Next Generation Contact Analysis

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How is the Situation about Contact Analysis?

- **Contact** is an omnipresent phenomenon in machines, vehicles, constructions.
- It describes the most nonlinear behavior of structures due to the binary character of contact: **There is contact or no contact but nothing in between**.
- Contact is very sensitive to small disturbances. **Stress** can change within wide ranges for having contact closed or not. Finer meshes provide a better stress resolution. This is a critical factor for predicting durability.
- **Computation times** are higher with contact than without contact. This often leads to models, where contact is represented only approximately in order to accelerate daily work (e.g. by MPC). But, any contact with tensional forces is no contact.
- This situation becomes even worse, when models are subject to automatic **optimization procedures**. An optimization is affordable only when the single basic contact analysis is performed in rather short time.
- **Accuracy and speed are both crucial conditions for any contact algorithm.**

Exact Contact Conditions

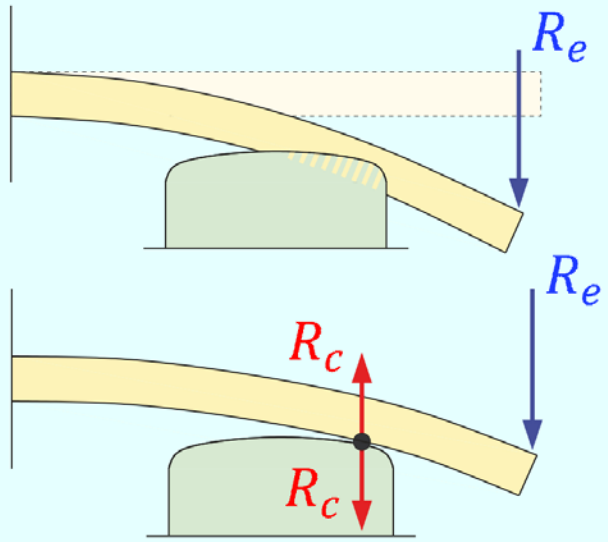
Hertz-Signorini-Moreau Conditions

(gap width δ and contact force R_c)

$\delta \geq 0$ bodies must not penetrate each other

$R_c \geq 0$ contact cannot transmit tensile forces

$\delta * R_c = 0$ contact forces only in case of a closed gap



$$K\, r_0 = R_e$$

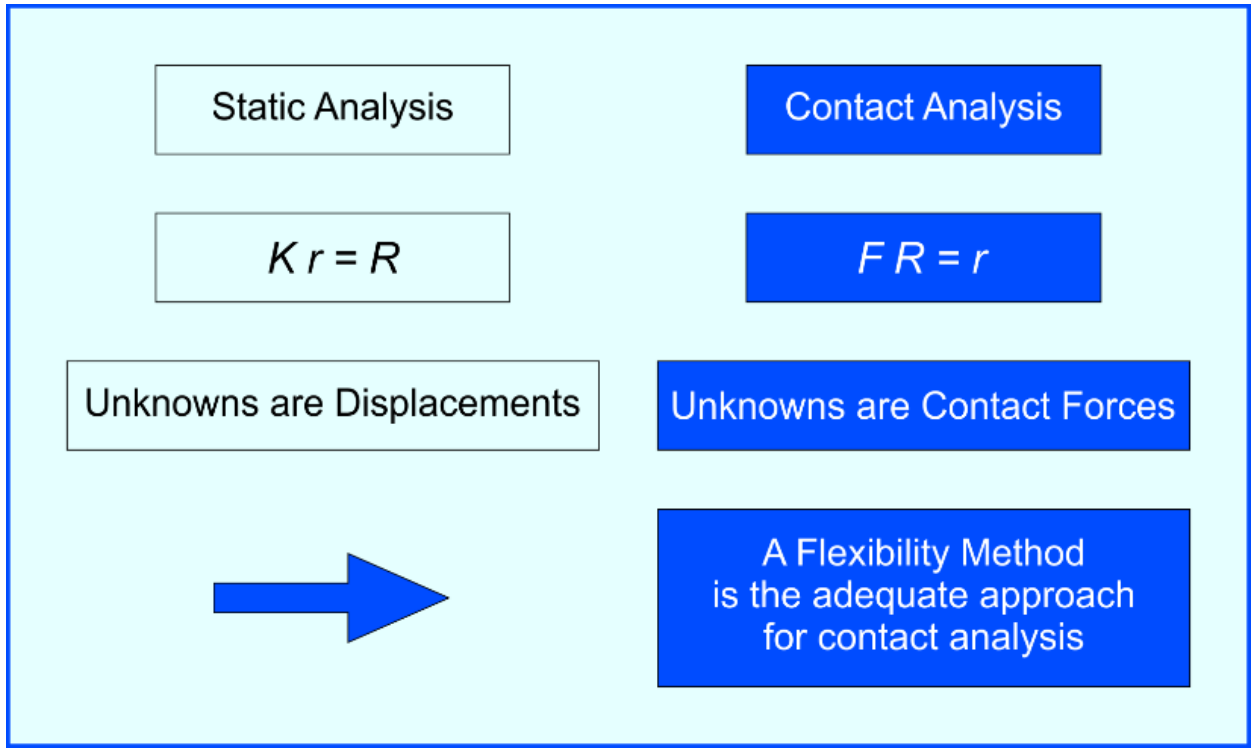
$$K\, r = R_e + R_c$$

$$r = r_0 + r_c$$

Peter Wriggers (2006). Computational Contact Mechanics. Springer. P. 71.

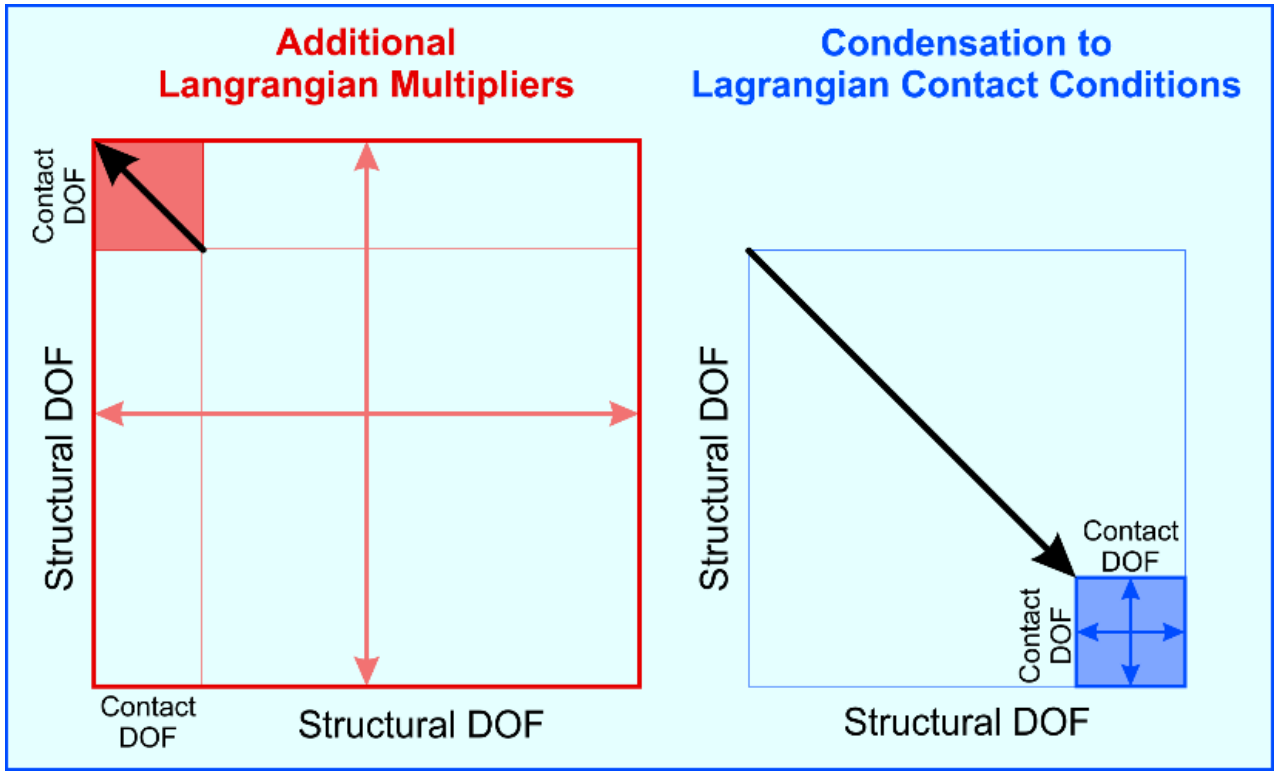
- **Definition**: All solvers, which fulfil these conditions are called exact contact solvers.
  - Lagrange multiplier methods are exact.
  - Penalty methods are not exact.

Alternative Flexibility Method



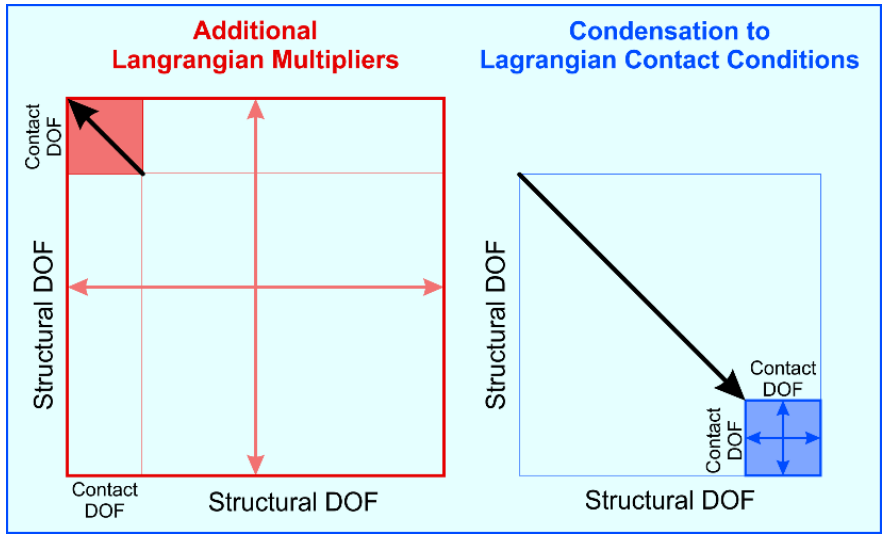
- Current solvers use stiffness with Lagrangian multiplier or penalty approach,
  - because the stiffness is also the basis to handle other nonlinearities like
    - nonlinear material,
    - geometrical nonlinearities.
- But there is a more natural approach:
  - In contact analysis contact forces are the unknowns,
  - Flexibility equation is directly solved for the unknown forces.
  - Displacements are related to contact gaps. Their initial values are known from the geometry.
  - **This method is exact.**

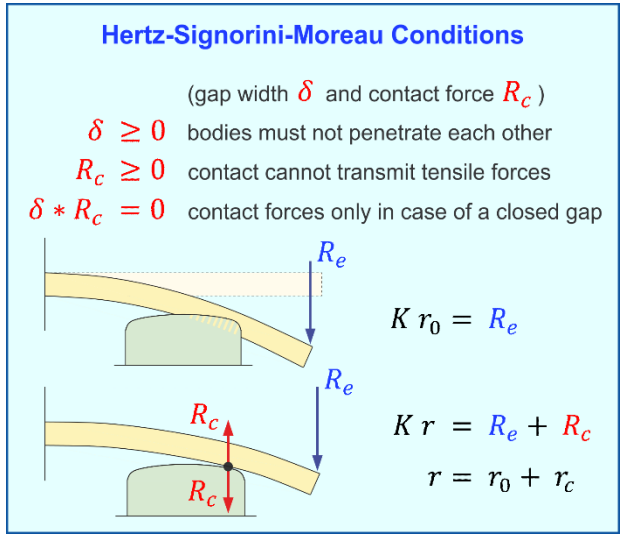
Innovation by Condensation

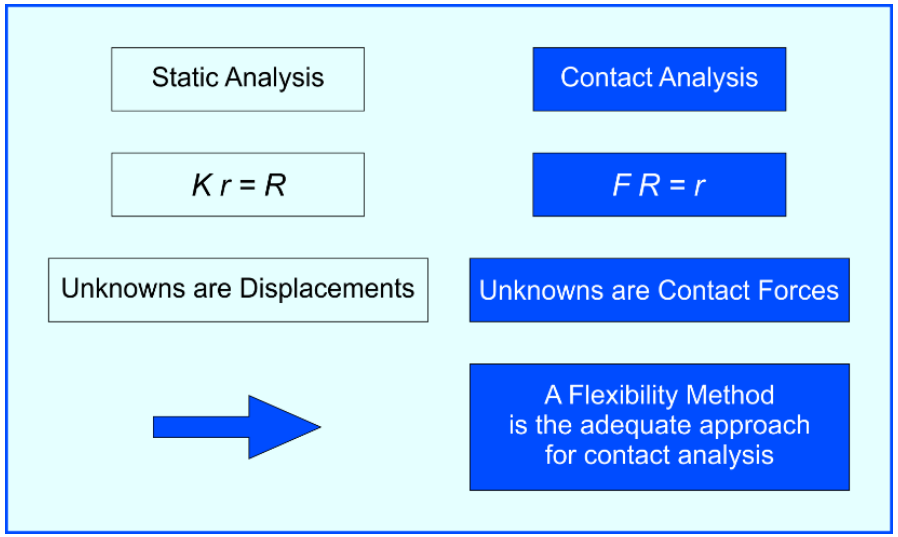


- In classical Lagrangian Multiplier methods, the multipliers add additional degrees of freedom to a system.
- In contrast, a **condensation** provides important benefits:
  - A smaller system,
  - Less degrees of freedom for non-linear solution,
  - Fast result for contact forces.

Condensed Lagrange Flexibility (CLF) Solver

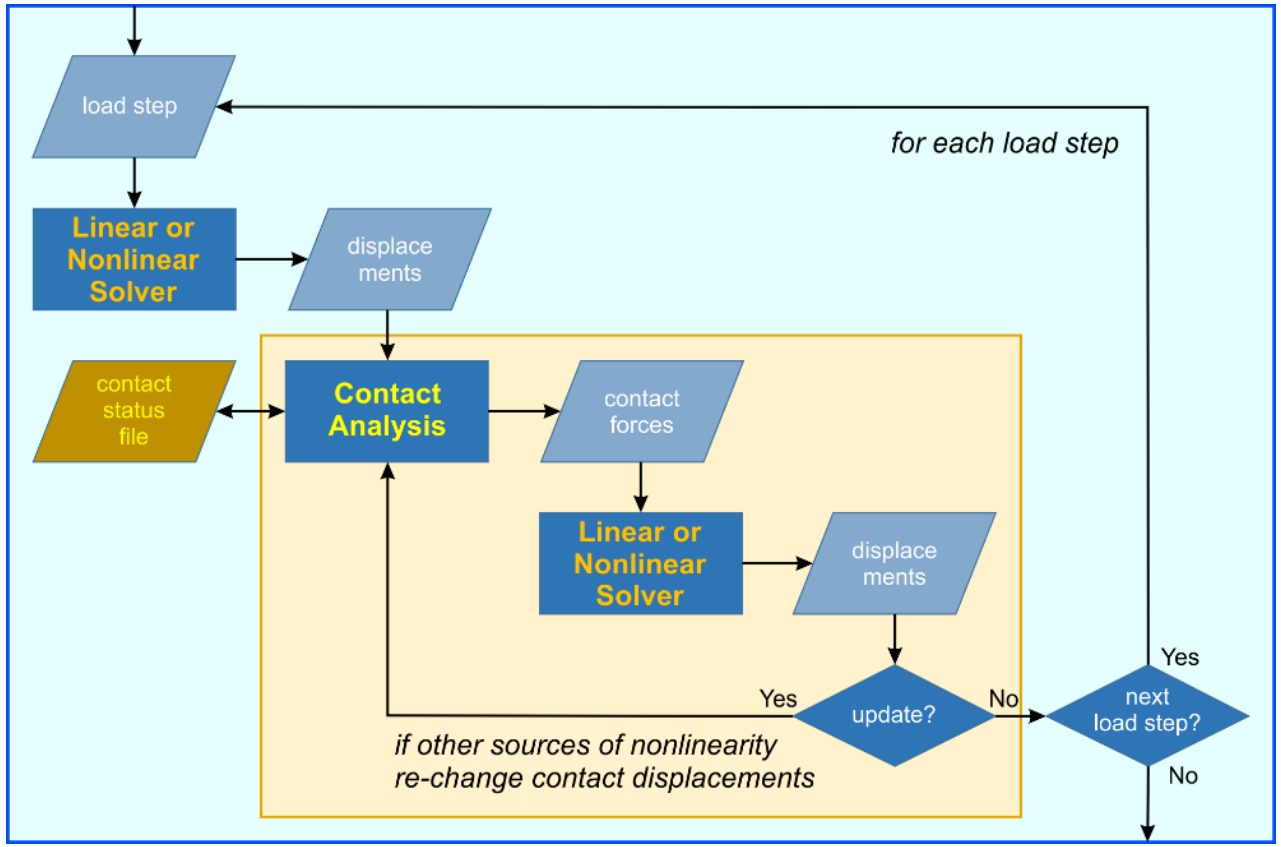






- The **CLF** solver is based on
  - the **Condensation** to contact DOF,
  - the exact contact conditions (formulated as **Lagrange** multipliers),
  - the alternative **Flexibility** method.
- The solution by a **Multi-Grid** approach provides next generation performance.

Embedding Contact in Static Analysis



- The contact solver provides contact forces in a very efficient manner.
- It has to be coupled with static analysis to get the final displacements of the structure.
- By embedding,
  - A linear static solver gets nonlinear contact analysis capabilities.
    - This provides top performance
    - for the most frequently used nonlinearity.
  - A nonlinear static solver provides additional material and geometrical nonlinearities.

Static Analysis with Embedded Contact

Feature	Nonlinear Static Solver	Linear Static Solver	Comment
Contact	2	2	
Gasket (loading and unloading)	2	2	Linear solver with high run time reduction
Bolt pretension	2	2	
Temperature dependent material	2	2	Linear solver with high run time reduction
Geometric non-linearities	2	2	Contact geometry update provides nonlinearity even in linear solver
Nonlinear material	2	-	
User nonlinear material subroutine	2	-	

Comparison with Theoretical Results

Hertzian Contact between Two Spheres

For two spheres with Radius R_1 and R_2, the maximum contact pressure is given as:

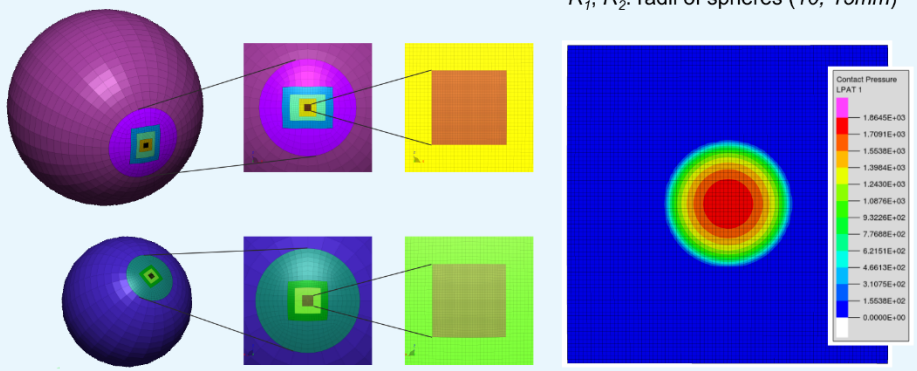
$$p_0 = \frac{3F}{2\pi a^2} = \frac{1}{\pi}\left(\frac{6FE^{*2}}{R^2}\right)^{1/3}$$

with

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}\ , \quad \frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$

and

F: applied point load (*100 N*)
E_1, E_2: Young's moduli (*200 GPa*)
ν_1, ν_2: Poisson's ratios (*0.3*)
R_1, R_2: radii of spheres (*10, 15mm*)

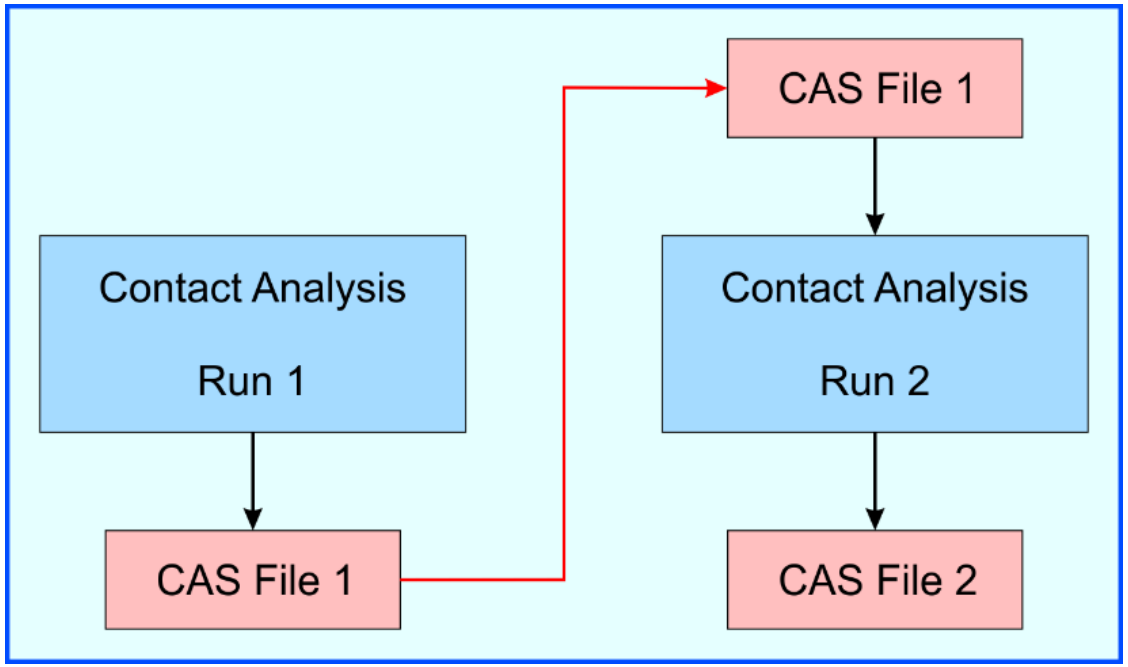


Hertz: p_0= 1865.40 Mpa
Permas: p_0= 1864.52 Mpa
Δ **= 0.05%**

Model: 1.5 MDOF, 40k contacts
Run time: **85 sec**
Computer: 4*28 Intel(R) Xeon(R) Platinum 8180 @ 2.5 /754.57 GB

- Hertzs‘ theoretical results provides a good means to compare with FEA results.
- Here, sphere-to-sphere contact is used to show the accuracy of the alternative contact solver.
- As for all exact methods, a mesh refinement improves the quality of the result.

Additional Speed-Up



- Usually, analyses are performed several times with slight model variants.
- In contact analysis, the iterative process can be shortened drastically,
  - when the contact status at the end of one contact analysis
  - is used as initial condition for the subsequent contact analysis.
- Contact status means for every contact node:
  - in contact or not in contact,
  - sliding or sticking in case of friction.

Example for Additional Speed-Up

Engine with Assembly and 360° Crank Shaft Revolution

Nodes	2,605,313
Elements	1,603,484
Unknowns	7,363,408

CA DOF	44,387
- normal	29,815
- frictional	14,572

Linear static analysis for 70 load steps:

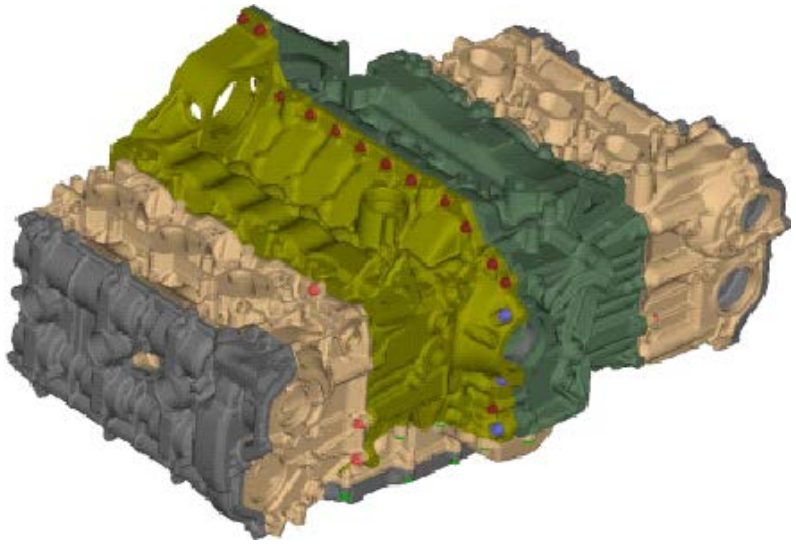
1. analysis (no CAS files): **07h23m**

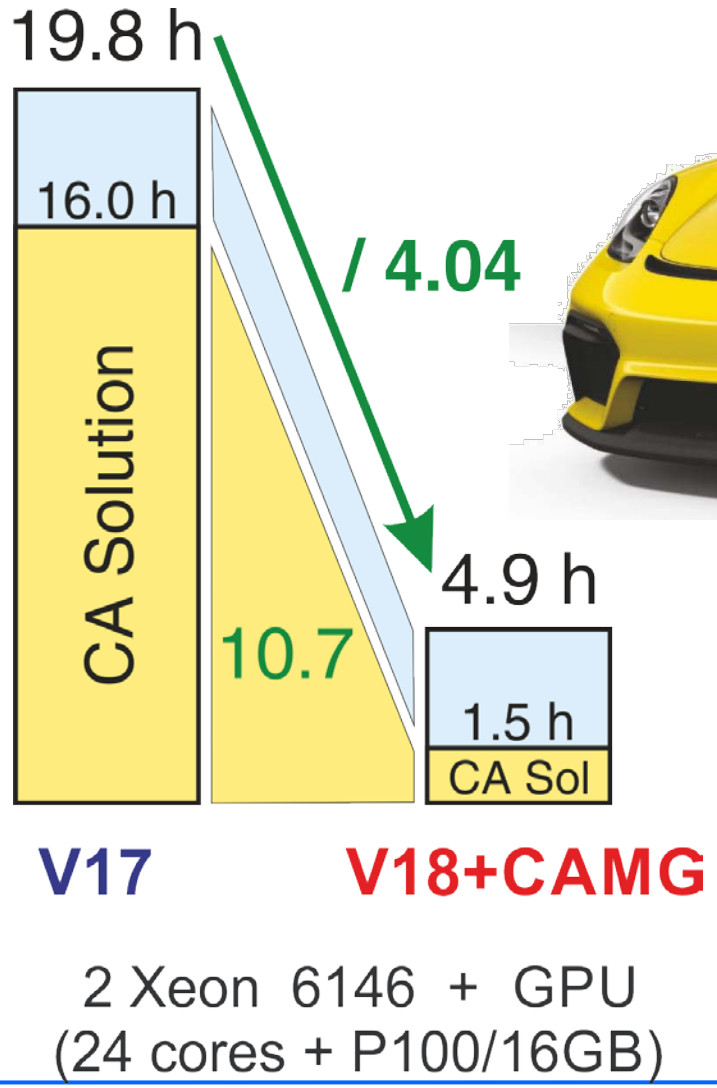
2. analysis (with CAS files): **47m** → **Factor 9.8**

*112 cores (4*Intel-Platinum-8180) @ 2.5 GHz, 768 GiB*

- Maximum speed-up is achieved, if the structural variant does not change the contact status.
- Contact status files can be used automatically.
  - All optimizations with contact highly benefit from this approach,
  - because optimizations typically make slight changes only.

Large Industrial Engine Project



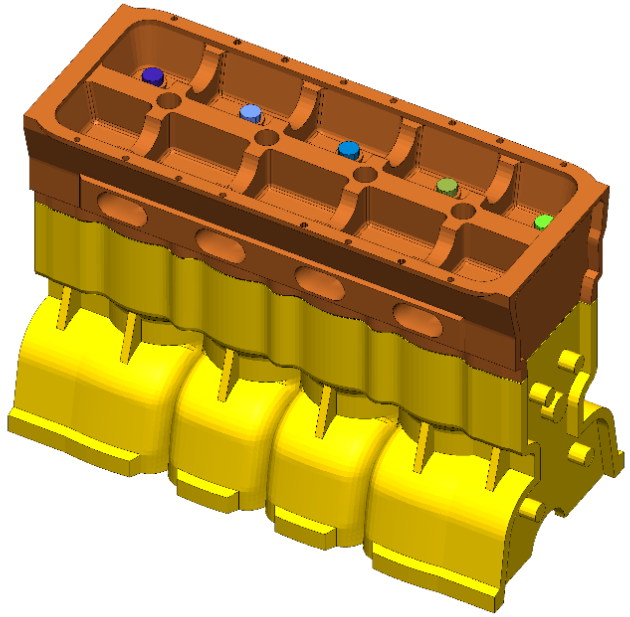


- **Model**:
- 19 Million nodes, 13 Million elements,
- 56 Million DOF, 145,000 contacts,
- gasket, bolt pretension,
- two temperature states.

- **Analysis**:
- Static analysis,
- 37 time steps with various loads,
- with contact status files.

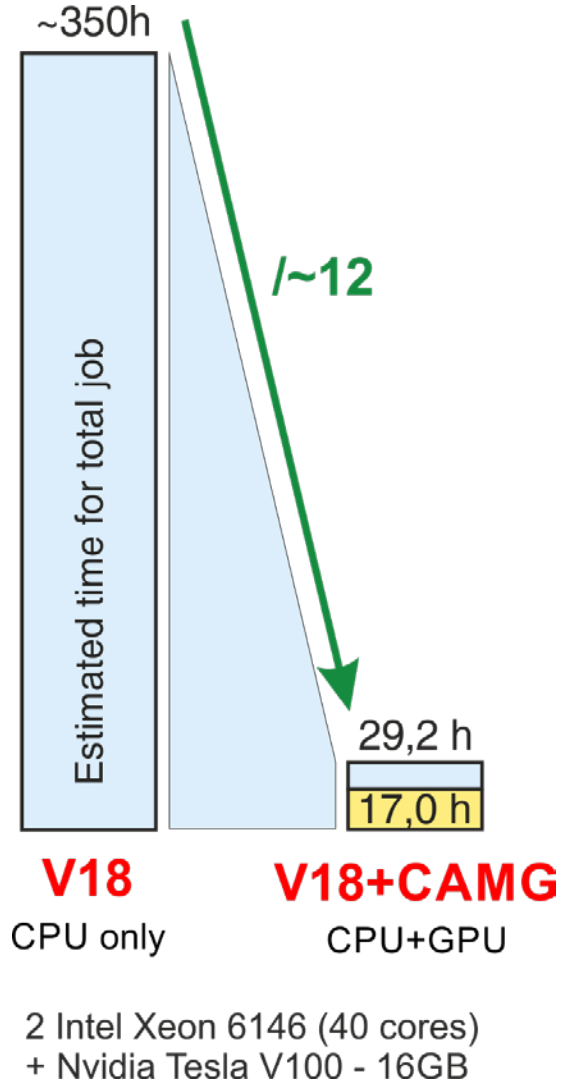
- Model sizes are generally increasing.
- The main motivation is to get better stresses for durability analysis with finer meshes.
- **Multi-Grid** solution for big jump in performance.

Very Large Contact Model



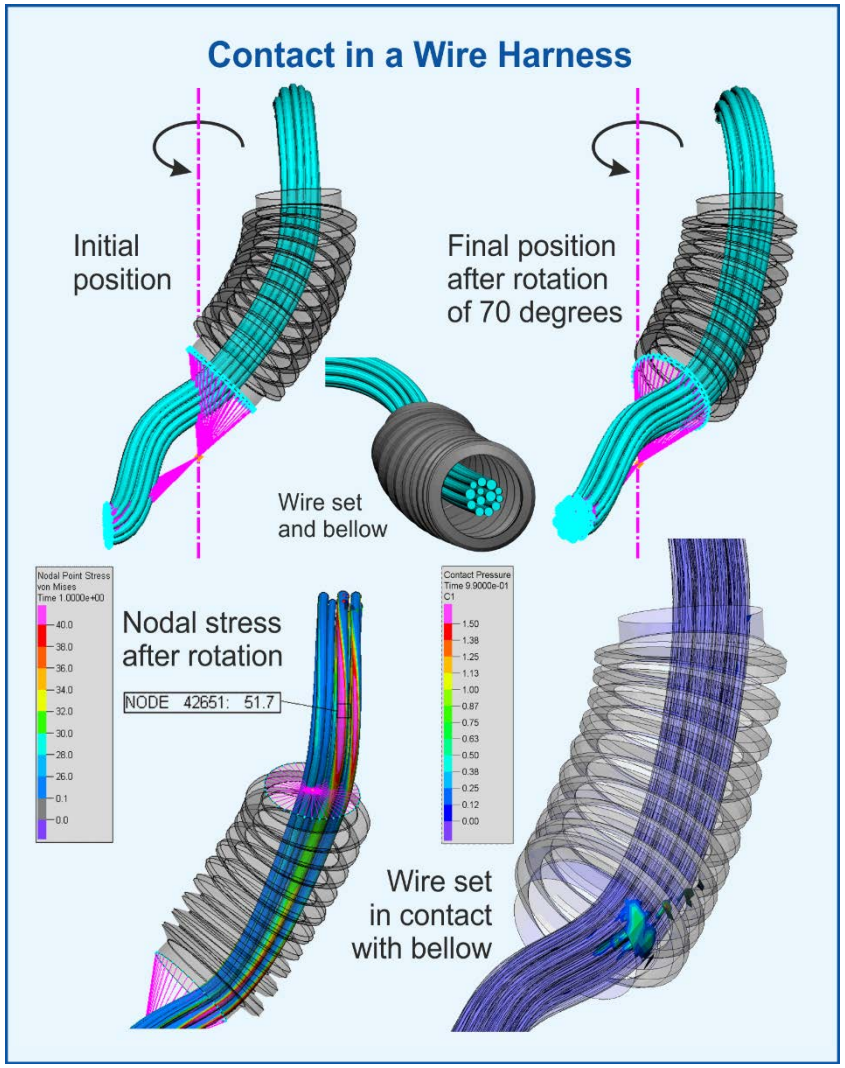
- **Model**:
- 61 Million nodes, 46 Million elements,
- 183 Million DOF, 320,000 contacts,
- gasket, bolt pretension,
- temperature load.

- **Analysis**:
- Static analysis,
- 12 time steps with various loads.

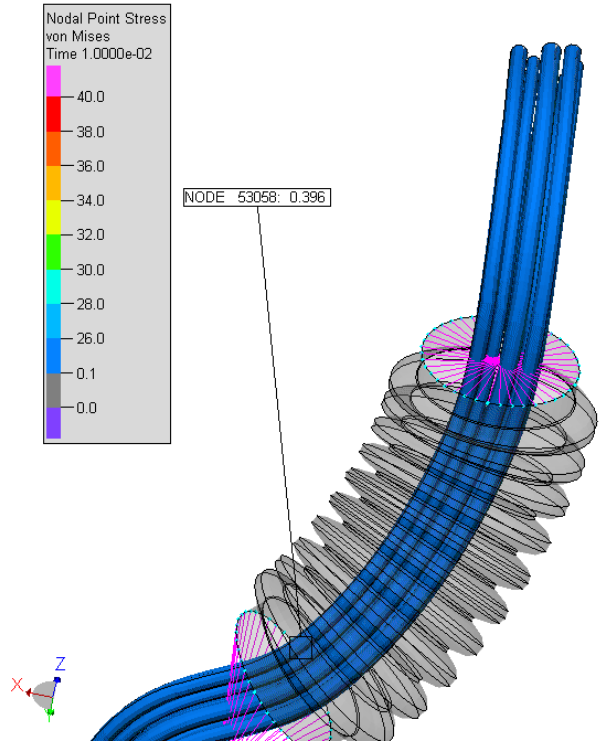


- This is a test model to check the performance for not yet quite usual model sizes with contact.
- While former solvers cannot solve such problems at all, one gets acceptable computation times using a new solver approach.

Self-Contact of Wire Harness



- Contact is between
  - wire harness and bellow,
  - between the folds of the bellow (inside and outside),
  - between the 13 wires.

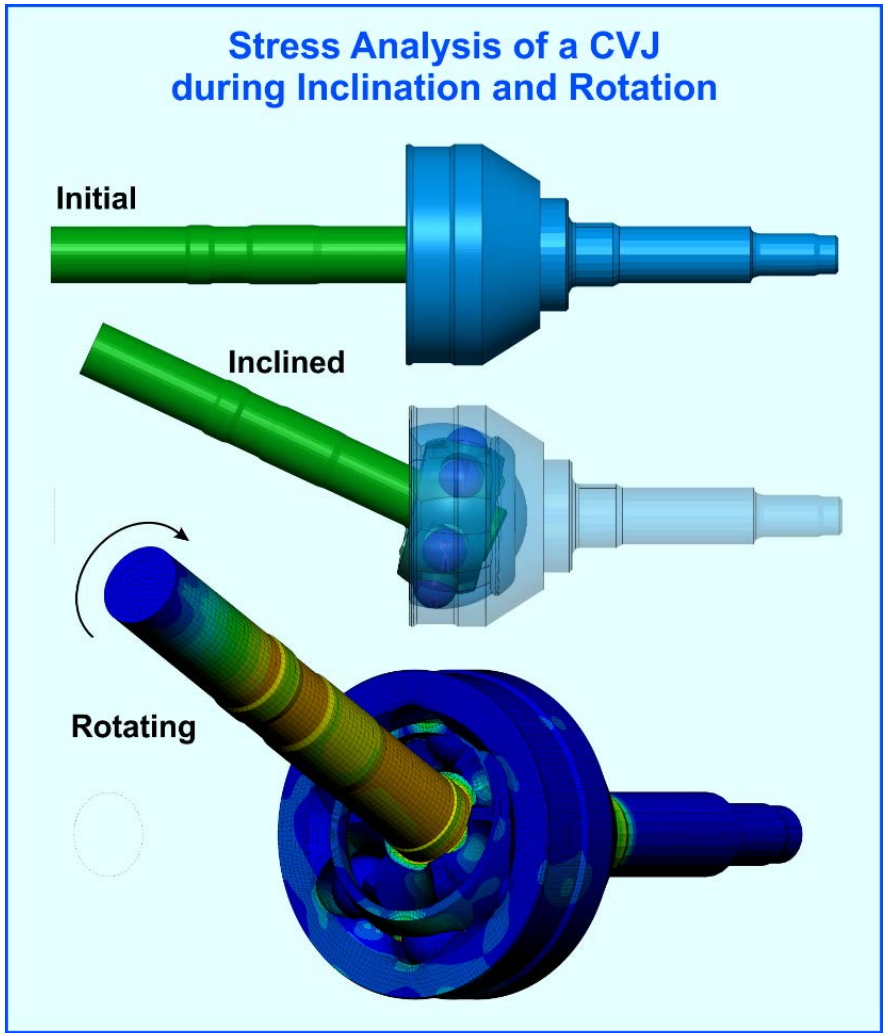


Model:		Analysis:
Nodes	34,100	Nonlinear static with contact,
Elements	25,130	Prescribed rotation,
Unknowns	107,600	100 time steps, CAS file.

Run time: **29m 53s**

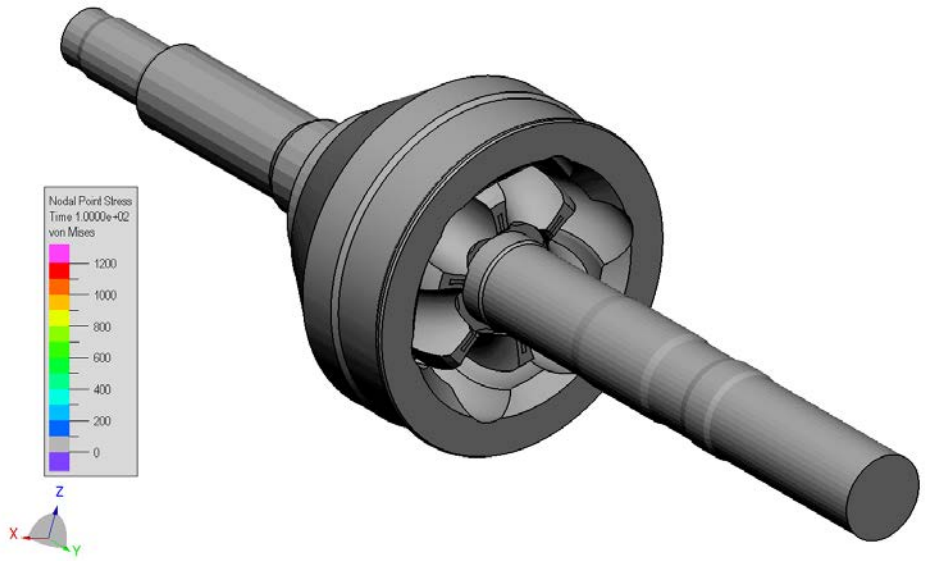
18 core,Intel(R) Xeon(R) CPU E5-2697 v4 @ 2.30GH, 110 GiByte Memory

Stress Analysis with Large Rotations



Contact is between

- outer race and balls,
- inner race and balls,
- retainer and inner race, balls, and outer race.



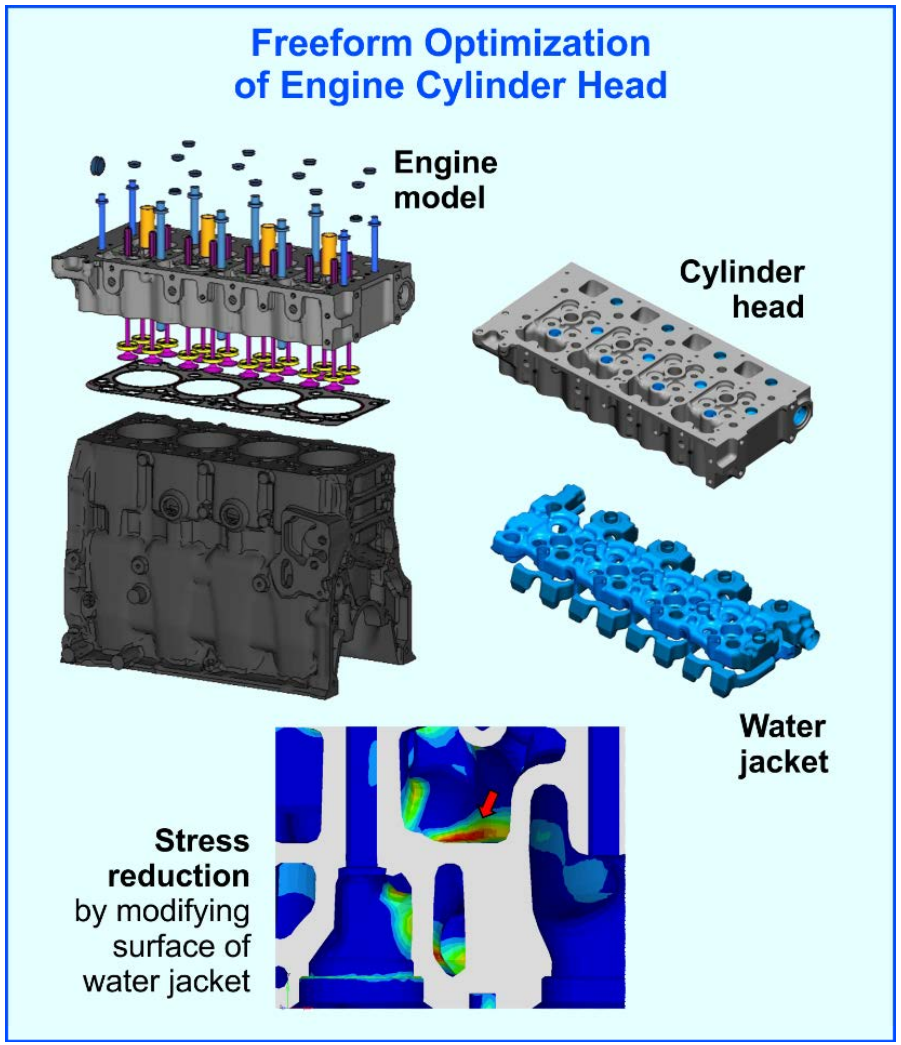
Model:	
Nodes	626,890
Elements	523,076
Unknowns	1,747,192
Contact	

Analysis:
Nonlinear static analysis,
Inclination 50 steps,
Torque,
Rotation 360° in 72 steps

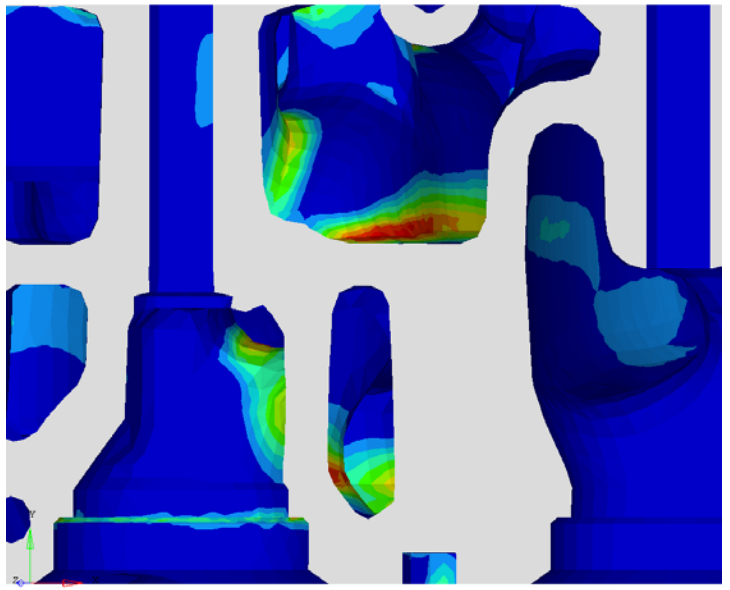
Run time 11h 2m → **~5m per load step**

*1*18 cores Intel(R) Xeon(R) CPU E5-2697 v4 @ 2.30GH / 110 GiByte*

Freeform Optimization of Cylinder Head



- Minimization of stress for the complete surface of the water jacket.
- Using a non-parametric shape optimization method.



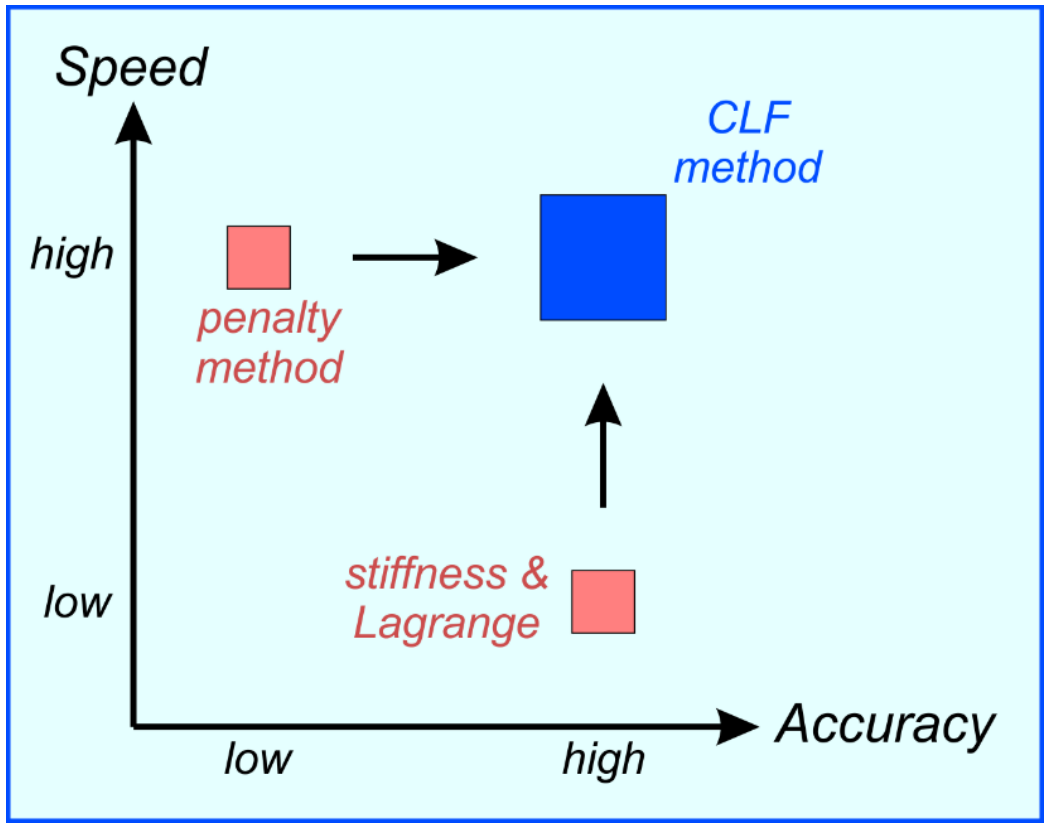
Model:	
Nodes	1,712,340
Elements	1,222,235
Unknowns	5,090,156
Contact	

Analysis:
Nonlinear thermal,
Static (Gasket, Pretension,
Temperature, Firing)
Optimization of stresses

Run time for 6 iterations **6h 25m**

*2*8 cores Intel(R) Xeon(R) CPU E5-2690 0 @ 2.90GHz / 117 GiByte*

Exact and Fast Contact Analysis



- The **CLF method** is now available for contact analysis in PERMAS.
- This method is not only exact but also very fast,
  - ✓ fully parallelized,
  - ✓ high time savings with contact status files,
  - ✓ linear analysis with nonlinear contact !

➢ Mission is accomplished to deliver an accurate and high-speed contact solver!

Thank You!

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