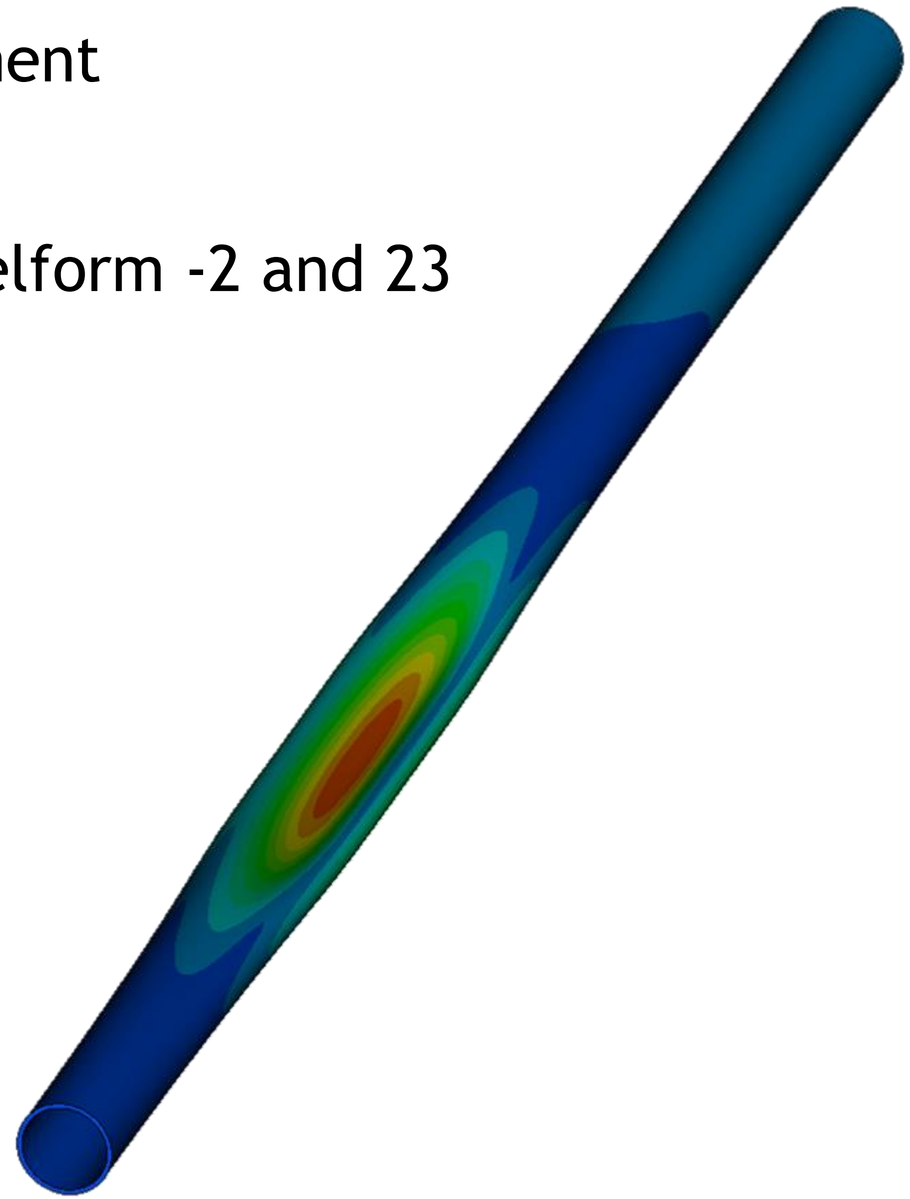
- *ELFORM* -18 on `*SECTION_SOLID`
  - 8 node hex element with enhanced assumed strain
  - 13 incompatible modes added to improve bending behaviour
  - Eliminate parasitic shear that causes 1st order elements to be too stiff in bending
- Example: tube compression, elforms -2, -18 and 23 (2nd order hexa)
  - Find critical loading (collapse / instability)



New enhanced assumed strain hexahedral element

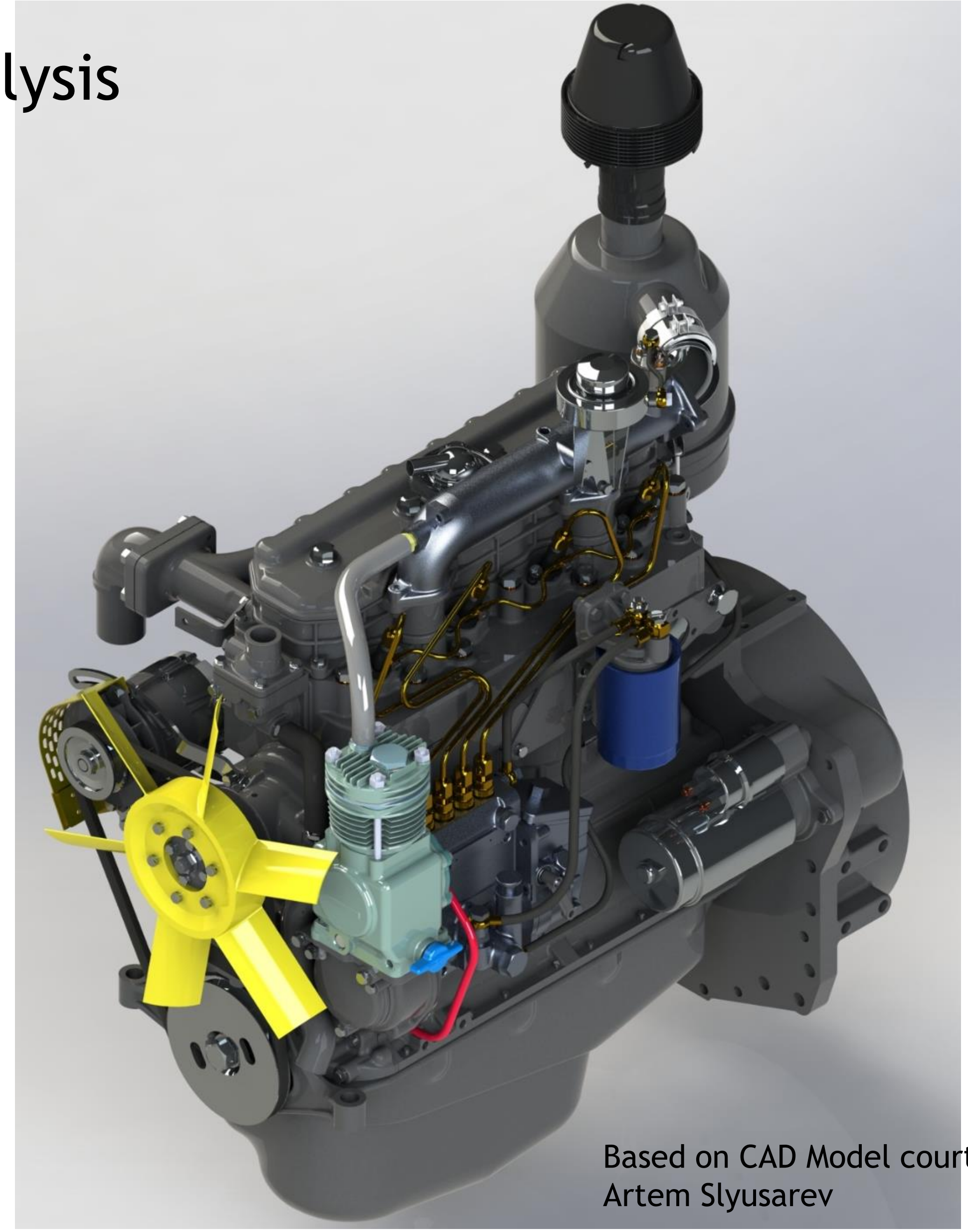
- *ELFORM* -18 on *SECTION_SOLID
- Example: tube compression, comparison to elform -2 and 23





Large-scale example: Combustion engine analysis

- Implicit
- Large-scale models
  - Many parts
  - 2^{nd} order tets
  - Contacts
  - Many load stages
- Thermal loading
- Bolt pre-tensioning
  - Including reduction of pre-tension
- Cyclic plasticity
- Gaskets
- Fatigue

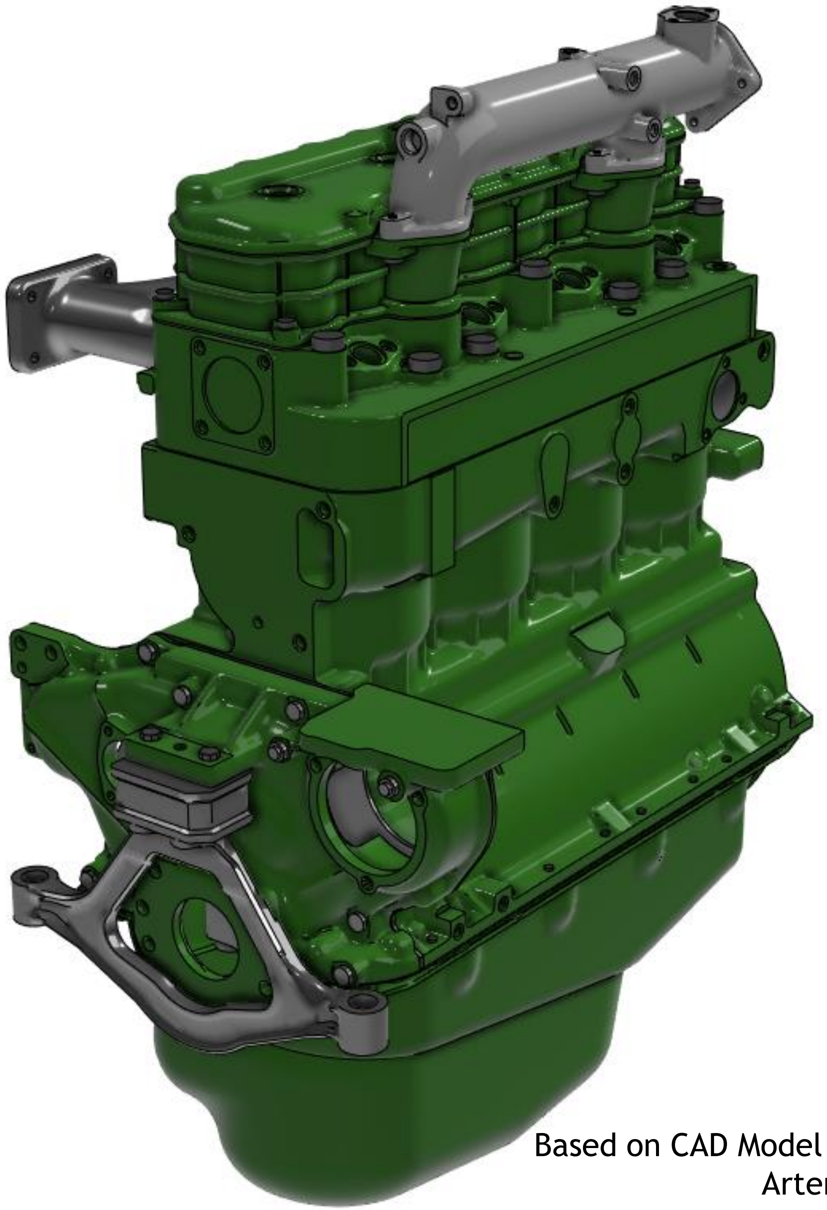


Based on CAD Model courtesy of
Artem Slyusarev

Large-scale example

- Test of many features in a large-scale model
- Demonstrate that LS-DYNA implicit can be used also for this analysis type
- Presented results are only for demonstrational purposes!

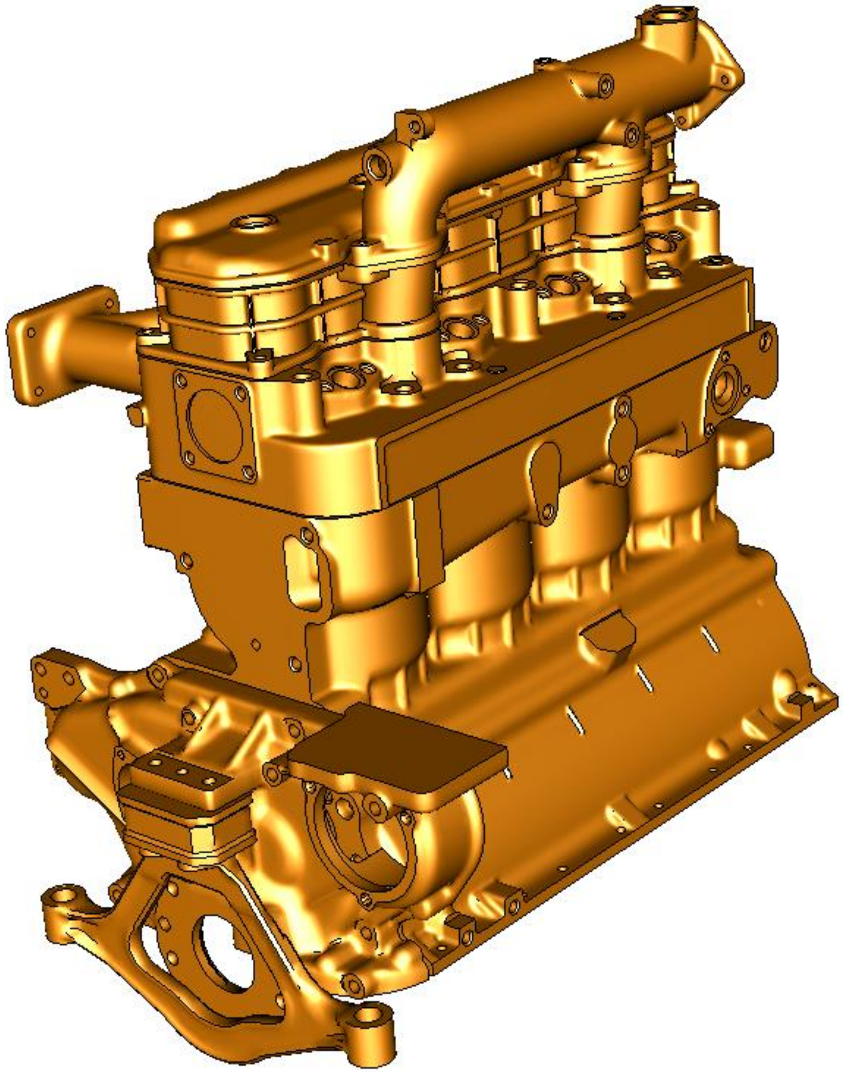
Entity type	Count
Nodes	3863630
Elements	2406553
2nd order tets	2280145
1st order hex	109483
Parts	33



Based on CAD Model courtesy of Artem Slyusarev

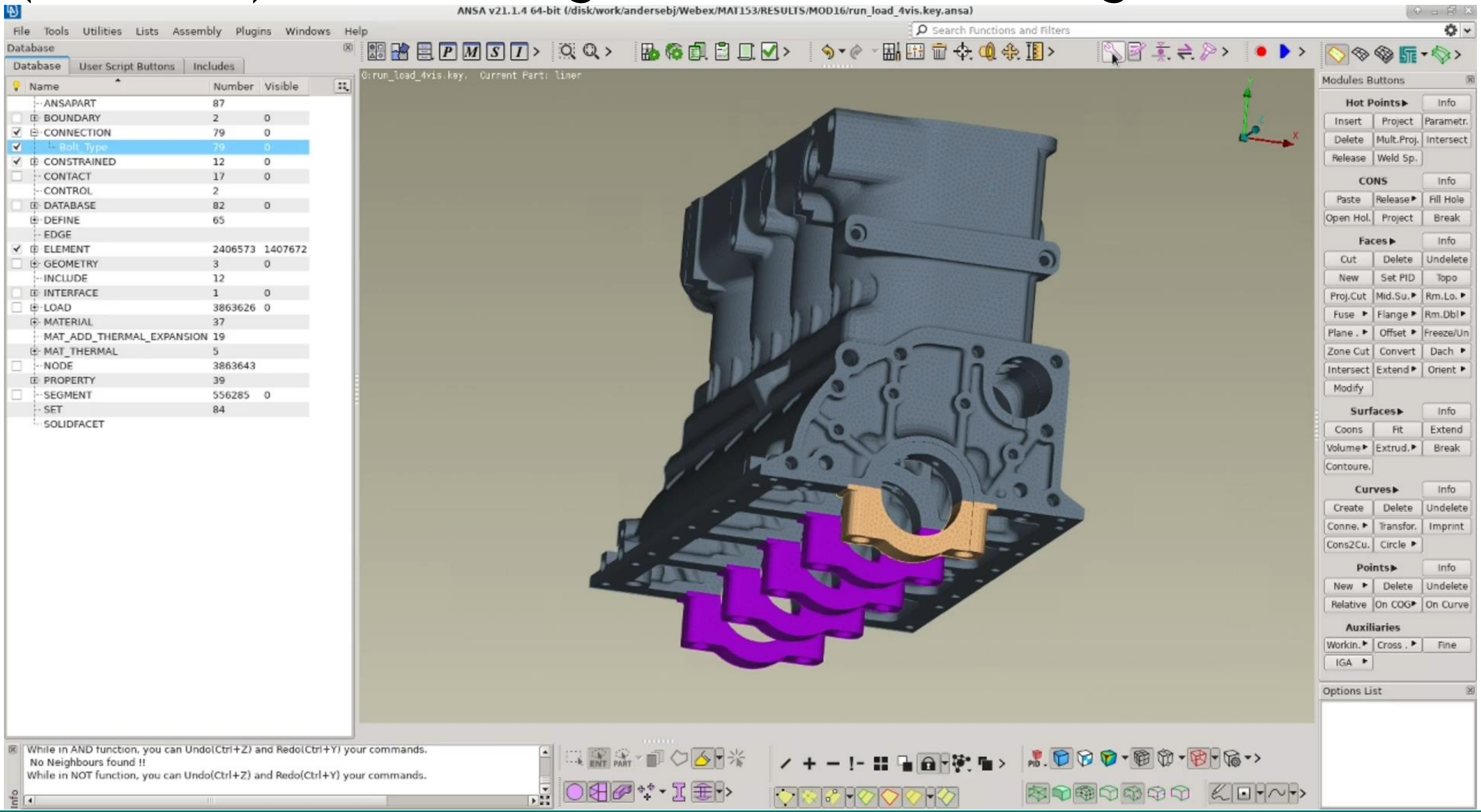
Elements and mesh

- Hexahedral elements with enhanced assumed strain (elform -18) used in cylinder lines and front spacer plate
- Gasket elements used for the cylinder head gasket, exhaust manifold gaskets and the oil sump gasket
- 2nd order tetrahedral element (elform 16) used in the engine block, cylinder head, front cover, and manifolds
- The oil sump uses shell elements (elform 16)



Elements and mesh

- 79 hexa bolts (elform -2) created using the Connection manager of Ansa



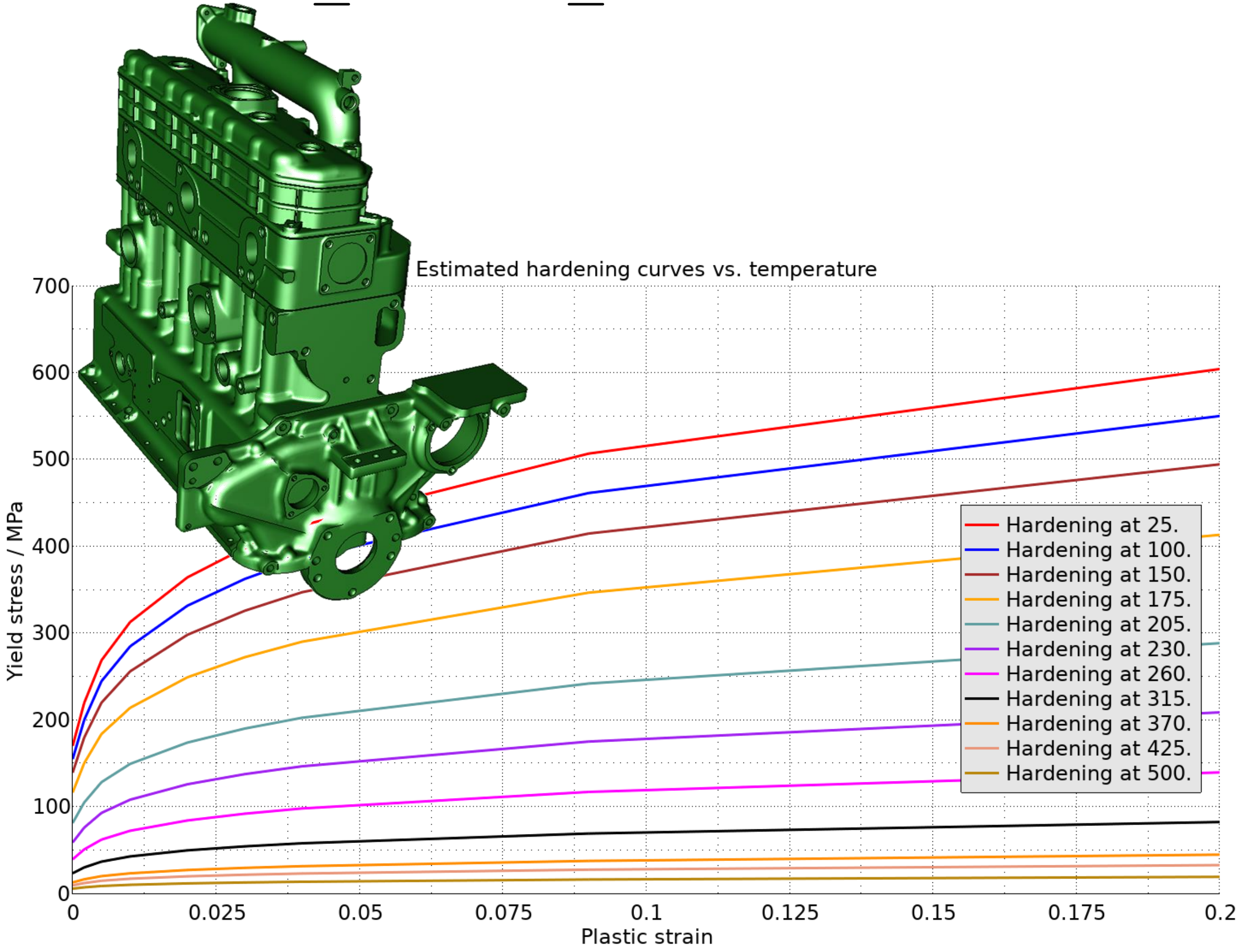
Material models

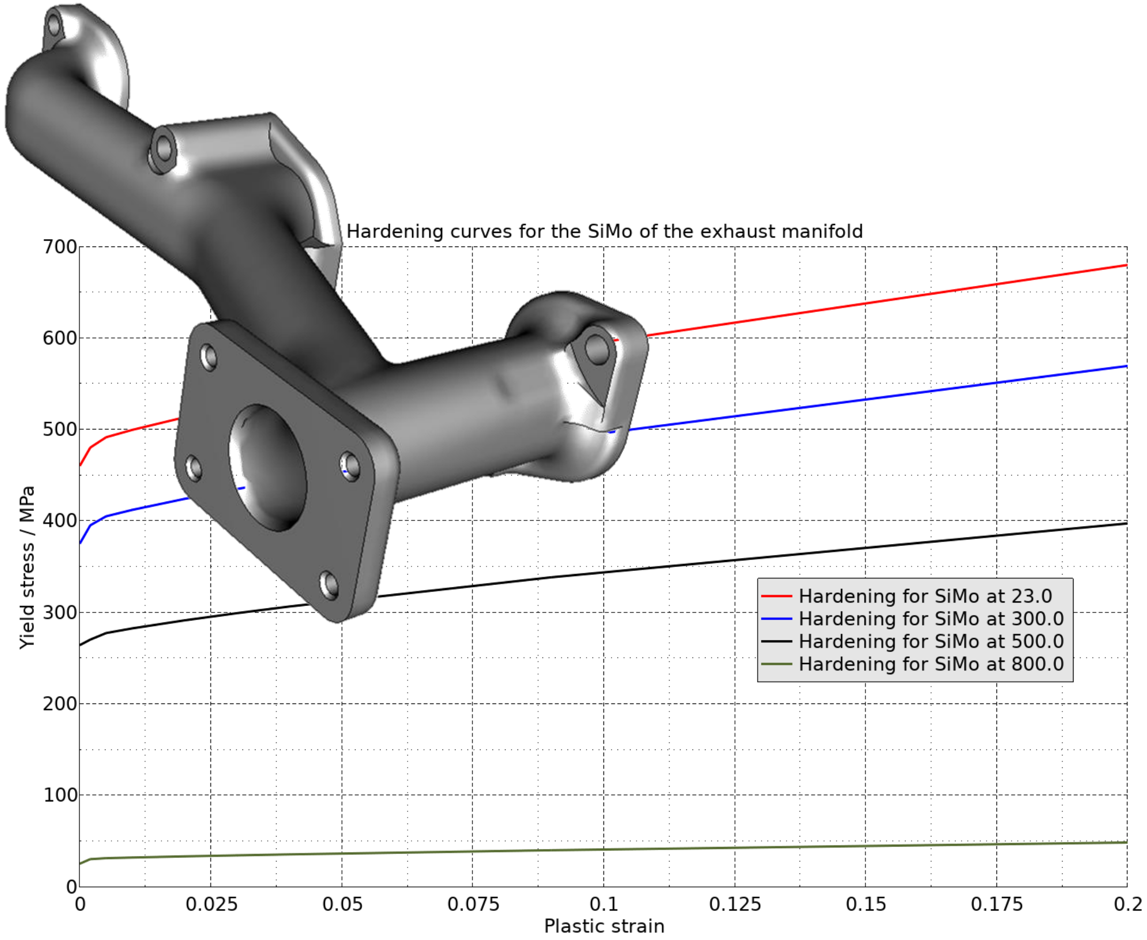
- `*MAT_DAMAGE_3` w. temperature dependence applied to ...
  - The engine block, cylinder head, front cover, valve cover and intake manifold
    - Estimated material data, inspired by aluminum
  - The exhaust manifold
    - Estimated material data, inspired by SiMo (nodular cast iron)

- `*MAT_COHESIVE_GASKET` applied to ...
  - The cylinder head gasket, and exhaust manifold gasket – based on guessed and estimated pressure/closure curves
  - The sump gasket – based on a detailed model of a rubber sealing

Material models

- *MAT_DAMAGE_3



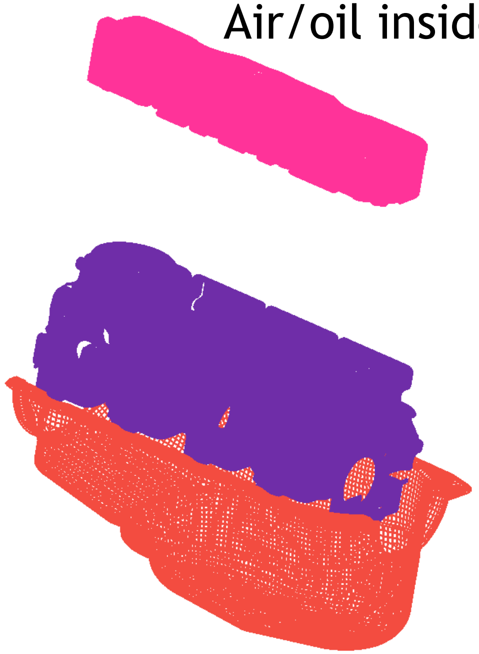


Load history

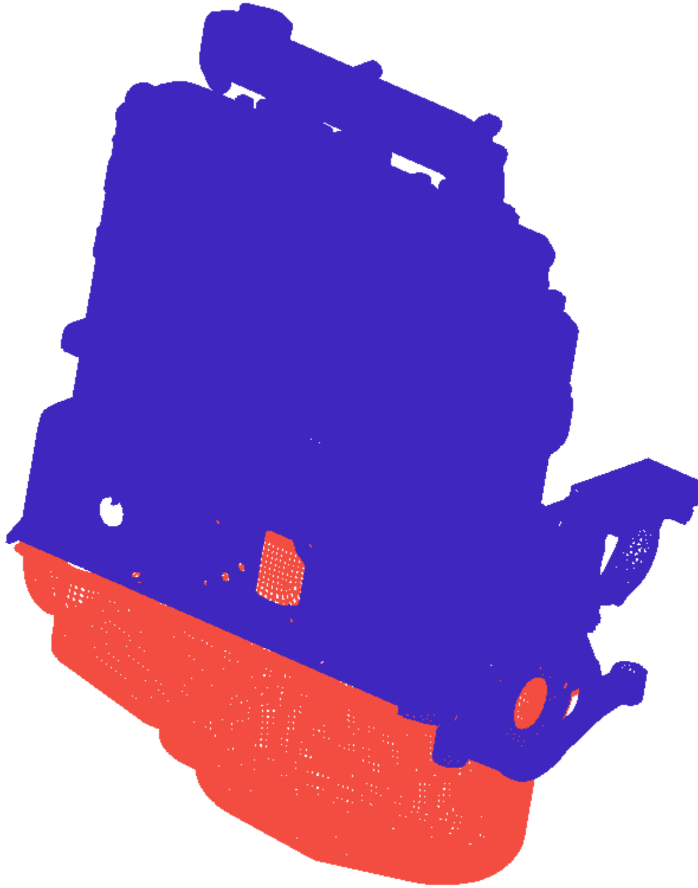
- Thermal loading
  - Steady state analysis
- Mechanical analysis
  - Five load stages

Load history

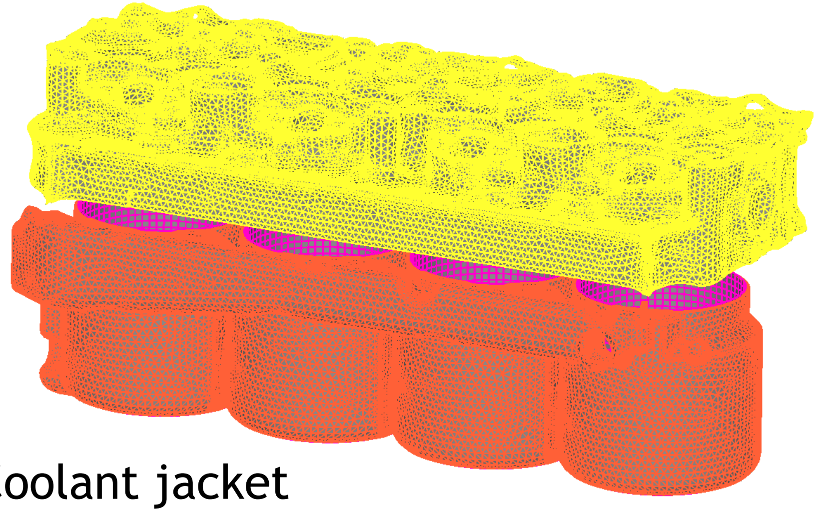
- Thermal loading
  - Separate analysis (uncoupled)
  - Steady state
  - Estimated Heat Transfer Coefficients and reference temperatures
  - Segment sets for convection boundary conditions



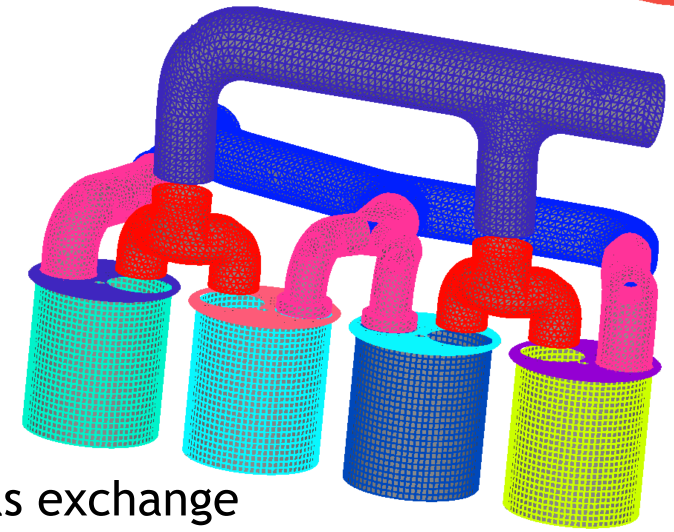
Air/oil inside



Engine outside



Coolant jacket



Gas exchange

Load history

- Mechanical loading

i. Bolt pre-tension
ii. Thermal up-down
iii. Re-application of bolts pre-tension
iv. Thermal up
v. Cylinder pressure history

Load history

- Mechanical loading

i. **Bolt pre-tension**

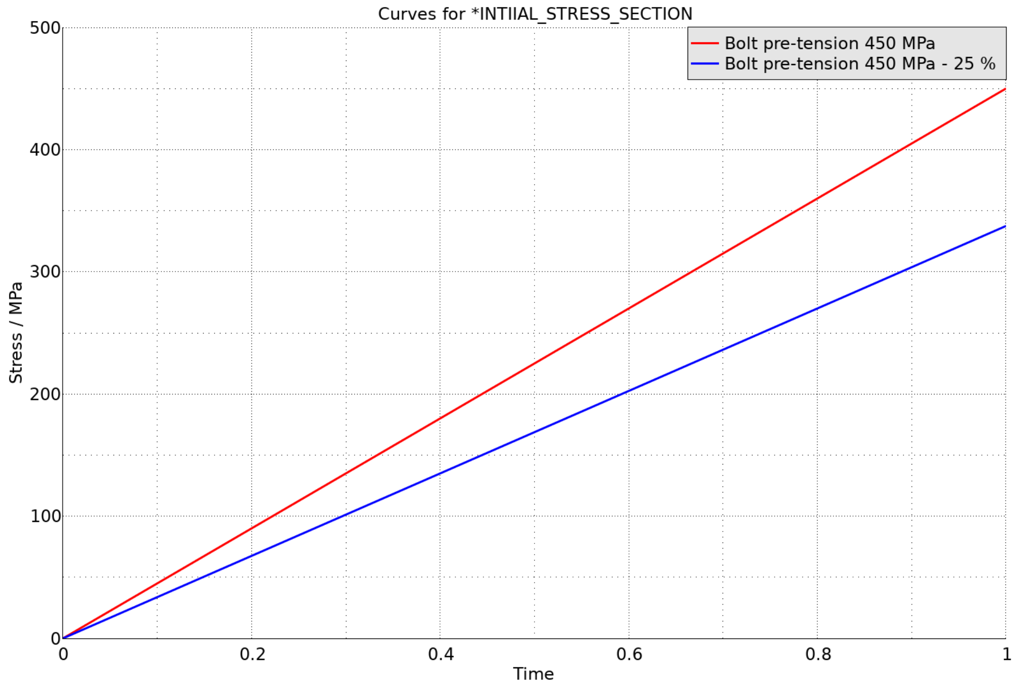
ii. Thermal up-down

iii. **Re-application of pre-tension**

iv. Thermal up

v. Cylinder pressure history

Bolt	Dimension	Force / kN		Reduction
		Stage i.	Stage iii.	
Main bearing cap	M16	87	70	20 %
Cylinder head	M14	67	50	25 %
Oil pan	M8	10	8	20 %
Front cover	M10	15	12	20 %



Load history

- Mechanical loading

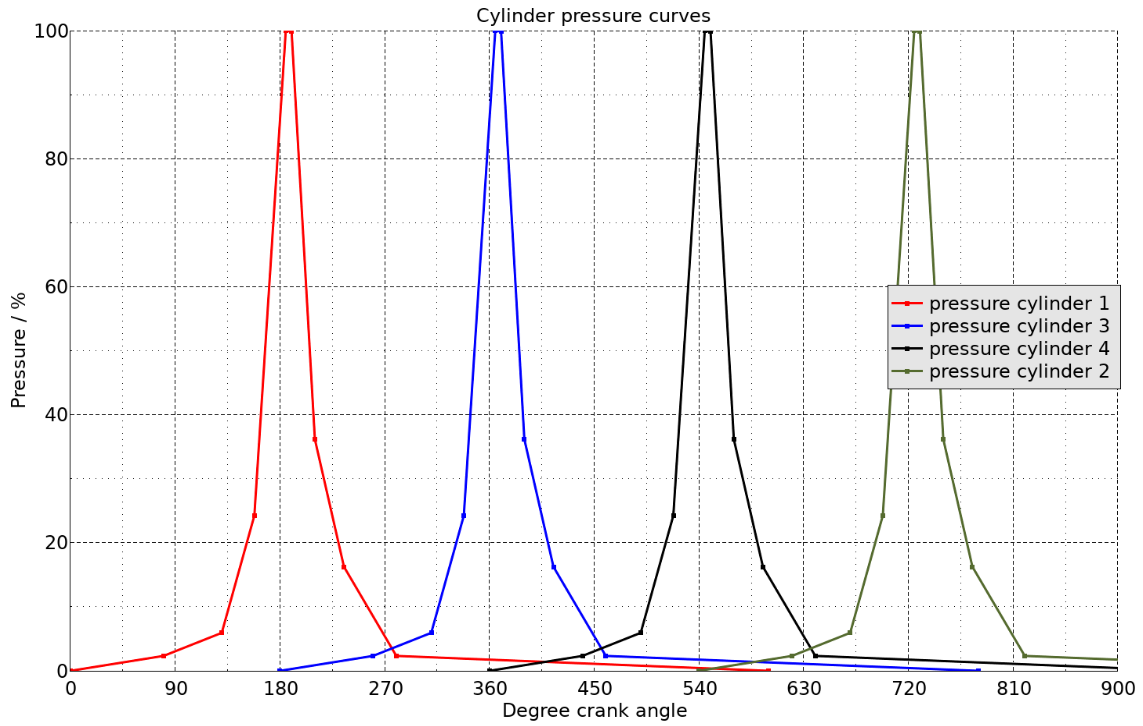
i. Bolt pre-tension

ii. Thermal up-down

iii. Re-application of bolts pre-tension

iv. Thermal up

v. **Cylinder pressure history**

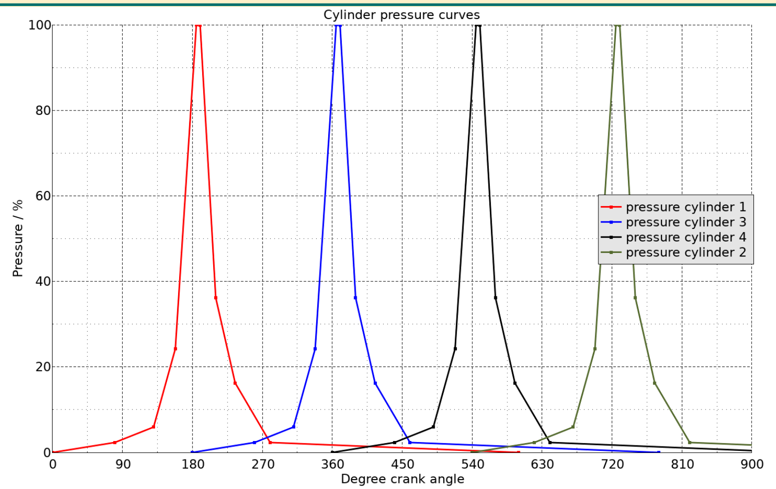


Assumed cylinder pressure curves vs. crank angle

Load history

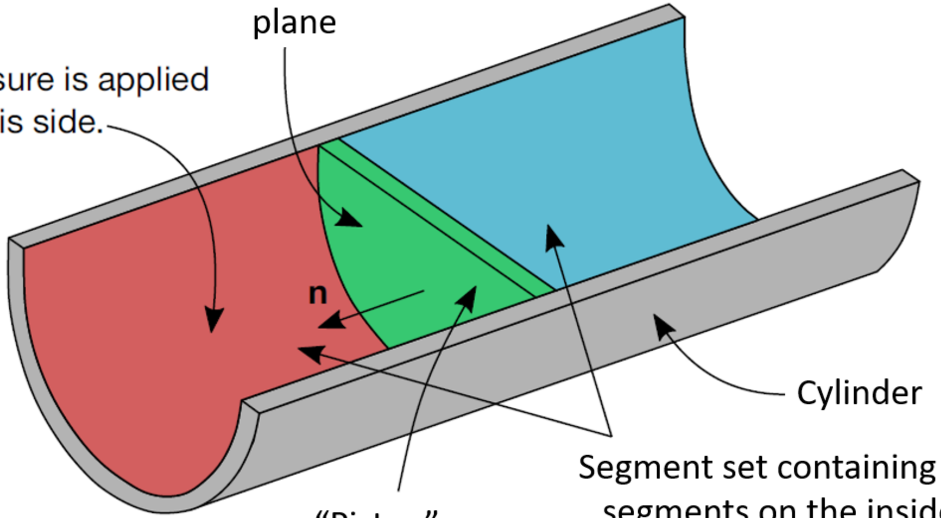
- Mechanical loading

i. Bolt pre-tension
ii. Thermal up-down
iii. Re-application of bolts pre-tension
iv. Thermal up
v. **Cylinder pressure history**



Assumed cylinder pressure curves

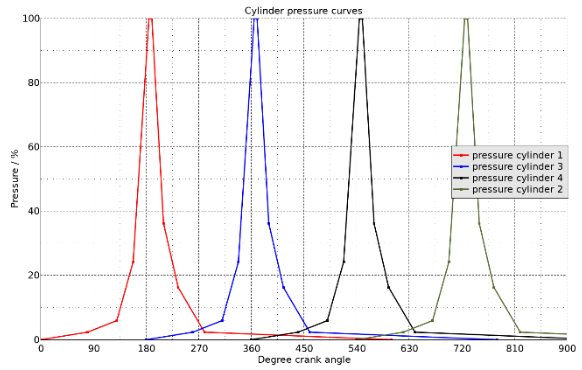
*LOAD_EXPANSION_PRESSURE



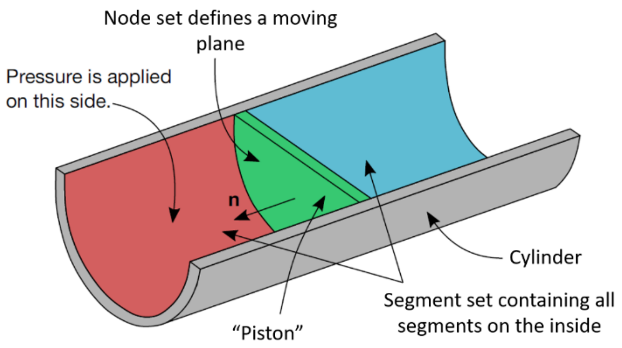
Load history

- Mechanical loading

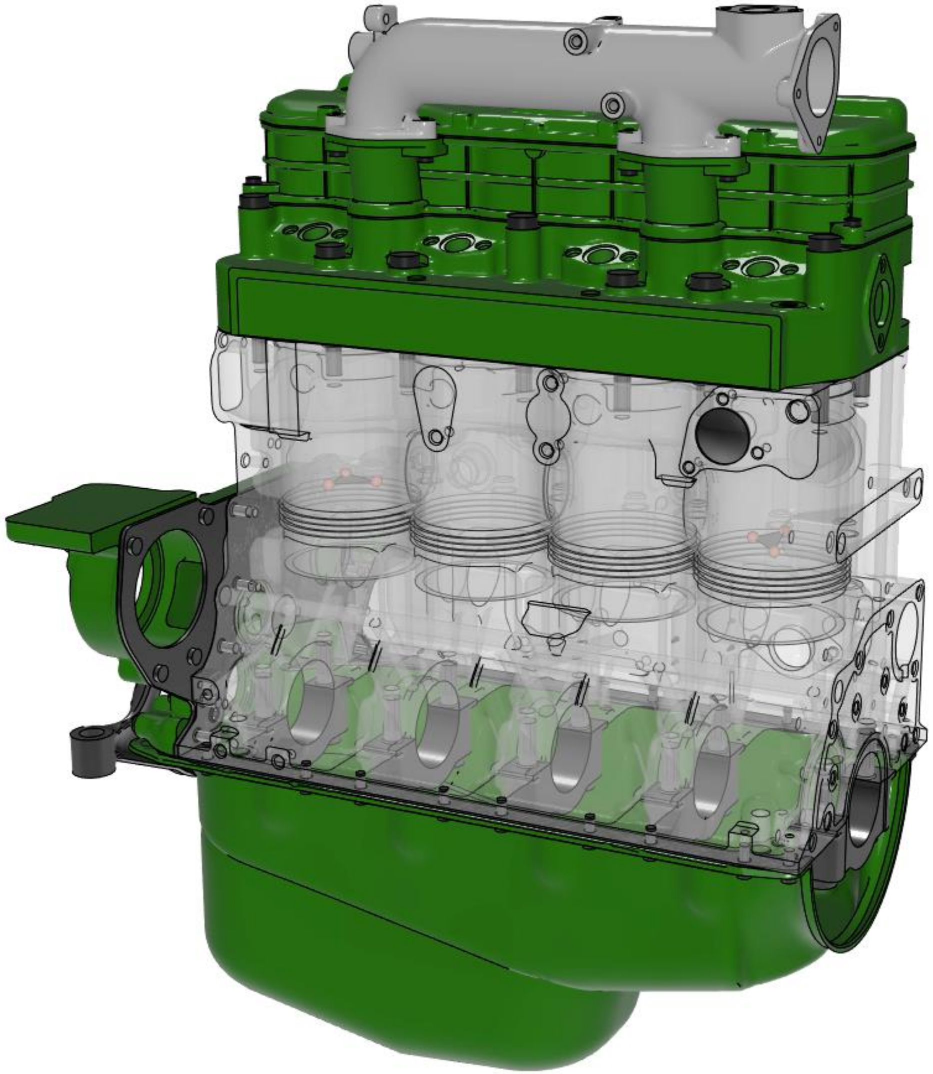
i. Bolt pre-tension
ii. Thermal up-down
iii. Re-application of bolts pre-tension
iv. Thermal up
v. **Cylinder pressure history**



Assumed cylinder pressure curves



*LOAD_EXPANSION_PRESSURE



Load history management

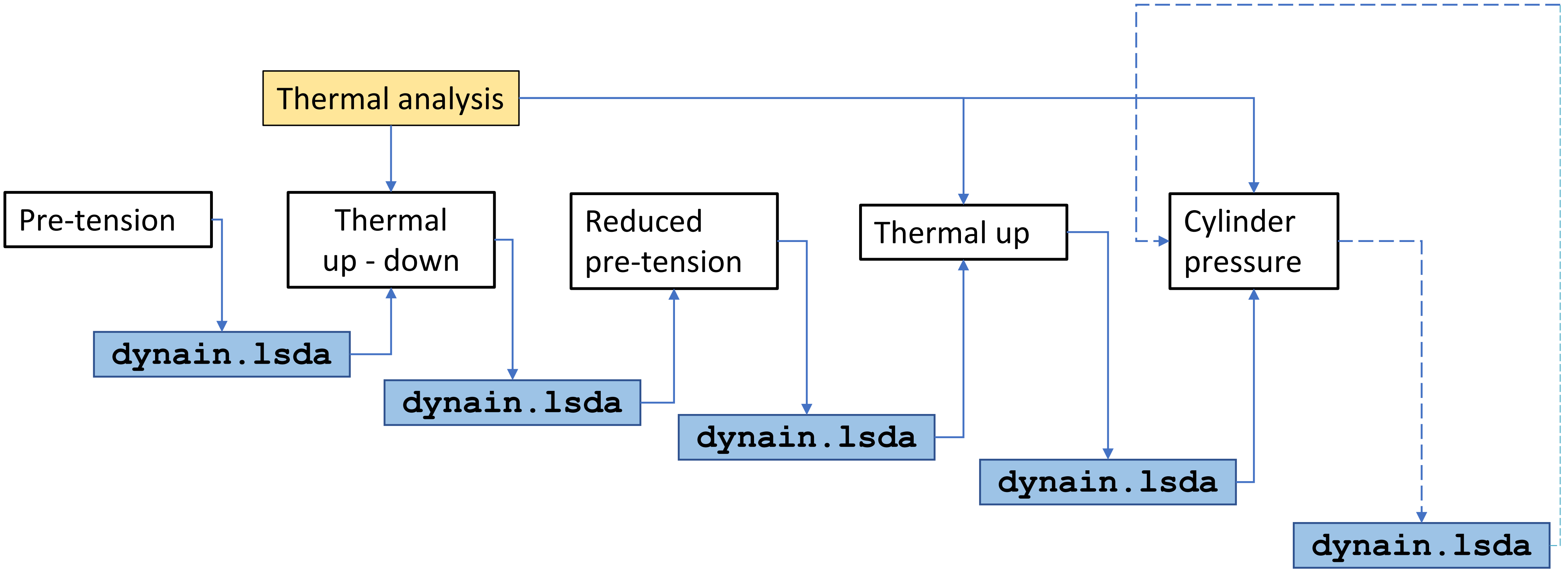
- Mechanical loading

i. Bolt pre-tension
ii. Thermal up-down
iii. Re-application of bolts pre-tension
iv. Thermal up
v. Cylinder pressure history

- Run as five separate analyses, in a sequence
- At the end of each stage, the final configuration is stored in a **`dynain.lsda`** – file
  - Contains deformed configuration
  - Stresses, strains, history variables
  - Contact state
  - etc.
- The following stage uses this as initial conditions

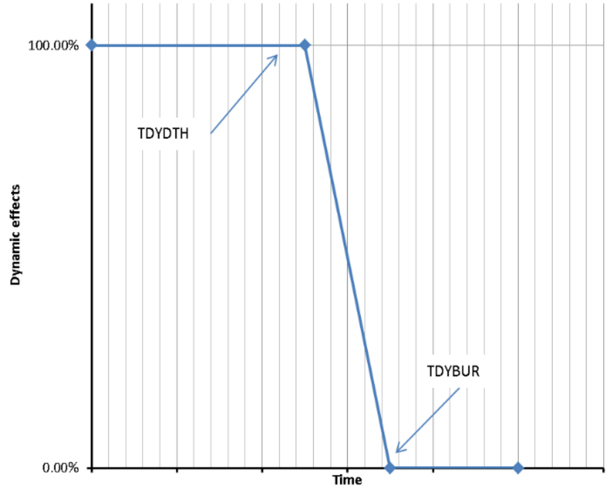
Load history management

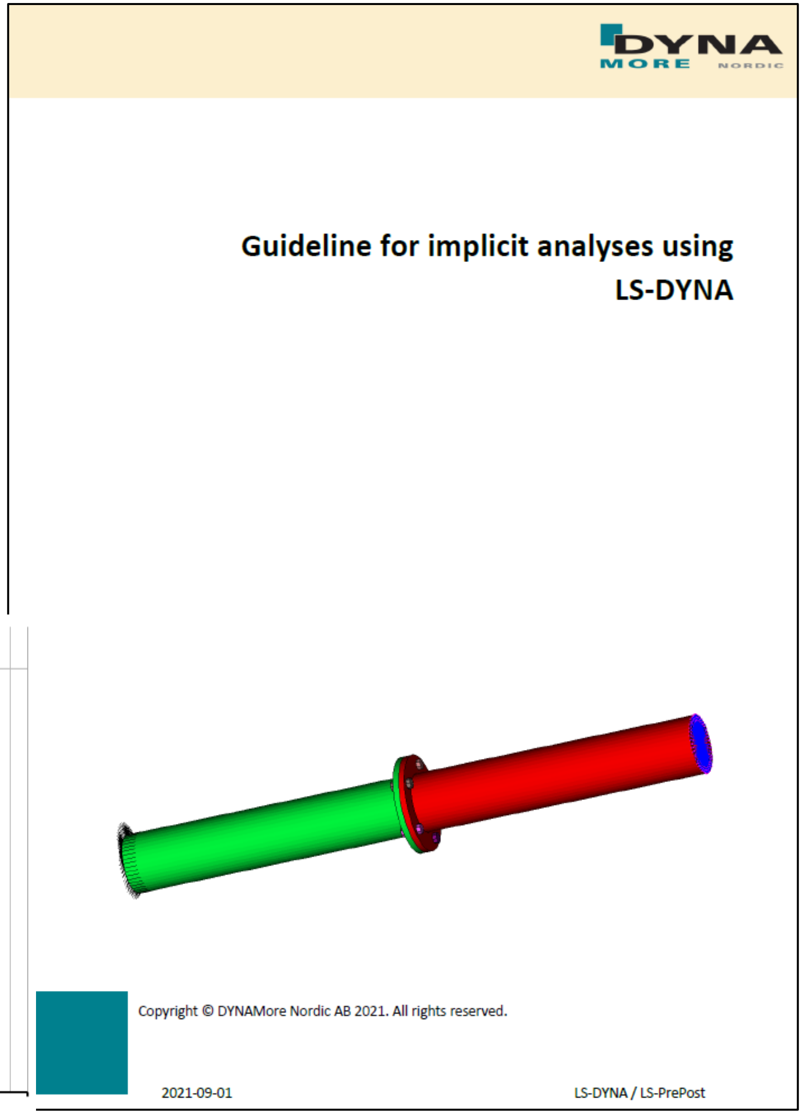
- Mechanical load history
  - divided in stages



Model set-up

- Mortar contacts
- Standard control card settings for non-linear implicit analyses were used
  - For R13.0.0, use LS-GPart for large-scale models
  - *ORDERING*=4 on `*CONTROL_IMPLICIT_ORDERING`
- Stages i) and iii) involving bolt pre-tensioning were run using implicit dynamics
  - Implicit dynamics active at beginning of stage, then gradually ramped down to static finish

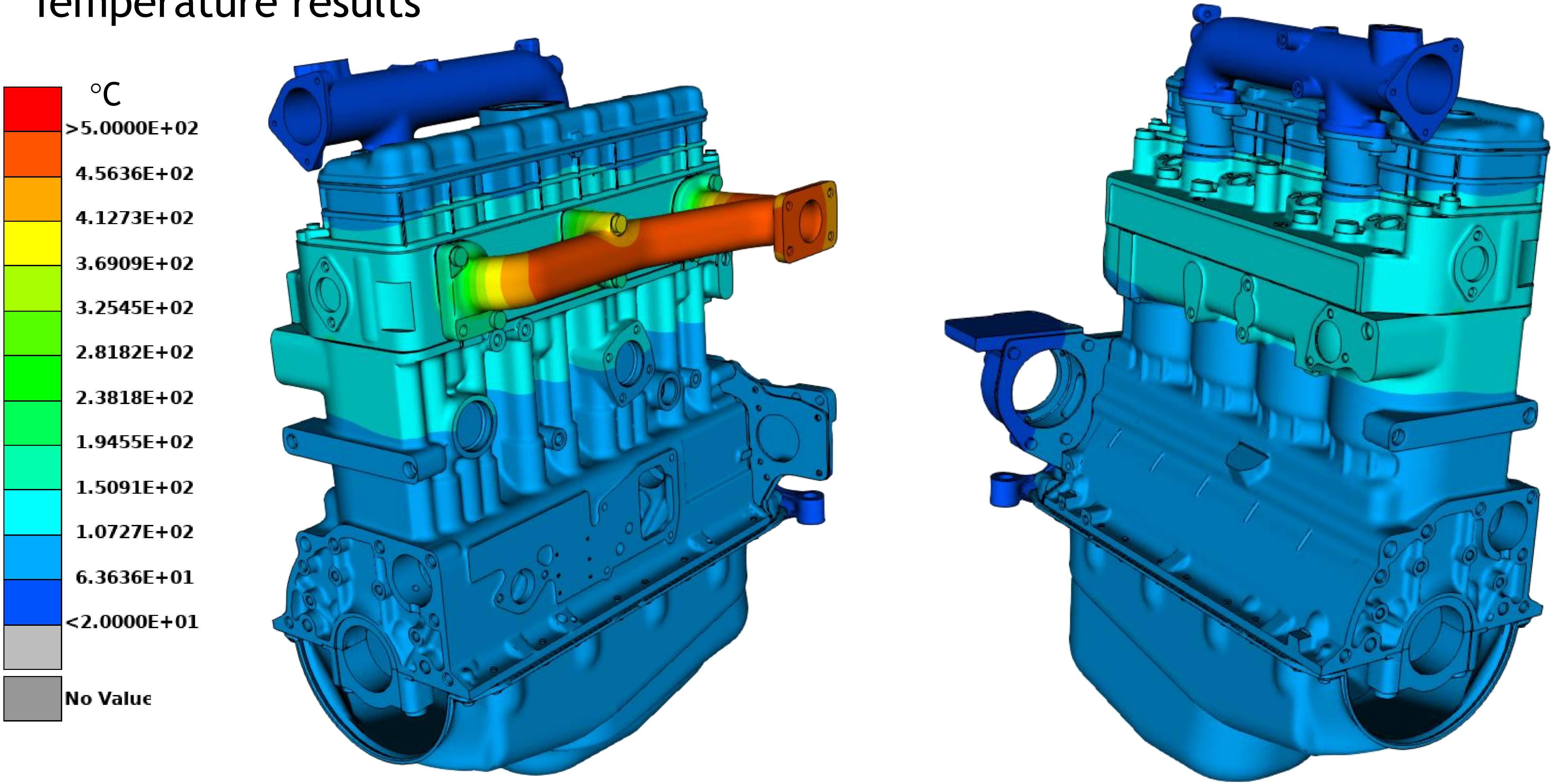




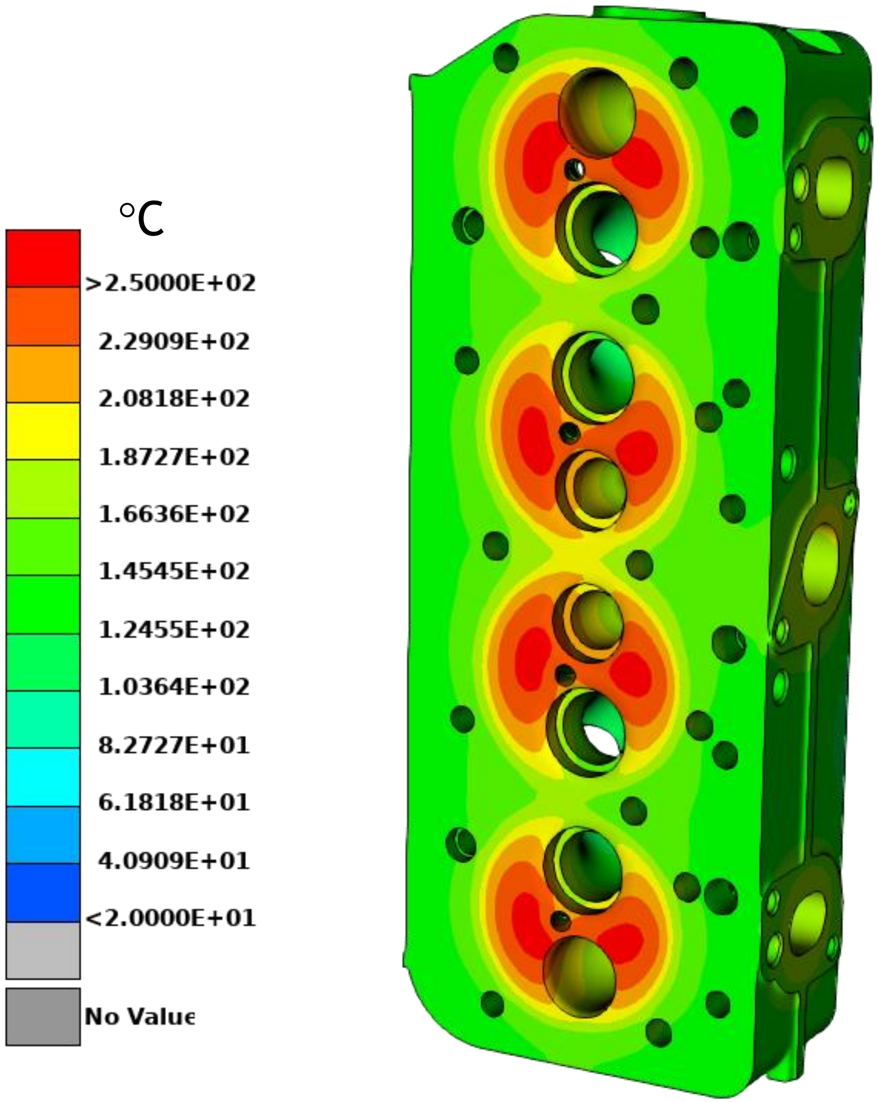
Some results

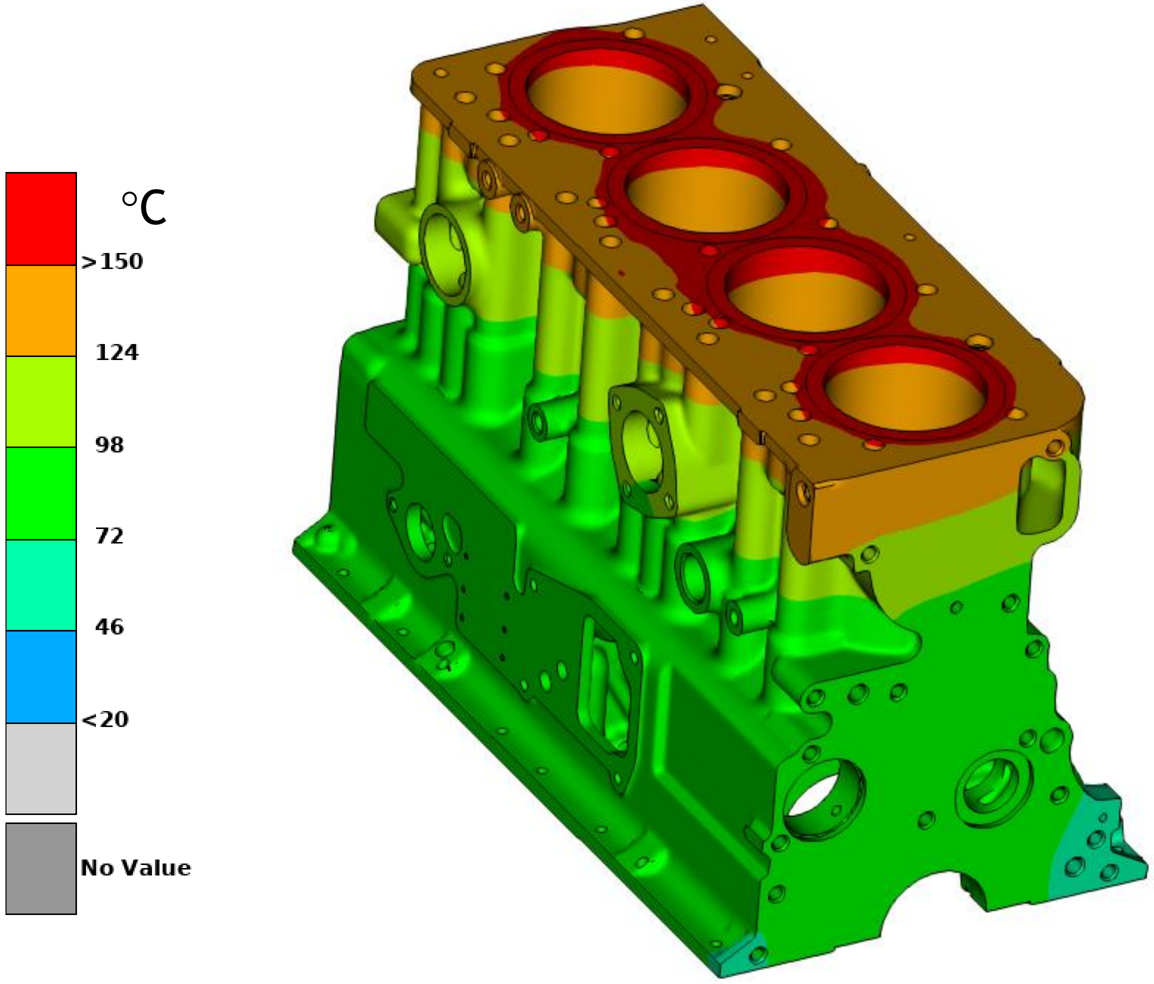
- Temperatures
- Stresses
- Plastic strain
- Gasket pressure and compression
- Bolt forces
- Fatigue damage
- Memory requirements

Temperature results

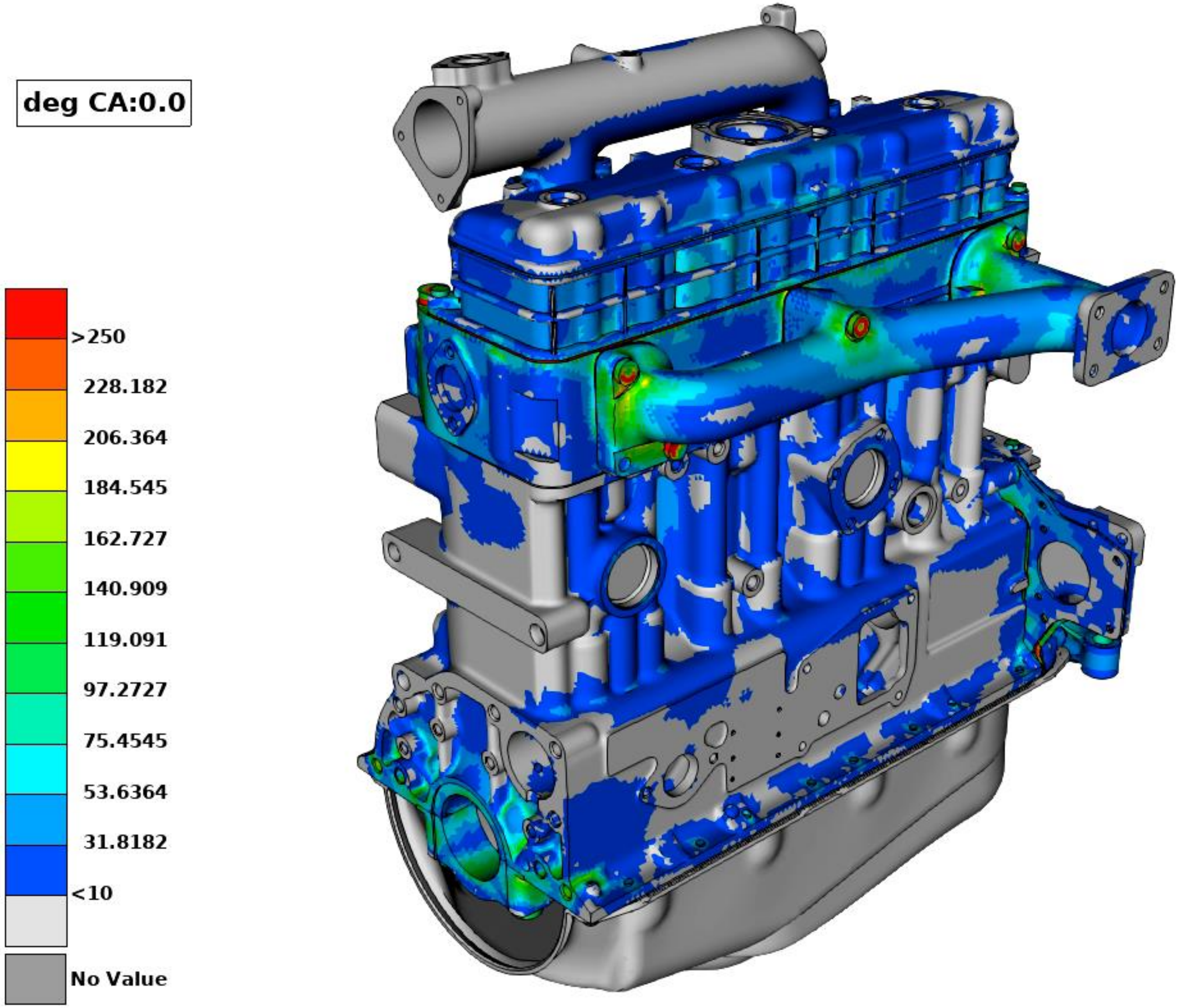


Temperature results



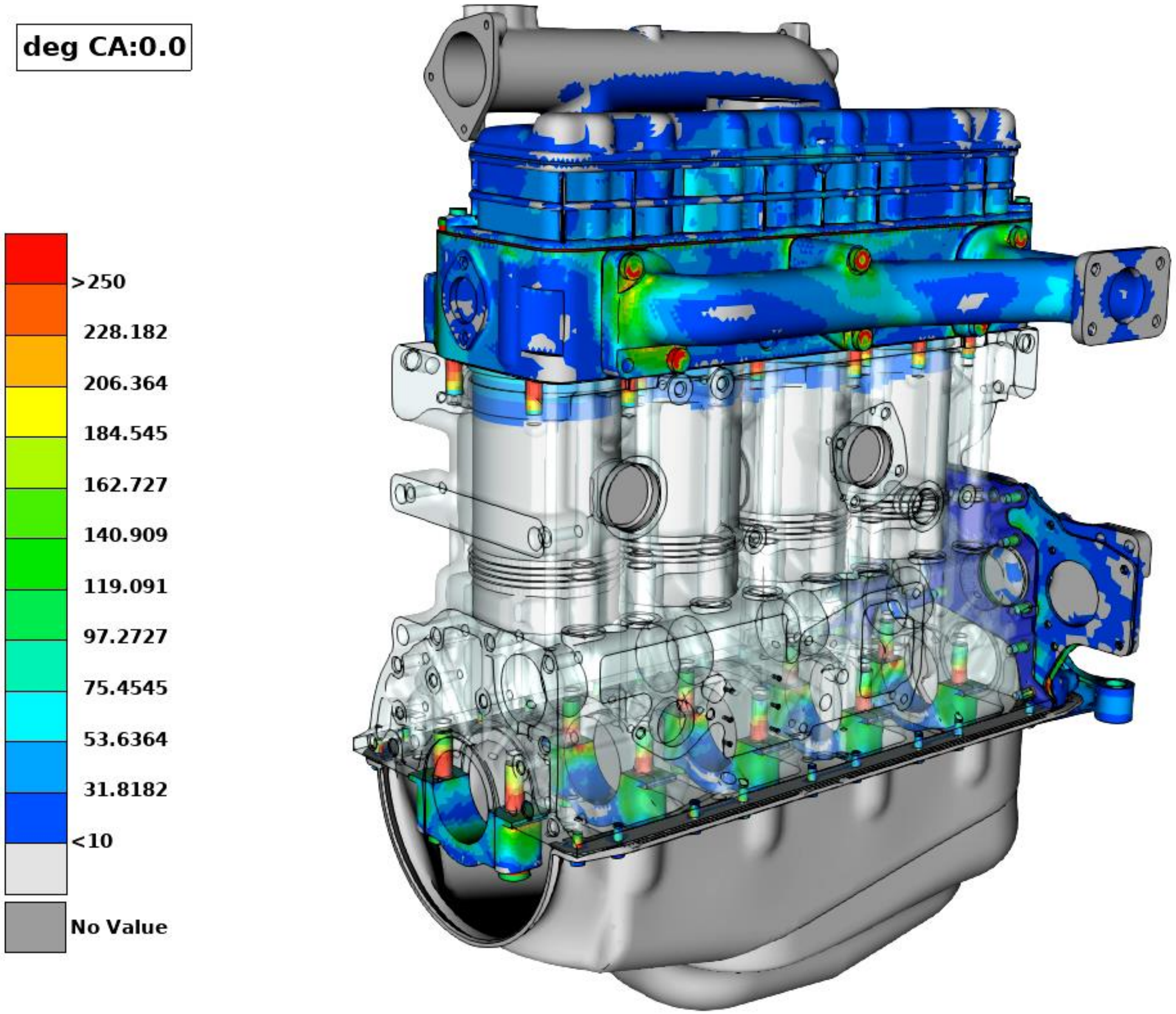


Stresses

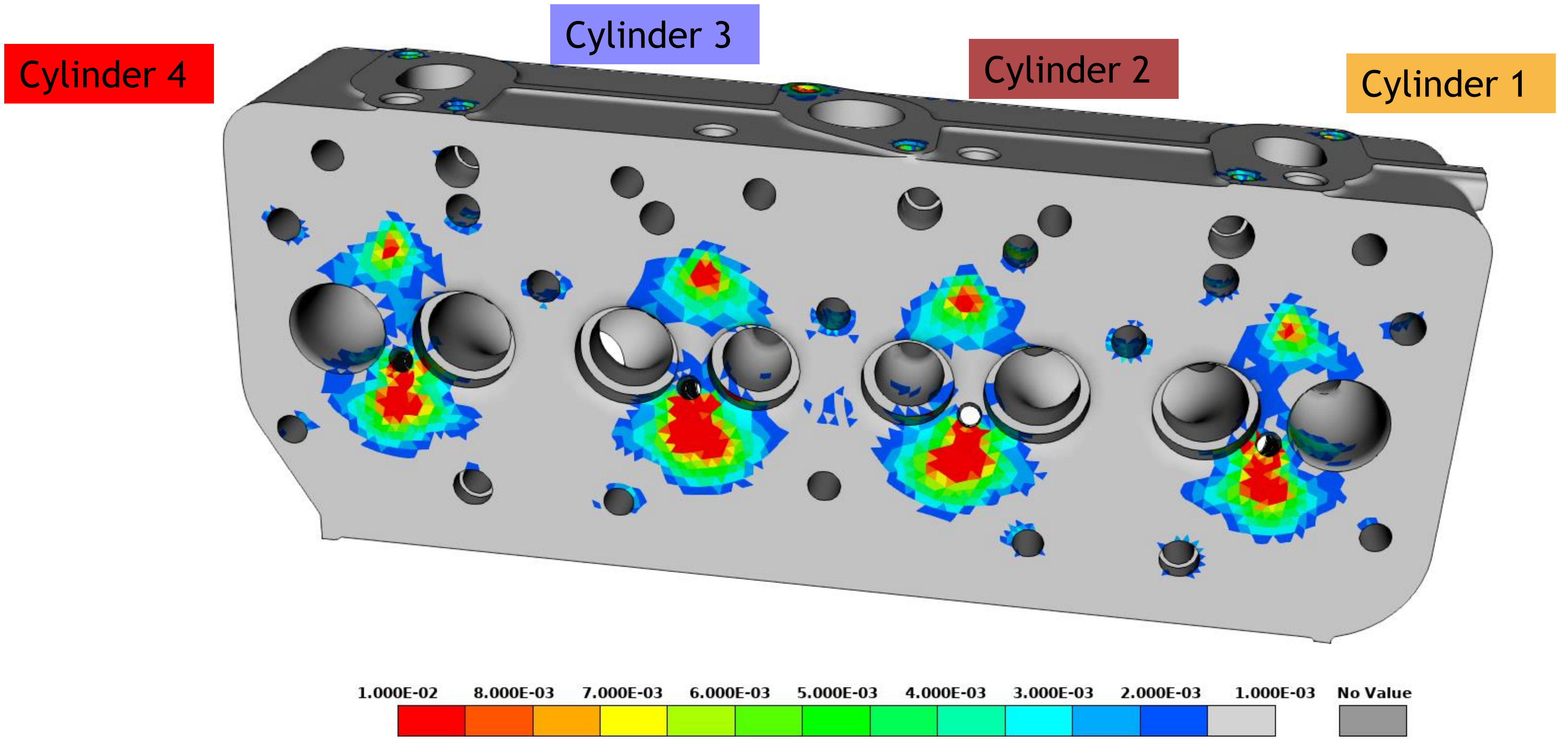


deg CA:0.0
>250
228.182
206.364
184.545
162.727
140.909
119.091
97.2727
75.4545
53.6364
31.8182
<10
No Value

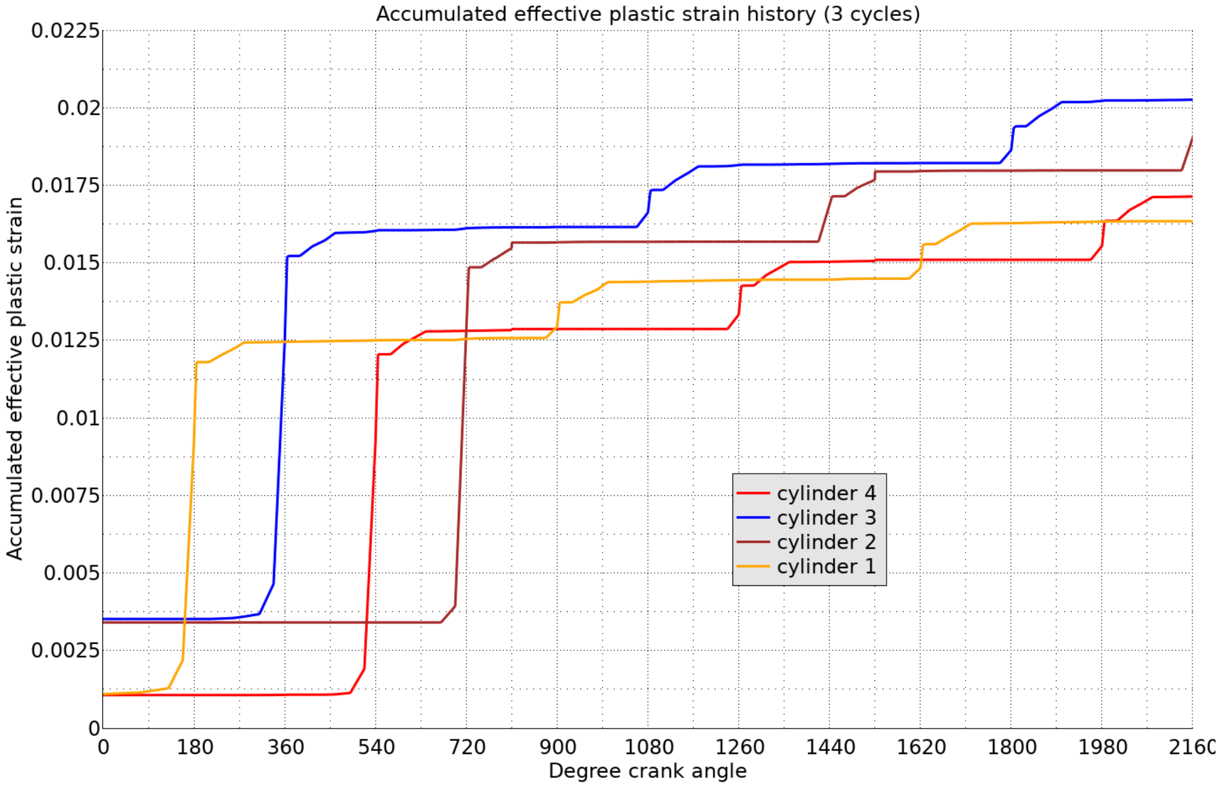
Stresses


deg CA:0.0
>250
228.182
206.364
184.545
162.727
140.909
119.091
97.2727
75.4545
53.6364
31.8182
<10
No Value

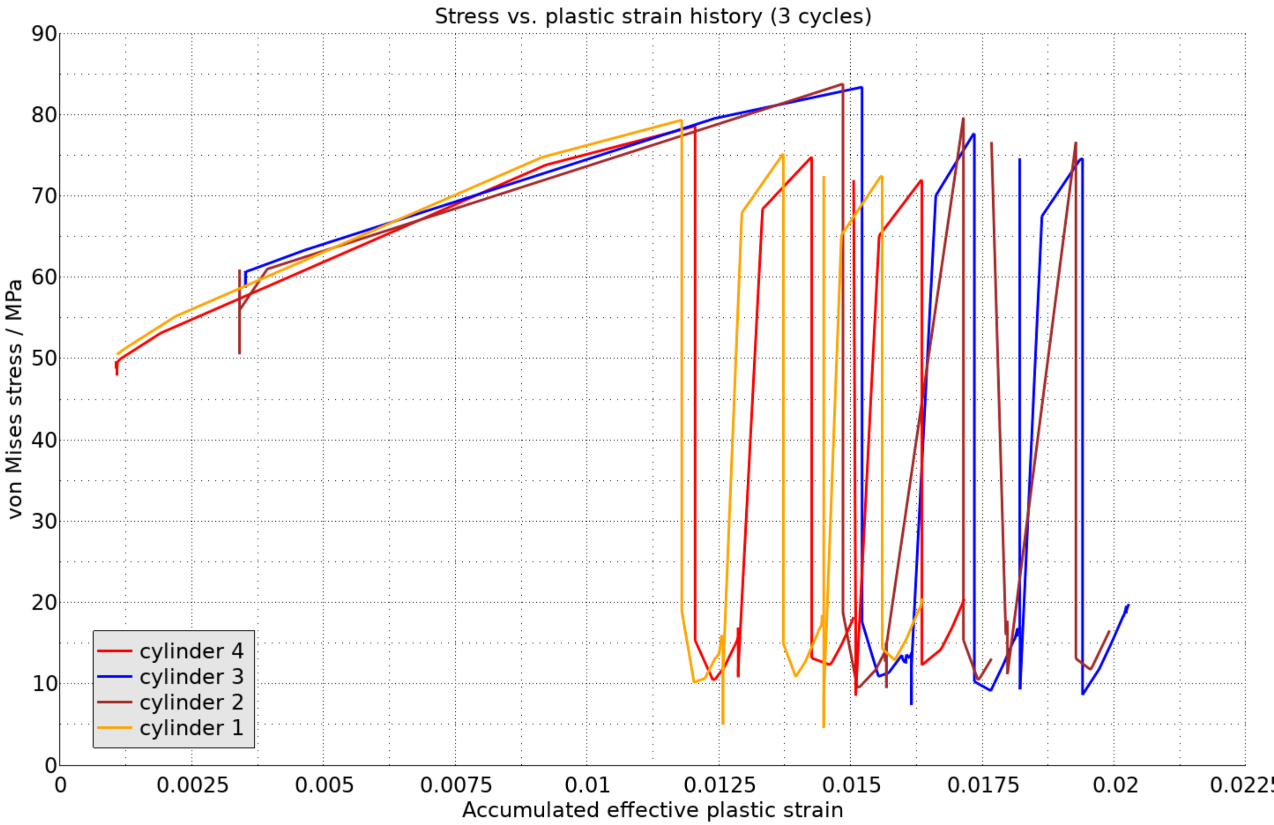
Plastic strain in the cylinder head after 3 cycles



Plastic strain in the cylinder head after 3 cycles

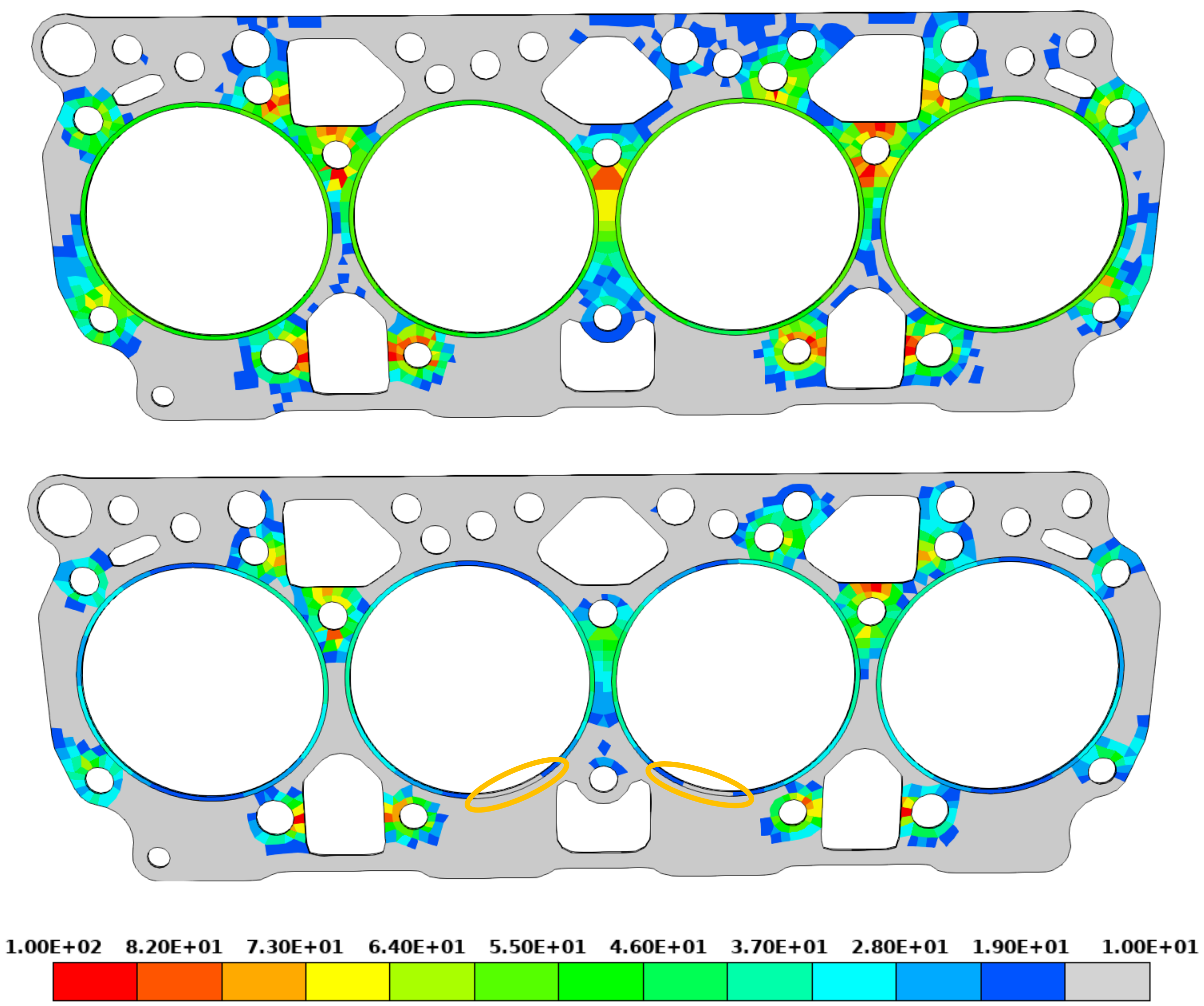


Accumulated plastic strain vs. degree CA



von Mises stress vs. accumulated effective plastic strain

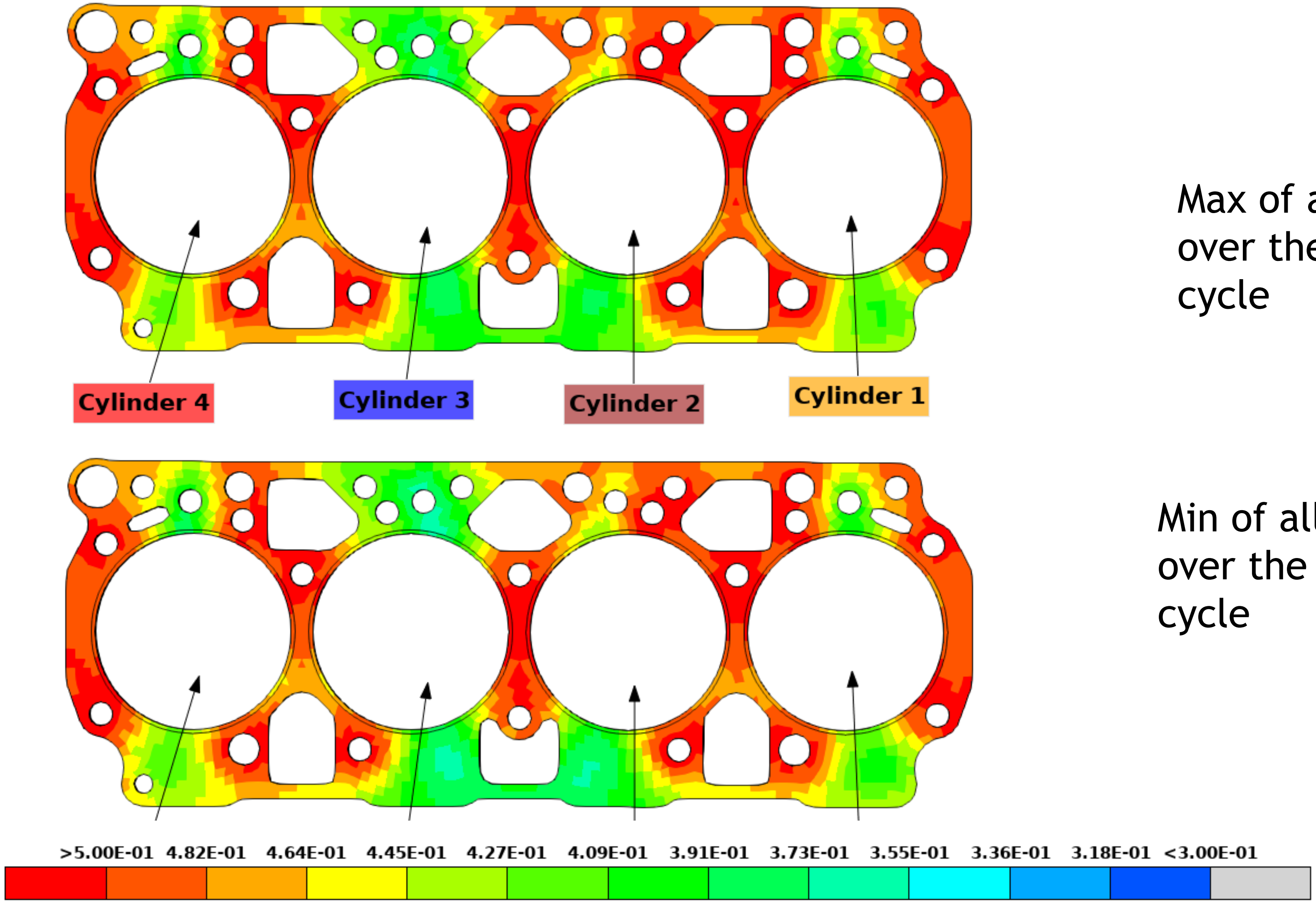
Gasket pressure ...



Max of all states
over the whole loading
cycle

Min of all states
over the whole loading
cycle

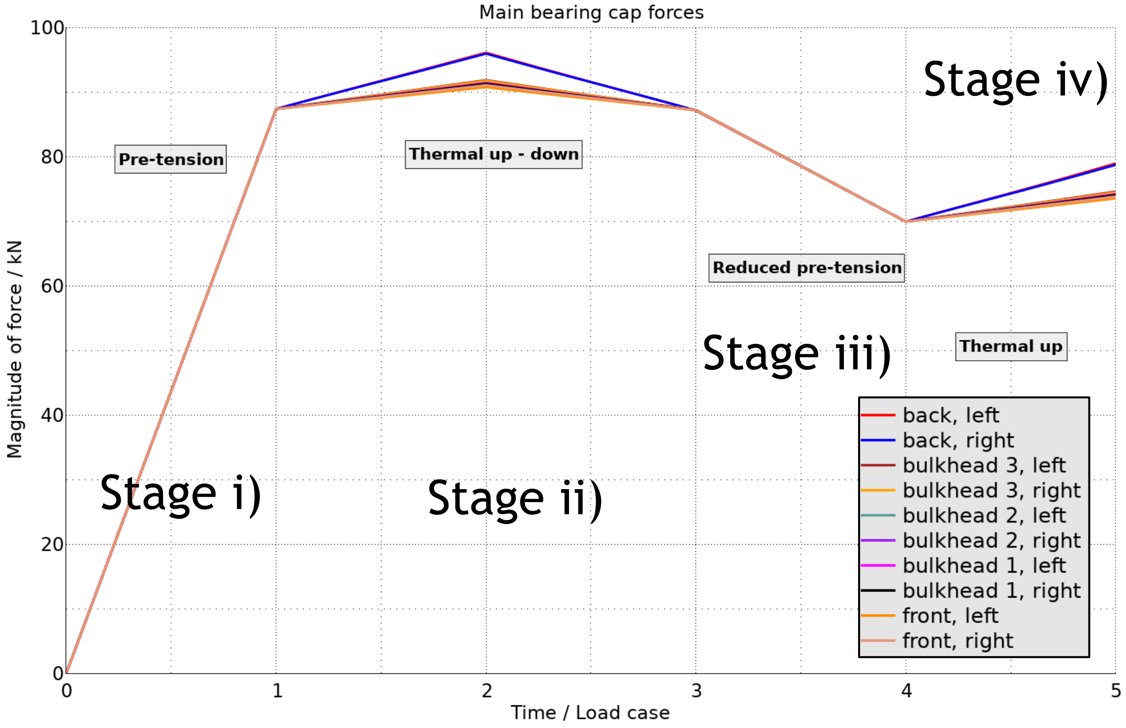
... and compression



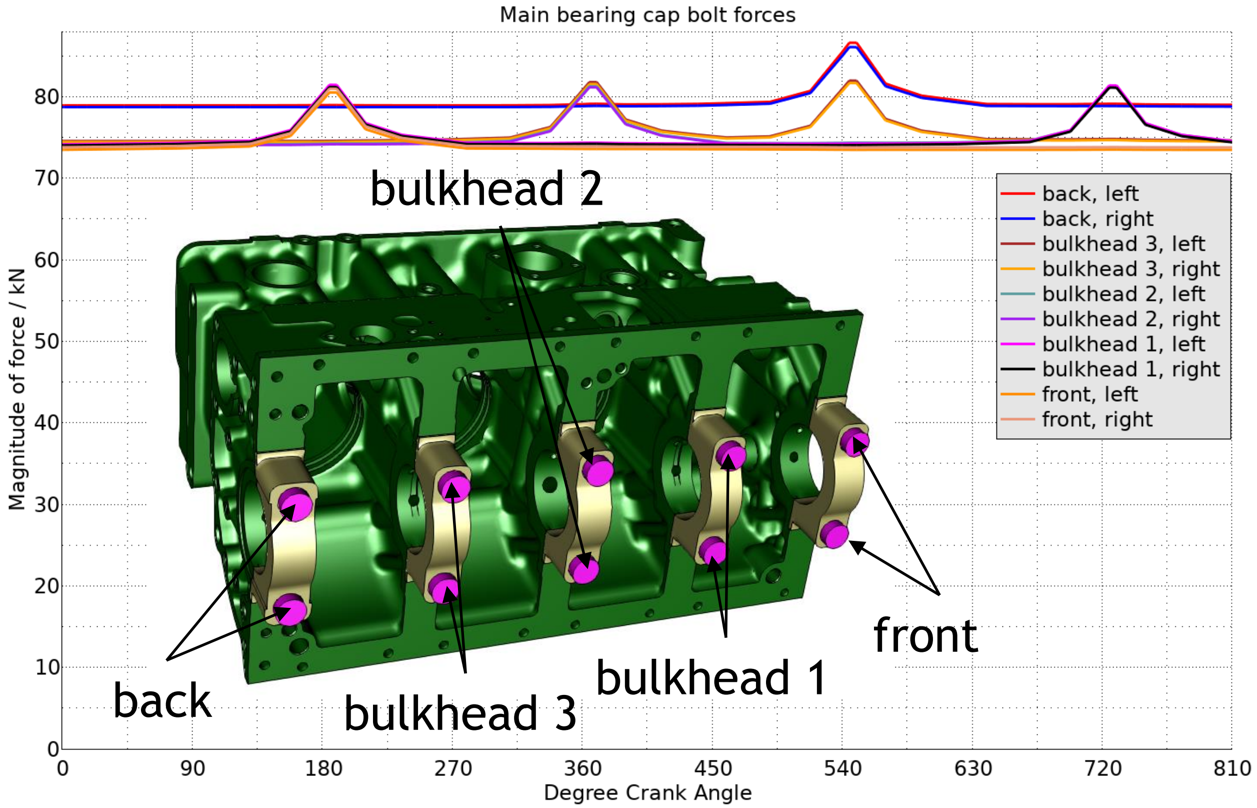
Max of all states
over the whole loading
cycle

Min of all states
over the whole loading
cycle

Bolt forces



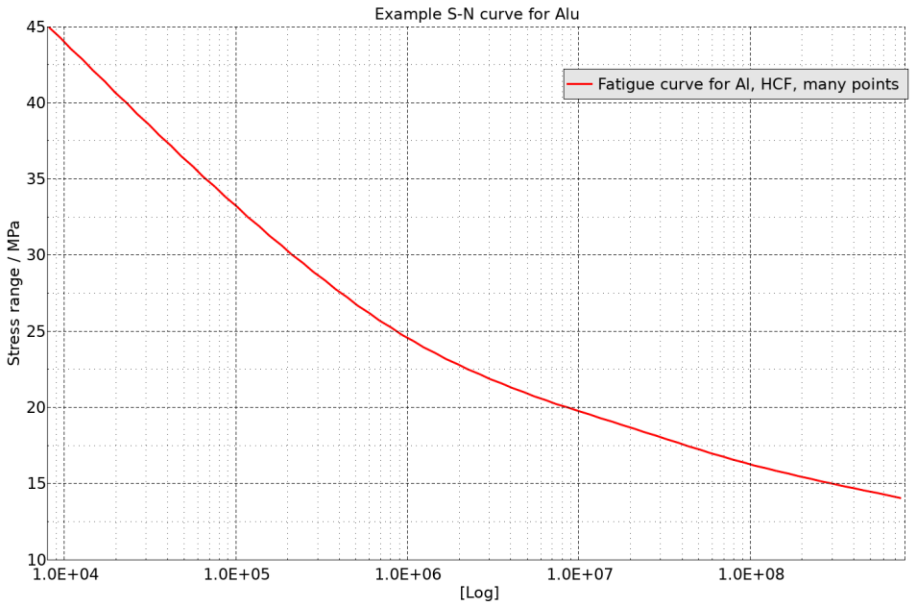
Main bearing cap forces
Magnitude of force / kN
Time / Load case
Pre-tension
Thermal up - down
Reduced pre-tension
Thermal up
Stage i)
Stage ii)
Stage iii)
Stage iv)
back, left
back, right
bulkhead 3, left
bulkhead 3, right
bulkhead 2, left
bulkhead 2, right
bulkhead 1, left
bulkhead 1, right
front, left
front, right



Main bearing cap bolt forces
Magnitude of force / kN
Degree Crank Angle
back, left
back, right
bulkhead 3, left
bulkhead 3, right
bulkhead 2, left
bulkhead 2, right
bulkhead 1, left
bulkhead 1, right
front, left
front, right
bulkhead 2
bulkhead 3
bulkhead 1
back
front

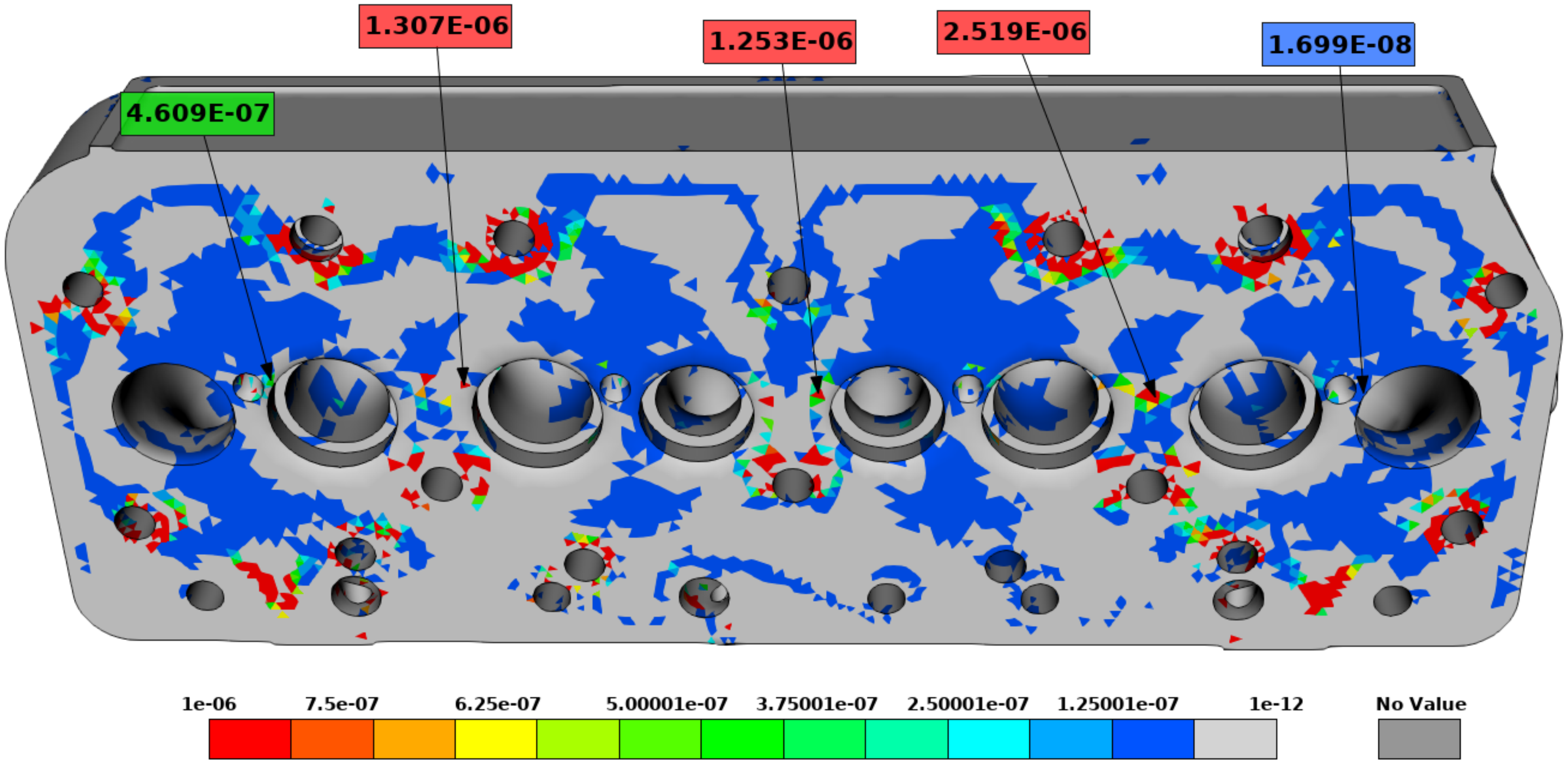
Fatigue damage

- Assumed fatigue curve for High Cycle Fatigue of Aluminium taken from Wikipedia
- *MAT_ADD_FATIGUE to assign fatigue data to a material
- *FATIGUE_ELOUT to perform the actual fatigue calculation
  - Performed as a separate analysis



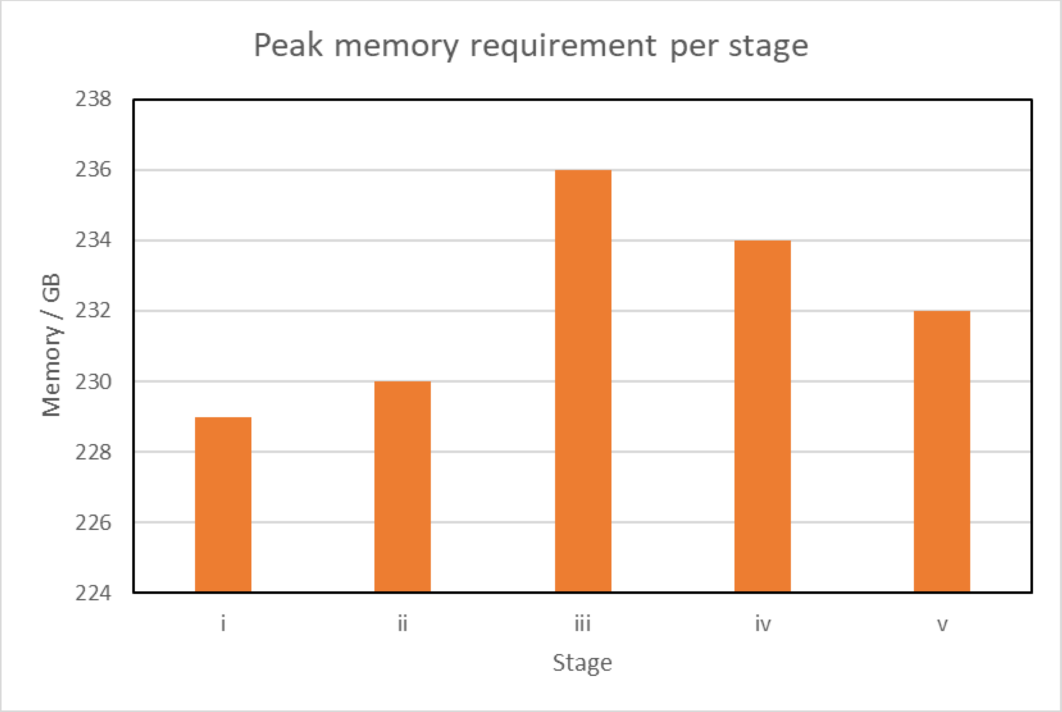
Fatigue damage

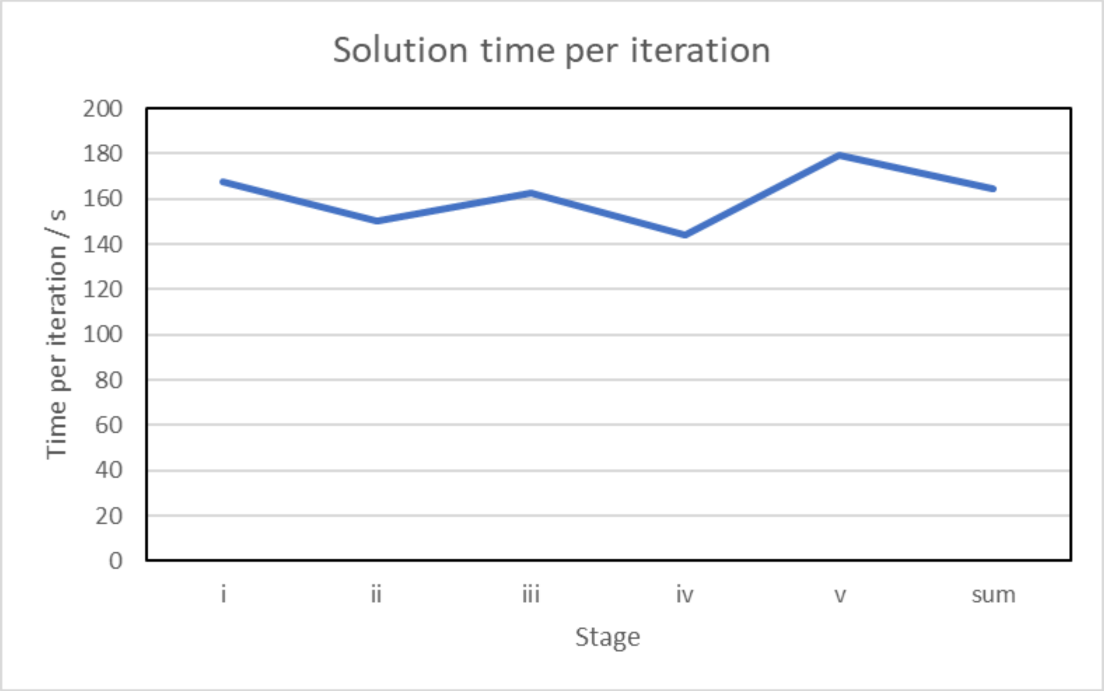
- *MAT_ADD_FATIGUE, *FATIGUE_ELOUT



Solution statistics

- 2x Xeon SP 6148 CPU (40 cores) 768 GB RAM, from 2018

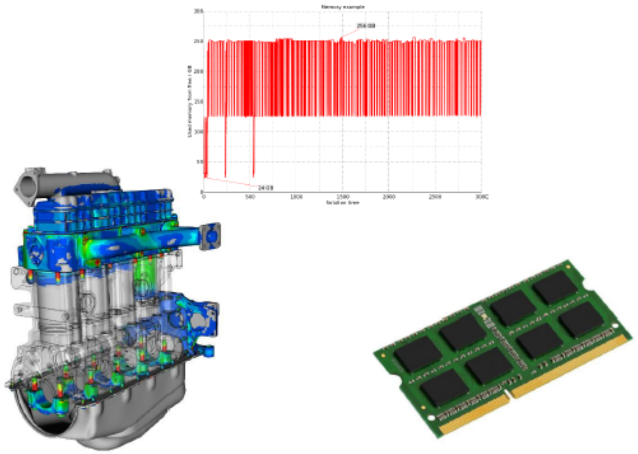




Required RAM: 230 – 236 GB

Guideline for implicit memory available from files.dynamore.se > Client Area

Memory management in LS-DYNA implicit



2021-10-14 LS-DYNA / LS-PrePost

Client Area 〉 1_LS-DYNA_Guidelines 〉 2_LS-DYNA_Implicit_Guide...

Name
ImplicitPackage_210901.zip
LS-dyna_implicit_memory_management.pdf

Summary

- Many new features in LS-DYNA R13.0.0 implicit
  - materials
  - elements
  - bolt pre-loading
- combined with existing features for
  - load history management
  - fatigue analysis
- were tested in a large-scale model
- Useful results were obtained for the studied test case
- LS-DYNA implicit will continue to improve and evolve also in the future

Thank you!

DYNA MORE

Your LS-DYNA distributor and more