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Simulation of containment-tests at a generic model of a large-scale turbocharger with LS-DYNA

Stefan Hennig[1], Prof. Dr.-Ing. Armin Huß[2], Heiko Honermeier[1], Marcel Jagic[1], Manuel Schönborn

[1] Ingenieurbüro Huß & Feickert GbR, Liederbach, Germany
[2] Frankfurt University of Applied Sciences, Frankfurt, Germany

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Overview

- Introduction
  - Company Profile
  - Why simulate Containment-Tests
- Motivation
- Containment Simulation today
- Generic Model
- Studies
  - different approaches of modeling bursting scenario of compressor flywheel
  - effect of lode-angle-parameter on the damage and failure behavior of the housing structures
- Summary

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Introduction - Company Profile

- 1992 Founded (managing partner: Prof. Dr.-Ing. W. Feickert and Prof. Dr.-Ing. A. Huß)
- Based in Liederbach / Frankfurt a.M.
- Providing CAE services for several branches: automotive industry and its components suppliers, machine and plant construction, aerospace, consumer goods, chemical industry
- Fields of activity:

Simulation explicit and implicit FE-Method	Software- und Product Development	Experimental Services	Software -Training
- Linear and nonlinear structural mechanics - Dynamic - Optimization - Thermal Transport - Fluid Dynamic - Crash - Drop Test - Containment Test	- Software Development - AutoFENA 3D - FKM inside ANSYS - WB/FKM - WB / Weld - ASME-Tool - Buckling-Tool - Product Development - Concept Development	- Durability Testing - Acceleration Measurement - Modal Analysis - Temperature- und Strain Gauge-Measurement	- Training Courses and Webinars - ANSYS - LS-DYNA - FKM Assessment

- Since 2010 office in northern germany (near Hamburg)
- Since 2015 office in Düsseldorf

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Introduction – Why simulate Containment-Tests

- Why simulation techniques are used?
  - Hardware test: extremely high kinetic energy
    - very dangerous → high safety precautions necessary
      - Example: A rotor with a mass of 20 kg rotates with 26.000 min-1 corresponding approximately 840.000 J of kinetic energy. In a car side crash about 105.000 J of kinetic energy have to be dissipated.
    - very expensive and time consuming
    - duration of damage process: approximately 2-15 ms
    - comprehension of high-speed deformation processes is restricted
    - possibilities for measurements and improvements are limited
  - using explicit finite element technique
    - reduce/minimize number of hardware tests
    - possibility to look into the machine during crash and analyze and comprehend load chains
    - nowadays essential tool used from the early stage of the development process of a turbocharger up to its certification and also afterwards accompanying the whole machine-life
      - Develop a safe design with regard to burst loads
      - Analyze and understand damage process, load chains and the causal correlations in the machine in detail
      - Qualify design concerning modified boundary or operating conditions

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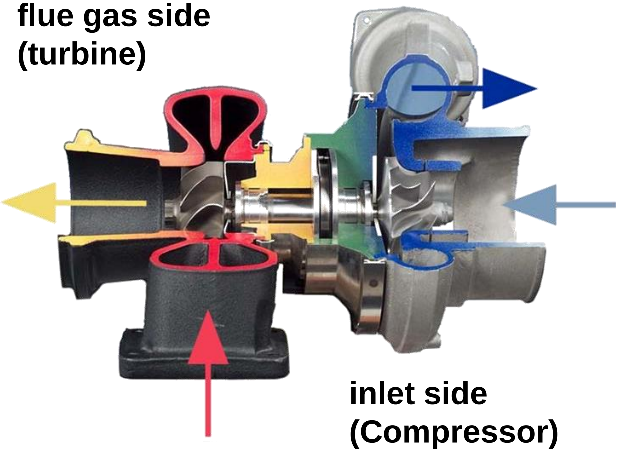
Motivation

- Simulation concepts and methodologies are developed continuously
  - Problem:
    - turbocharger structures become more and more complex and sophisticated
    - the bursting and damage procedure should predicted as exact as possible
    - increasing demand in the precision of the CAE model (e.g. all cast structures are meshed with 3D elements, preferably hexahedrons)
      - strong increase in effort for modeling
      - strong increase of computing time



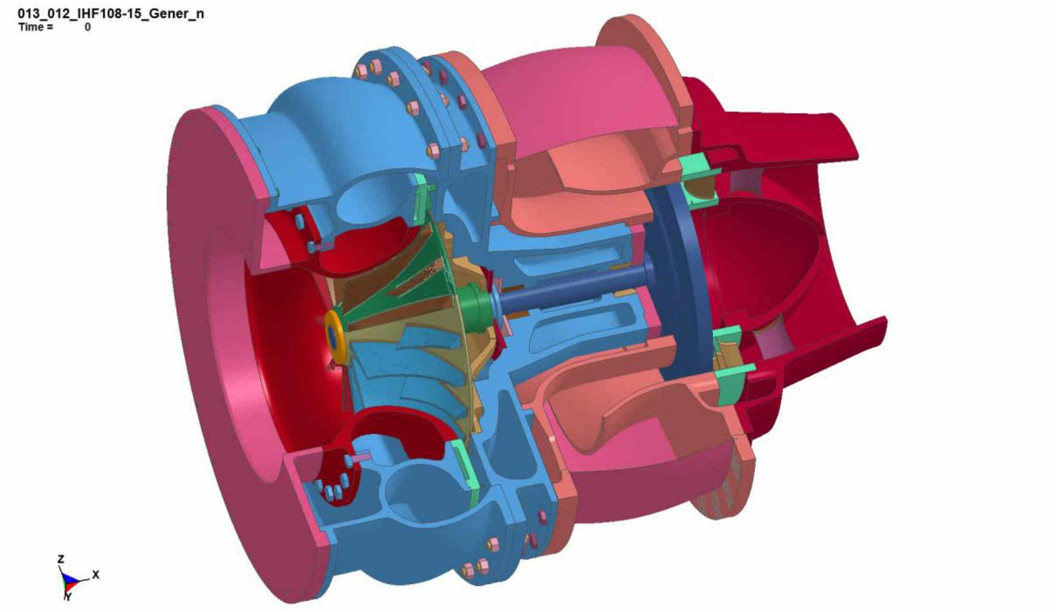
Source: NASA

  - Further investigations (e.g. new approaches for different idealizations of certain areas, new material laws, different boundary conditions or robustness studies) at a model of a specific turbocharger and on that high level of detail is not really economical.

→ The idea of a generic CAE model of a large-scale turbocharger was born

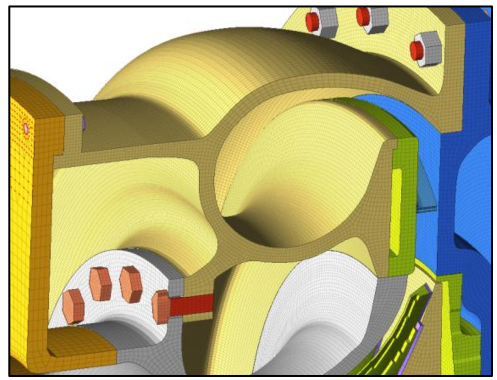
Containment-Simulation Today

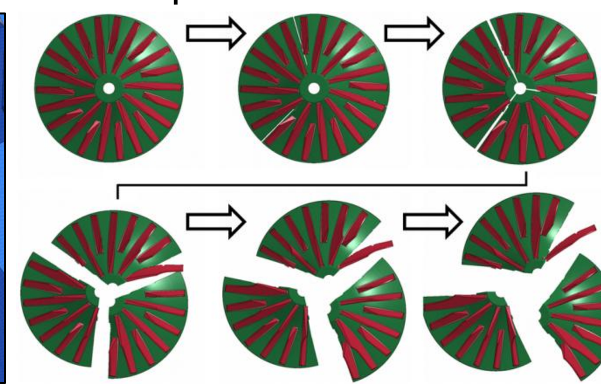
- What are the tasks today?
  - compressor impeller burst and turbine wheel burst or blade loss scenarios and combinations of both
  - several load cases and structure variants
    - different burst scenarios, rotational velocities, impact positions, impeller/blade sizes, different design sizes (not scaled ideally)
  - lead to complex and varying load paths and high loadings in different sections
  - long load chains with multiple sites of fracture



Containment-Simulation Today

- ➢ detailed model of the whole turbocharger is necessary which is able to accurately represent all areas
  - ○ fine mesh with 3D-elements (preferably Hexahedrons) for structure parts and fasteners
    - min. 3 – 5 elements over wall thickness
    - consider cast radii
    - consider ribs
  - ○ reduce connection via tied contacts
  - ○ impeller: separate wedges
    (merged over 50-60% of height beginning from the top of the impeller → closer reproduction of the real weakening)





  - ○ boundary conditions: pretensions, internal pressure, propulsion of rotor
  - ○ complex material models:
    - differentiation of behavior under tension and compression load with consideration of strain-rate dependencies (e.g. MAT124)
    - multi-axial fracture including damage (*MAT_ADD_EROSION – GISSMO)

➢FE-Data:
- > 5 million nodes
- > 5 million elements
- 4,5 mm average element length
- ca. 0,5 mm min. element length
- very small timestep
- simulation time: 8ms → calculation time: ca. 40-60 h (16 CPU-Cores)

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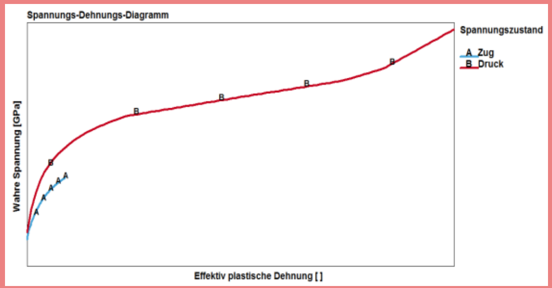
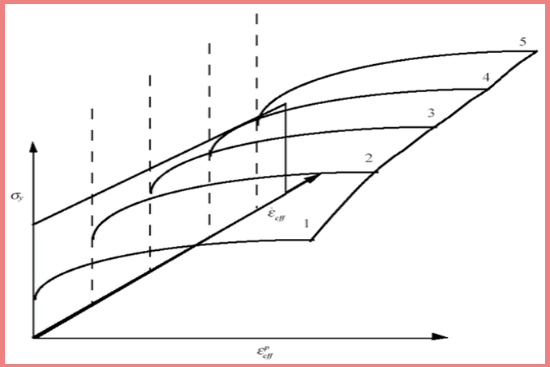
Containment-Simulation Today

- Example: material law for a cast housing: *MAT124 + *MAT_ADD_EROSION (GISSMO)

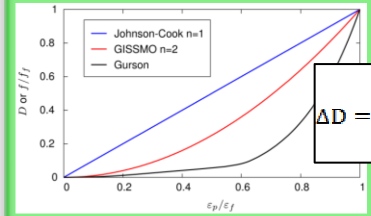


Stress-strain-diagramm (quasistatic)



strain rate dependency[3]

Damage



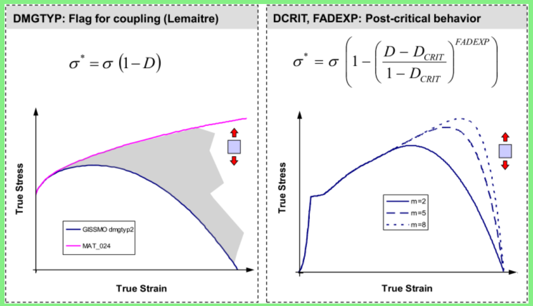
$$\Delta D = \frac{n}{\varepsilon_f(\eta,\xi)} \cdot D^{\left(1-\frac{1}{n}\right)} \cdot \Delta\varepsilon_p$$

Damage accumulation [1]

Material instability:

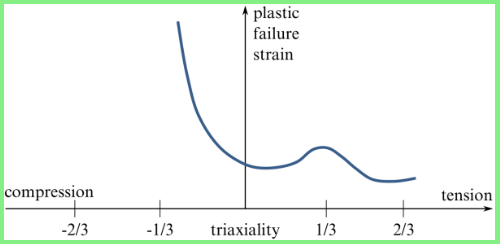
$$\Delta F = \frac{n}{\varepsilon_{v,loc}(\eta,\xi)} \cdot F^{\left(1-\frac{1}{n}\right)} \cdot \Delta\varepsilon_p$$

curve / surface



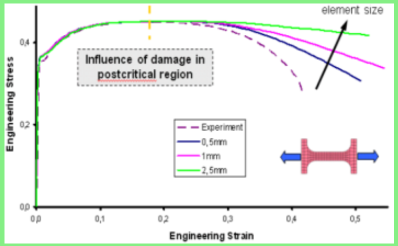
Influence of coupling damage to flow stress [1] [2]

Failure



Typical failure curve for metal sheet [3]

3D: add. lode-angle-dependency → failure surface



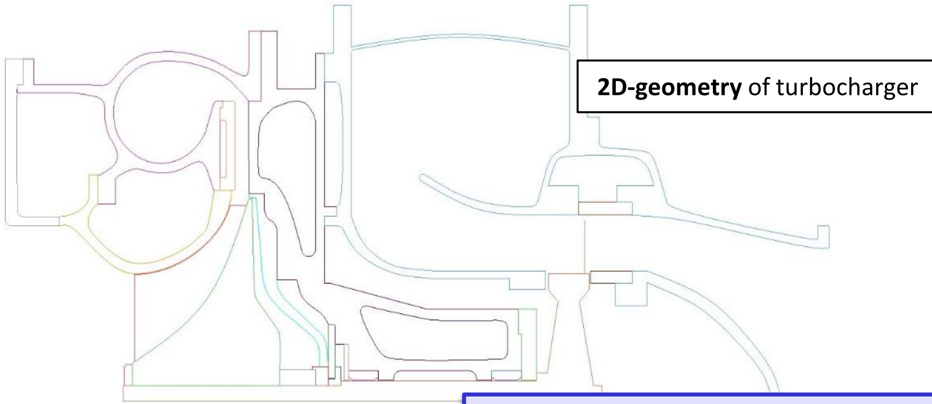
Influence of element size on stress-strain-curve [2]

- Strain rate dependency of failure strain and material instability

[1] M. Basaran, „Stress State Dependant Damage Modeling with a Focus on the Lode Angle Influence,“ RWTH Aachen, Aachen, 2011, Dissertation.
[2] A. Haufe, P. DuBois, F. Neukamm und M. Feucht, „GISSMO - Material Modeling with a sophisticated Failure Criteria,“ Dynamore GmbH, Stuttgart, 2011.
[3] Livermore Software Technology Corporation (LSTC), „LS-DYNA Keyword User´s Manual - Volume II Material Models,“ LSTC, Californien, 2015

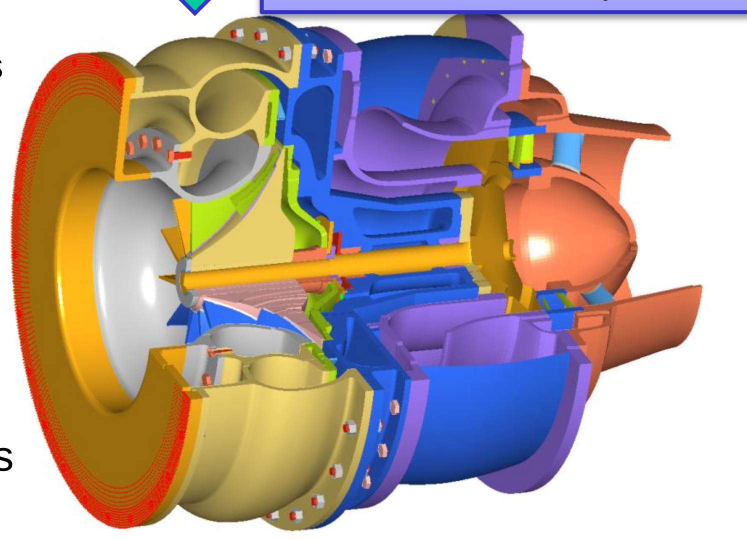
Generic Turbocharger Model

- Requirements:
  - usable for compressor and turbine damage
  - as simple as possible
    - reduce simulation time
    - quick and easy modifiable
    - possible parameterization
  - as accurate as possible
    - depict the principle behavior of real containment tests with all its complex load chains
- Objective:
  - no assessment of containment safety
  - influence check (A-B-comparisons)
  - robustness studies
  - test new approaches (modeling, material, BC´s)
  - benchmark new software releases or other codes



360° rotated

- mass = 2300 kg
- max. diameter d = 1160 mm
- Rotational speed n = 14340 1/min
  = circumferential velocity 475 m/s



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Generic Turbocharger Model

- Turbocharger is build up modular: **3 sections and rotor**:
  - Compressor
  - Bearing
  - Turbine
  - Rotor

  2 versions of each (coarse and fine - differentiation of compressor and turbine containment)

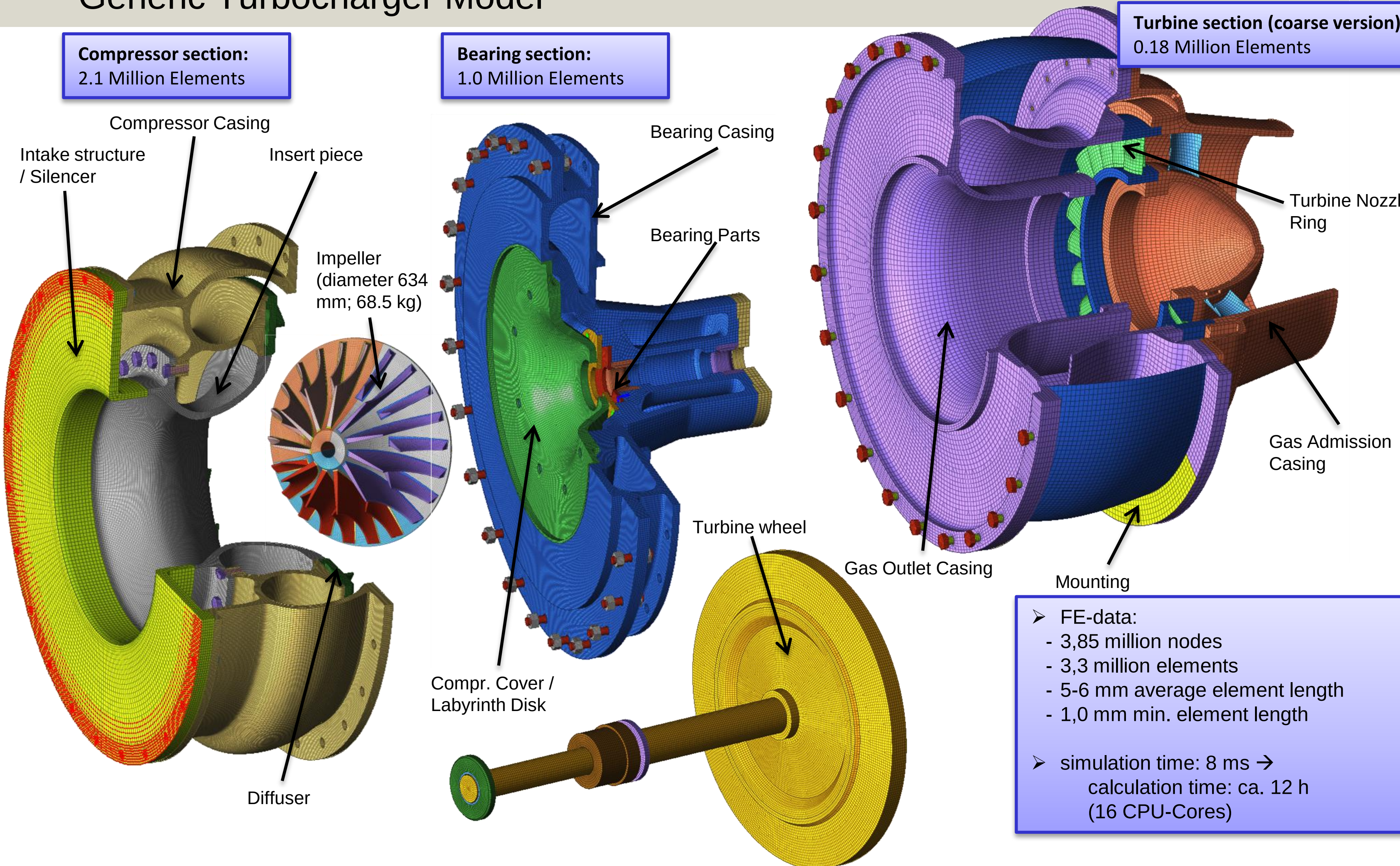
- **rotational symmetric structure**
  - no inlet and outlet openings
- no base / foot structure
  - **mounting via BC´s at lower area of circumference of turbine casing**
- silencer heavy idealized
  - back plane/flange + lumped masses
  - **retention mass inertia**

Generic Turbocharger Model

Compressor section:
2.1 Million Elements

Bearing section:
1.0 Million Elements

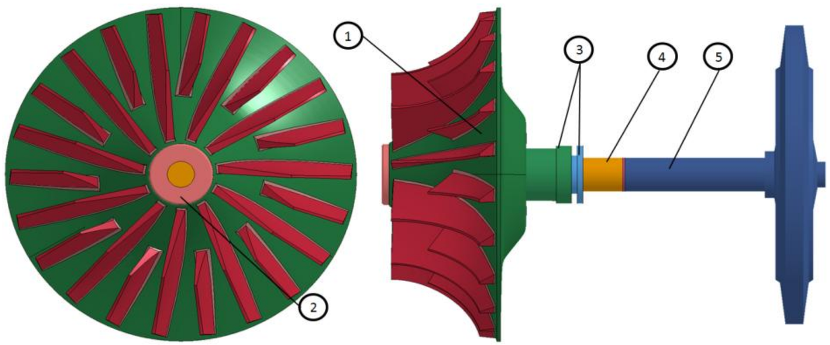
Turbine section (coarse version):
0.18 Million Elements



- FE-data:
  - 3,85 million nodes
  - 3,3 million elements
  - 5-6 mm average element length
  - 1,0 mm min. element length
- simulation time: 8 ms → calculation time: ca. 12 h (16 CPU-Cores)

Study 1 - Modeling bursting scenario and pretension of compressor wheel

- Modeling of bursting scenario:
  - 1 – Compressor wheel
  - 2 – Clamping Nut
  - 3 – Clamping elements / rotor parts
  - 4 – deformable shaft
  - 5 – rigid shaft with turbine wheel

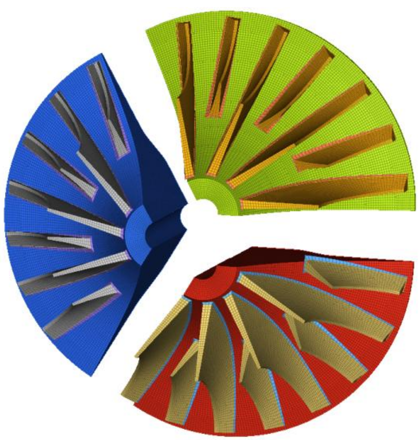


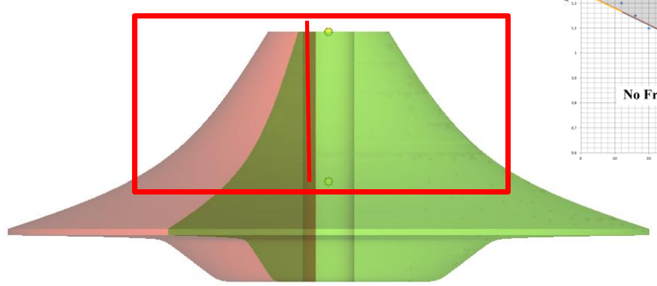
- 3 approaches of modeling bursting scenario:

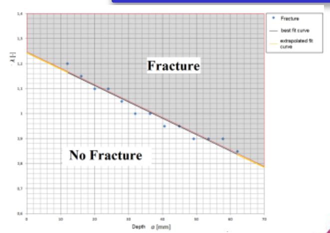
Var 1: Detached Segments
- formerly used

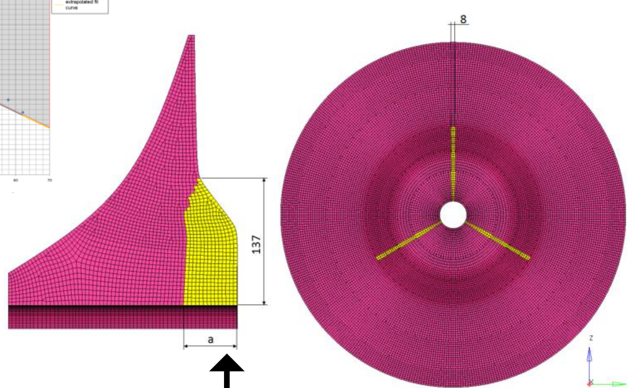
Var 2: 60% Merged
(partial node connection)
- Currently used

Var 3: Slotted (analog test procedure)
- under discussion
- preliminary study: relationship: speed – slot depth – fracture



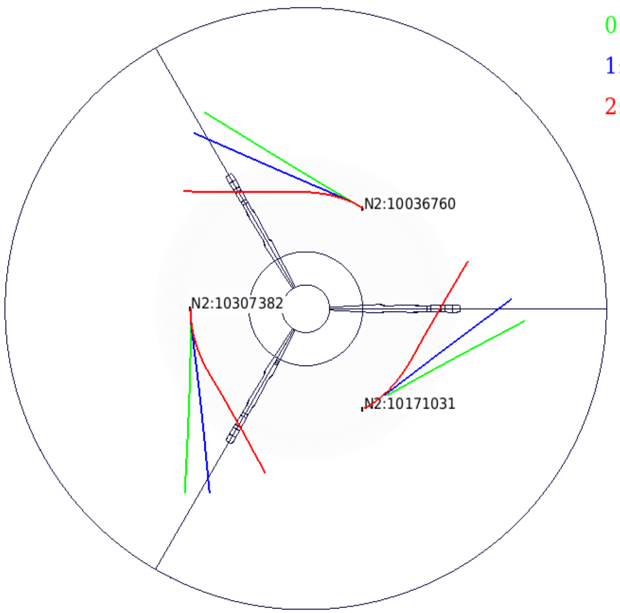






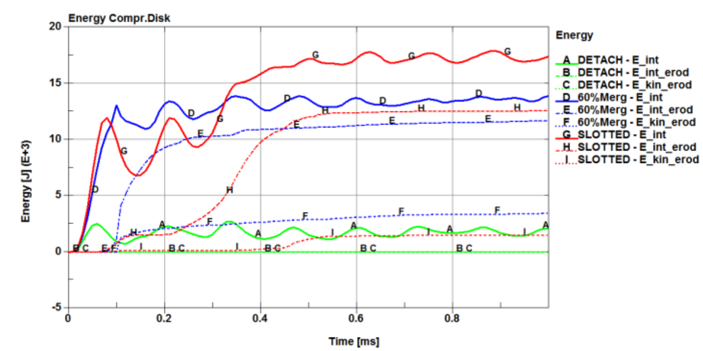
Start of fracture
on rear side

Study 1 - Modeling bursting scenario and pretension of compressor wheel

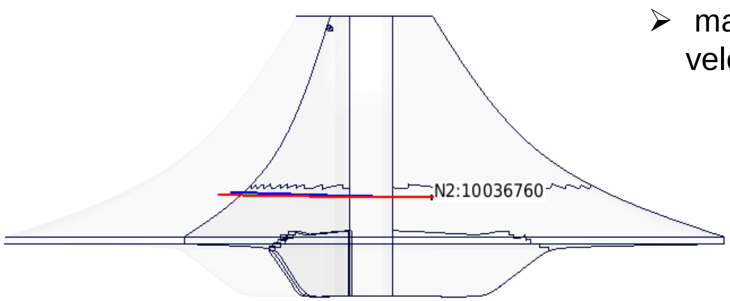


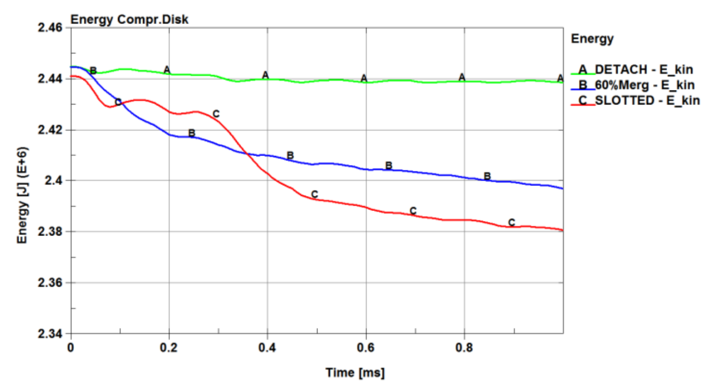
0: Detached
1: Merged 60%
2: Slotted

	T_{frac} [ms]	E_{int} [kJ]	E_{kin} [kJ]	$E_{int,erod}$ [kJ]	$E_{kin,erod}$ [kJ]	ΔE_{kin} [%]	
DETACHED	0,00	2,1	2439	0,0	0,0	0,2	
60% MERGED	0,25	13,9	2397	11,7	3,5	2,0	
SLOTTED	0,47	17,4	2380	12,6	1,5	2,5	+0,2% slot

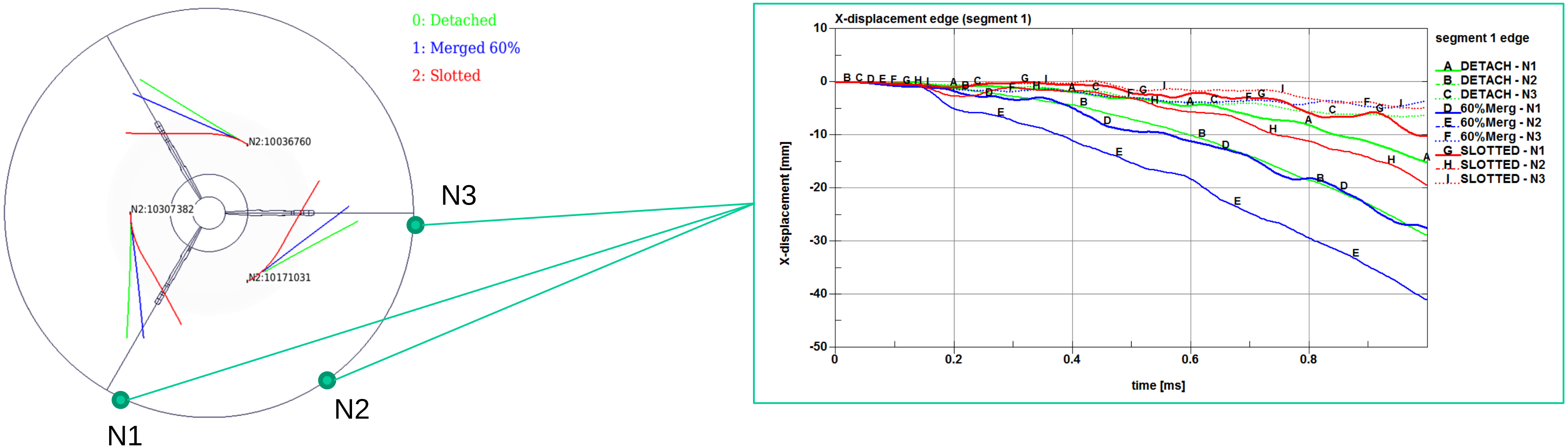


- Affect fracture time → different trajectories
- Elimination effect of fracture time lead to divergence of only 3-4° after fracture
- marginal influence on CG-velocities

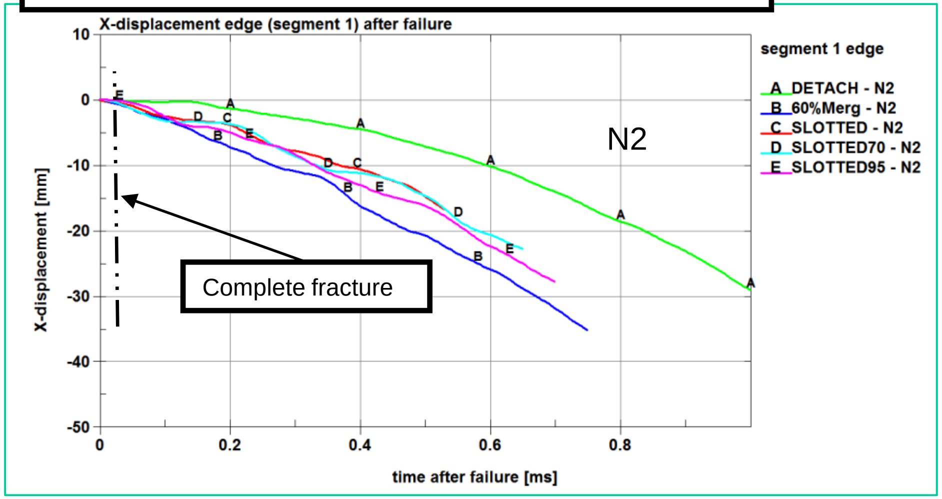




Study 1 - Modeling bursting scenario and pretension of compressor wheel

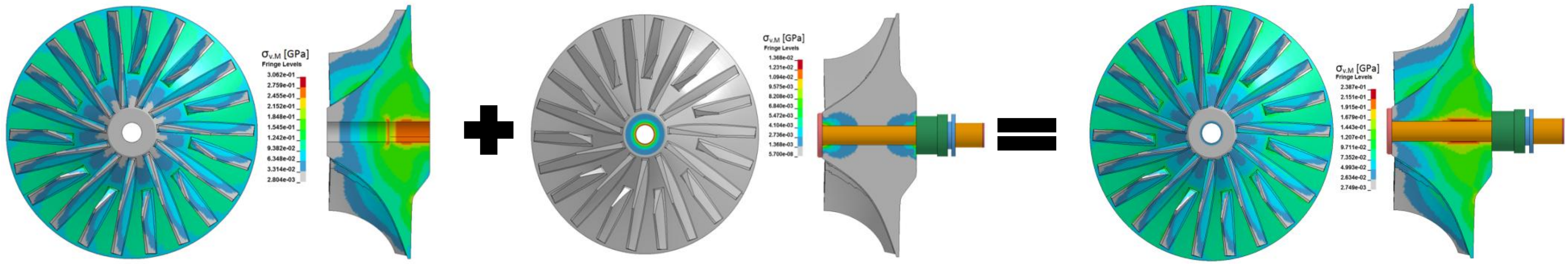


Synchronized at fracture point: Relative x-displ. after fracture



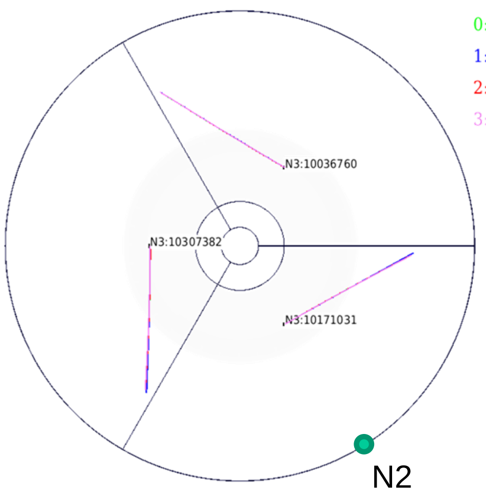
Study 1 - Modeling bursting scenario and pretension of compressor wheel

- Pretension:



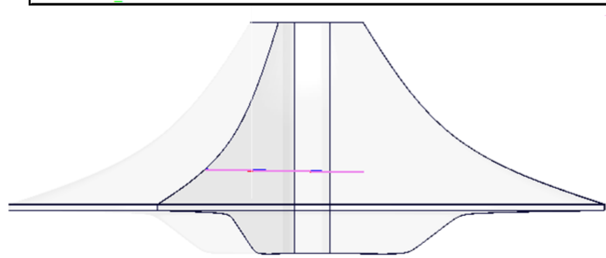
radial pretension | axial pretension | combined pretension

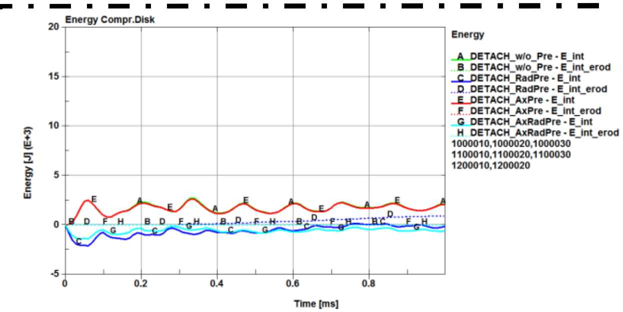
- Var 1: DETACHED

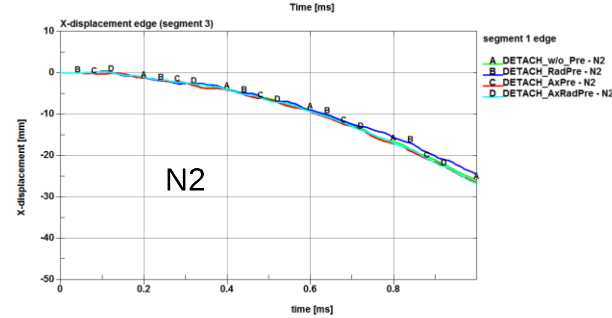


0: Detached - w/o pretension
1: Detached - radial pretension
2: Detached - axial pretension
3: Detached - radial+axial pretension

	T_{frac} [ms]	E_{int} [kJ]	E_{kin} [kJ]	$E_{int,erod}$ [kJ]	$E_{kin,erod}$ [kJ]	ΔE_{kin} [%]
DETACHED	0,00	2,1	2439	0,0	0,0	0,2
DETACHED_RadPre	"	-0,2	2440	0,9	0,1	0,2
DETACHED_AxPre	"	2,1	2439	0,0	0,0	0,2
DETACHED_AxRadPre	"	-0,6	2442	0,0	0,0	0,1







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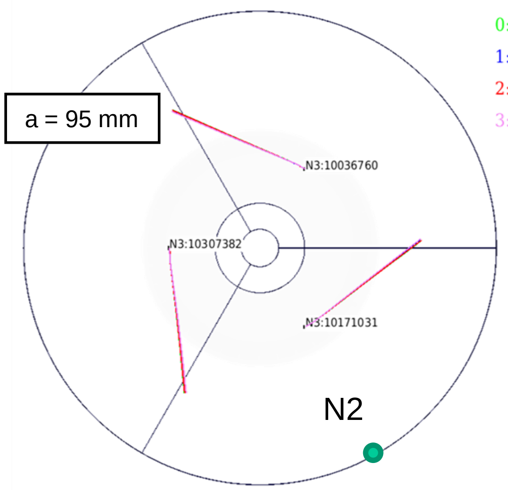
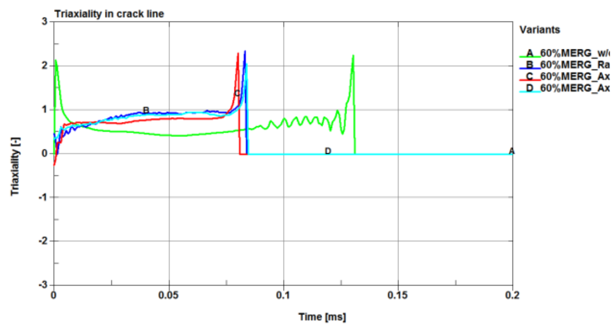
Study 1 - Modeling bursting scenario and pretension of compressor wheel

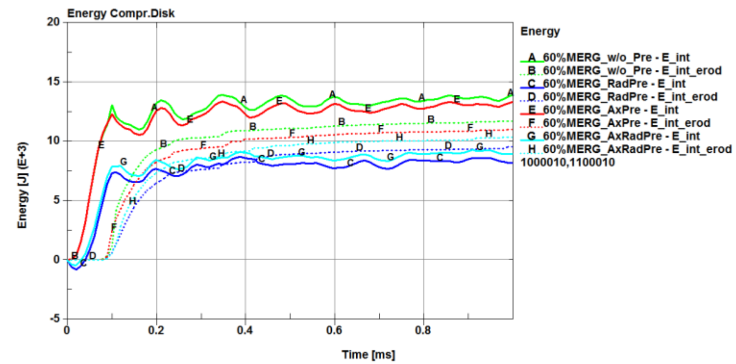
➢ Var 2: 60% Merged

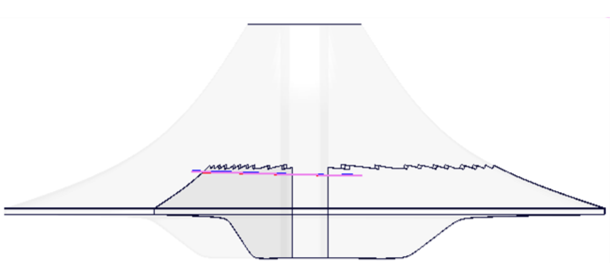
	T_{frac} [ms]	E_{int} [kJ]	E_{kin} [kJ]	$E_{int,erod}$ [kJ]	$E_{kin,erod}$ [kJ]	ΔE_{kin} [%]
60% MERGED	0,25	13,9	2397	11,7	3,5	2,0
60% MERGED_RadPre	0,25	8,2	2404	9,6	2,1	1,7
60% MERGED_AxPre	0,25	13,3	2398	11,0	2,9	1,9
60% MERGED_AxRadPre	0,25	9,0	2404	10,3	2,8	1,7



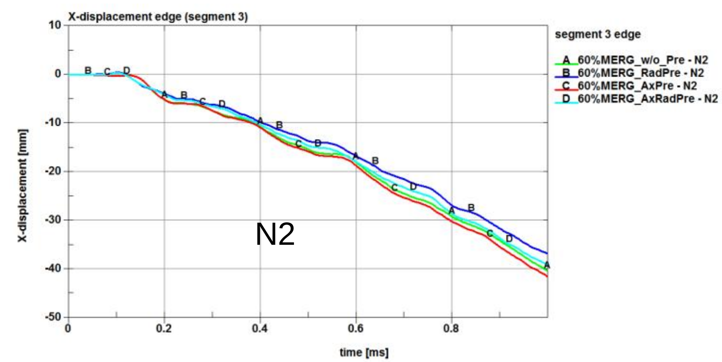
0: 60%Merged - w/o pretension
1: 60%Merged - radial pretension
2: 60%Merged - axial pretension
3: 60%Merged - radial+axial pretension





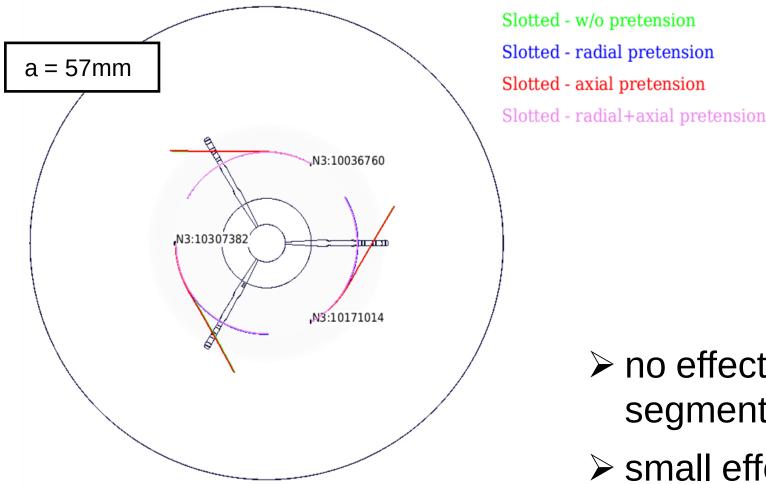


➢ No effects on velocities of segment center

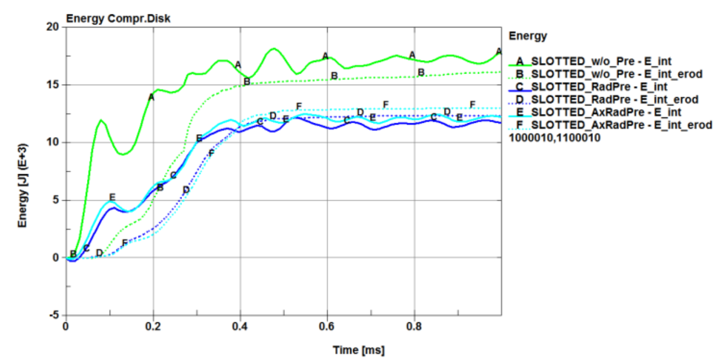


Study 1 - Modeling bursting scenario and pretension of compressor wheel

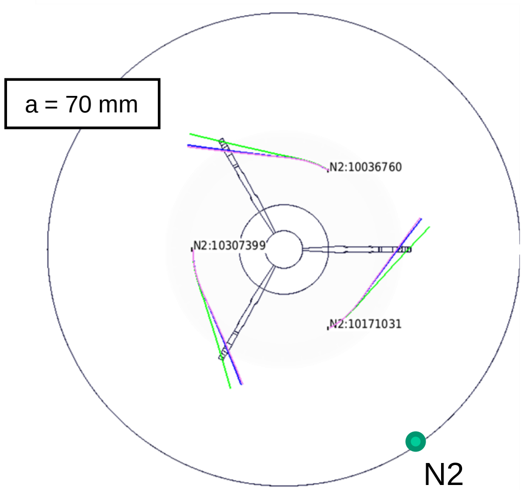
➢ Var 3: SLOTTED

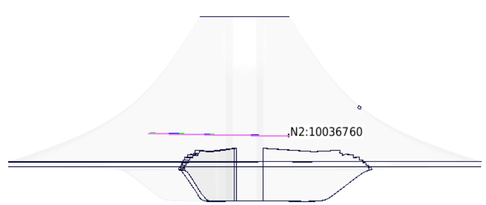


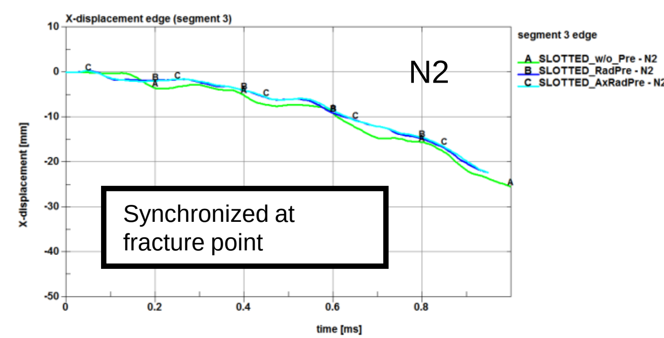
	T_{frac} [ms]	E_{int} [kJ]	E_{kin} [kJ]	$E_{int,erod}$ [kJ]	$E_{kin,erod}$ [kJ]	ΔE_{kin} [%]
SLOTTED	0,47	17,4	2380	12,6	1,5	2,5
SLOTTED70	**0,35**	**17,9**	**2375**	**16,2**	**7,0**	**2,7**
SLOTTED70_RadPre	**0,40**	**11,7**	**2385**	**12,4**	**1,6**	**2,3**
SLOTTED_AxPre	0,47	17,7	2381	12,9	1,5	2,5
SLOTTED70_AxRadPre	**0,40**	**12,3**	**2384**	**13,0**	**2,9**	**2,3**



- no effects on velocities of segment center
- small effect on fracture time → different trajectories
- elimination effect of fracture time lead to divergence of <1° after fracture

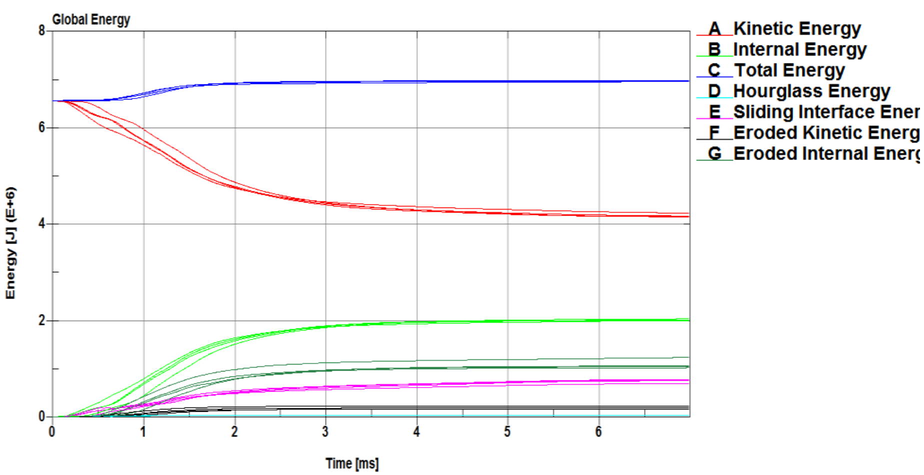


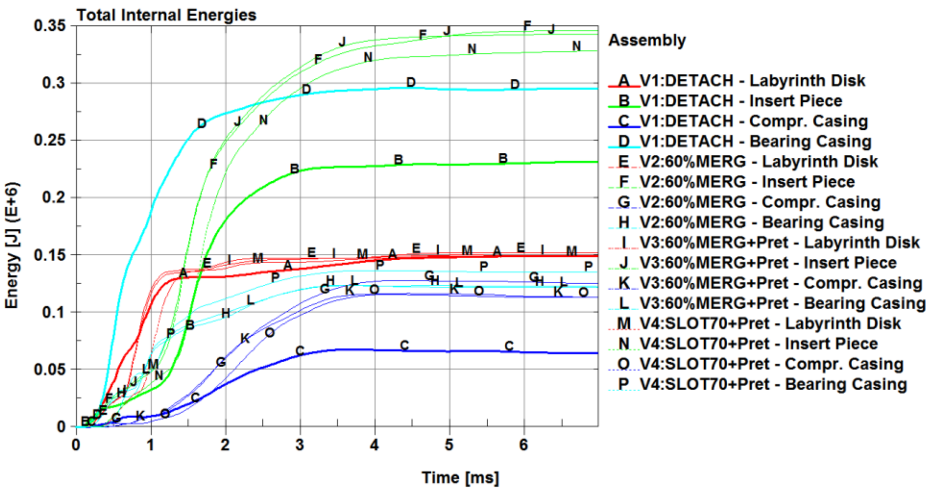




Study 1 - Modeling bursting scenario and pretension of compressor wheel

- review results in complete turbocharger model (generic model):
  - Implemented rotor variants:
    - **Var 1**: DETACHED: 3 separate segments of compressor wheel without pretension
    - **Var 2**: 60%MERGED: partially coupled segments without pretension
    - **Var 3**: 60%MERGED_AxRadPre: partially coupled segments; axial + radial pre-stressed
    - **Var 4**: SLOTTED70_AxRadPre: Slotted compressor wheel (a=70mm); axial + radial pre-stressed
  - evaluation of simulation on the basis of energies, displacements and kinematic of compressor insert piece, compressor casing, bearing casing and labyrinth disk





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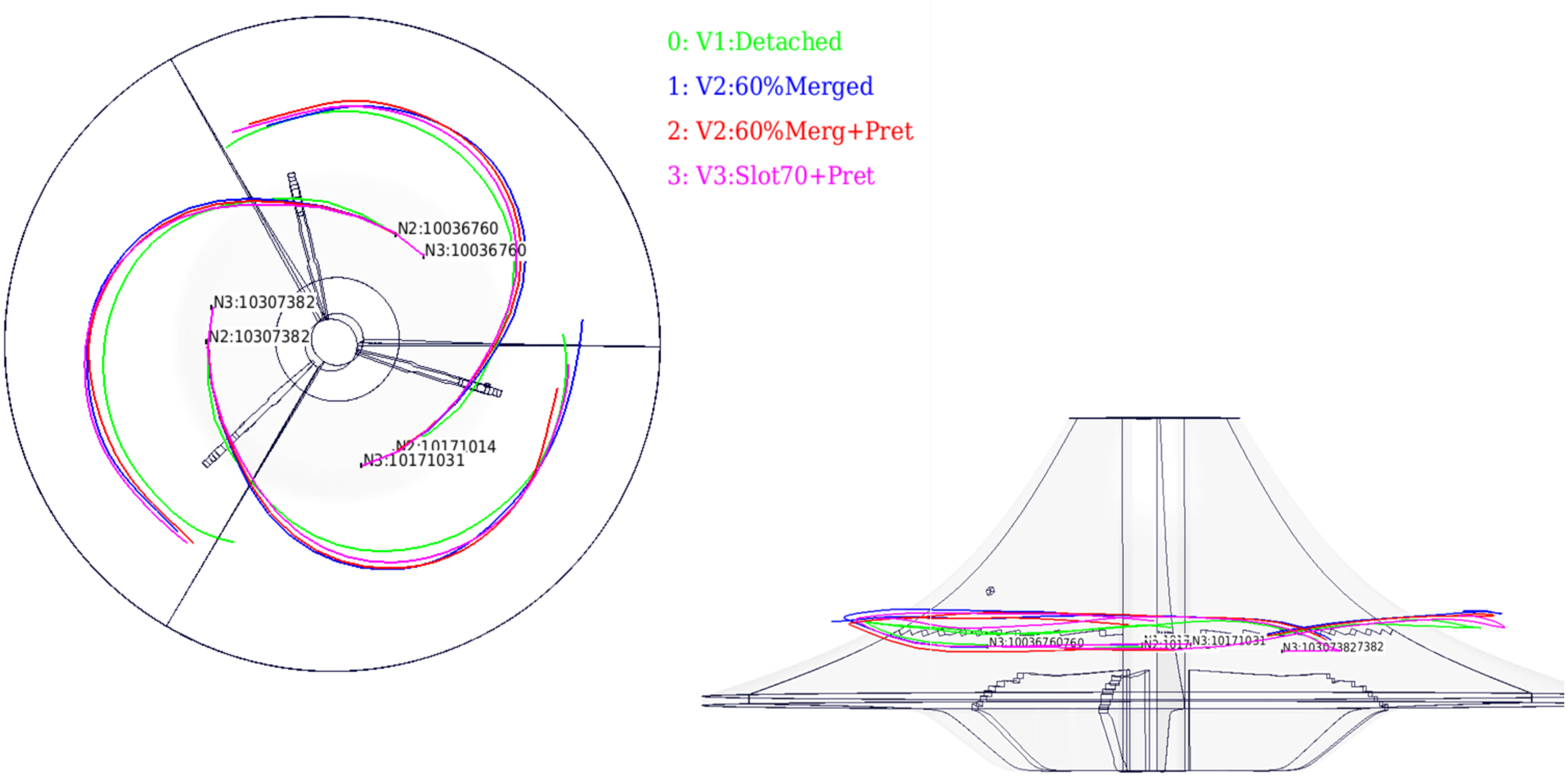
Study 1 - Modeling bursting scenario and pretension of compressor wheel

- Kinematic:

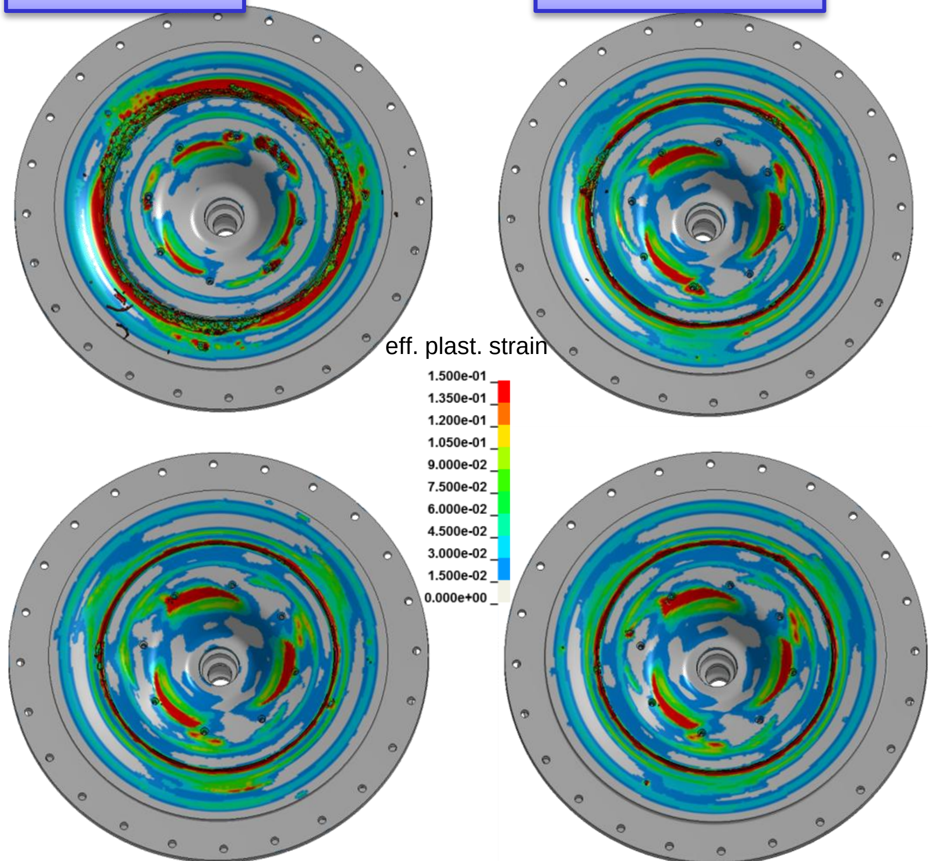


Study 1 - Modeling bursting scenario and pretension of compressor wheel

- Bearing Casing + Labyrinth Disk:

V1: DETACHED

V4: SLOT70+PRET

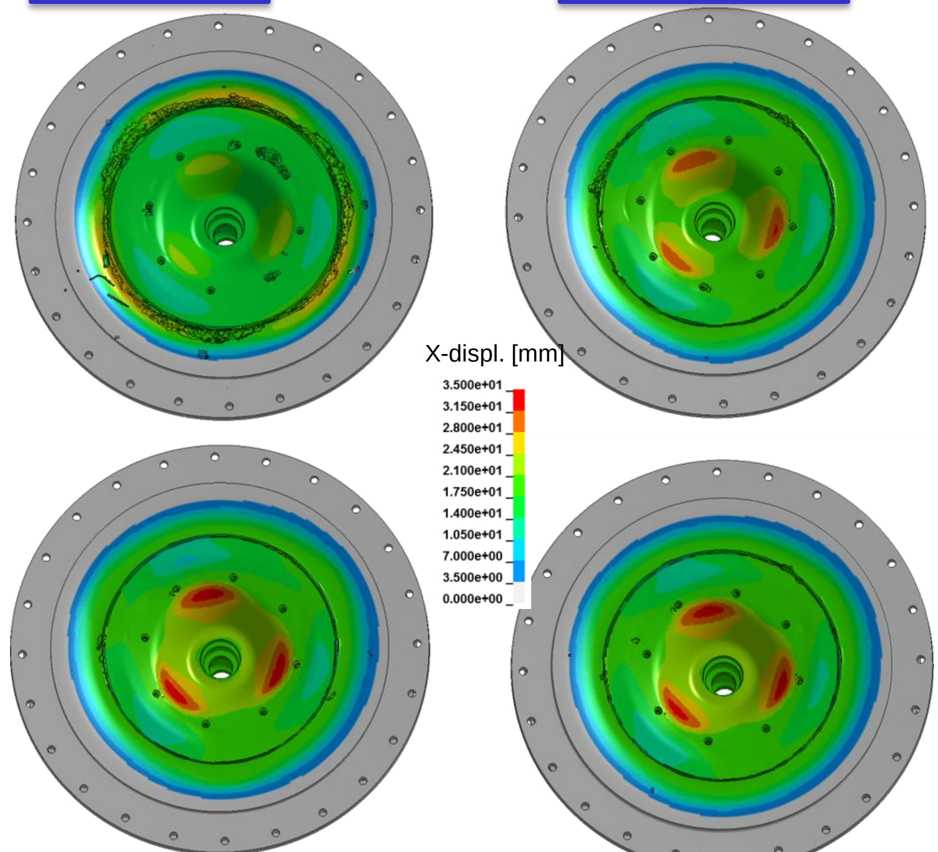


V2: 60%MERG

V3: 60%MERG+PRET

V1: DETACHED

V4: SLOT70+PRET



V2: 60%MERG

V3: 60%MERG+PRET

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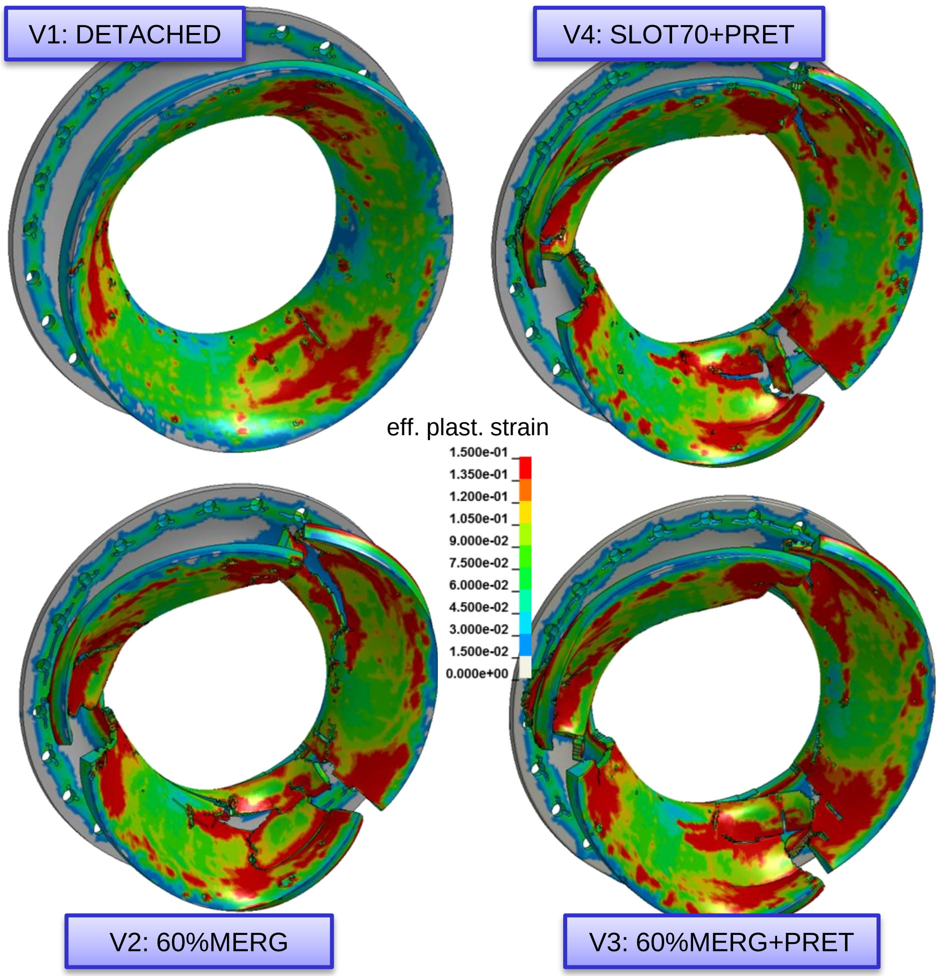
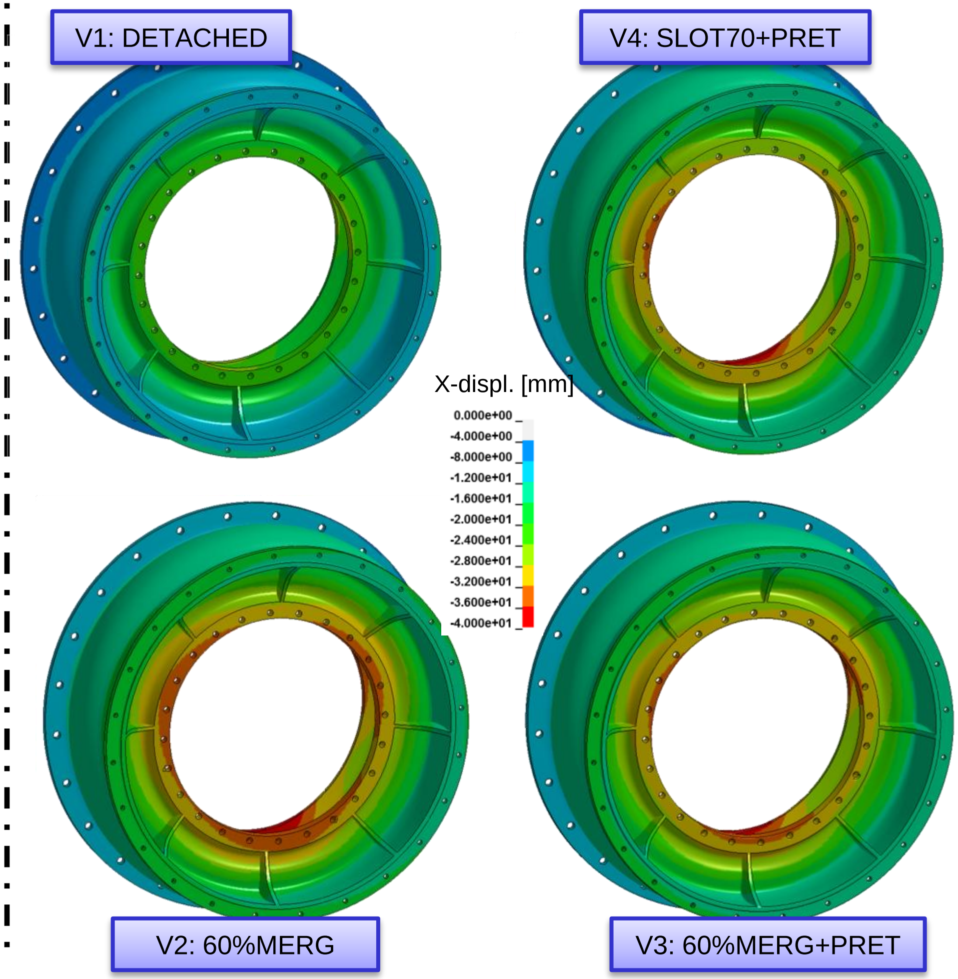
- Insert Piece:



- Compressor Casing:



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Study 1 - Modeling bursting scenario and pretension of compressor wheel

- implementation of bursting scenario:
  - small influences on energy balance (red. 2-3%)
  - difference in time till fracture (depending on slot depth) → variance of segment kinematic
    - small divergence in radial and tangential movement and segment rotation : trajectories differ < 4°
    - obvious influence on axial movement / overturning (in particular Var1)
- axial pretension → no significant influences
- radial pretension → reduced $E_{internal}$ for fracture + reduced loss of $E_{kinetic}$
  - no influence on degree of damage of compressor wheel
  - small influence on time till fracture → small variance of segment kinematic (overturning)
- pretension eliminates peak in triaxiality at the beginning

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Study 1 - Modeling bursting scenario and pretension of compressor wheel

- influences in complete turbocharger model (generic model):
  - small differences in global energies + partially heavy differences in energies of main assemblies
  - different impact loads on surrounding parts: differences in plastic strain, axial displacements and damage
  - → **different kinematic of compressor wheel**
    - in particular Var1 (DETACHED) differ from the rest significantly
    - marginal divergences between Var2 and Var3 (60%MERGED with and without Pretension)
    - small divergences between Var3 (60%MERGED+PRET) and Var4 (SLOTTED70+PRET)
  - initial splitted or only slotted impeller make the great difference; the kind of modeling the slot is secondary
  - axial pretension → no influence; radial pretension → small influence

↳
- **compressor bursting: prefer variant with partially merged segments** (coupling over ca. 60% of height beginning from the top of the impeller) **without pretension**

  (good kinematic + heaviest loads on surrounding structure + no slot-modeling and implicit analysis needed)

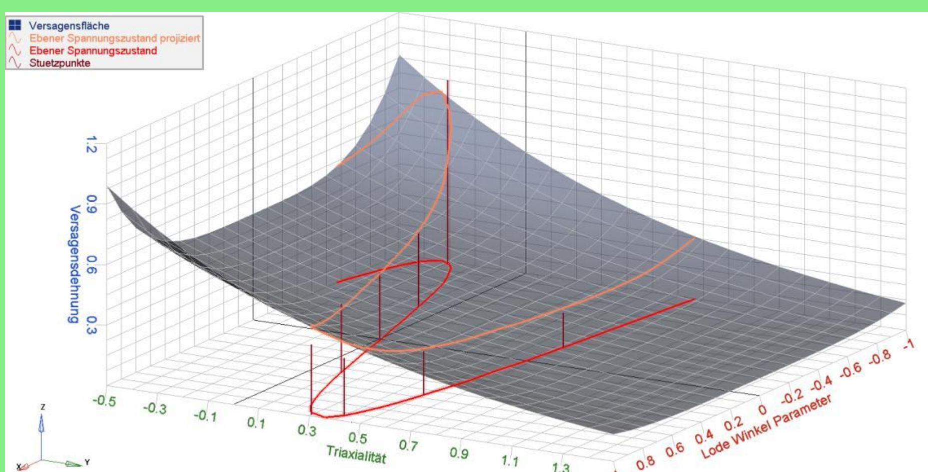
Study 2 – Effect of lode-angle-parameter on the failure behavior in a CT-Simulation

- Example: material law for a cast housing: *MAT124 + *MAT_ADD_EROSION (GISSMO)

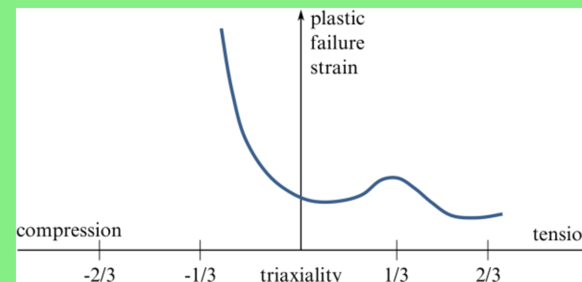
Extension: Lode angle dependence

Lode angle parameter: $$\xi = \frac{27}{2} \frac{J_3}{{\sigma_{vM}}^3}$$

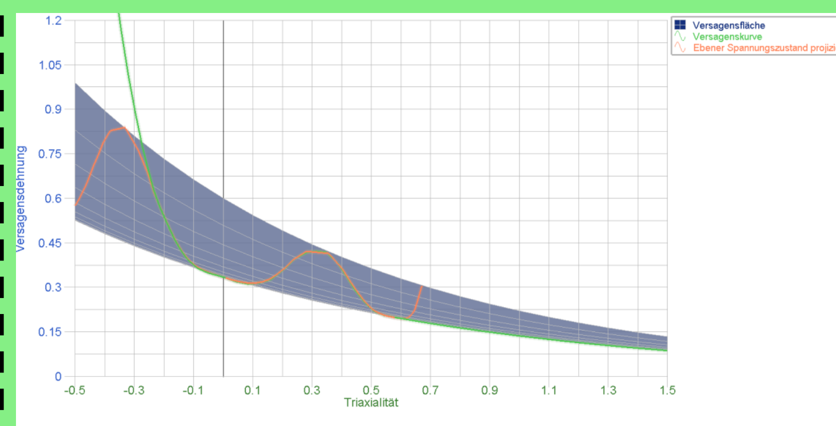
Lode angle parameter (only for plane stress): $$\xi = -\frac{27}{2}\eta\left(\eta^2 - \frac{1}{3}\right)$$



Failure

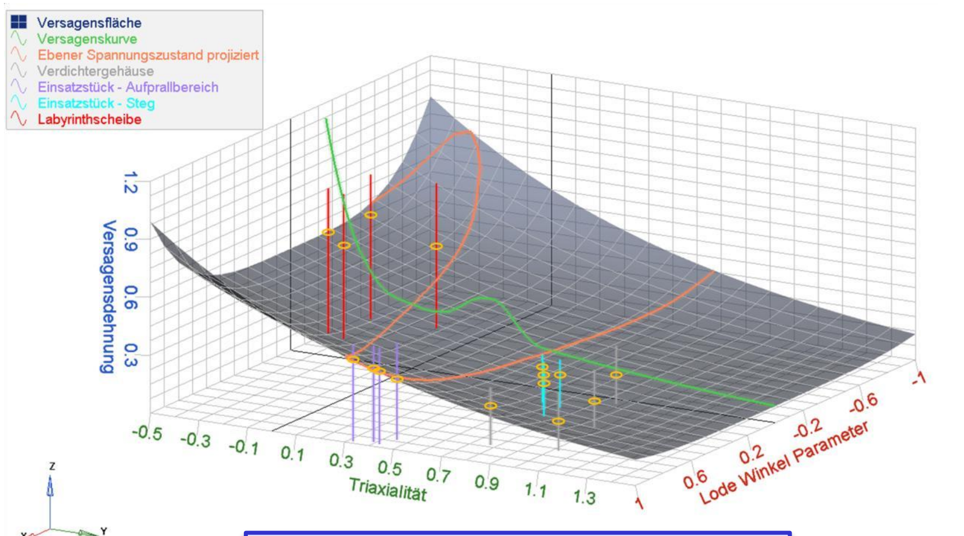


3D: add. lode-angle-dependency → failure surface

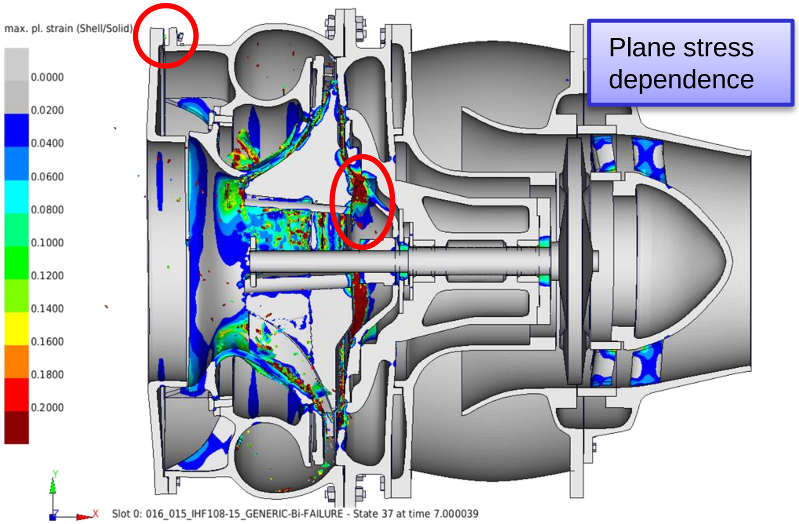


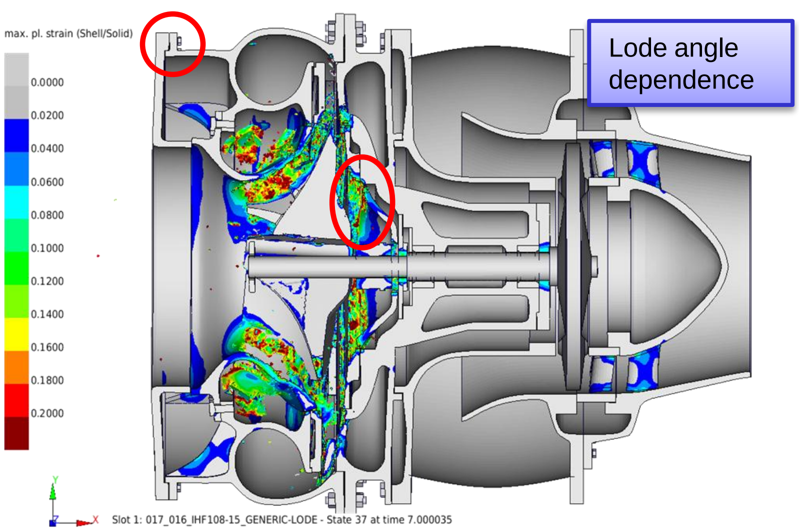
Study 2 – Effect of lode-angle-parameter on the failure behavior in a CT-Simulation

- Different behavior in the kinematics if the 3D stress state is considered.
- More damage due to the radial impact in the model with lode angle dependence.
- Due to less damage in the first model the axial forces get bigger and the screws start to fail.



Lode angle parameter and triaxiality in the elements of failure

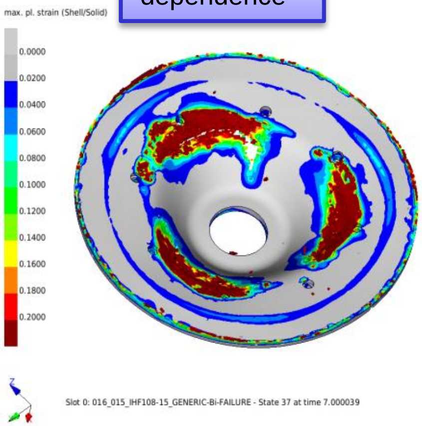




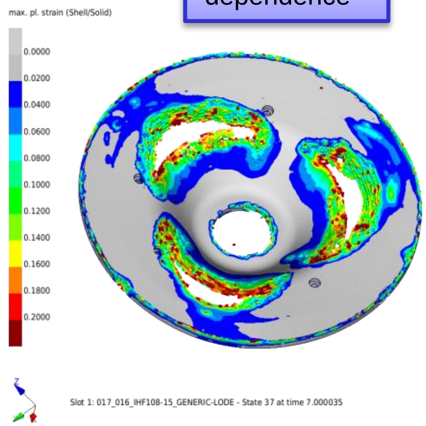
Study 2 – Effect of lode-angle-parameter on the failure behavior in a CT-Simulation

- Results – Comparison with/without lode angle dependence:
  - Results of the labyrinth disk
    - triaxiality: -0,5 to -0,2
    - lode angle parameter: -0,55 to -0,2
    - → failure strain differ strongly from that of the approach with only plane stress dependence.
    - Shows possible differences if a 3D stress state is considered in the failure model. More damage in the model with lode angle dependence.

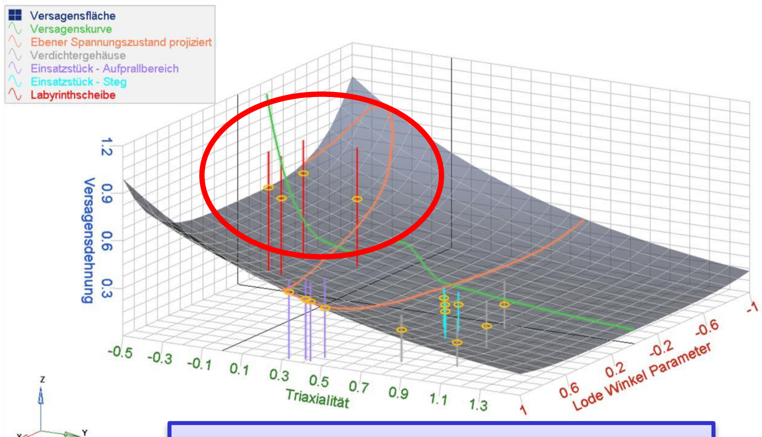
Plane stress dependence



Lode angle dependence



- **Lode angle dependence:**
  - significant influence on the behavior of failure
  - strong dependency of shape of the failure surface
  - more possibilities to adjust the failure behavior to test data
  - more material tests necessary, which cover different stress states



Lode angle parameter and triaxiality in the elements of failure

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Summary

- models become more and more complex → high effort for meshing + long calculation time →cost driver
  - studies of modifications and improvements (e.g. in material laws, meshing, geometry, boundary conditions, simulation methodology) are very expensive and long-lasting

- the developed generic model has proved itself a very helpful instrument
  - depicts the principle behavior of real containment tests with all its complex load chains
  - enables studies, sensitivity and robustness analyses in a fast and efficient way
  - improvements, new features and simulation approaches can be tested and assessed comprehensively before considering them in a detailed containment simulation

- kind of implementation of bursting scenario can affect simulation results significantly
  - Currently used approach is very good and efficient

- Lode angle dependence is a very important point
  - can have strong influence depending on shape of the failure surface and the existing stress state
  - more effort for validation needed

Ingenieurbüro
Huß & Feickert

Thank you for your Attention?

Ingenieurbüro Huß & Feickert GbR
Im Kohlruß 1-3
65835 Liederbach
Telefon: +49 (0)6196 / 67071 – 0
Fax: +49 (0)6196 / 67071 – 28
Mail: mail@ihf-ffm.de
www.ihf-ffm.de
Managing Partner: Prof. Dr.-Ing. Wolfgang Feickert, Prof. Dr.-Ing. Armin Huß