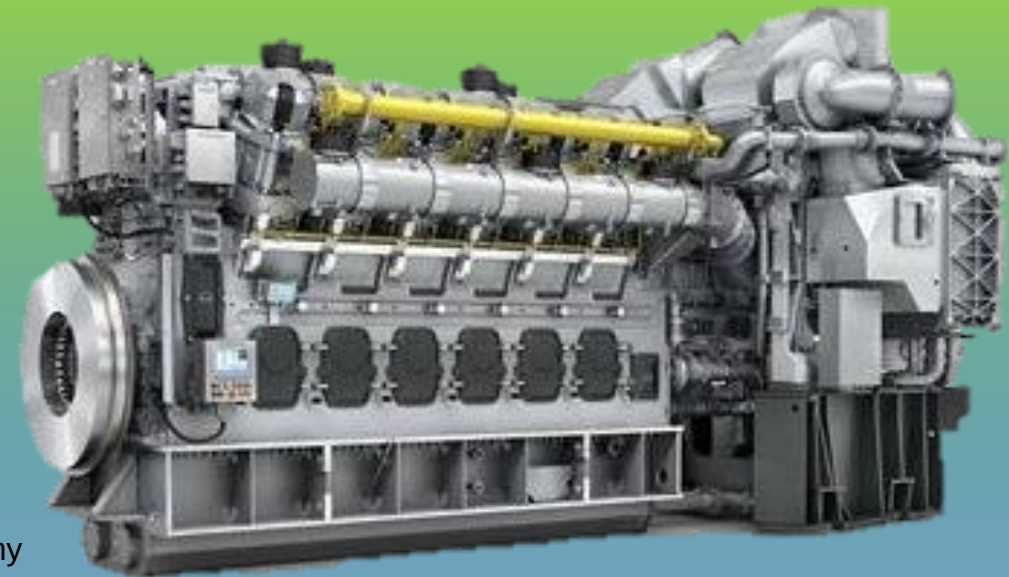


Efficient Structural Durability Assessment Strategy for Future Fuel Engines



Stefan Averbeck, Roman Petz, Alexander Rieß, Jens Wolter, Peter Böhm, Ulf Waldenmaier
MAN Energy Solutions SE, Base Engine Development, Stadtbachstrasse 1, 86153 Augsburg, Germany



Agenda

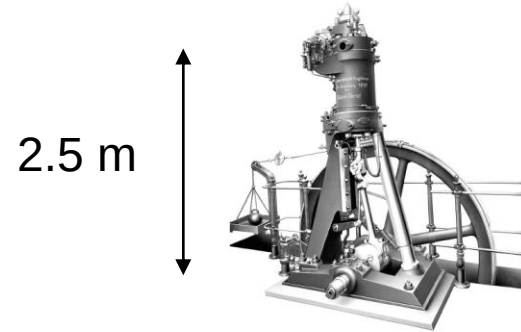
- 1 Introduction**
- 2 Future Fuel Challenges**
- 3 Simulation Strategy**



1 Introduction

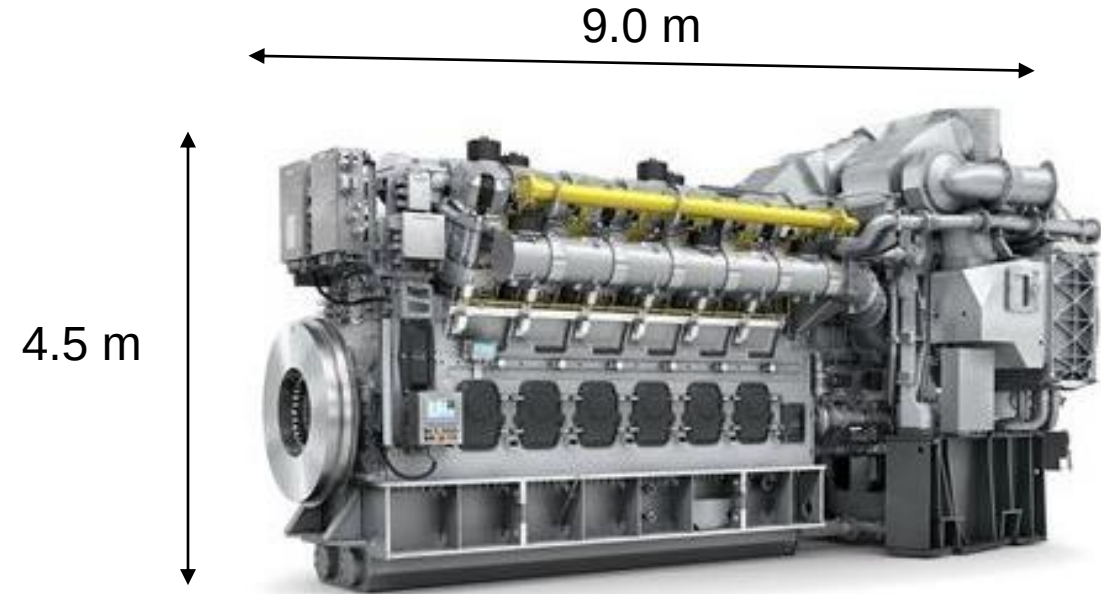
Engine Development (I)

Historical Perspective



1897: 1st diesel engine by Rudolf Diesel

Power: $P_0 = 15 \text{ kW/cylinder}$, efficiency factor $\eta = 26\%$



2023: MAN 12V35/44G TS

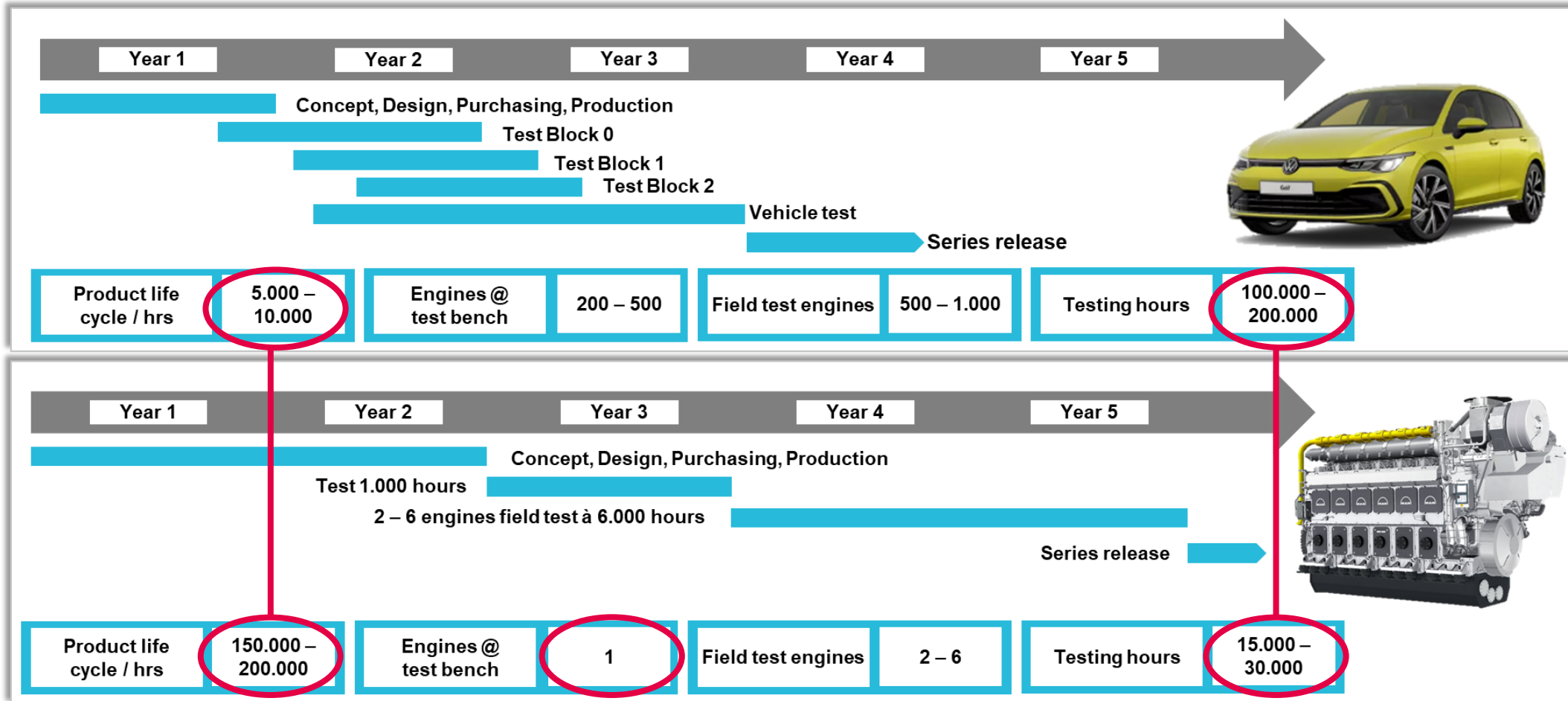
Power: $P_0 = 12 \times 620 \text{ kW/cylinder}$, efficiency factor $\eta \sim 50\%$

Issues in new and continuous engine development:

Efficiency, power density, emissions, multi-fuel capability, comfort

Engine Development (II)

Automotive Sector vs. Large-bore ICEs



Adapted from [LKBR2020] Jochen Lang, Gunter Knoll, Peter Böhm und Alexander Rieß. *Thermo-Elastohydrodynamic Connecting Rod Simulation of a Four Stroke Medium Speed Engine*. In: Liebl, J. (eds) Experten-Forum Powertrain: Simulation und Test 2020. Springer Vieweg, Berlin, Heidelberg, 2021.

Giga [10^9]

Mega [10^6]

Kilo [10^3]

5'000'000'000

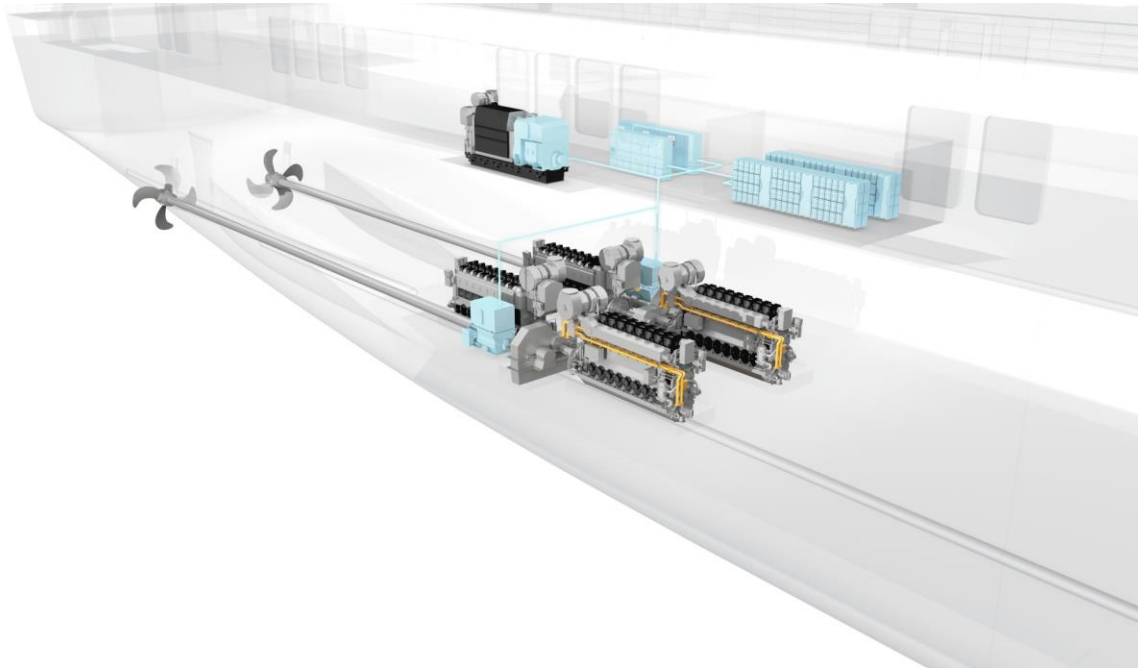
Load cycles for a typical large-bore engine during its lifetime.



Large-bore Internal Combustion Engines

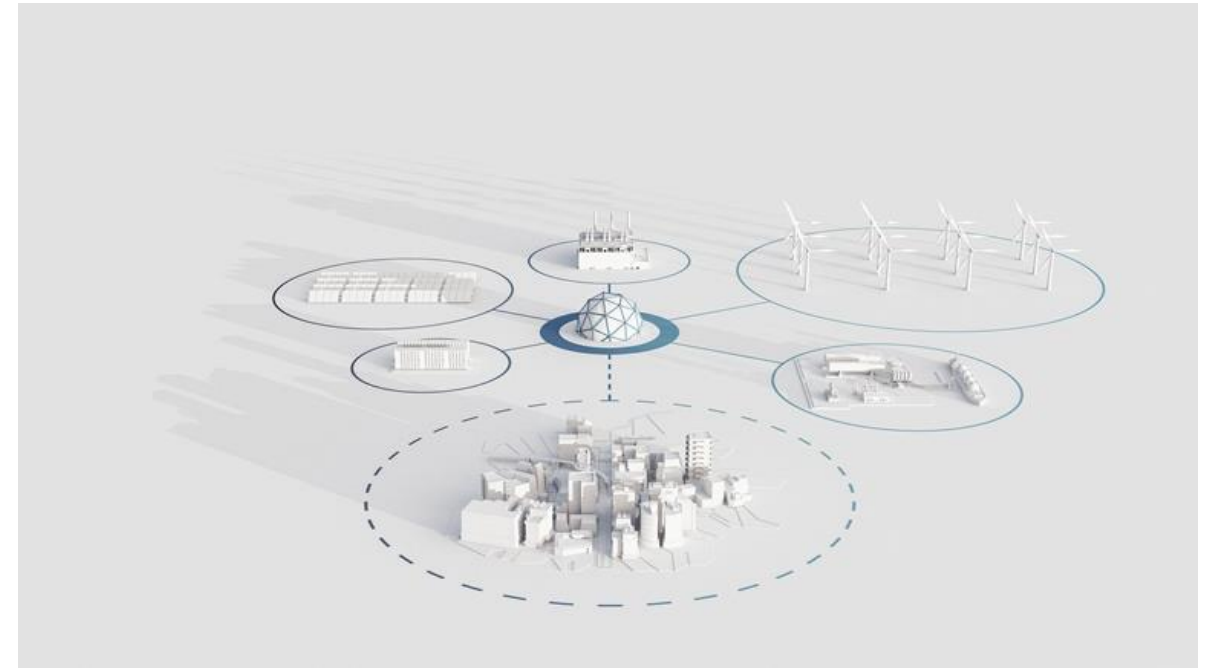
Applications

Marine Systems



- Long-time continuous operation at medium load
- Short bursts of full power demand

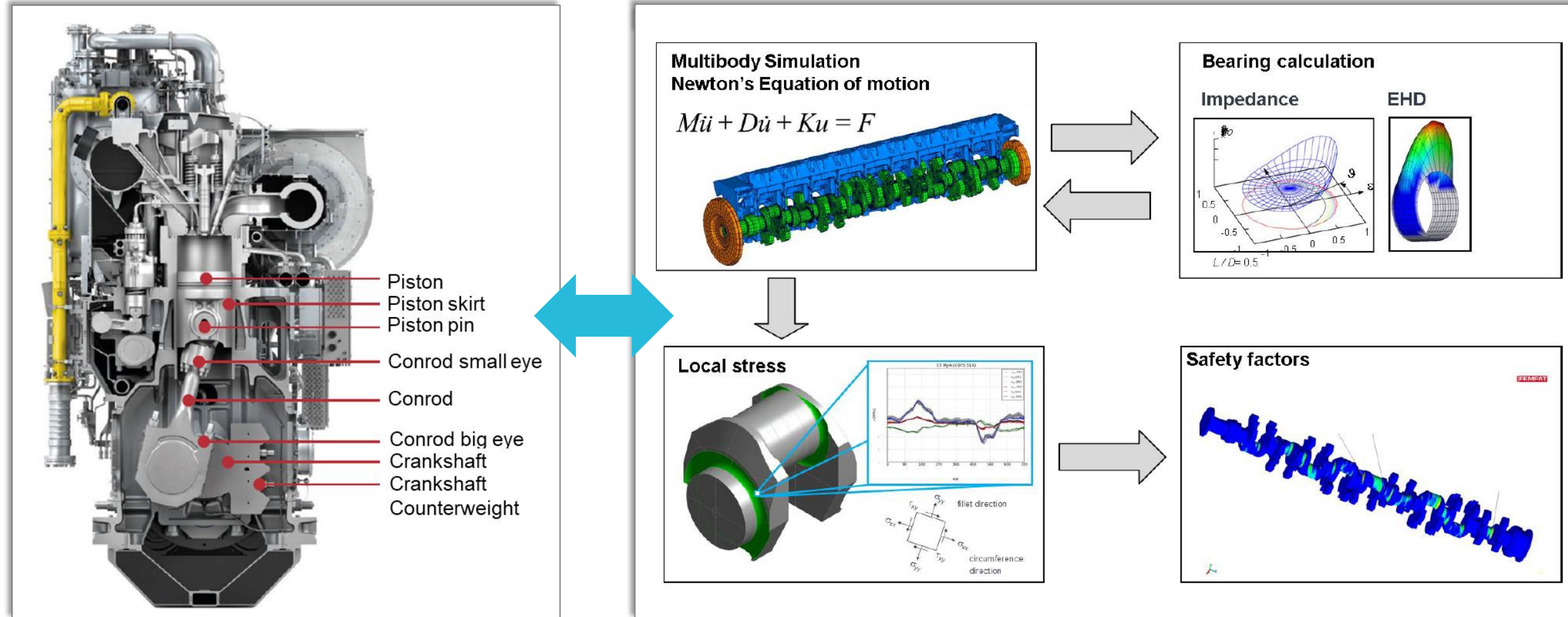
Power Plants / Microgrids



- Peaker and Base Load Application
- On demand: Frequent start/stop and steep load ramps with high share of full load

Large-bore Internal Combustion Engines

Multi-physics System – Multi-physics Simulation

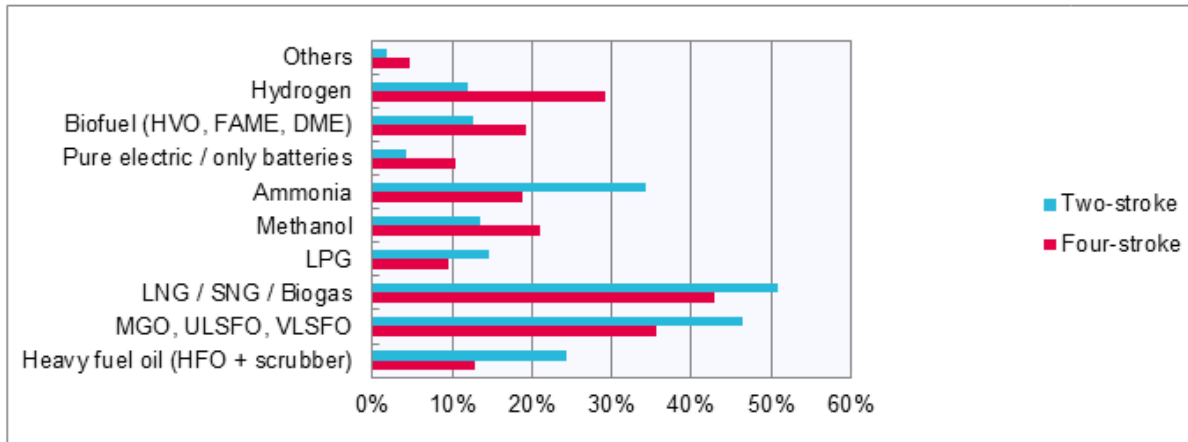


2 Future Fuel Challenges

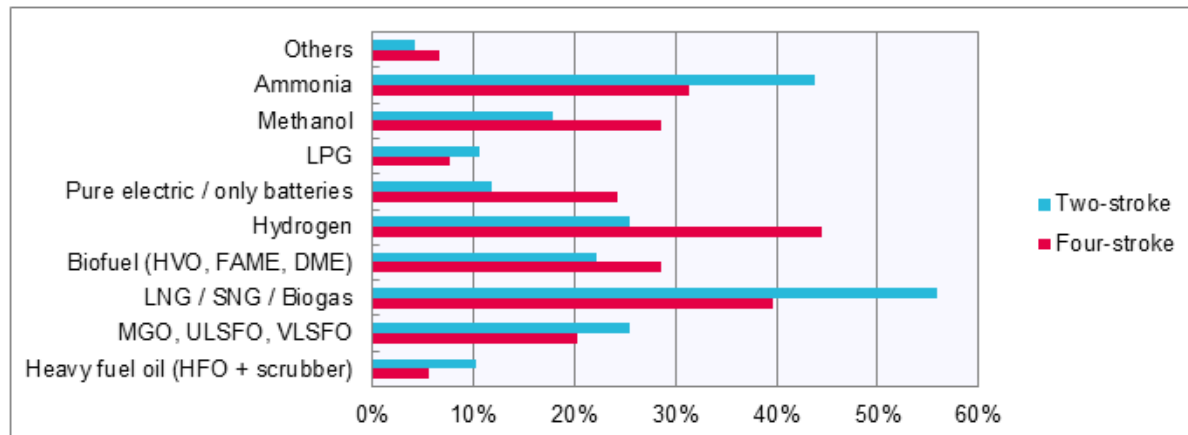
Future Fuels

Market Expectations

Which type of fuel are you planning to use for your next new-building project?



Which fuels do you see most relevant for your new-building project in 2035 onwards?



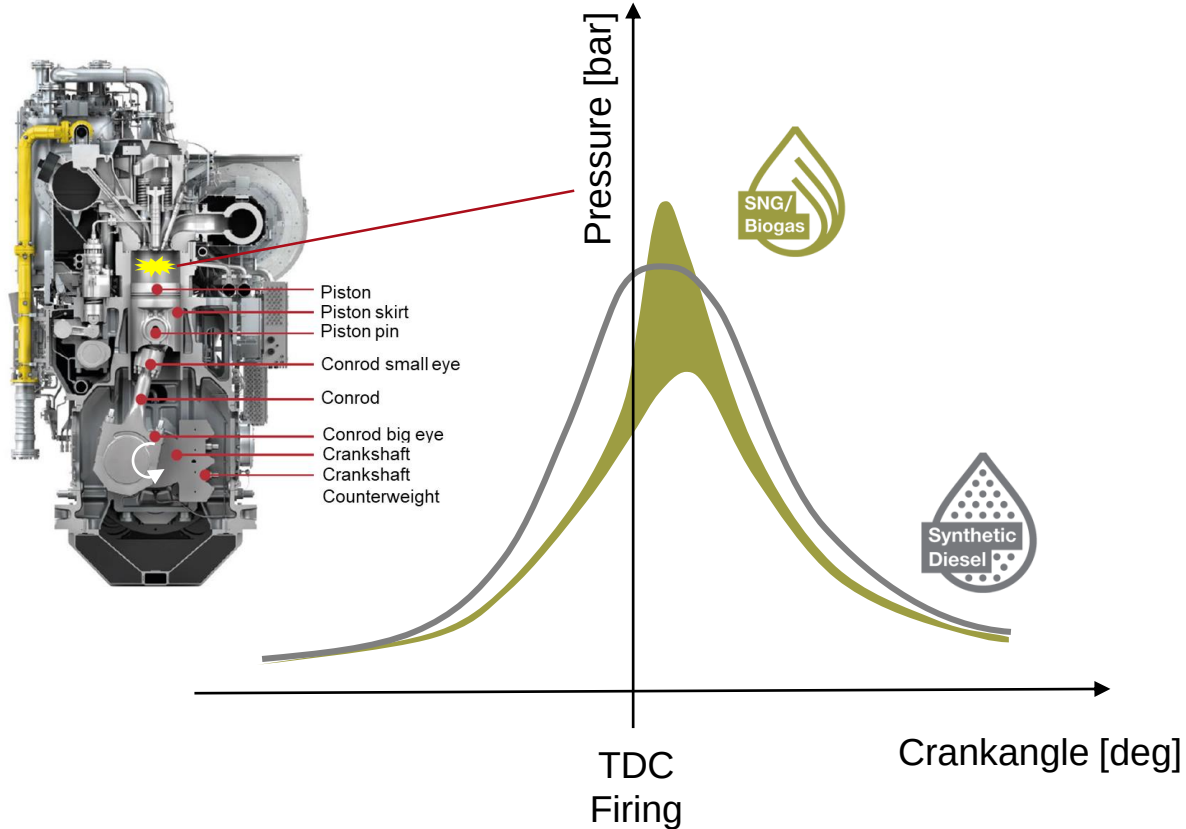
MAN ES customer survey (n=504, multiple answers possible)

- Customers expect a **variety of fuel options**, including multi-fuel capability
- This poses great challenges, especially for **injection systems, tribology and combustion development**
- For structural strength, **higher firing pressure and temperature** are the most important issues
- **Corrosion and material degradation** (e.g. hydrogen embrittlement) add further challenges for some fuel types

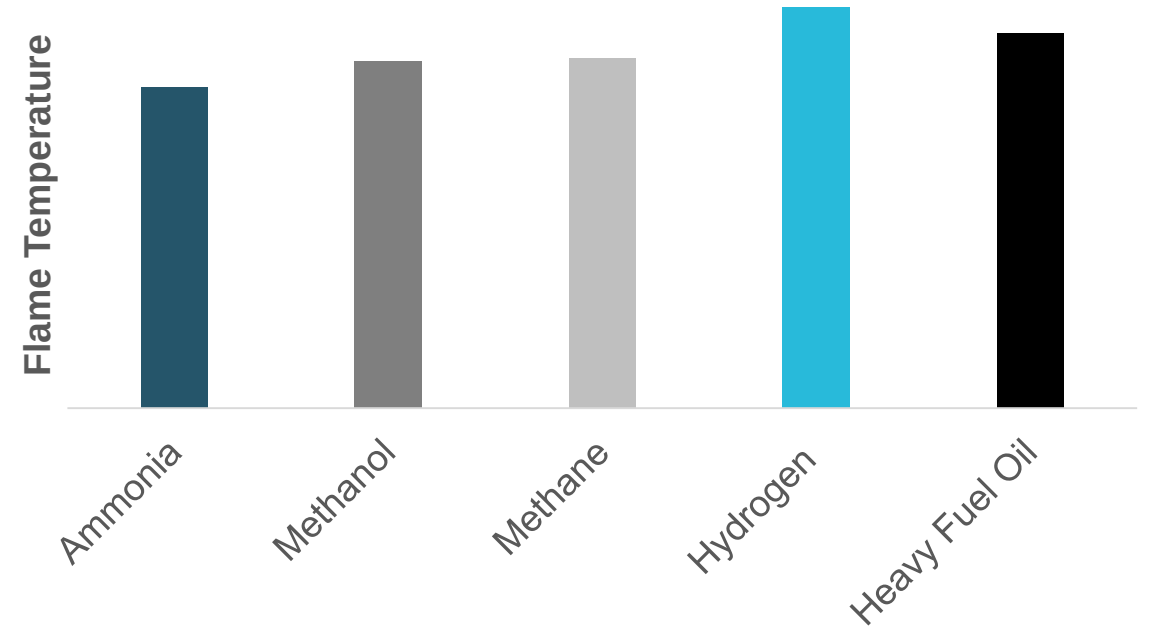
Future Fuels

Strength Challenges (I)

Scattering of peak firing pressure



Temperature Changes

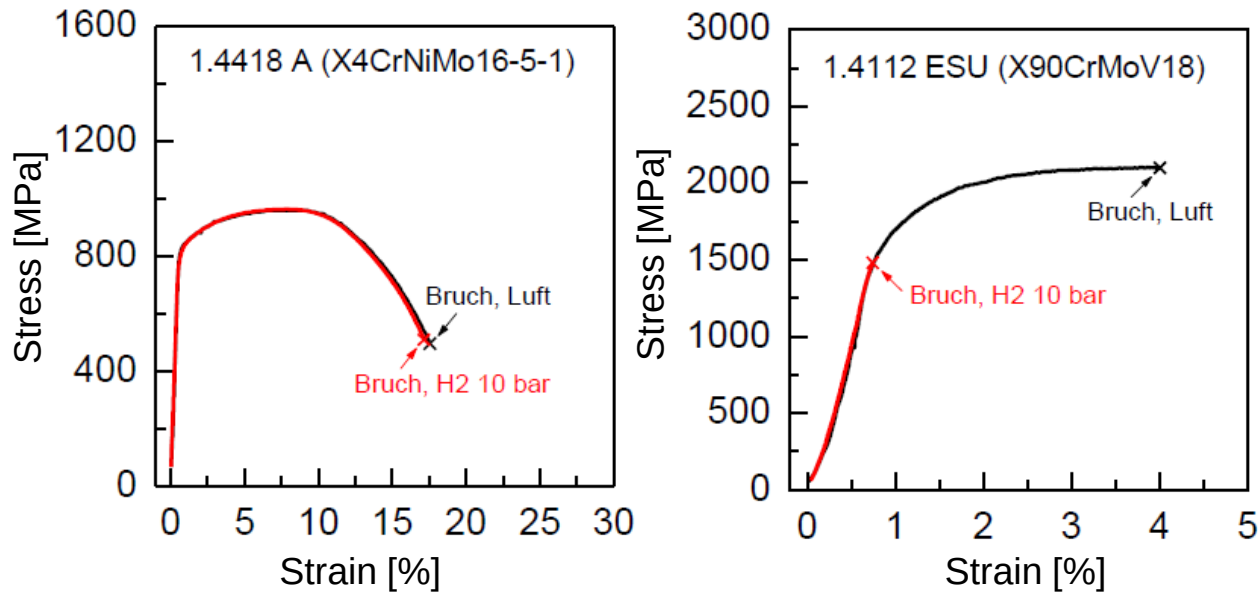


+ additional effects (e.g. quenching distance, heat of vaporization etc.)

Future Fuels

Strength Challenges (II)

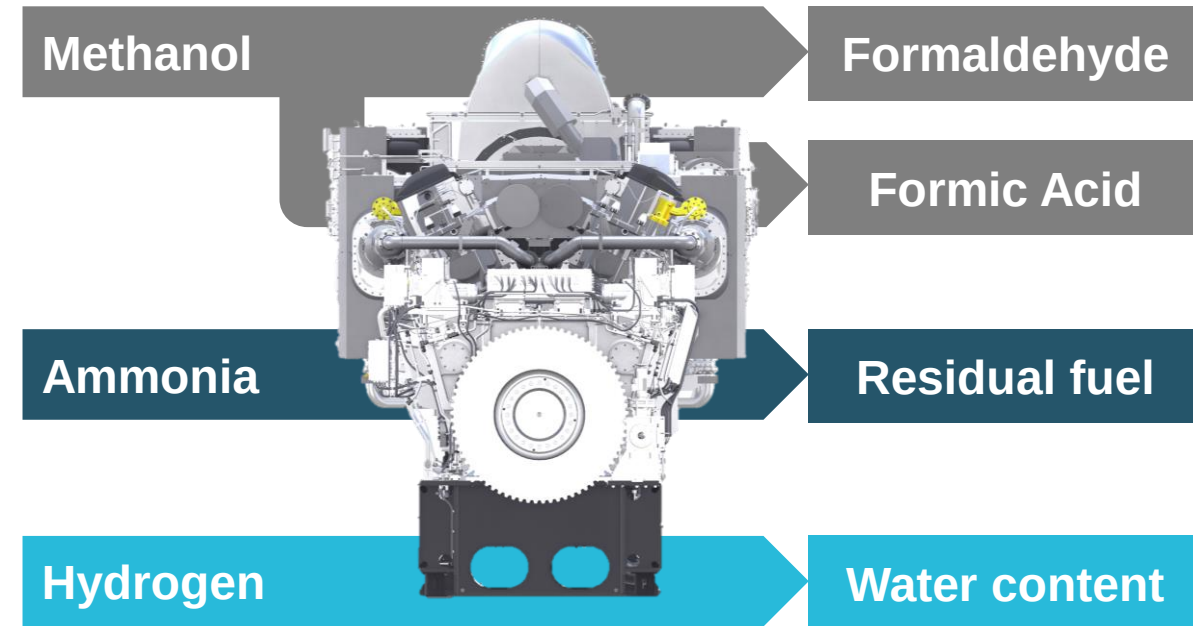
Embrittlement



Reduction of strength, especially of static properties (tensile strength, elongation at fracture)

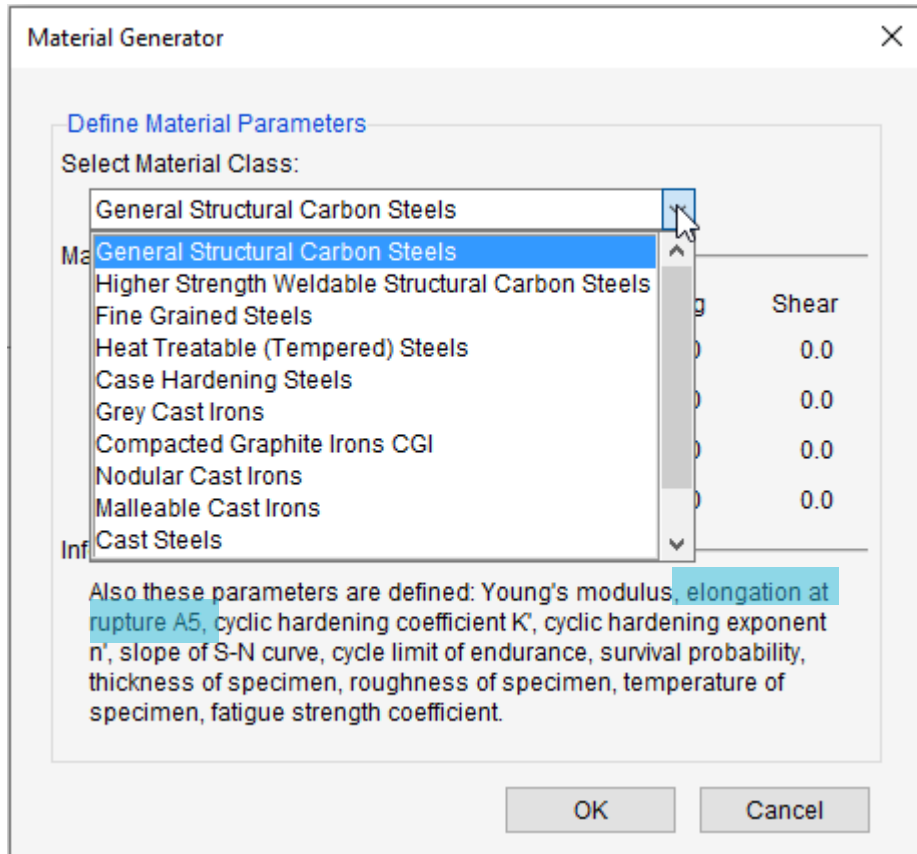
G. Schauer, *Auslegungsansatz für Stahlbauteile bei Ermüdungsbeanspruchung in Druckwasserstoff-atmosphäre*, Dissertation, MPA Universität Stuttgart, 2018

Corrosion



+ additional effects (e.g. fuel-lubrication interaction)

Hydrogen Effects in FEMFAT



- Hydrogen embrittlement is strongly dependent on **material class**
- **High-strength steels** most affected
- **Safety factors** can be raised to conform with existing hydrogen standards
- For a quick estimation of static effects, the **elongation at rupture** can be reduced or set to 0%

Simulation of Future Fuel Components

Safety Factors

Conventional designs



Emission-optimized designs



Future fuel designs



Vast knowledge and experience



New emissions regulations
(e.g. IMO Tier III)

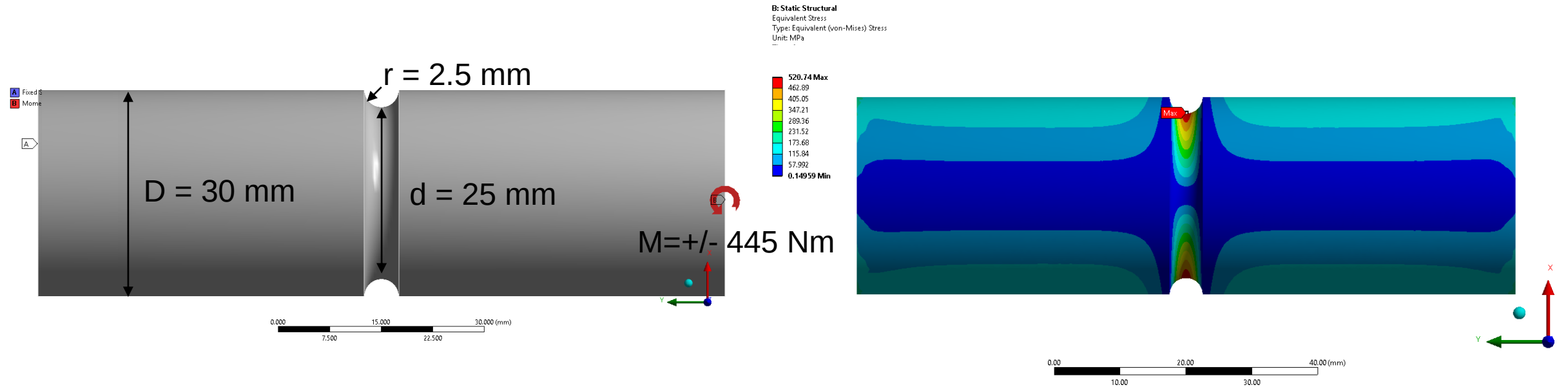


Fast adaption to new boundary
conditions

3 Simulation Strategy

Simulation

Investigated Model



In order to illustrate our workflow we will mostly use a rounded bar (34CrNiMo6) with $K_{t,b}=2$ at a fatigue failure load of $M=\pm 445 \text{ Nm}$ (St1, 50%).

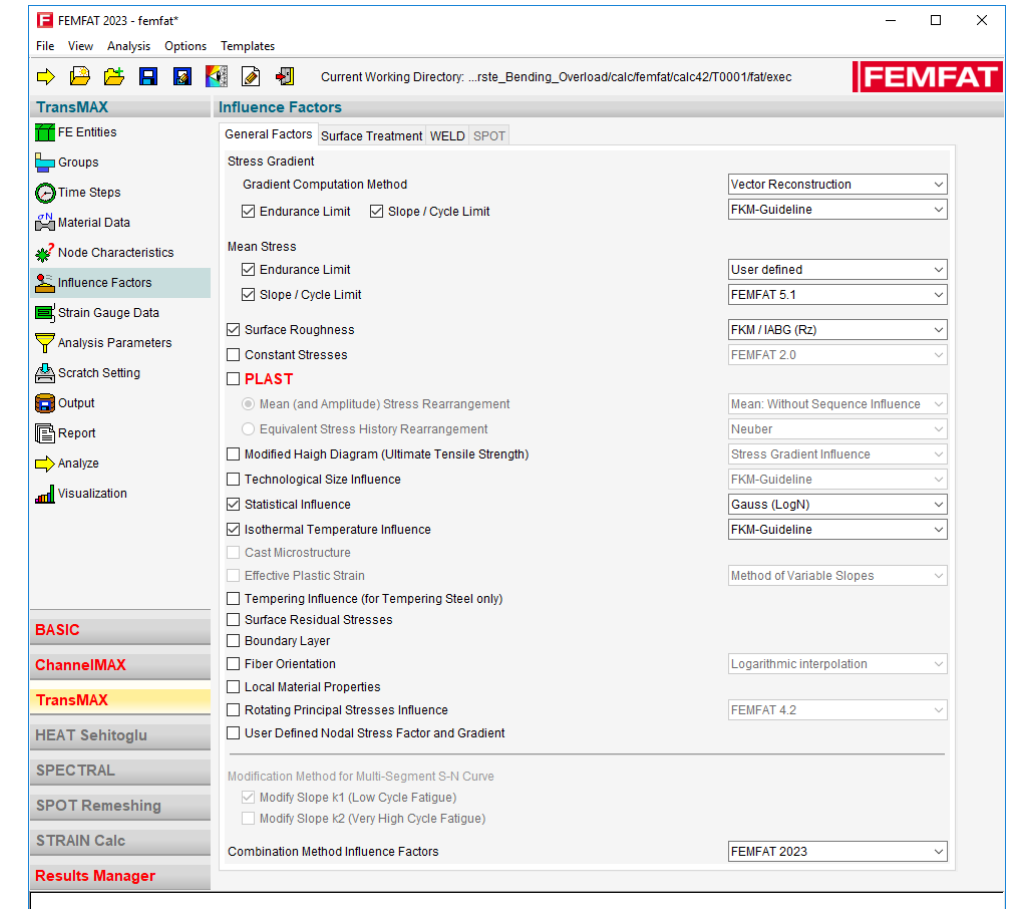
Reference: Dirk Harste, Dissertation: *Untersuchungen zur Auswirkung von Überlasten auf die Dauerschwingfestigkeit*, Technische Universität Clausthal, 1996

Simulation

Requirements

- Democratize and Automate the use of FEMFAT
- Strength assessment as close as possible to FKM Guideline*)
 - Double Strength Assessment for Fatigue with open Haigh diagram and Static (global and local failure mode)
 - Required safety factors j to compute consumed load capacity $a = j / sf$
 - Stress gradient support depends on type of strength assessment
 - User define temperature influence for all assessments
 - ...
- Efficient Reporting

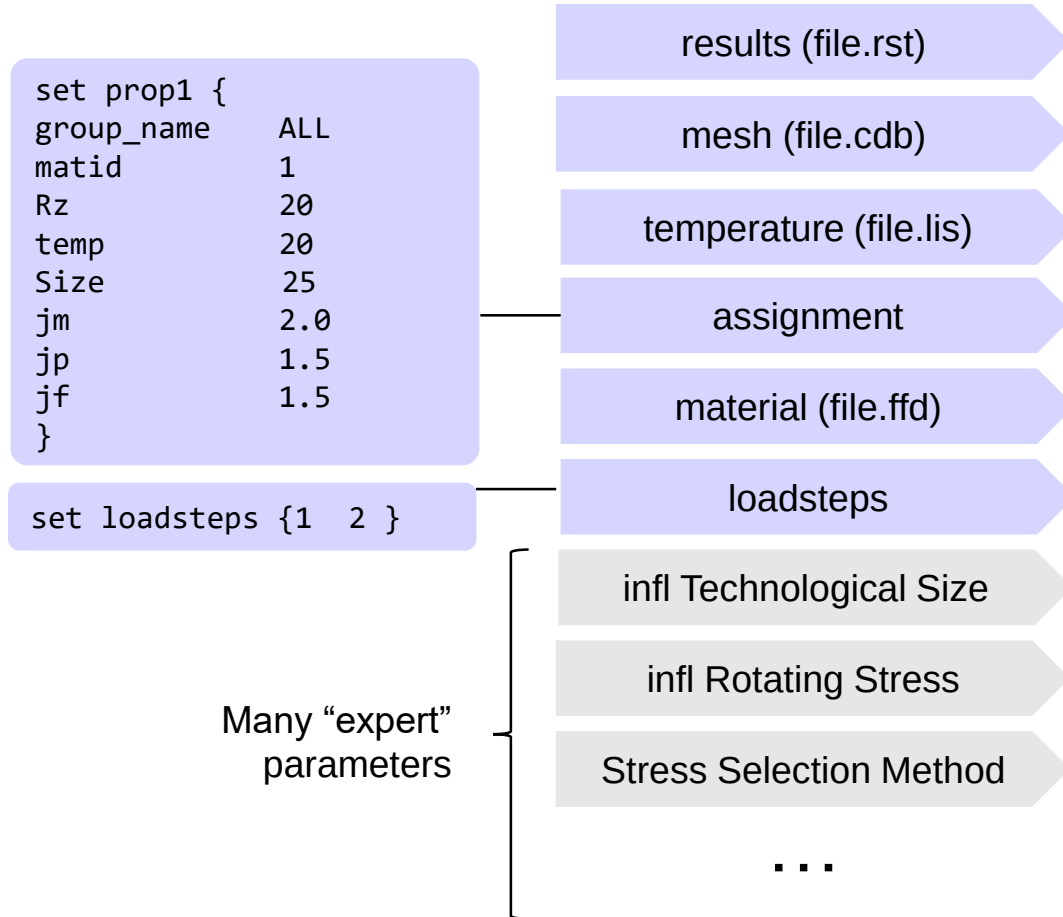
*) FKM Guideline, ANALYTICAL STRENGTH ASSESSMENT OF COMPONENTS, Made of Steel, Cast Iron and Aluminum Materials in Mechanical Engineering, 6th (2012) and 7th edition (2020)



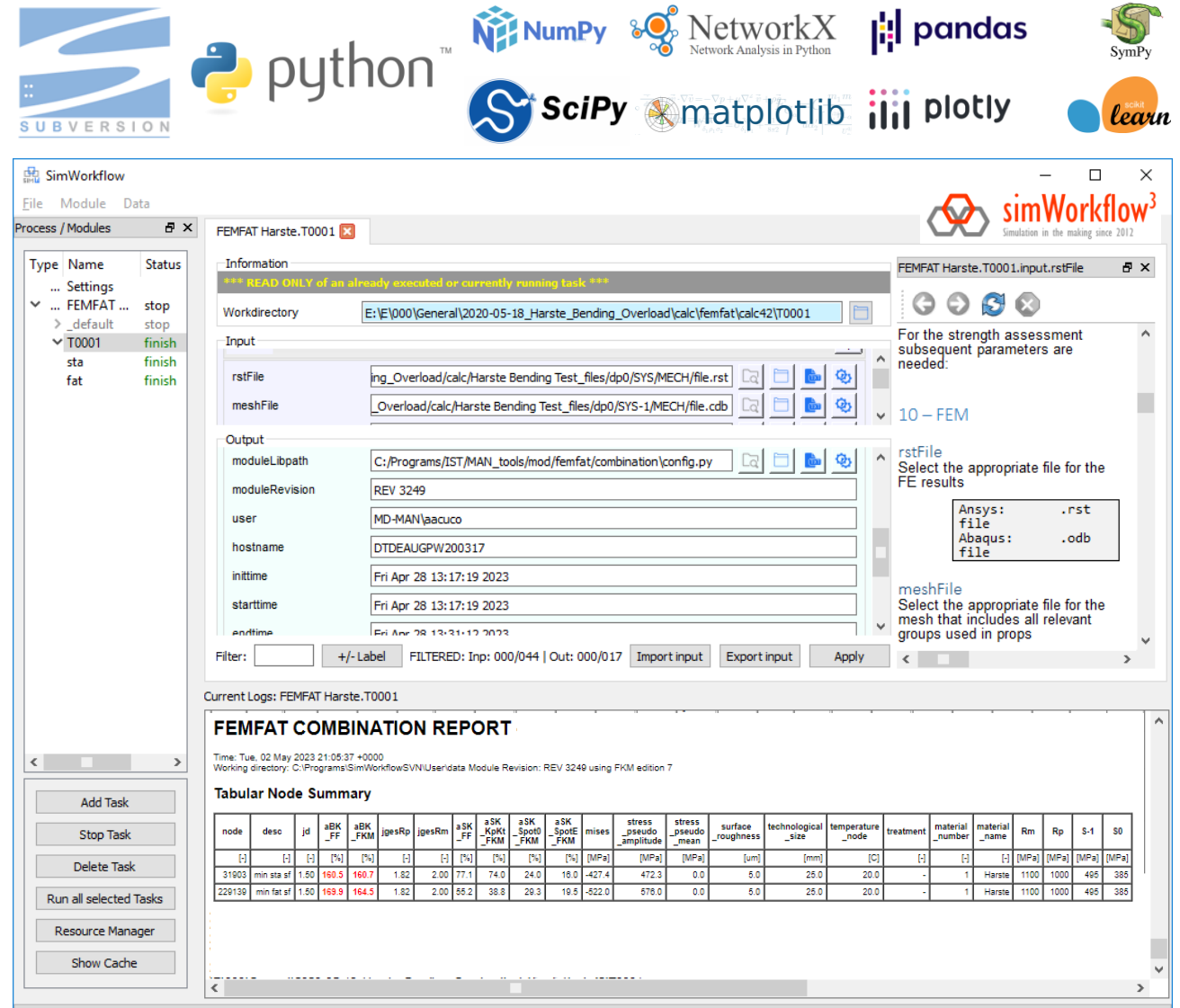
Although FEMFAT allows various options for a strength assessment we needed to develop some enhancements to meet our requirements

Simulation

Democratize and Automate



Only ~10 input parameters are required to configure a strength assessment



Our in-house program simWorkflow offers a simplified and efficient interface to several CAE softwares.

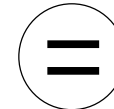
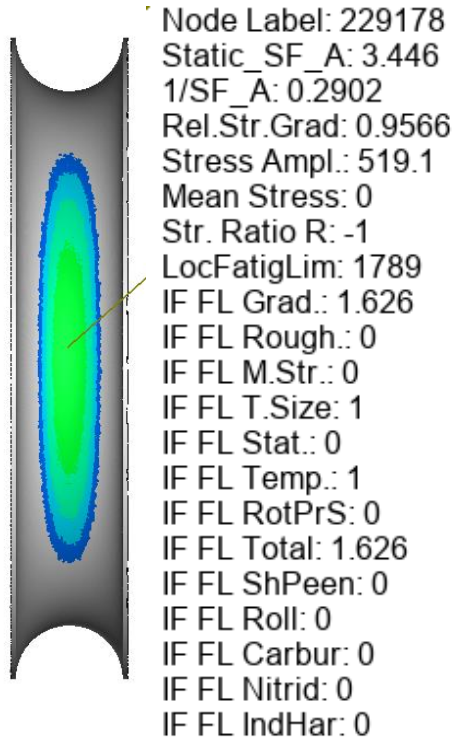
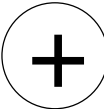
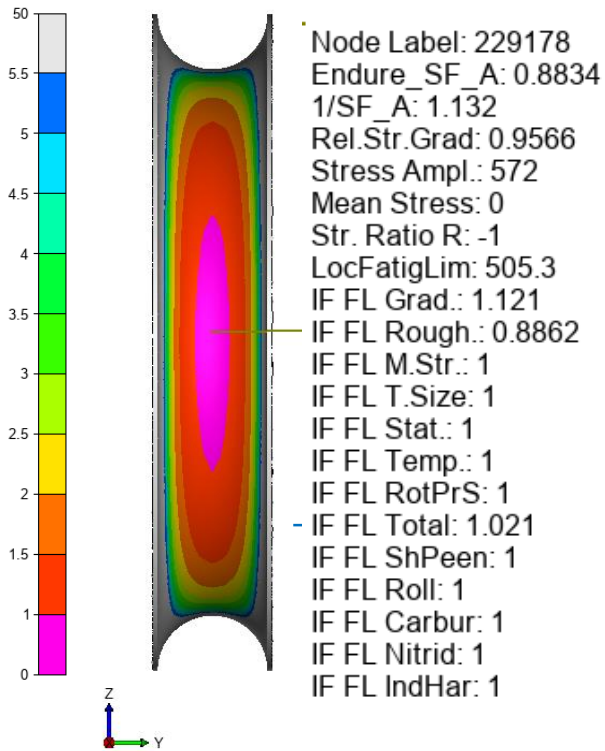
Simulation

Double Strength Assessment and its Combination

sf	a=j/sf (j=1.5)
30	5.0%
5.5	27.3%
5	30.0%
4.5	33.3%
4	37.5%
3.5	42.9%
3	50.0%
2.5	60.0%
2	75.0%
1.5	100.0%
1	150.0%
0.8834	169.8%

j: required safety
a: consumed load capacity
BK: Fatigue
SK: Static
FF: FEMFAT
FKM: FKM
KpKt, FF: Global failure
Spot: Local failure

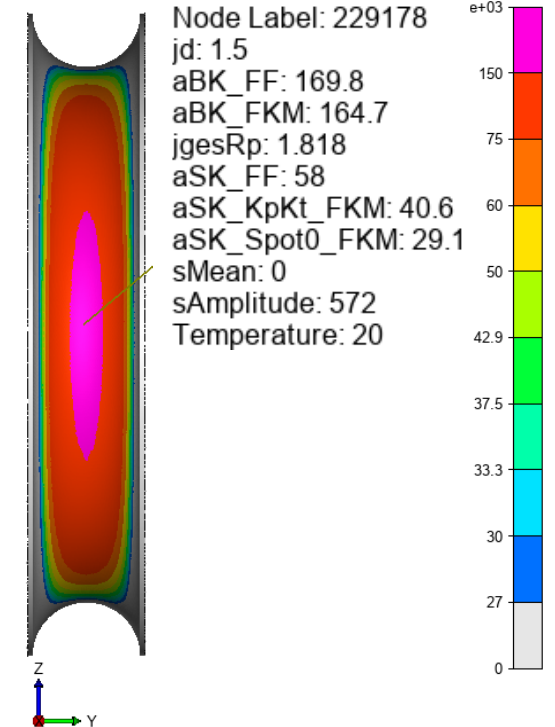
sf



Visualizer 2023 - ...analysed with FEMFAT 2023)
RESULT: Result 2
SCALE: LINEAR
MIN: 5 MAX: 170

FEMFAT

a



Input

Fatigue [fps]

FEMFAT



Static [fps]

FEMFAT

Postprocessing

Combined [fps]

FEMFAT

Simulation

Required Safety

Table 3.5.1 Basic safety factors

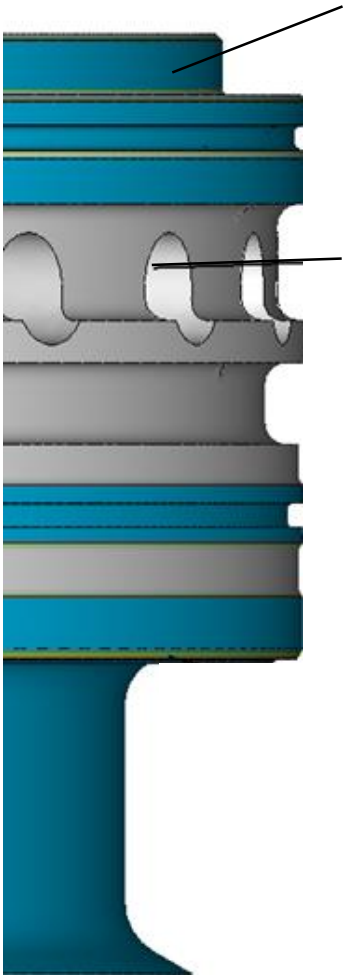
j_m j_p j_{mt} j_{pt}		Consequences of failure		
		high	mean	moderate ◇1
Probability of the occurrence of the stress or the stress combination ◇2	high	2,0	1,85	1,75
		1,5	1,4	1,3
		1,5	1,4	1,3
		1,0	1,0	1,0
	low ◇3	1,8	1,7	1,6
		1,35	1,25	1,2
		1,35	1,25	1,2
		1,0	1,0	1,0

- ◇1 moderate consequences of failure of a less important component in the sense of "no catastrophic effects" being associated with a failure; e.g. due to a load redistribution towards other members of a statically undeterminate system. Reduction by a factor of 1,15 (rounding 0,05).
- ◇2 generally with reference to the magnitude of the load, not the frequency. Reduction by a factor of 1,10 (rounding of 0,05).
- ◇3 including exactly estimable loads which can safely be assumed to occur infrequently due to e.g. the testing and assembling conditions.

Table 4.5.1 Material safety factors j_F for non-welded steel and for wrought aluminum alloys

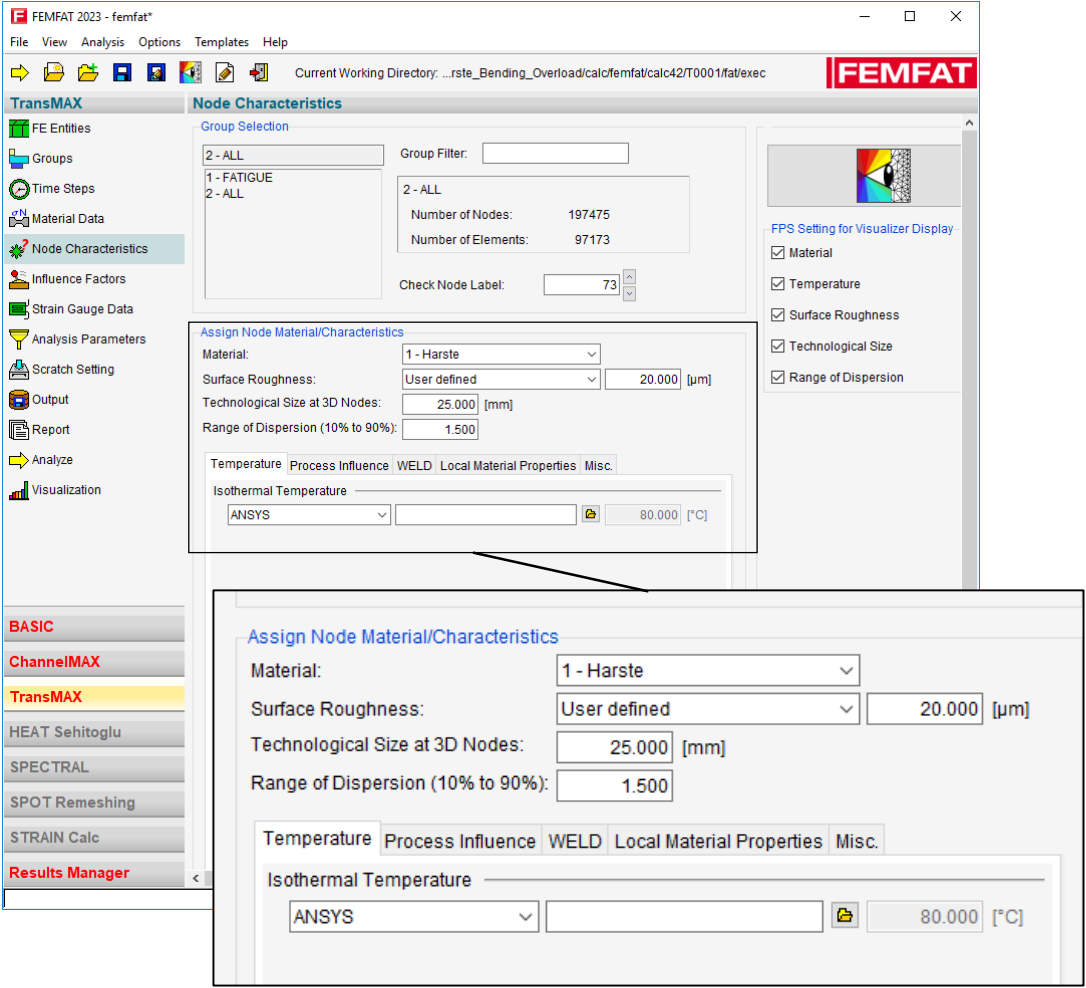
j_F		Consequences of failure ◇1		
		severe	mean	moderate
Regular inspections ◇2	no	1,5	1,4	1,3
	yes	1,35	1,25	1,2

- ◇1 Severe consequences of failure: loss of human life.
Mean consequences of failure: loss of the entire structure, reduction by about 7,5 %.
Moderate consequences of failure: loss of secondary components; possibilities for load redistribution in statically indeterminate system, reduction by about 15 %.
- ◇2 Regular inspection in the sense of monitoring for early detection of damage: reduction by about 10 %.



safety-relevant
higher strength
requirement

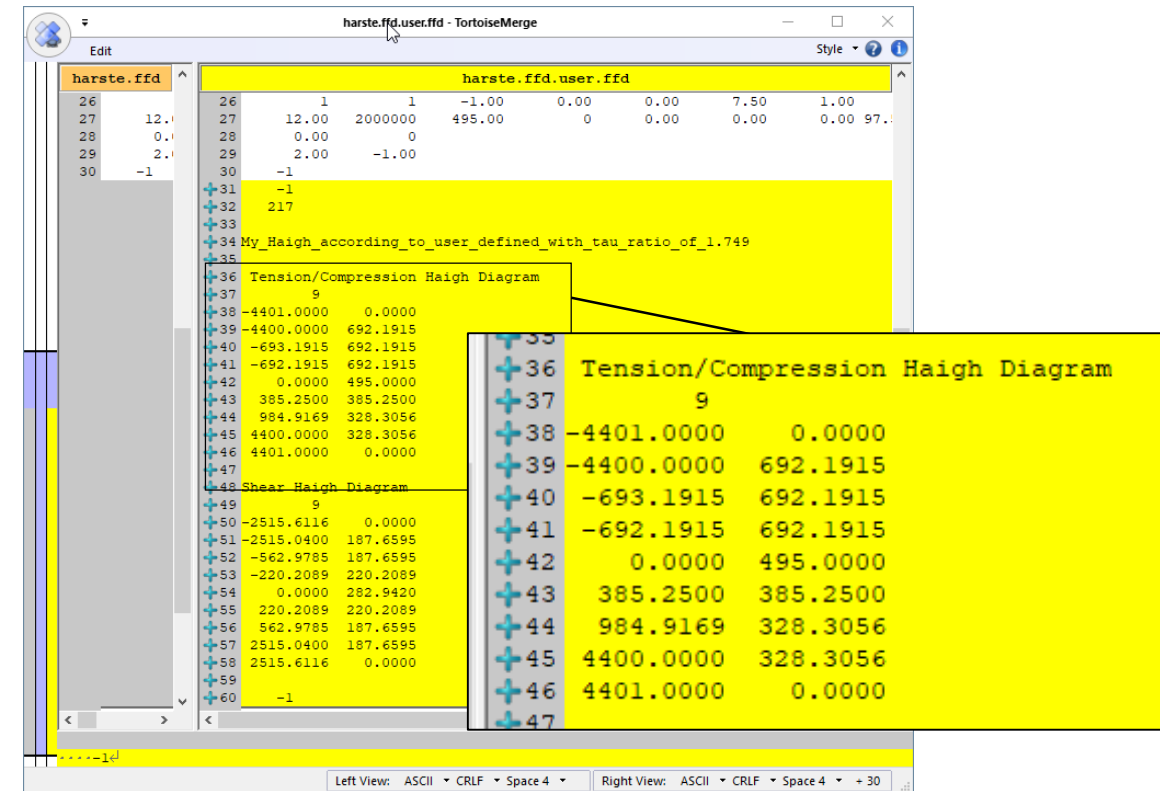
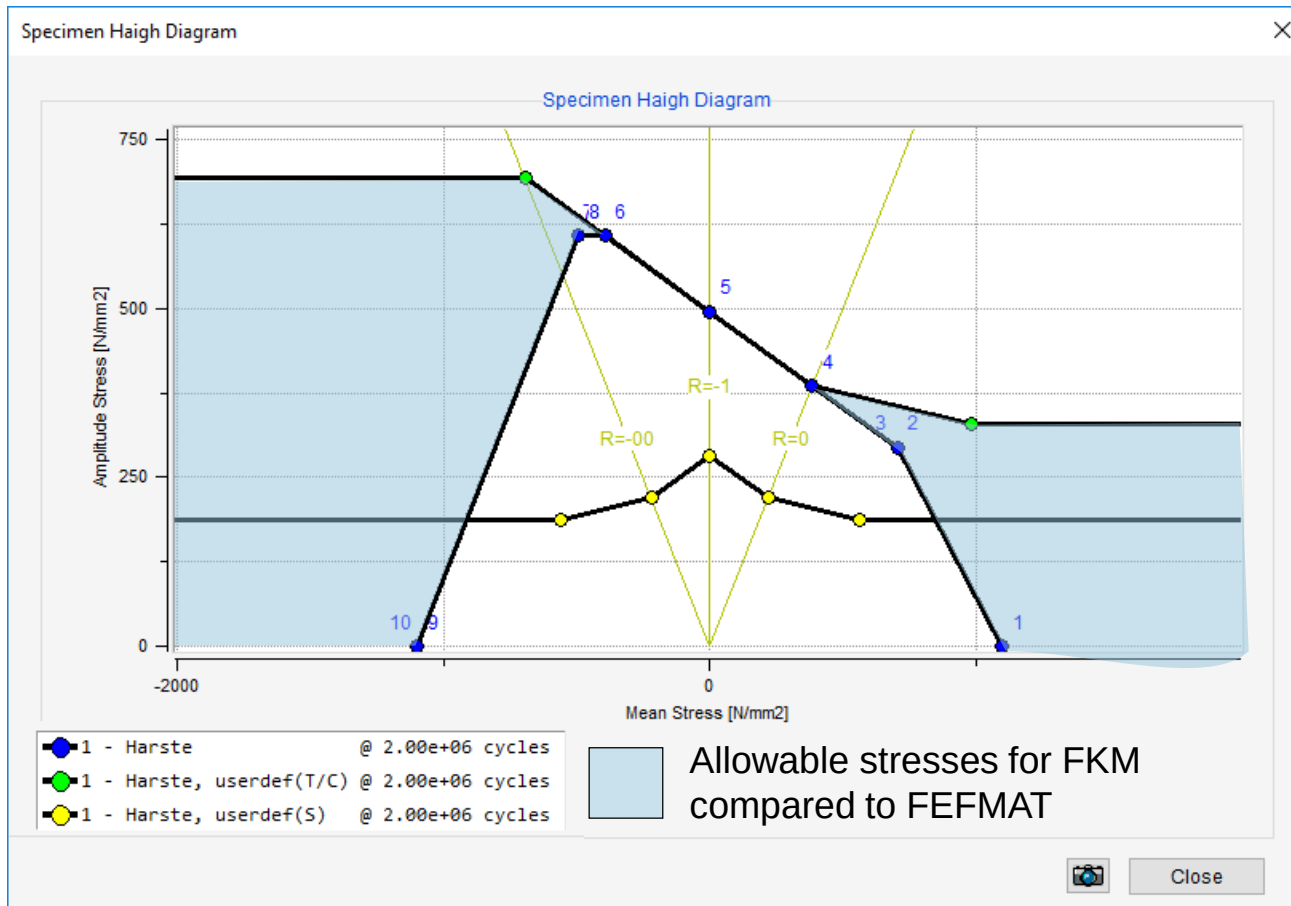
other locations:
lower strength
requirement



The required safety factor j is a node dependent value.
We “use” the parameter range of dispersion to store this information.

Simulation

Fatigue Strength Assessment – Open Haigh diagram



```
# Activate user specified haigh diagramm from the material file to eliminate static limit
# the corresponding material file need included user spec. haigh diagram
setValue {} {} InfluenceMeanStressMethod 39
# switch off the extention on static limits within haigh diagram - like plastic notch factor K_p
setValue {} {} InfluenceOnHaigh 0
# [AUTO] -- [Automatically added due to: openHaigh = 1 (=yes)] -- END
```

We make use of user defined Haigh diagrams to generate an “open” Haigh diagram (no static limit for fatigue strength assessment).

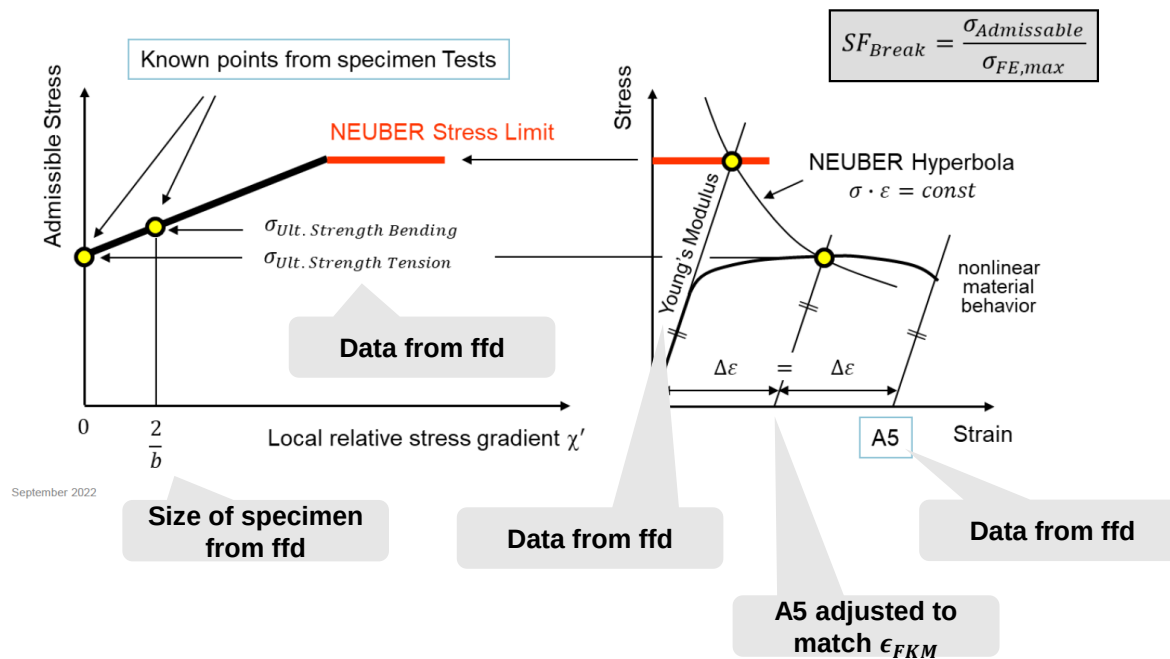
Simulation

Static Strength Assessment - Stress gradient support

NEUBER stress limit is defined by the stress-strain curve and ultimate tensile strength. Thus the influence of the local relative stress gradient is limited.



Stress limit for ultimate tensile strength criterion



FEMFAT Break does not consider the size of a component where the stress gradient is apparent.

Limit curve for local critical strain

Critical strain ϵ_{ertr} depends on
 $\epsilon_{ref} = f$ (elongation at break A, material group),
 $\epsilon_0 = f$ (material group) und
 $h = \sigma_{hydrostatic} / \sigma_{GEH}$

$$\epsilon_{ertr} = \begin{cases} \epsilon_{ref} & \text{für } h \leq 1/3 \\ \epsilon_0 + 0,3 \cdot \left(\frac{\epsilon_{ref} - \epsilon_0}{0,3} \right)^{3h} & \text{für } h > 1/3 \end{cases}$$

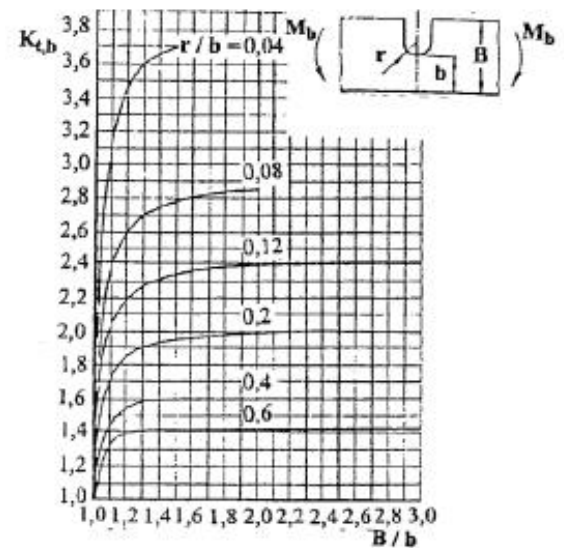
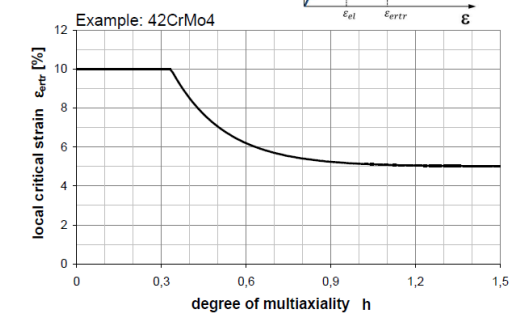
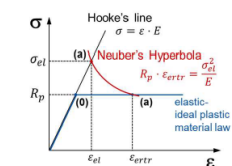


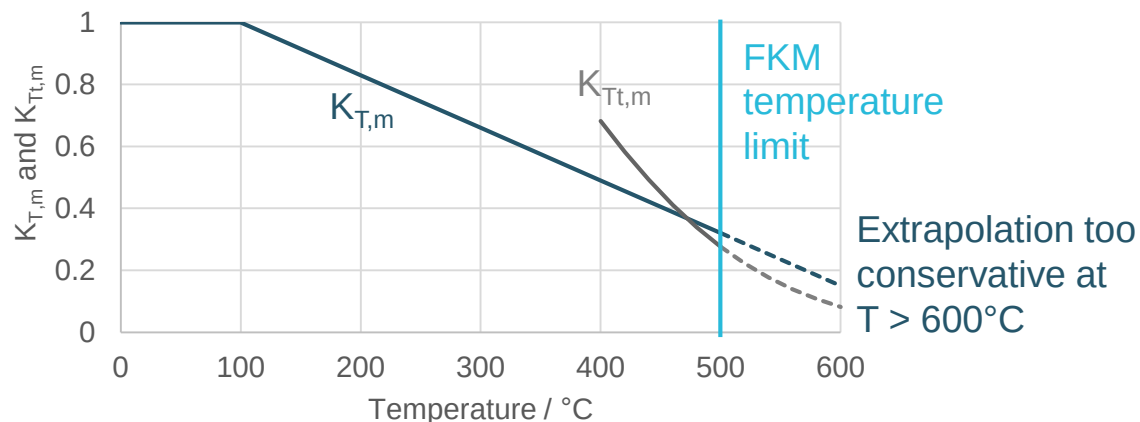
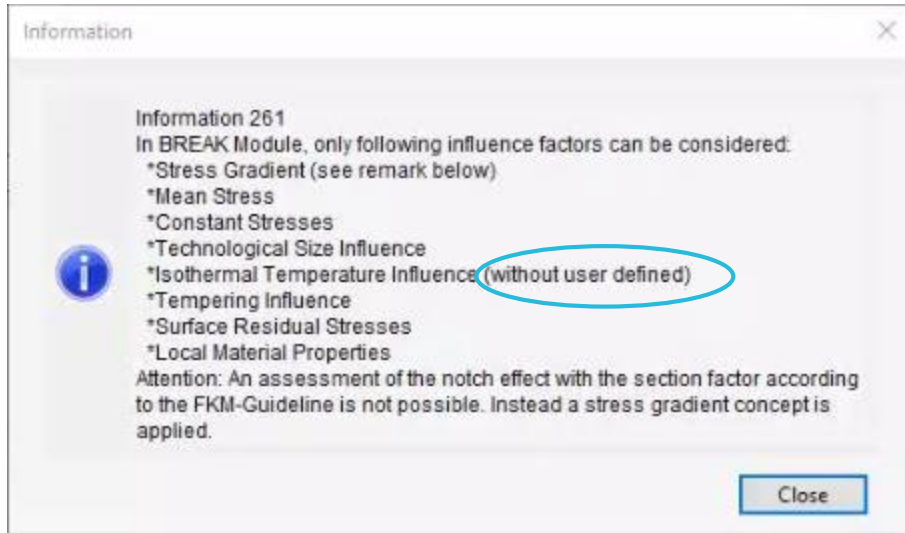
Figure 4.3-1: Stress concentration factor for the substitute structure in accordance with Figure 5.2-15, B/b high

$$n_{pl} = \text{Min} \left\{ \sqrt{E \cdot \epsilon_{ertr} / R_p} ; K_p \right\}$$

Adjustment of the actual influence according to FKM-guideline during post-processing

Simulation

Static Strength Assessment - User defined Temperature Influence in Static Strength Assessment



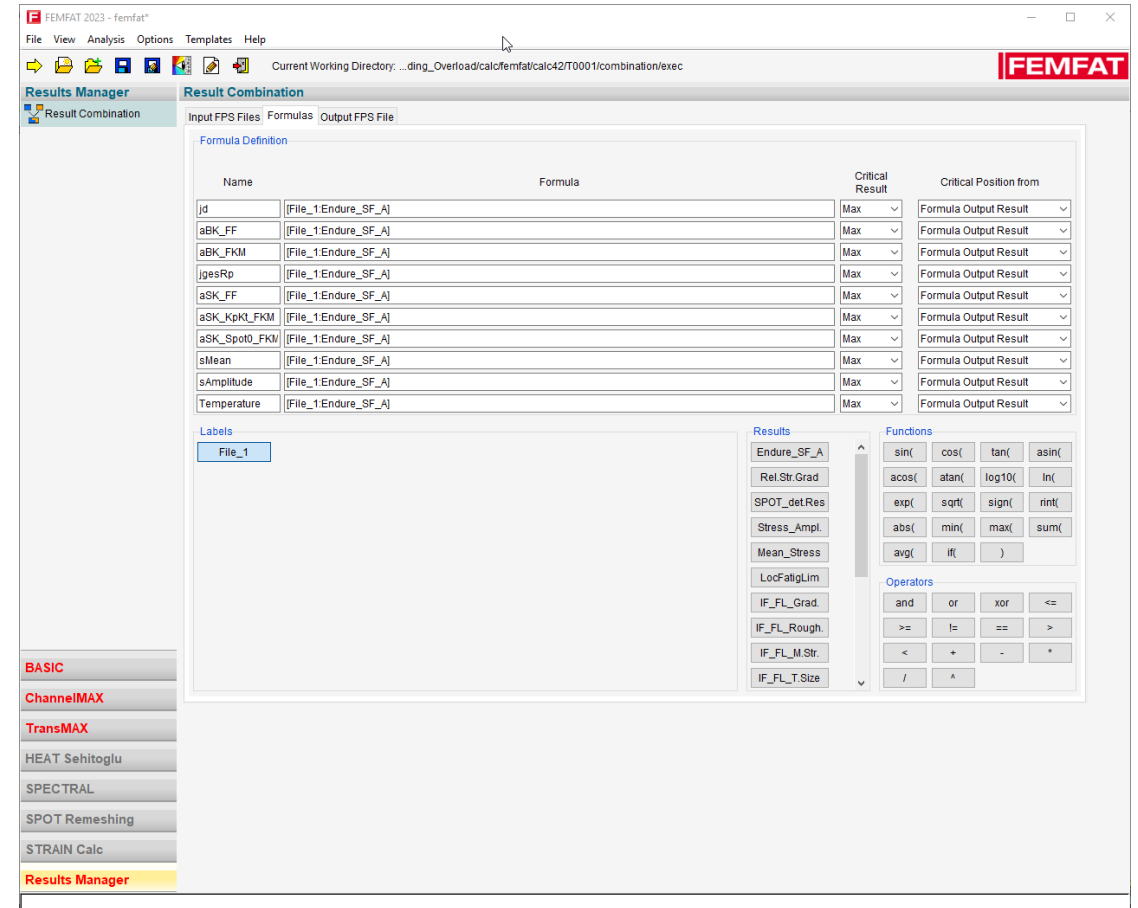
- User defined temperature influence is useful in high-temperature applications, especially when experimental material data are available
- Solution: Replace temperature influence value according to FKM by user-defined value according to experimental data
- Relevant for following components:
 - exhaust gas piping
 - cylinder head
 - valves and valve seats

Adjustment of the actual influence according to user definition during post-processing

Simulation

Combine FPS: Create Template

```
1  set dir {}
2
3  setValue () {} FemfatVersionNumber {FEMFAT 5.4.1}
4  setValue () {} MAXmod 8
5  setValue () {} GUI_ResManager:FpsFile "$dir/../../fat/exec/femfat.fps"
6  setValue () {} GUI_ResManager:CombinationMethod 3
7  setValue () {} GUI_ResManager:ReadFpsFile
8  setValue () {} GUI_ResManager:FormulaName 0 {jd}
9  setValue () {} GUI_ResManager:FormulaName 1 {aBK_FF}
10 setValue () {} GUI_ResManager:FormulaName 2 {aBK_FKM}
11 setValue () {} GUI_ResManager:FormulaName 3 {jgesRp}
12 setValue () {} GUI_ResManager:FormulaName 4 {aSK_FF}
13 setValue () {} GUI_ResManager:FormulaName 5 {aSK_KpKt_FKM}
14 setValue () {} GUI_ResManager:FormulaName 6 {aSK_Spot0_FKM}
15 setValue () {} GUI_ResManager:FormulaName 7 {sMean}
16 setValue () {} GUI_ResManager:FormulaName 8 {sAmplitude}
17 setValue () {} GUI_ResManager:FormulaName 9 {Temperature}
18 # Fill data with dummy values that are replaced by Python
19 setValue () {} GUI_ResManager:Formula 0 {[File_1:Endure_SF_A]}
20 setValue () {} GUI_ResManager:Formula 1 {[File_1:Endure_SF_A]}
21 setValue () {} GUI_ResManager:Formula 2 {[File_1:Endure_SF_A]}
22 setValue () {} GUI_ResManager:Formula 3 {[File_1:Endure_SF_A]}
23 setValue () {} GUI_ResManager:Formula 4 {[File_1:Endure_SF_A]}
24 setValue () {} GUI_ResManager:Formula 5 {[File_1:Endure_SF_A]}
25 setValue () {} GUI_ResManager:Formula 6 {[File_1:Endure_SF_A]}
26 setValue () {} GUI_ResManager:Formula 7 {[File_1:Endure_SF_A]}
27 setValue () {} GUI_ResManager:Formula 8 {[File_1:Endure_SF_A]}
28 setValue () {} GUI_ResManager:Formula 9 {[File_1:Endure_SF_A]}
29 # Export fps
30 setValue () {} GUI_ResManager:ExportFile "$dir/result.fps"
31 setValue () {} GUI_ResManager:WriteFpsFile
32
```

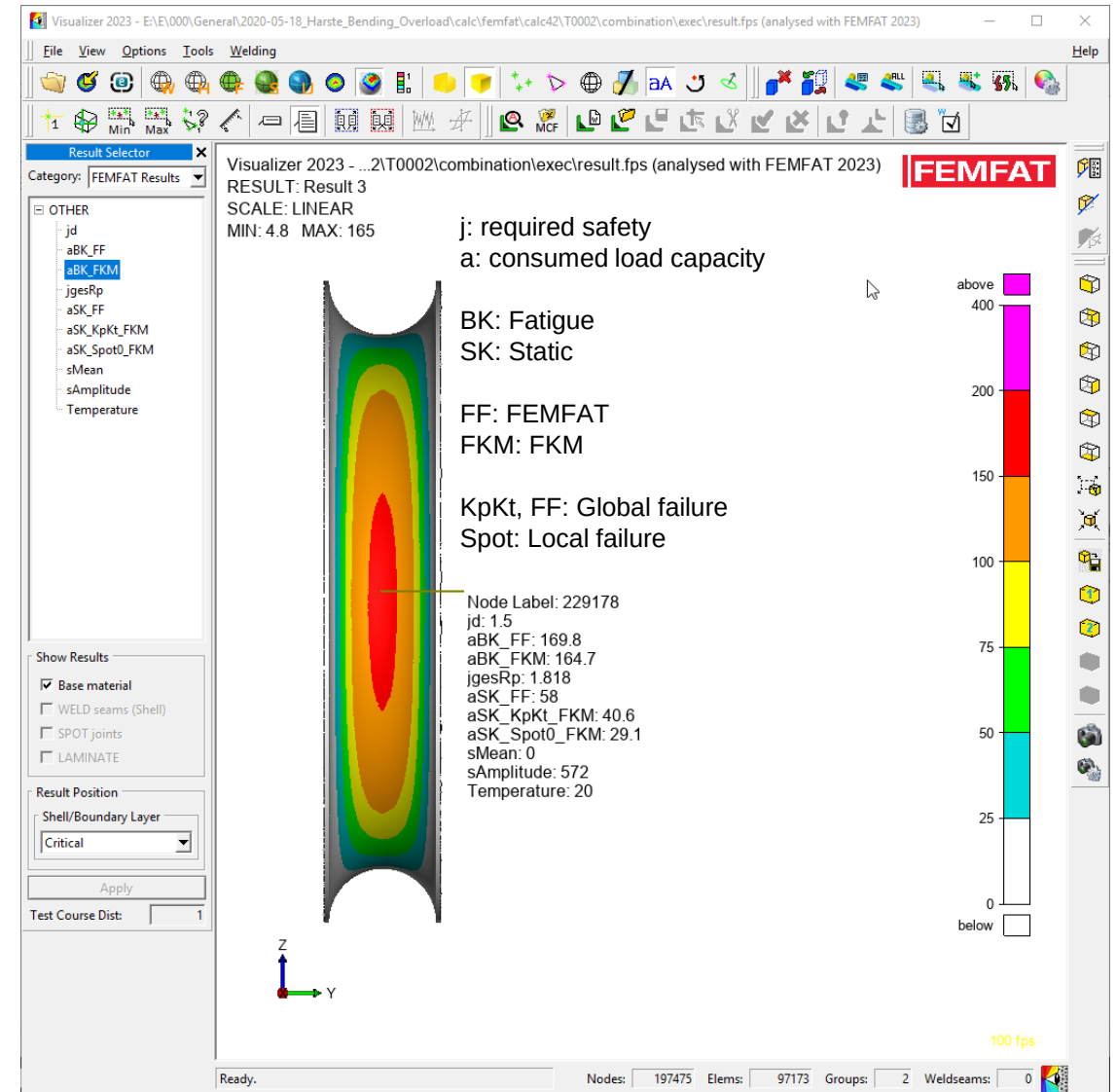


Simulation

Combine FPS: Insert actual data

```
207 m.logger.info("Open FPS file and initialize")
208 out = h5py.File(resultFPS, 'r+')
209
210 allNodes = out["Structure/Nodes/LABEL"]
211 nodesInStructure = allNodes[:]
212 resultNodes = out["Results/BaseNodes/LAYERINFO"]
213 nodesInFpsFemfatIndex = resultNodes[:,0]
214 results = out["Results/BaseNodes/LAYERRESULTS"]
215
216 # Clear data with zero results
217 results[:, :] = np.zeros(results.shape)
218
219 m.logger.info("Generate Mapping FEMFAT <-> FE")
220 nodesMapping = []
221 for i, femfatNodeIndex in enumerate(nodesInFpsFemfatIndex):
222     nodesMapping.append(nodesInStructure[femfatNodeIndex])
223
224 m.logger.info("Store results with shape %s" % str(results.shape))
225 outData = []
226 for i, n in enumerate(nodesMapping):
227     try:
228         # Store the results node by node from the report pickled results
229         outData.append([
230             float(fatigue[n]["jd"]), # 0
231             np.round(float(fatigue[n]["aBK_FF"])*1000.)/10., # 1
232             np.round(float(fatigue[n]["aBK_FKM"])*1000.)/10., # 2
233             float(static[n]["jgesRp"]), # 3
234             np.round(float(static[n]["aSK_FF"])*1000.)/10., # 4
235             np.round(float(static[n]["aSK_KpKt_FKM"])*1000.)/10., # 5
236             np.round(float(static[n]["aSK_Spot0_FKM"])*1000.)/10., # 6
237             float(fatigue[n]["stress_pseudo_mean"]), # 7
238             float(fatigue[n]["stress_pseudo_amplitude"]), # 8
239             float(fatigue[n]["temperature_node"]), # 9
240         ])
241     except:
242         m.logger.error("Error during step %d at node %d" % (i,n))
243         raise
244 # Store everything
245 results[:, :] = np.array(outData)
246 out.close()
```

The h5py package is a Pythonic interface to the [HDF5](https://www.h5py.org/) binary data format; <https://www.h5py.org/>



Simulation

Reporting: Result-Table

FEMFAT COMBINATION REPORT - T0002

Time: Tue, 02 May 2023 21:05:37 +0000
Working directory: C:\Programs\SimWorkflowSVN\User\data Module Revision: REV 3249 using FKM edition 7

Tabular Node Summary

node	desc	jd	aBK_FF	aBK_FKM	jgesRp	jgesRm	aSK_FF	aSK_KpKt_FKM	aSK_Spot0_FKM	aSK_SpotE_FKM	mises	stress_pseudo_amplitude	stress_pseudo_mean	surface_roughness	technological_size	temperature_node	treatment	material_number	material_name	Rm	Rp	S-1	S0
[-]	[-]	[-]	[%]	[%]	[-]	[-]	[%]	[%]	[%]	[%]	[MPa]	[MPa]	[MPa]	[um]	[mm]	[C]	[-]	[-]	[-]	[MPa]	[MPa]	[MPa]	[MPa]
31903	min sta sf	1.50	160.5	160.7	1.82	2.00	77.1	74.0	24.0	18.0	-427.4	472.3	0.0	5.0	25.0	20.0	-	1	Harste	1100	1000	495	385
229139	min fat sf	1.50	169.9	164.5	1.82	2.00	55.2	38.8	29.3	19.5	-522.0	578.0	0.0	5.0	25.0	20.0	-	1	Harste	1100	1000	495	385

Conclusion

We have illustrated how to efficiently

- Democratize and Automate the use of FEMFAT
- Implement the Double Strength Assessment
- Create Reports

We are ready for analyzing the influence of future fuels!

Enhancement Requests

- More than 10 user defined results in combined results
- Export of nodal Haigh Diagrams (only image export in GUI possible)
- Definition of own nodal information (currently: “mis-use” of range of dispersion for required safety)



Thank you very much!