# Expo Engine 2011

# Analysis of crankshaft under virtual engine operation using Ansys APDL routines and Ansys WB software

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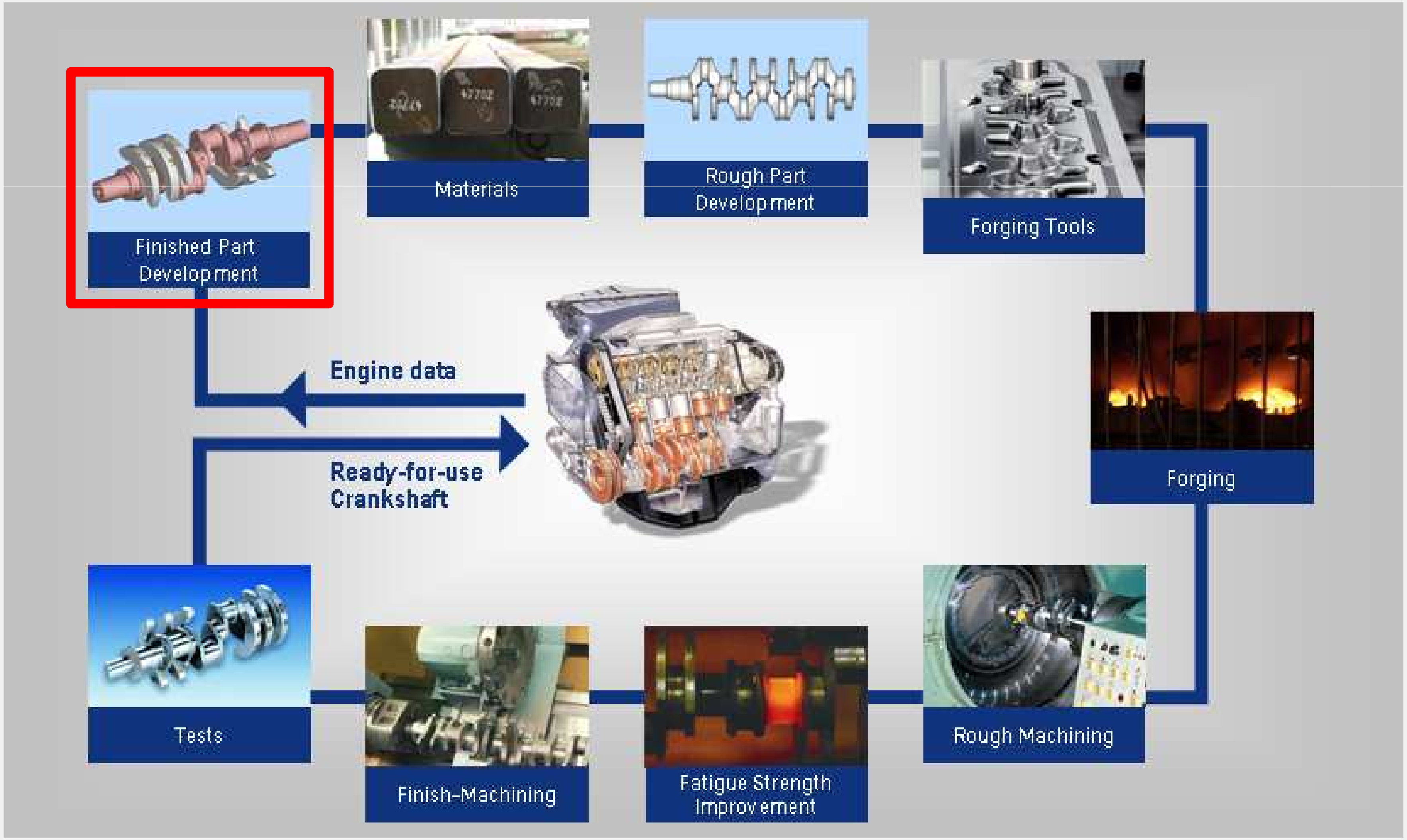
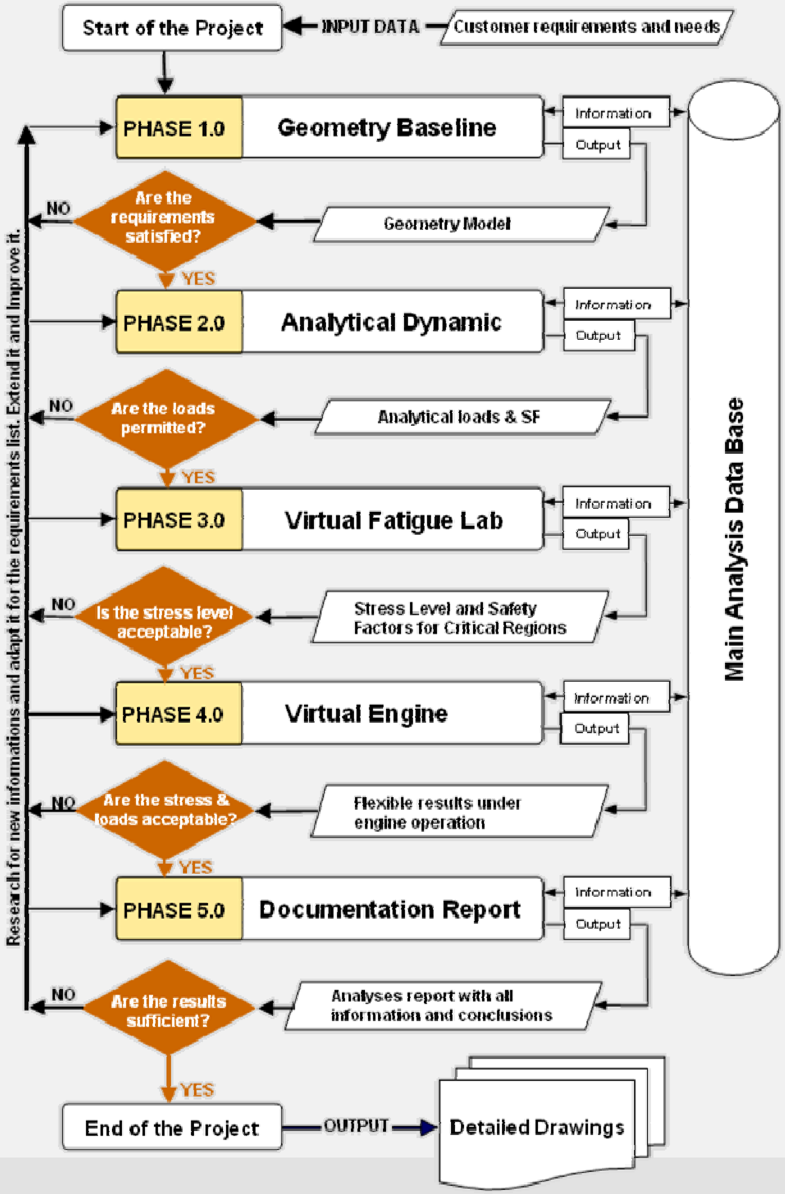
# 1. Agenda

1. Conventional Bending and Torsion Tests;
2. Under virtual Engine Operation
3. Super Crank

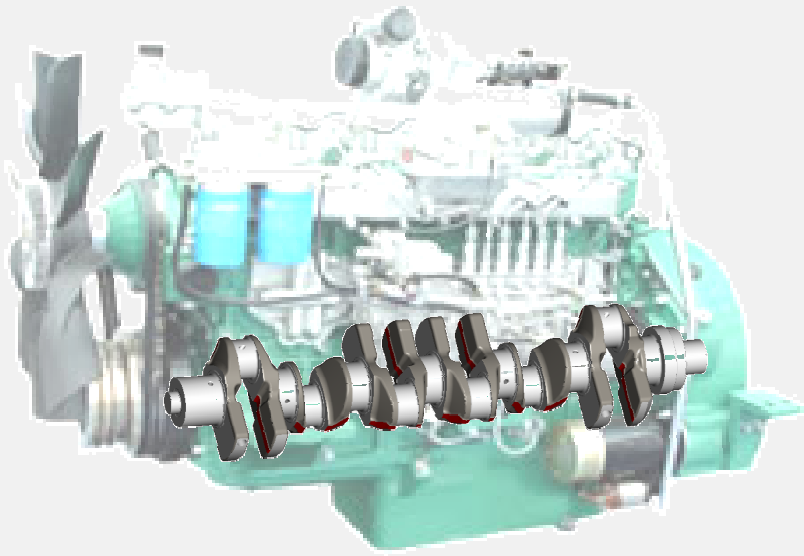
# 2. Development cycle

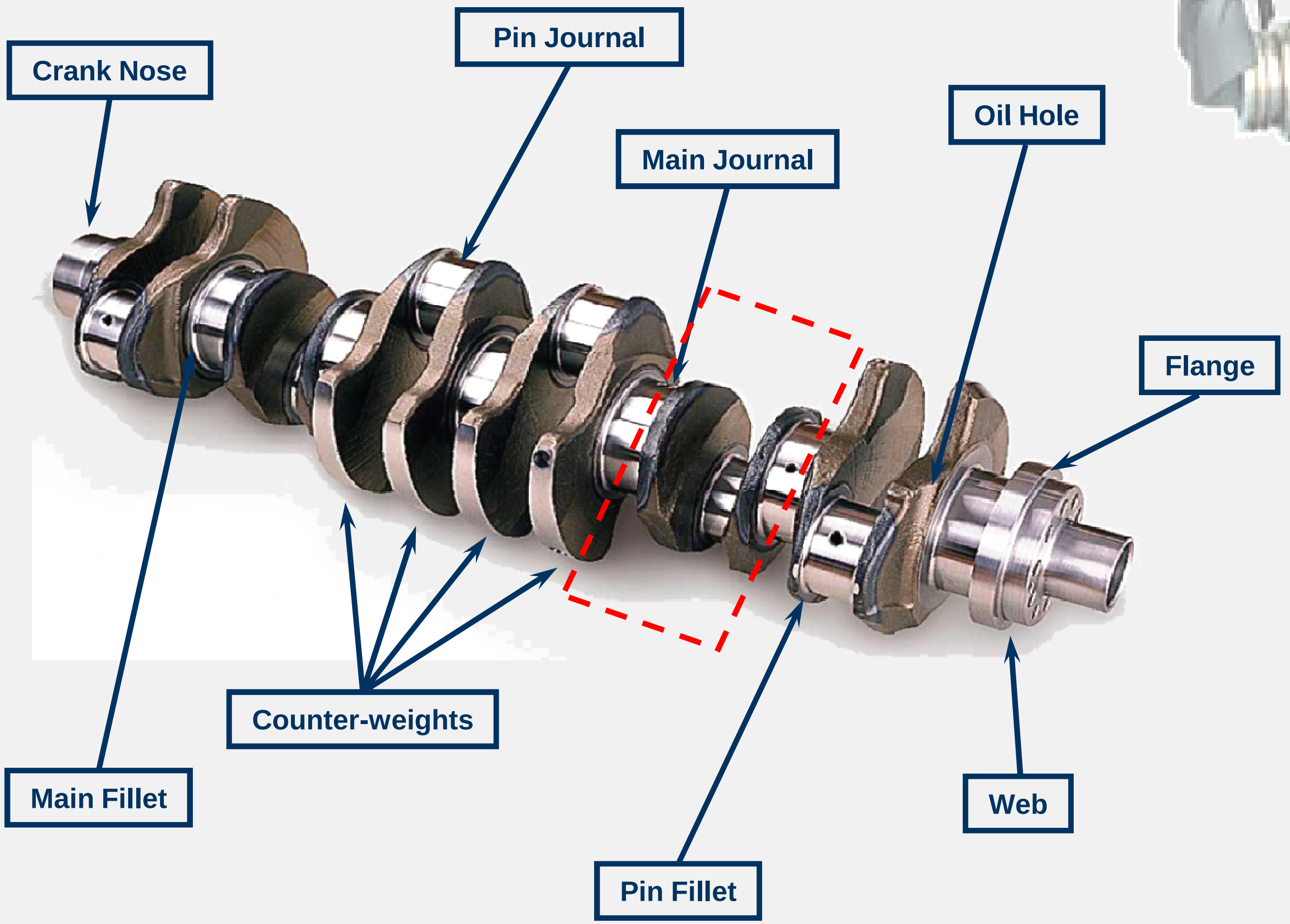


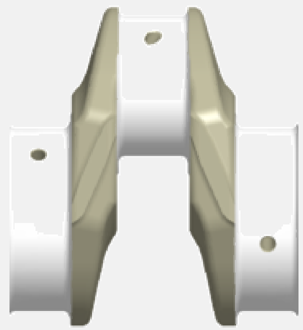
# 3. Finished Part Development



# 4. Technical Nomenclature



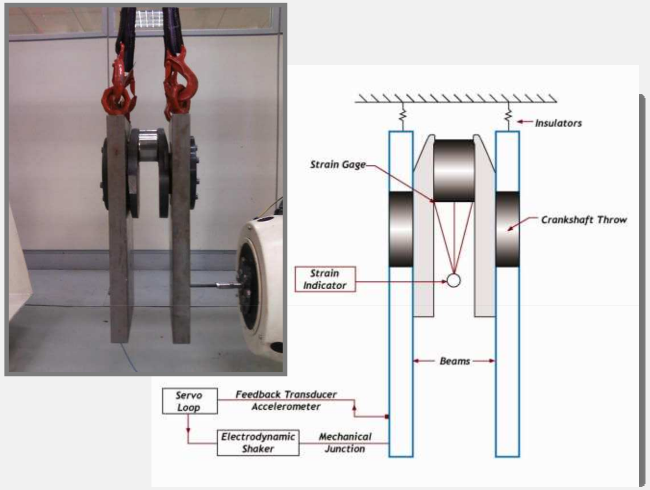


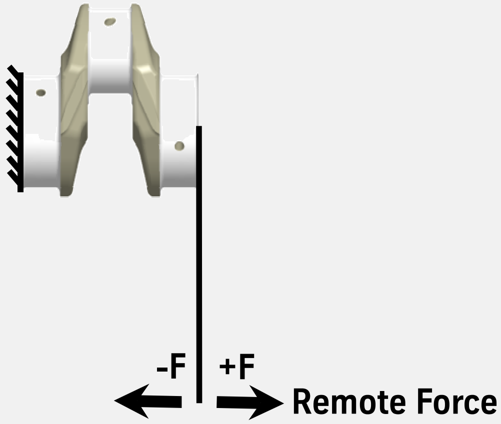
Crankshaft Throw

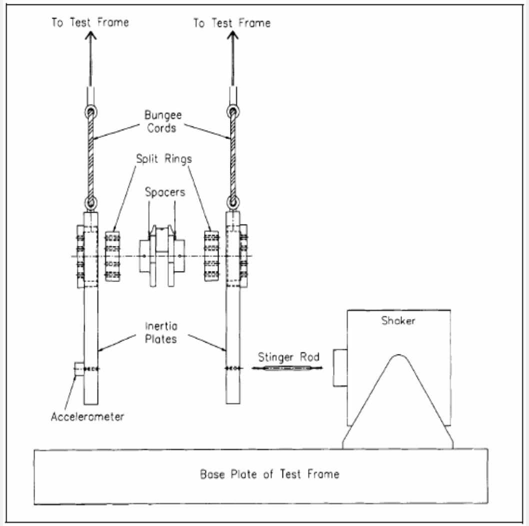
# 5. Bench Test

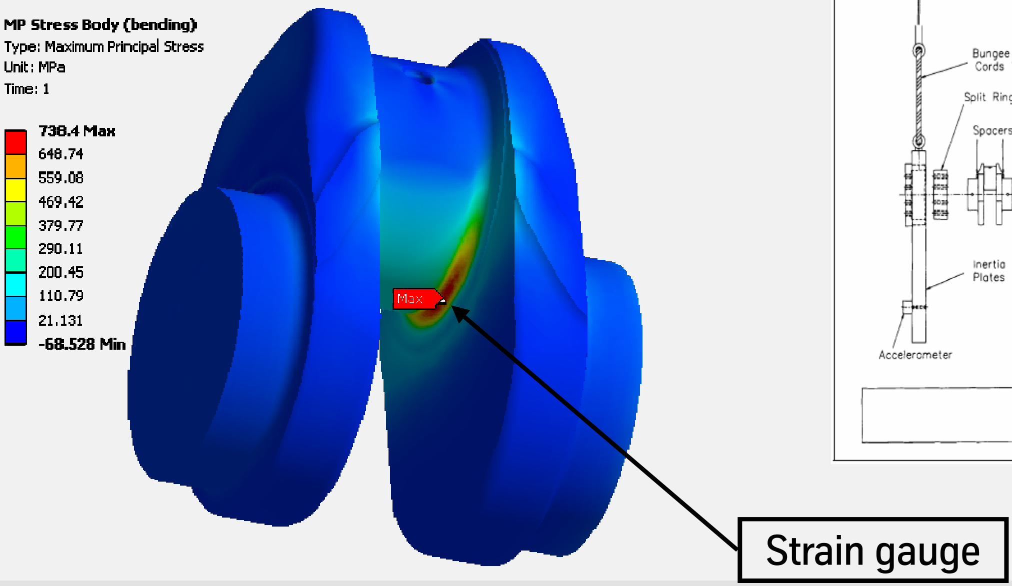
## Bench Bending Test




## Virtual Bending Test




**Material Properties identification based on experimental tests with crankshafts under bending load**

- Stair Case Method is applied for endurance limit evaluation
- 10 million cycles
- The stresses are measured directly in the bearings fillets by strain gauges (positions 1, 2, 3 and 4)
- Endurance limit is calculated for bearings fillets based on measured data and statistical treatment

**Material Properties**

- SR: ultimate tensile strength
- SE: yield tensile strength
- E: Young's modulus
- Poisson
- NC and NL: number of load cycles
- SC and SL: endurance limits

**SN Methodology**

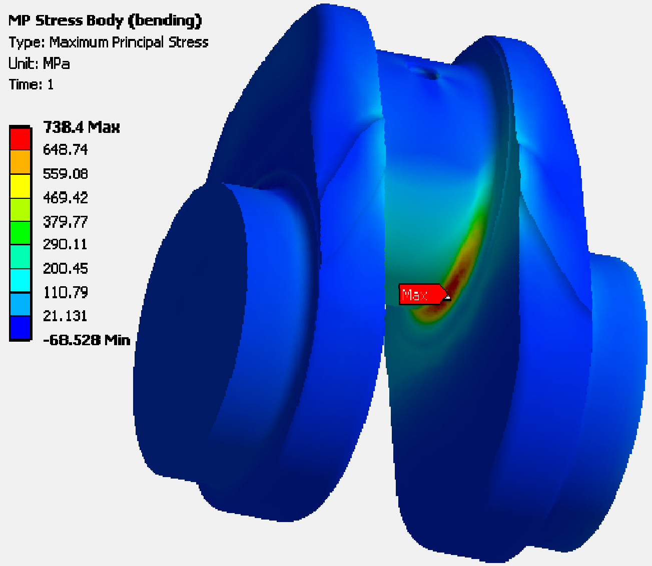
- PUC Criteria

# 5. Bench Test

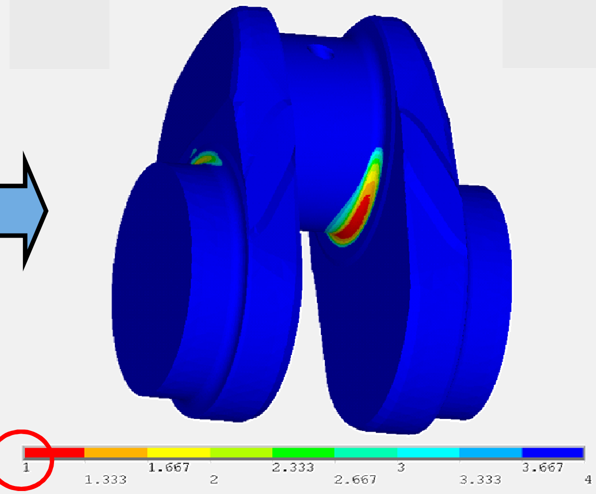
## Stair Case Method for Bending

Table 1: Data Sheet

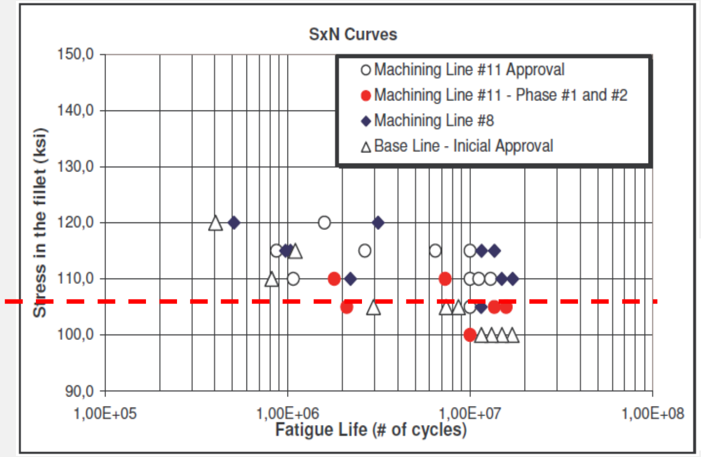
| SAMPLE ID # | PIN # | Stress in the Pin Fillet (ksi) | # of cycles | Failure Location |
|---|---|---|---|---|
| 1:3 | 3 | 120,0 | 1.595.264 | 4 |
| 1:5 | 5 | 115,0 | 870.672 | 3 |
| 2:4 | 4 | 110,0 | 1.077.320 | 2 |
| 2:6 | 6 | 105,0 | 10.000.000 | - |
| 3:1 | 1 | 110,0 | 10.000.000 | - |
| 3:3 | 3 | 115,0 | 6.450.144 | 4 |
| 4:2 | 2 | 110,0 | 10.000.000 | - |
| 4:4 | 4 | 115,0 | 2.656.608 | 4 |
| 5:1 | 1 | 110,0 | 10.000.000 | - |
| 5:3 | 3 | 115,0 | 10.000.000 | - |




Fatigue Safety Factor




Minimum SF=1 for infinite life




107.1

Endurance Limit (SC) for 1 million cycles (NC)

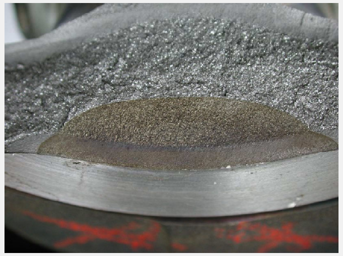
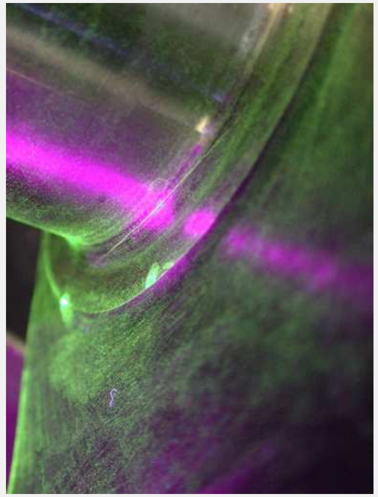


Table 2: Bending fatigue Results

| Results | |
|---|---|
| 50% (mean) | 112,5 ksi |
| 95% | 107,1 ksi |
| Std Deviation | 3,5 ksi |

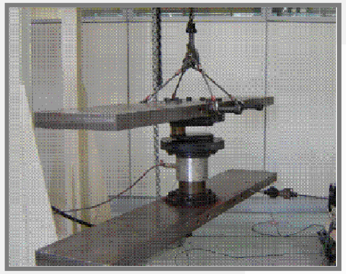
738 MPa

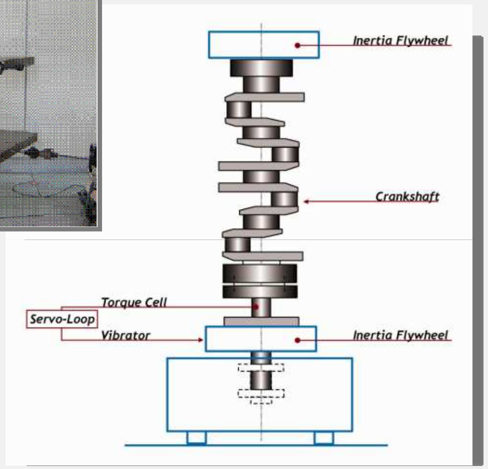


Endurance Limit (SL) for 10 million cycles (NL)

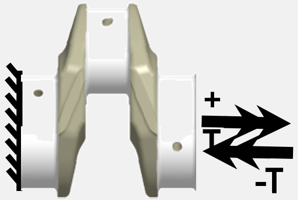
# 5. Bench Test

## Bench Torsion Test

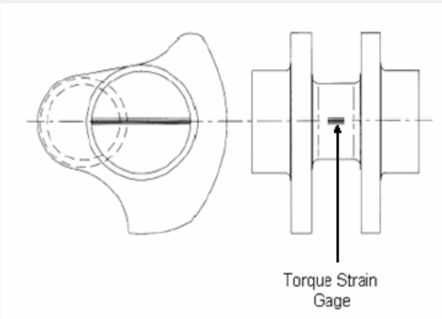


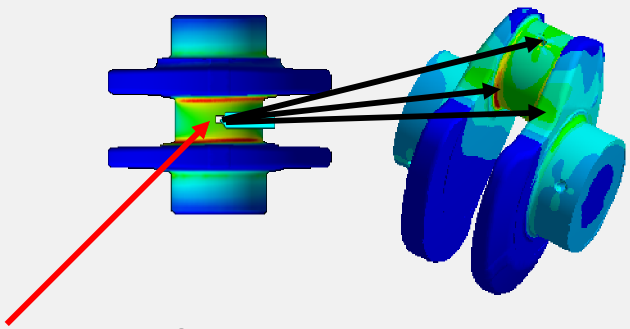



## Virtual Torsion Test




### Torsional Strain Gauge Position



**Max Principal Stress have excellent correlation with strain gauge measurement**

**Material Properties identification based on experimental tests with crankshafts under torsion load**

- Stair Case Method is applied for endurance limit evaluation
- 10 million cycles
- The stresses are measured in the bearings center by torque strain gauges
- Endurance limits are calculated for bearings fillets, webs and oil hole regions based on measured data and FEA results extrapolation
- The number of specimen tested in torsional stair cases is not enough to allow statistical treatment. Thus, the endurance limit is obtained from critical specimen result

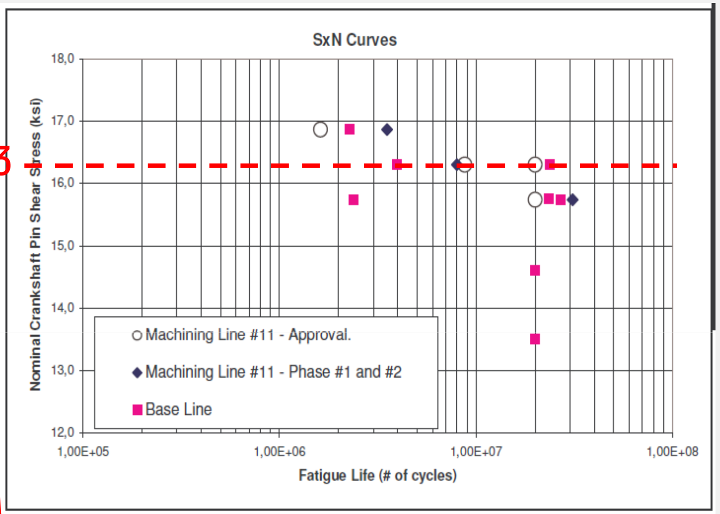
**Material Properties**

- SR: ultimate tensile strength
- SE: yield tensile strength
- E: Young's modulus
- Poisson
- NC and NL: number of load cycles
- SC and SL: endurance limits

**SN Methodology**

- PUC Criteria

# 5. Bench Test

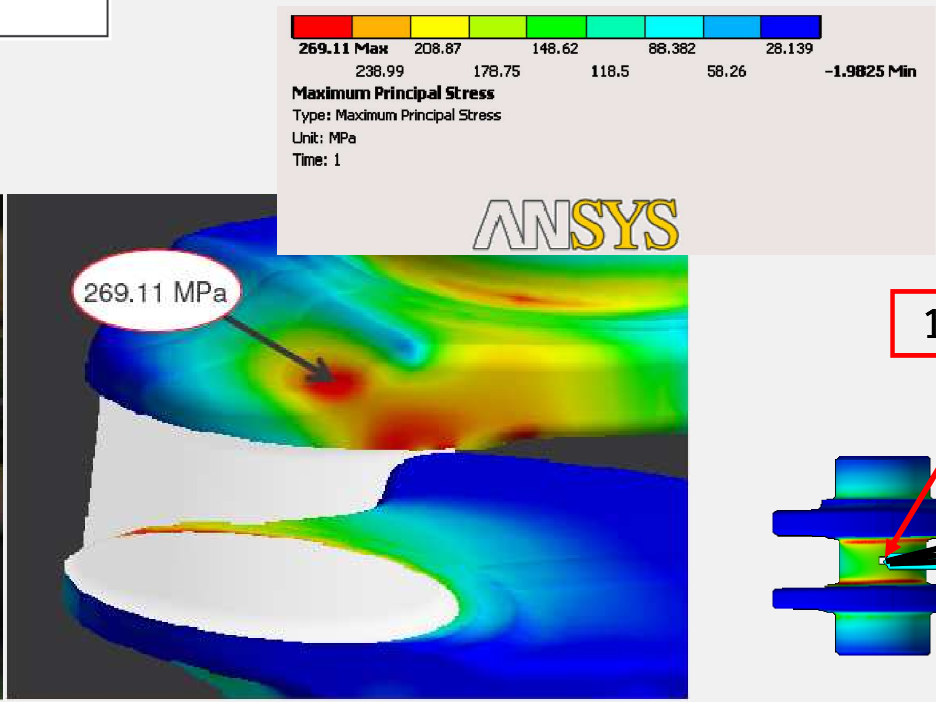


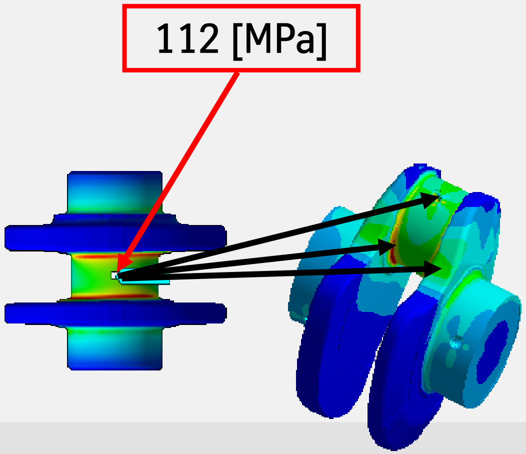

Endurance Limit (SC) for 1 million cycles (NC)

## Stair Case Method for Torsion

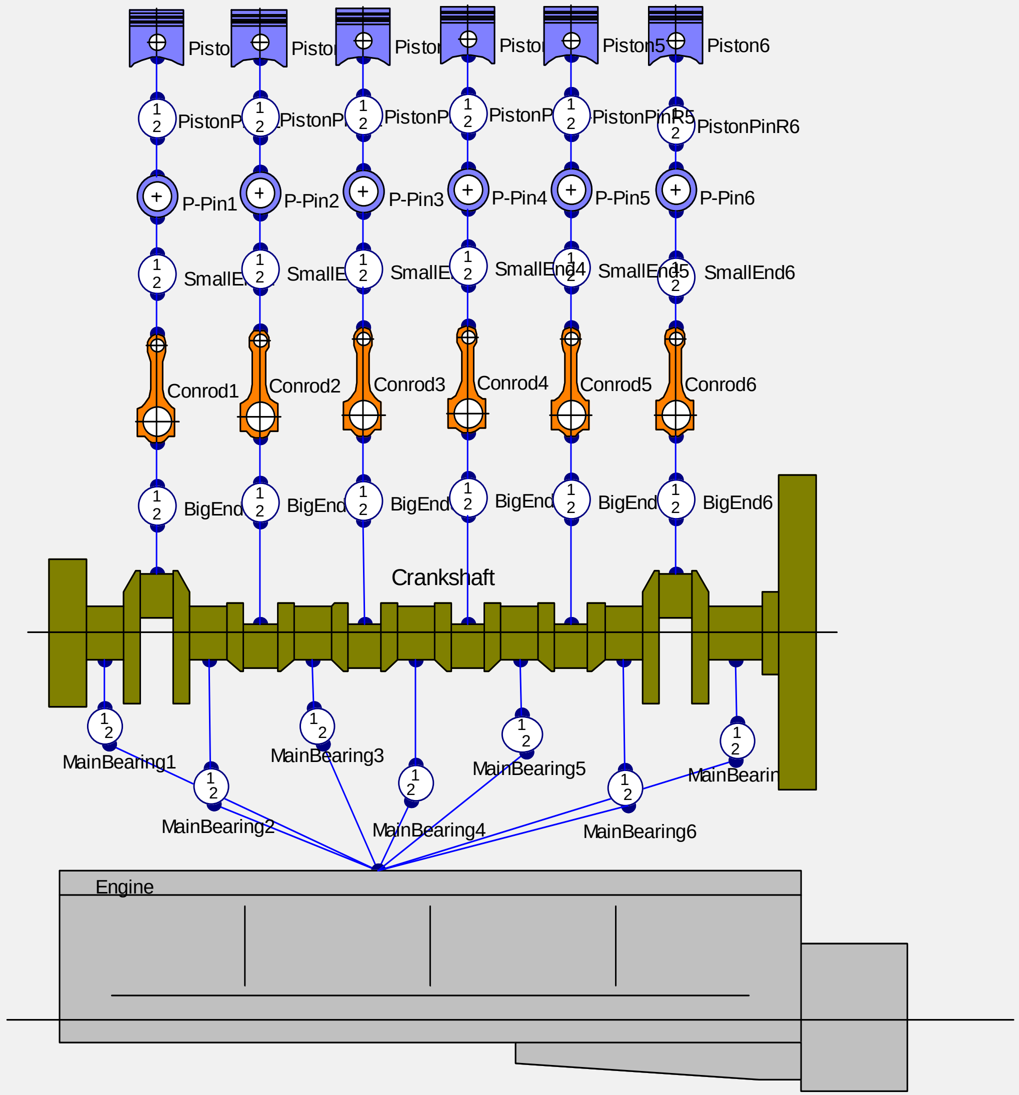
Endurance Limit (SL) for 10 million cycles (NL) @ strain gage

| PIN Journals # | Torsional Moment (KNm) | Nominal Crankshaft Pin Shear Stress | | # of cycles | Failure Location |
|---|---|---|---|---|---|
| | | ksi | MPa | | |
| 1:1 | 7,50 | 16,9 | 116,3 | 1.616.000 | Oil hole |
| 2:2 | 7,25 | 16,3 | 112,4 | 8.782.544 | Oil hole |
| 3:5 | 7,00 | 15,7 | 108,5 | 20.000.000 | - |
| 4:6 | 7,25 | 16,3 | 112,4 | 20.000.000 | - |

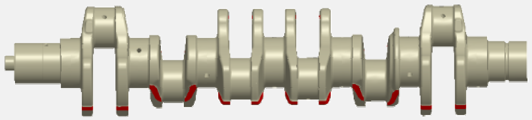


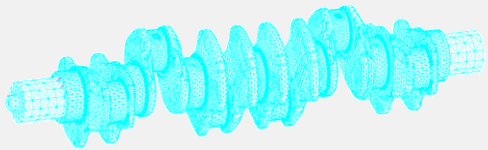
# 6. Dynamic Analysis



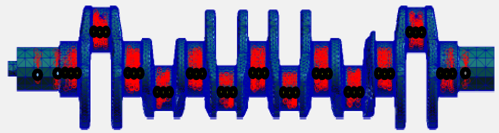
# 6. Dynamic Analysis



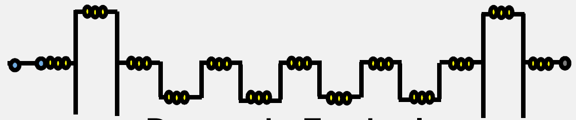
CAD Model



Modal analysis



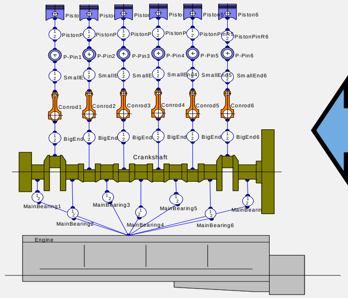
Master Nodes &
Rigid connections



Dynamic Equivalent
Substitute Model

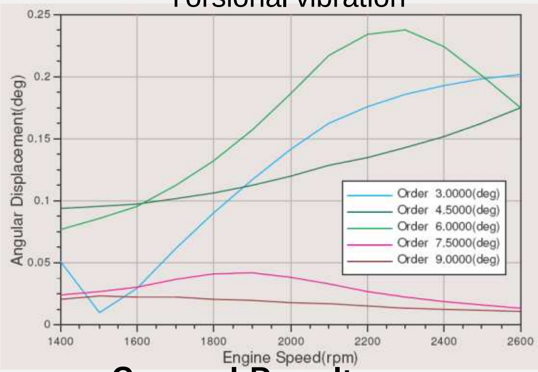
| Name | Size | Type |
|---|---|---|
| .job | | File Folder |
| Crankshaft.bdf | 19,108 KB | BDF File |
| Crankshaft_MFF.OUT4 | 8,184 KB | OUT4 File |
| Crankshaft.OUT4 | 1,174 KB | OUT4 File |
| Crankshaft_X2OA.OUT4 | 607,123 KB | OUT4 File |
| Crankshaft.MASTER | 2,080 KB | MASTER File |
| Crankshaft.OUT2 | 18,544 KB | OUT2 File |
| Crankshaft.DOFT | 2,599 KB | DOFT File |

Results from
sub structuring

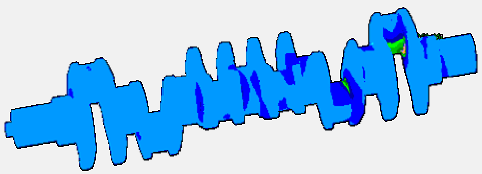


Dynamic Analysis
Joints Definition

Torsional vibration

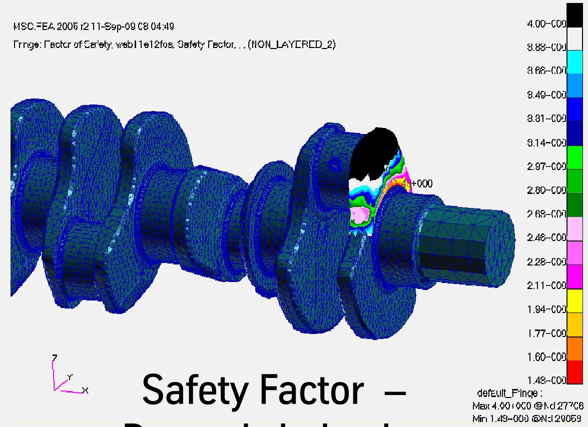



General Results –
Dynamic behavior



Max Principal
Stress

Stress Recovery –
Dynamic behavior



Safety Factor –
Dynamic behavior



ThyssenKrupp Forging Group

# 7. EFR Stress Theory
# Sorted Principal Fatigue Criteria

Sorted principal stress

- Calculate $\sigma_{1max}$ and $\sigma_{3min}$ over the engine cycle.
- Calculate mean and amplitude stress:

$$\sigma_a = \frac{(\sigma_{1\max} - \sigma_{3\min})}{2}, \ \sigma_m = \frac{(\sigma_{1\max} + \sigma_{3\min})}{2}$$

- Calculate EFR stress:

$$\sigma_{efr} = \frac{\sigma_a}{1 - \frac{\sigma_m}{\sigma_{tfs}}}$$

where $\sigma_{tfs}$ – true fracture strength, $\sigma_1$, $\sigma_2$, $\sigma_3$ – principal stresses.

* PIRANER ILYA et. all, *Cummins Crankshaft and Bearing Analysis Process*, North American MDI User Conference, 2002 18p.

# 7. EFR Stress Theory
# Equivalent von Mises Fatigue Criteria

Von Mises based EFR stress

- Calculate maximum and minimum for all individual components of the stress tensor.
- Calculate amplitude for all individual stress components and the average hydrostatic pressure $\sigma_p$ over the engine cycle.
- Combine the amplitudes of the stress components in the Von Mises amplitude stress:

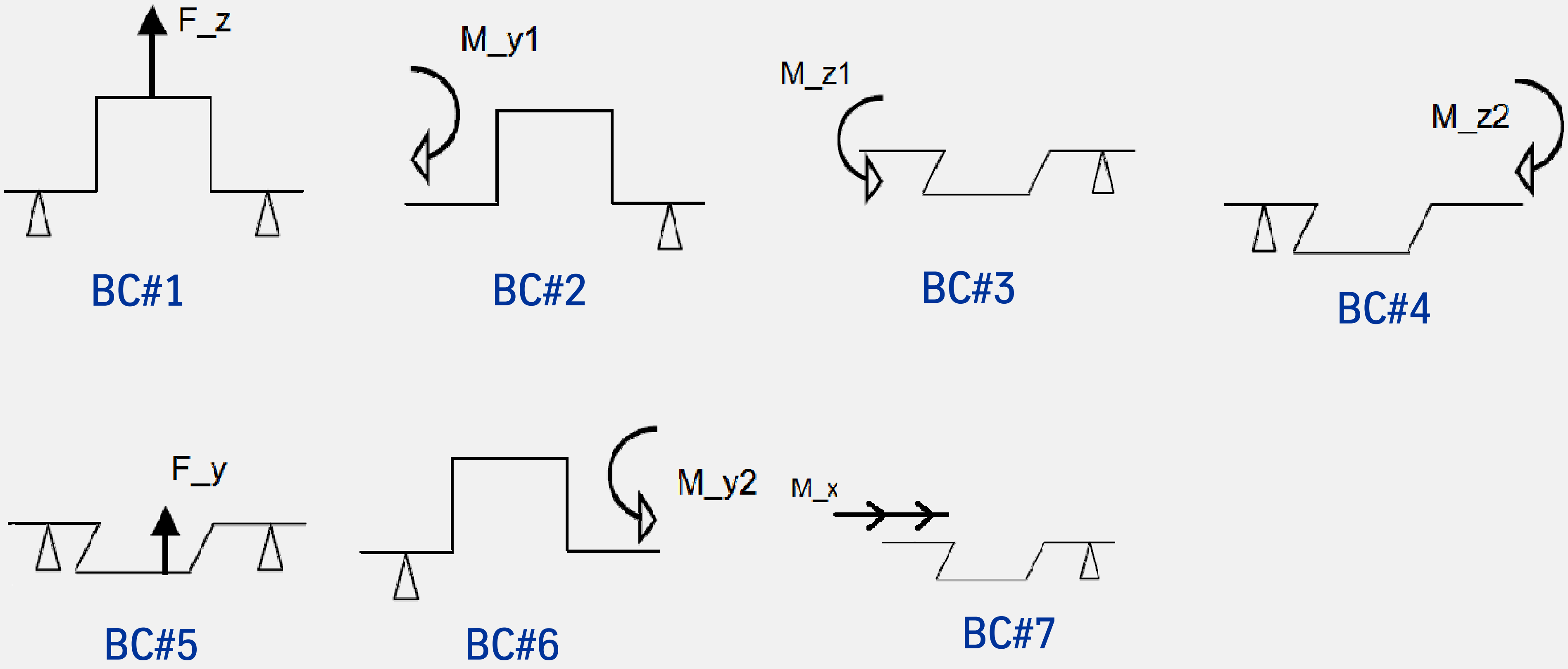
$$\sigma_{ae} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_{a1} - \sigma_{a2})^2 + (\sigma_{a2} - \sigma_{a3})^2 + (\sigma_{a3} - \sigma_{a1})^2}$$

- Calculate EFR stress:

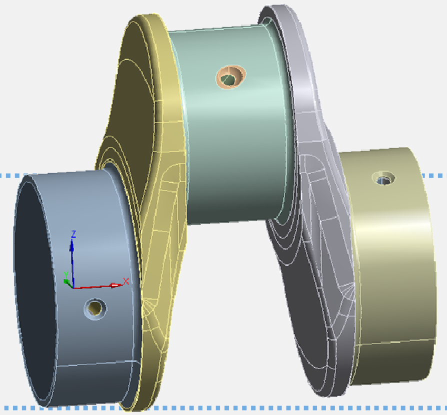
$$\sigma_{efr} = \frac{\sigma_{ae}}{1 - \frac{\sigma_p}{\sigma_{tfs}}}$$

* PIRANER ILYA et. all, *Cummins Crankshaft and Bearing Analysis Process*, North American MDI User Conference, 2002 18p.

# 8. Dynamic Results
# Crankpin forces (1/3 of total load)

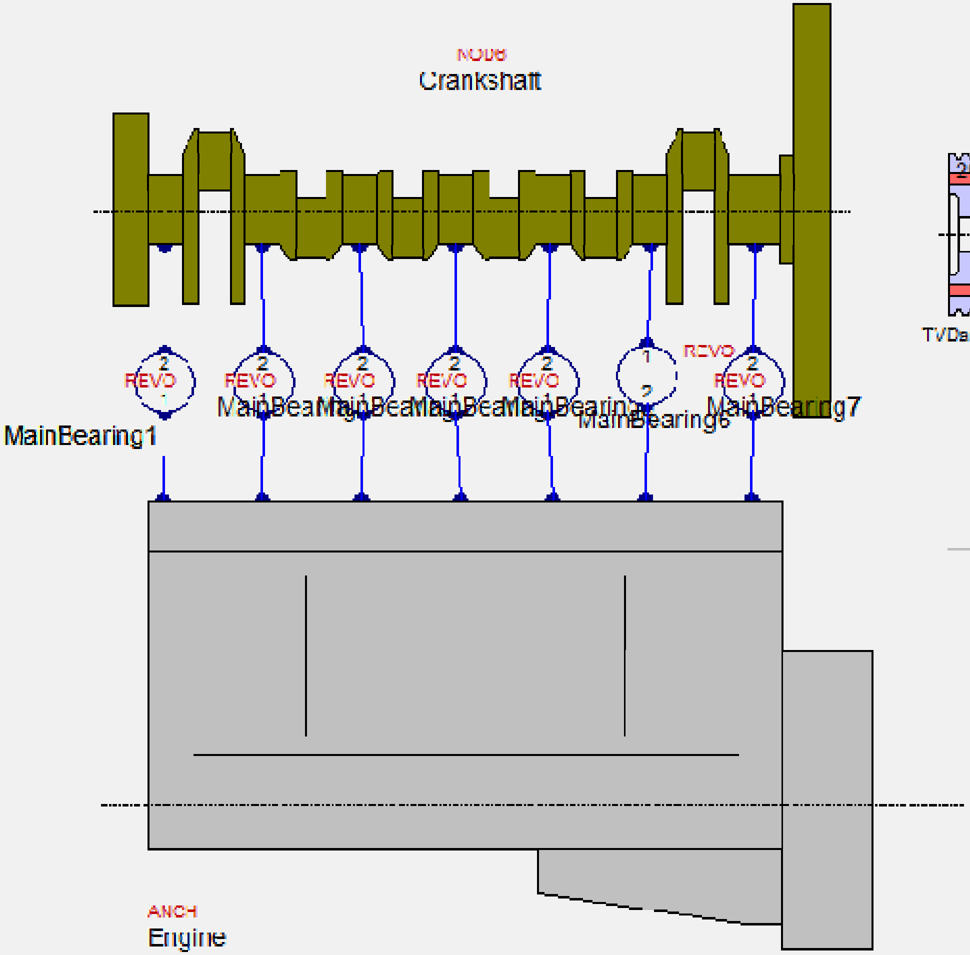


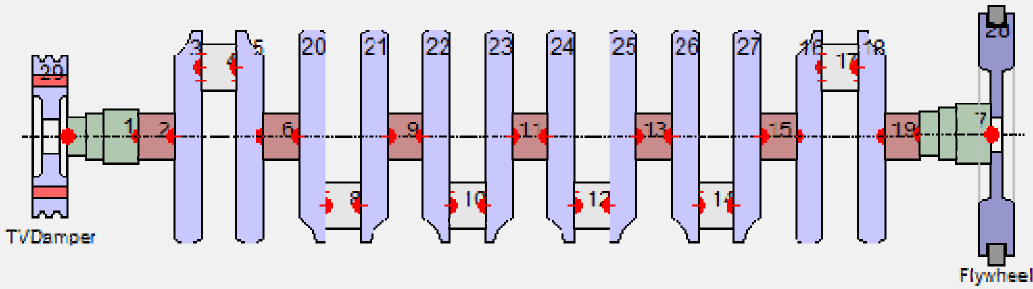
# 9. Unit Load Static Results
# Equivalent von Mises stress

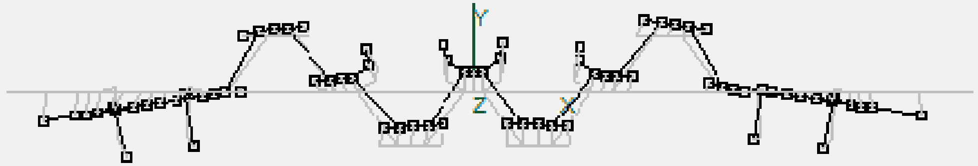


| | von Mises Stress |
|---|---|
| **Force Boundary Condition** | |
| o Fz | 0.42 MPa/kN |
| o Fy | 0.70 MPa/kN |
| **Moment Boundary Condition** | |
| o My1 | 0.087 MPa/Nm |
| o My2 | 0.087 MPa/Nm |
| o Mz1 | 0.044 MPa/Nm |
| o Mz2 | 0.044 MPa/Nm |
| o Mx | 0.021 MPa/Nm |
| **Counter Weight Boundary Condition** | |
| o CW1 | 9 MPa/kN |
| o CW2 | 9 MPa/kN |

# 10. Dynamic Analysis
# AVL Model NOD6 crankshaft (Shaft Modeler)



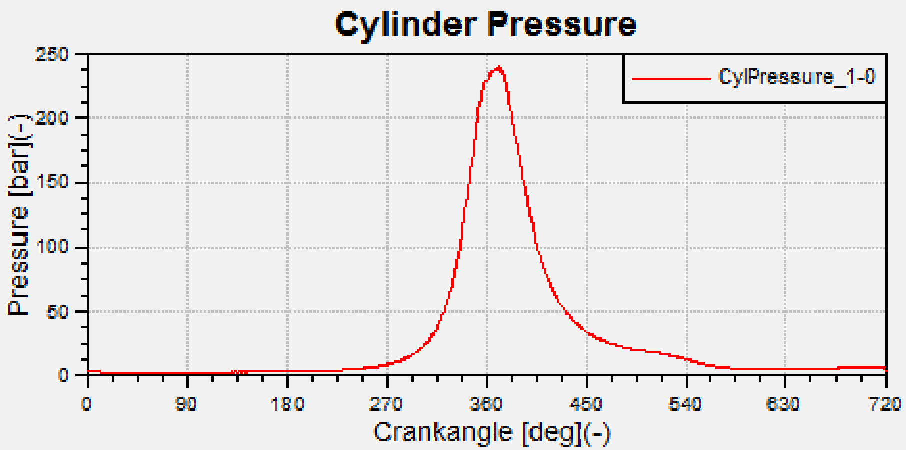



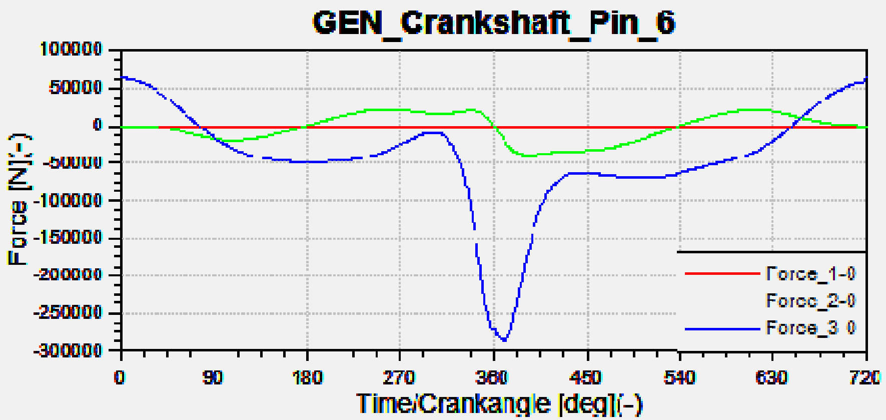



**Mode Browser**

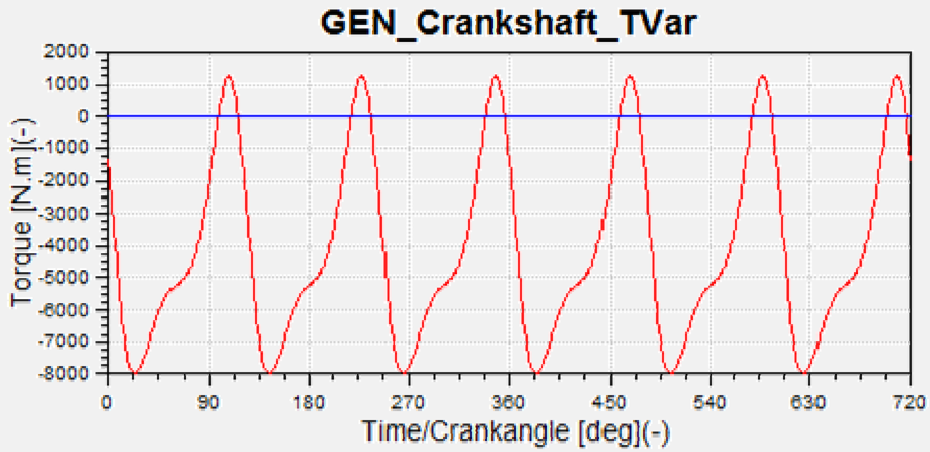
| Mode | Freq. [Hz] | Dominant | %Torsion | %Tension | %Bending |
|---|---|---|---|---|---|
| 7 | 102.14 | bending | 0.0 | 0.9 | 99.0 |
| 8 | 119.37 | bending | 0.0 | 1.1 | 98.9 |
| 9 | 279.98 | bending | 2.3 | 2.5 | 95.2 |
| 10 | 292.67 | bending | 0.1 | 27.9 | 72.0 |
| 11 | 340.32 | tension | 1.5 | 57.7 | 40.7 |
| 12 | 395.14 | torsion | 74.8 | 3.8 | 21.4 |
| 13 | 502.54 | bending | 2.9 | 16.9 | 80.2 |
| 14 | 553.21 | tension | 3.2 | 56.6 | 40.2 |

# 11. Dynamic Analysis
# Input Loads



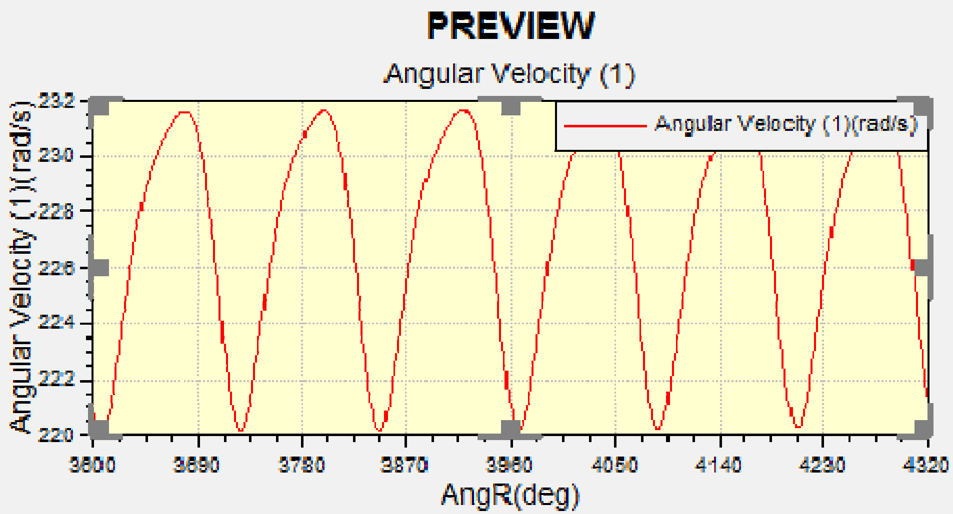



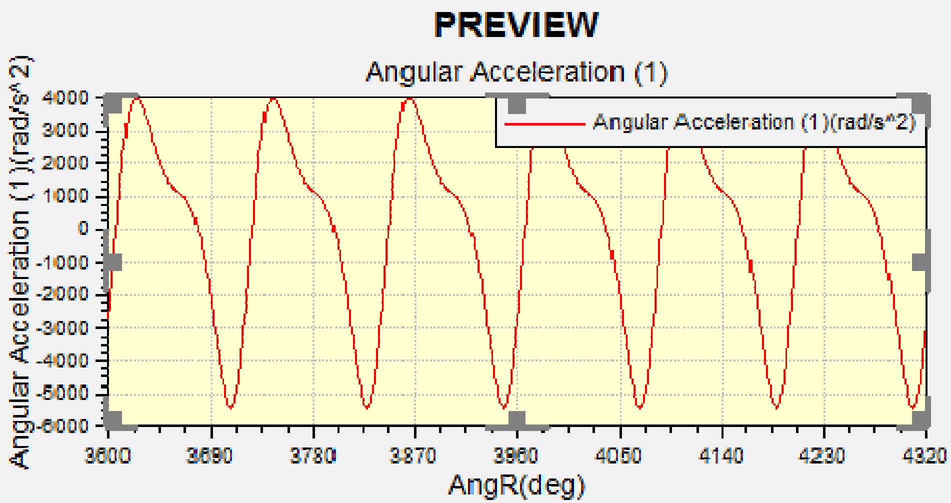

| Min Y | at X | Max Y | at X | Mean Y (arith.) |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| -39546.0 | 395 | 21507.6 | 256 | -2351.79 |
| -288844 | 370 | 63147.3 | 0 | -44026.6 |



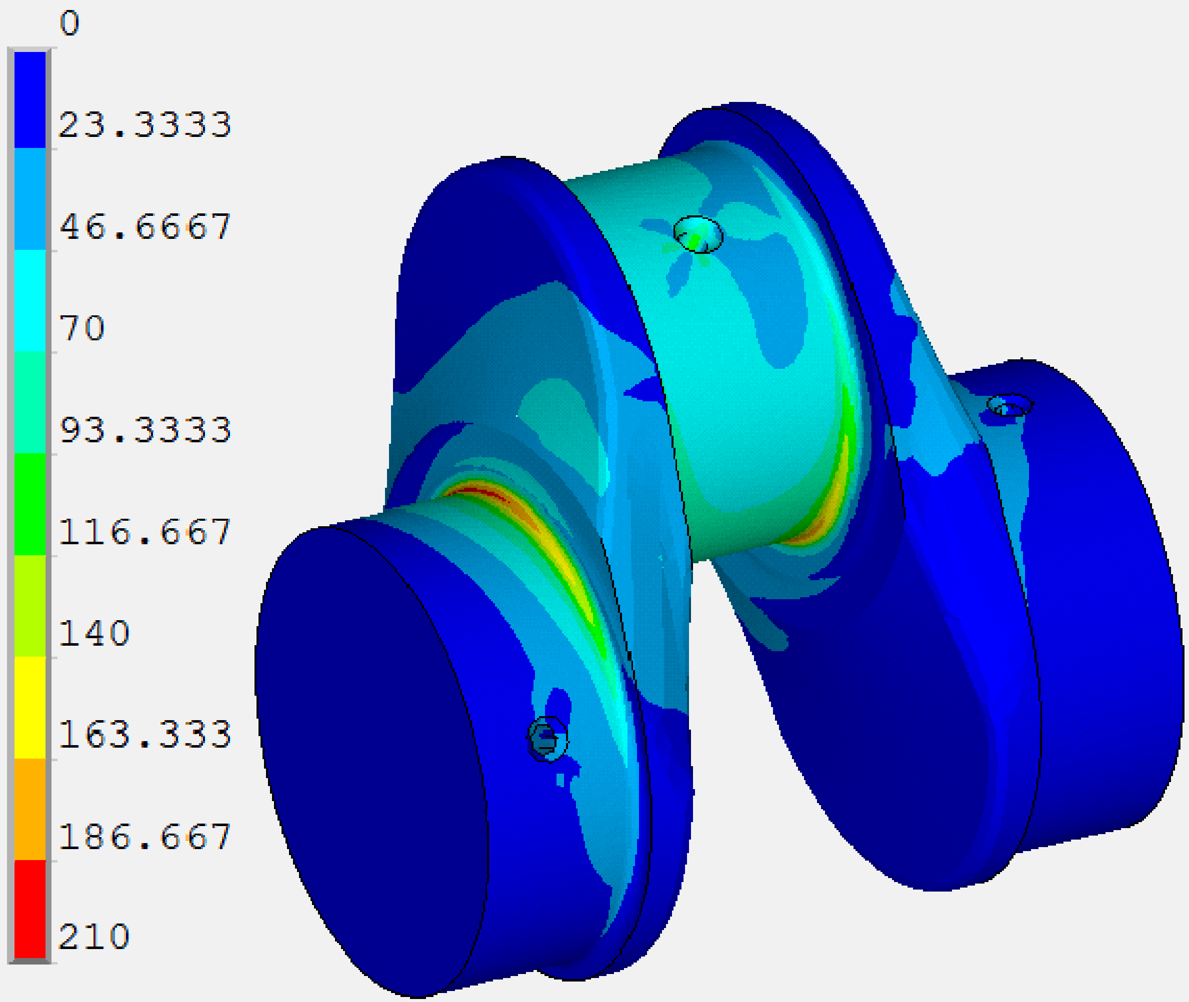

| Min Y | at X | Max Y | at X | Mean Y (arith.) |
|---|---|---|---|---|
| -7980.19 | 505 | 1264.79 | 468 | -4078.82 |

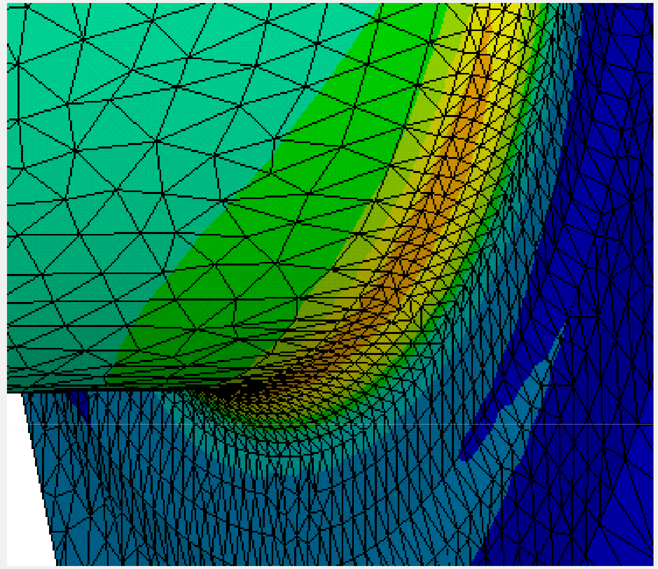
# 12. Dynamic Results
# Crankshaft angular velocity and acceleration

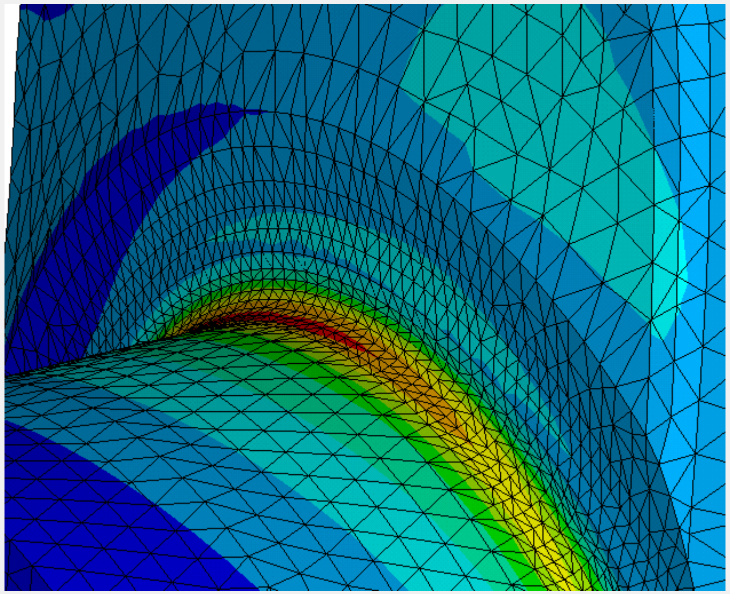


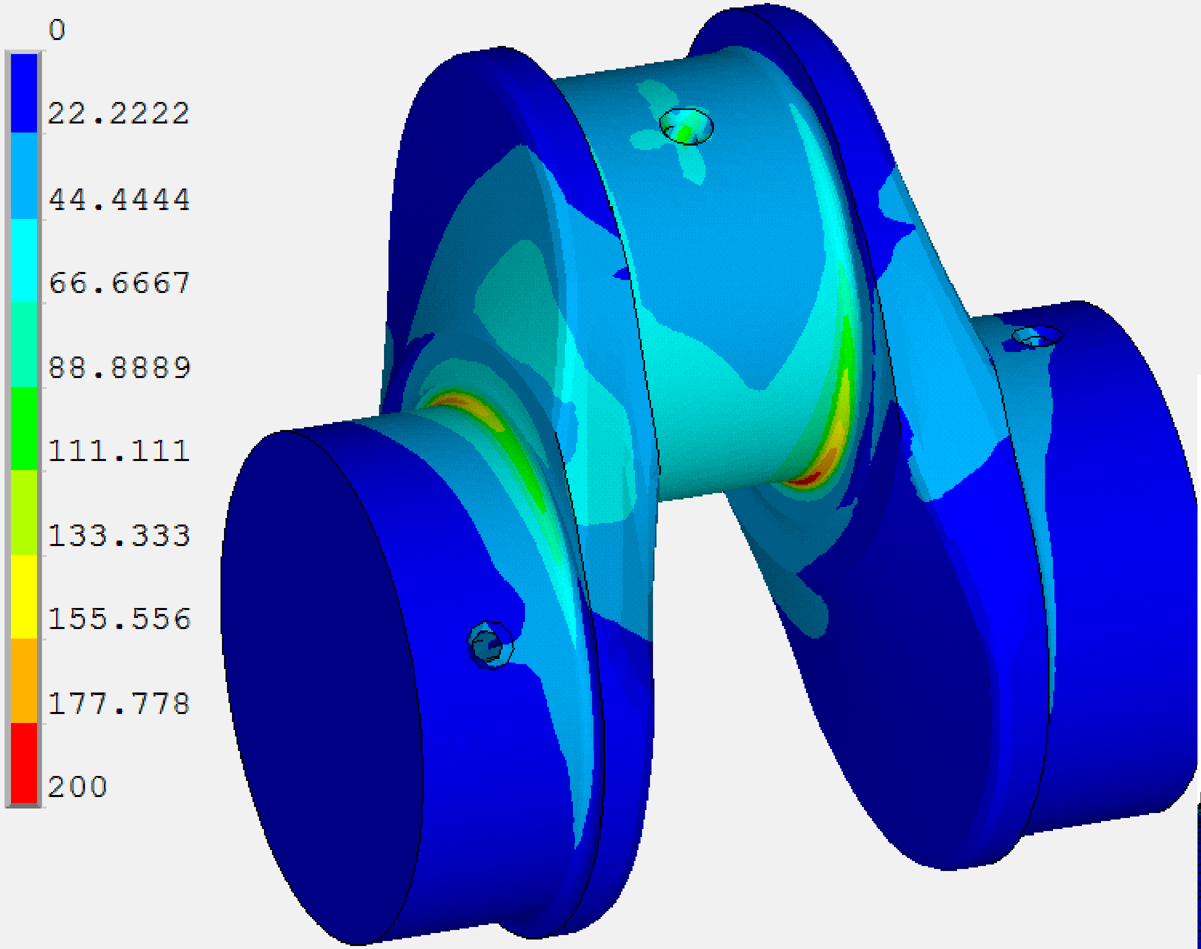
# 13. Fatigue Analysis
## Von Mises EFR Stress

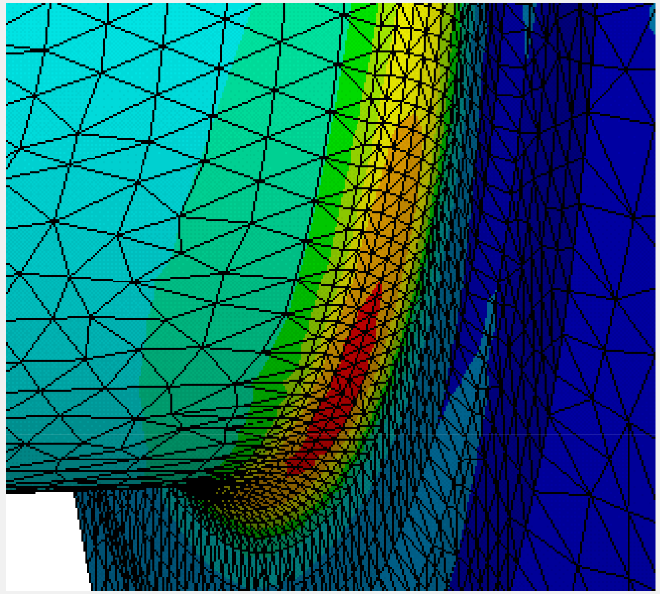


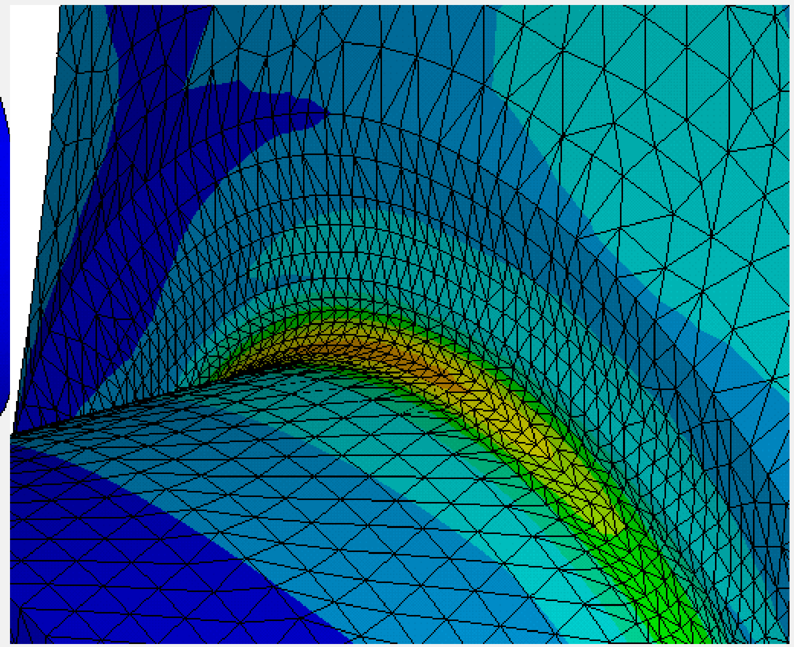





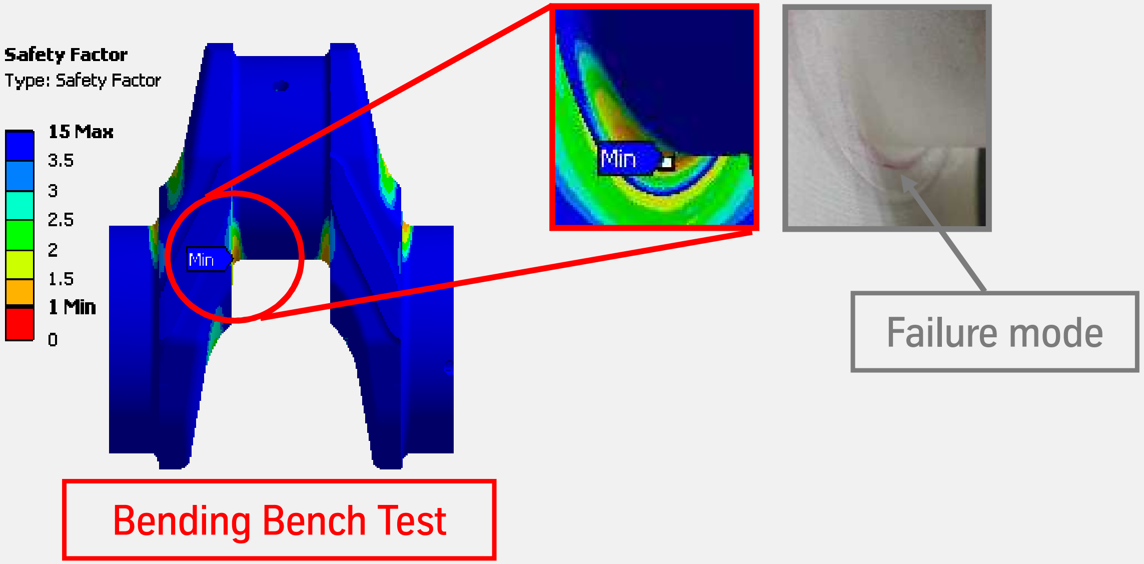
# 14. Fatigue Analysis
# Sorted Principal EFR Stress

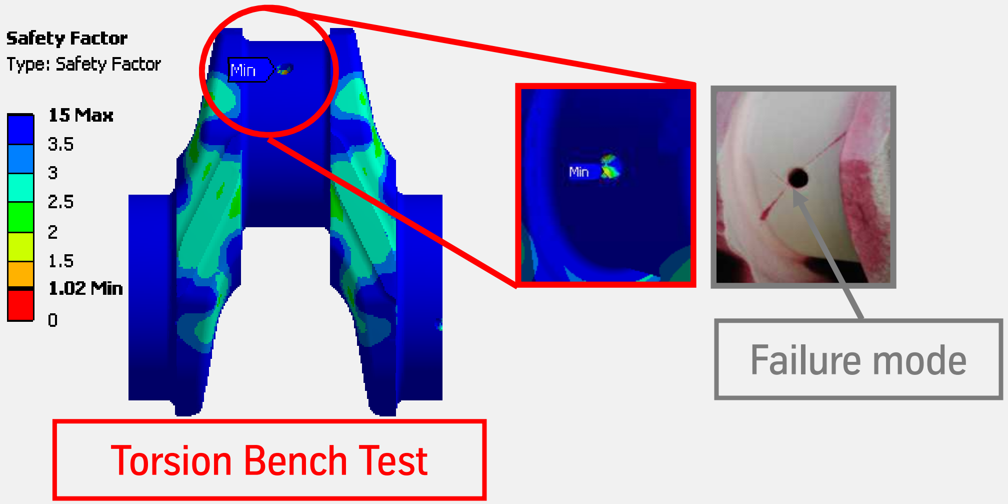


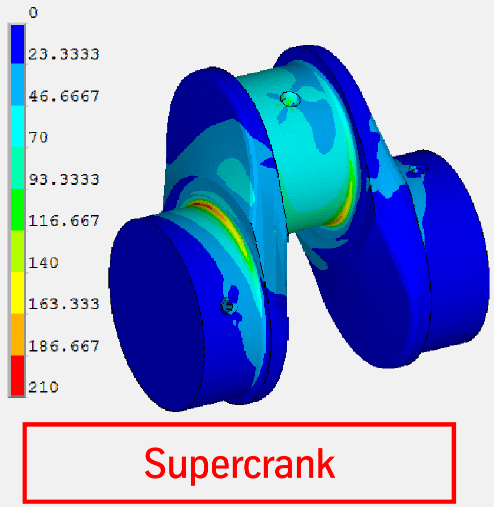



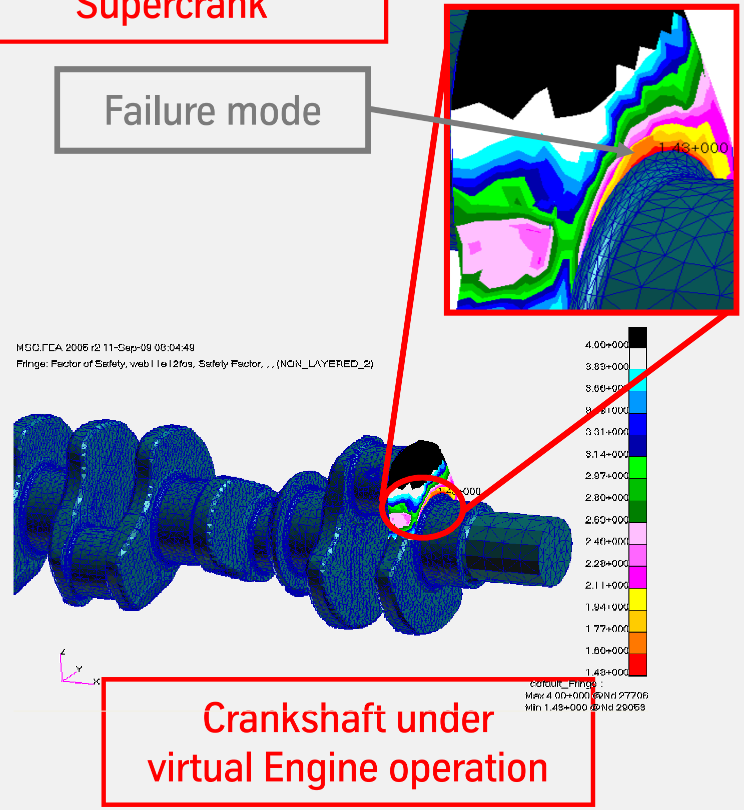


# 15. Conclusion



# 16. Final

Thank you!

Obrigado!

Danke schön!