Structural Optimization of a Four-Stroke Engine Connecting Rod: From High-Fidelity FEM Simulation to Artificial Intelligence

Department of Enterprise Engineering
Bachelor's Degree in Mechanical Engineering
Academic Year 2023/2024

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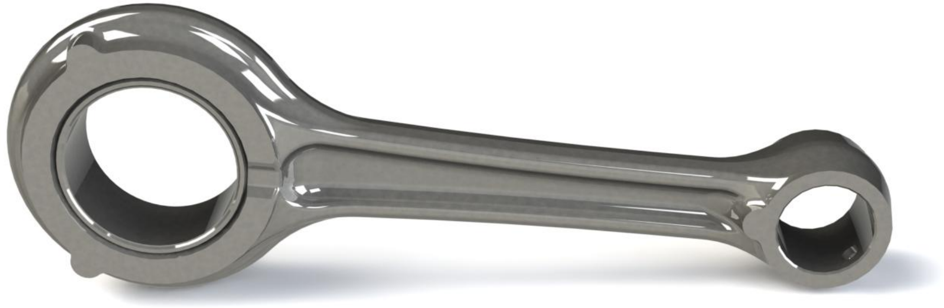
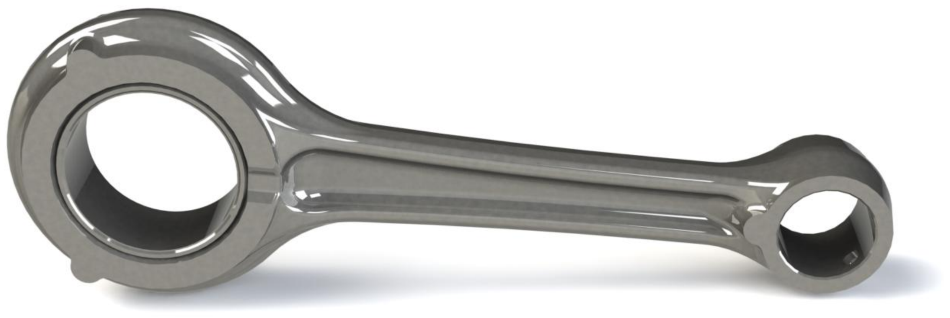
Thesis Objectives

- Two Optimization Campaigns
  - Stress reduction with constant weight
    - Unaltered engine dynamics
    - Increased safety factors and fatigue life
  - Weight reduction with constant stress
    - For a complete redesign from scratch
    - Lower emissions
- Development of a static ROM
  - Fast results
  - Reliable results



Materials

- Connecting Rod and Bearing Shell from Aprilia SR GT Scooter
- Engine: 4-stroke single-cylinder
  - 125 cc
  - Max Power: 11kW at 8900 RPM
  - Max Torque: 12 Nm at 6750 RPM
  - Max RPM: 10600 RPM
- Material: Shot-peened quenched and tempered 42CrMo4 steel
  - Yield Strength: 650 MPa
  - Ultimate Tensile Strength: 1000 MPa

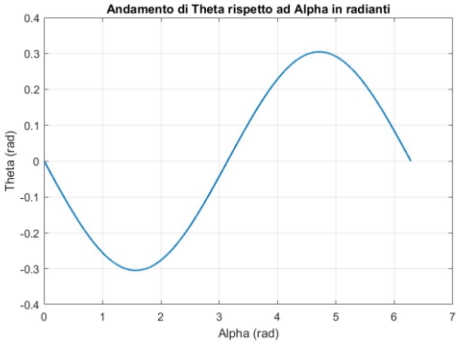


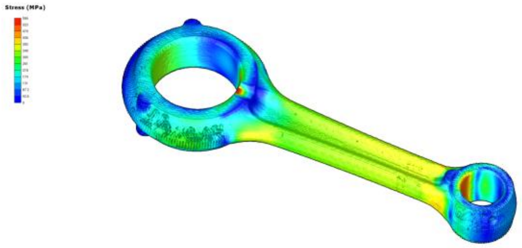
Methods

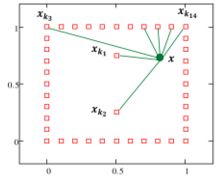
- Kinematic analysis using loop-closure equations and dynamic analysis (MATLAB)
- Finite Element Analysis (Ansys Workbench)

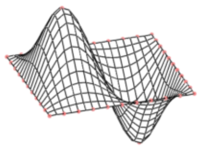
- Optimization
  - RBF-based mesh morphing (Ansys RBF Morph add-on)
  - Design of Experiments (Ansys DesignXplorer)
  - Geometry reconstruction (SolidWorks - Power Surfacing)

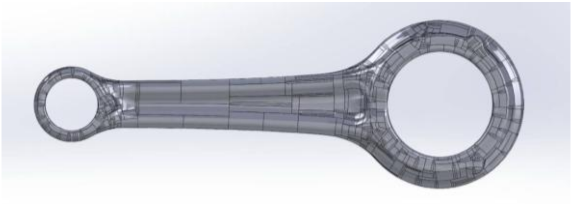
- Reduced Order Model (Ansys Twin Builder – Static ROM Builder)





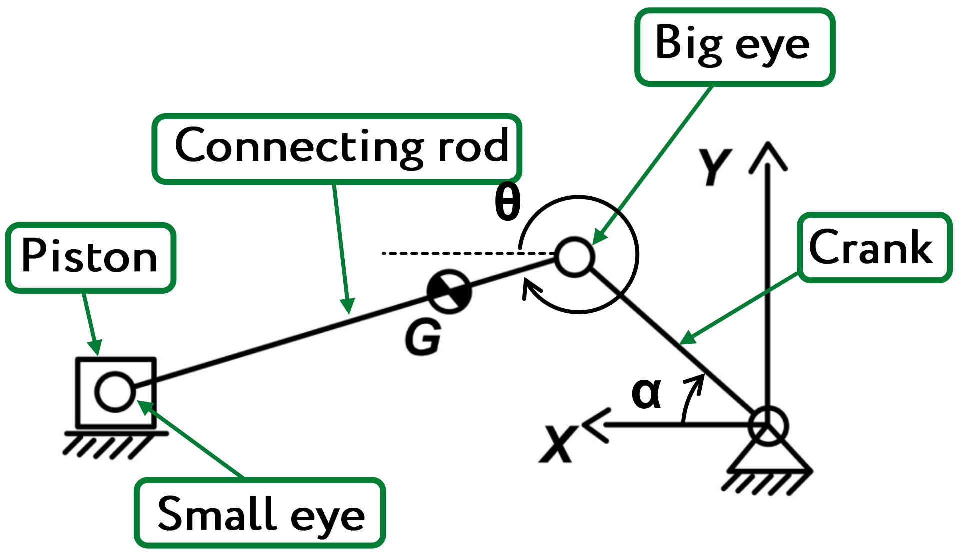






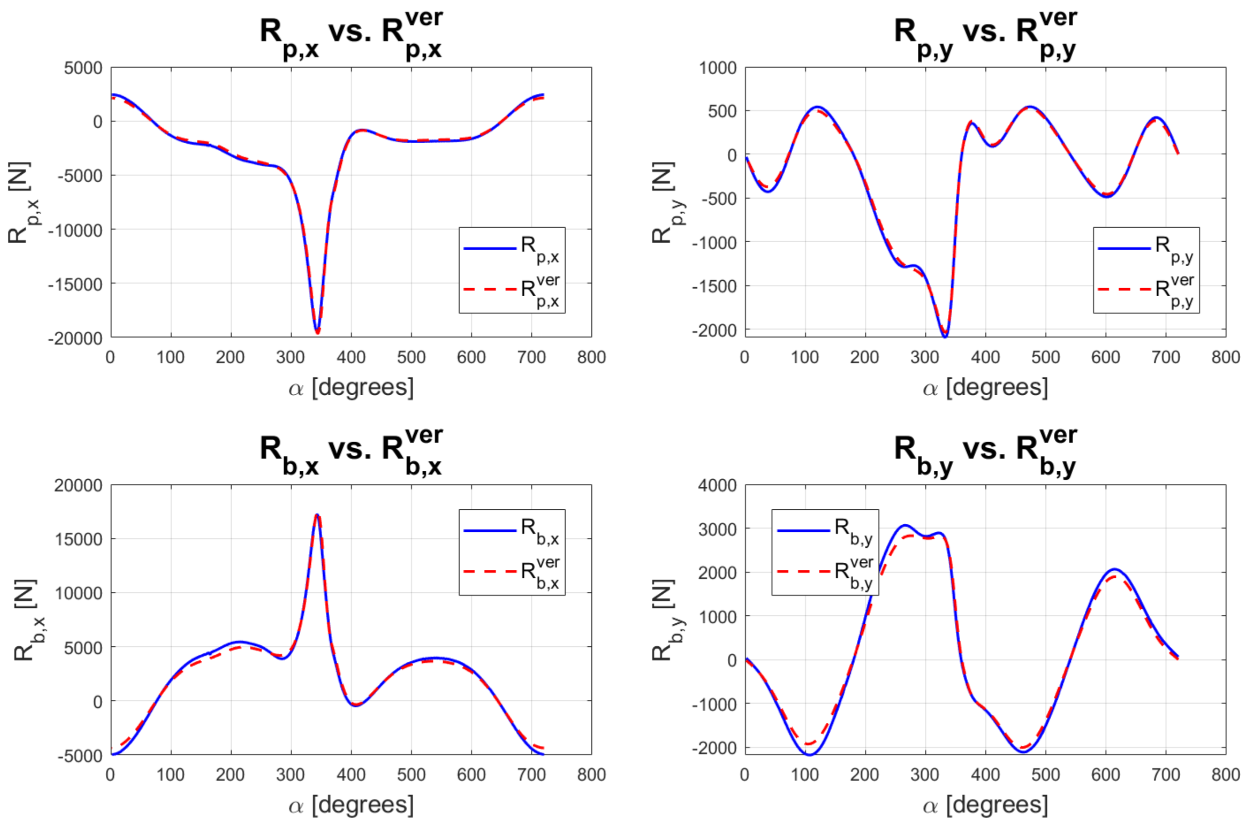
Slider-Crank Mechanism Analysis

- Kinematic Analysis
- Dynamic Analysis



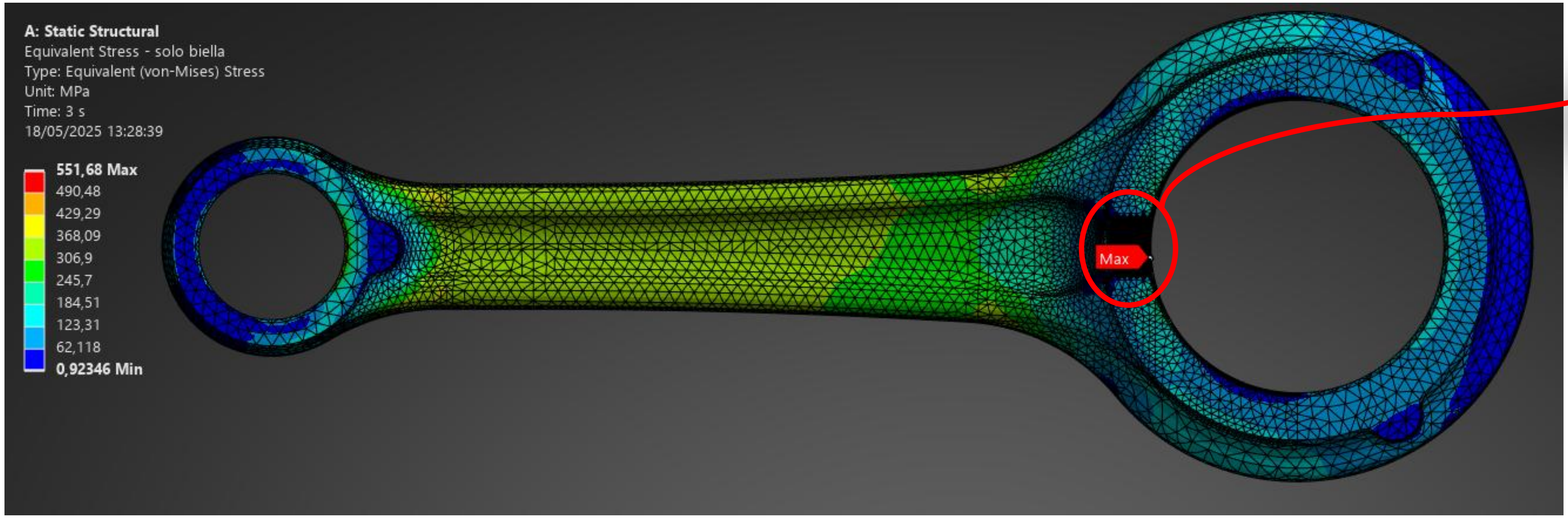
- Comparison with multi-body model ADAMS

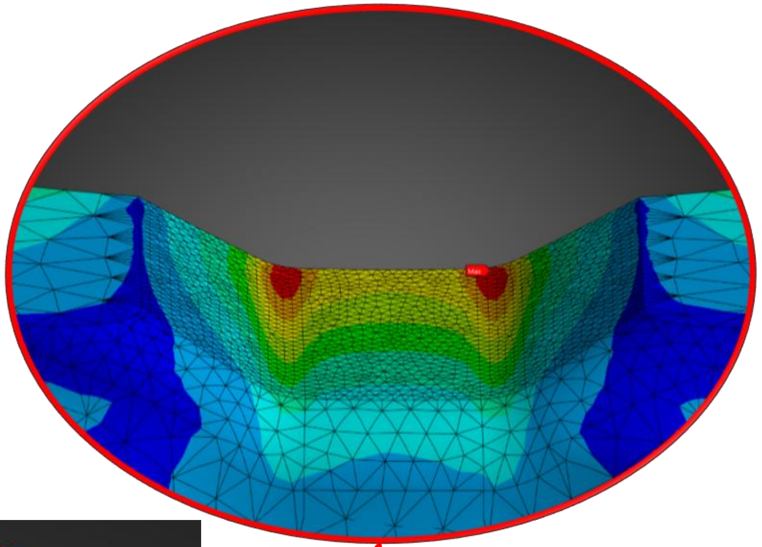
Comparison of dynamic reactions: provided vs. verified at 6500 RPM



Structural Analysis baseline

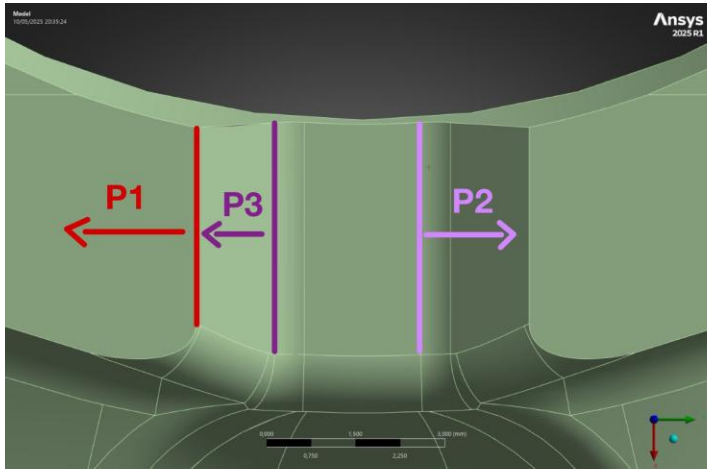
- Most onerous load condition:
  - Maximum pressure
  - 6500 RPM, $\alpha=344.7°$, $\theta=4.5°$

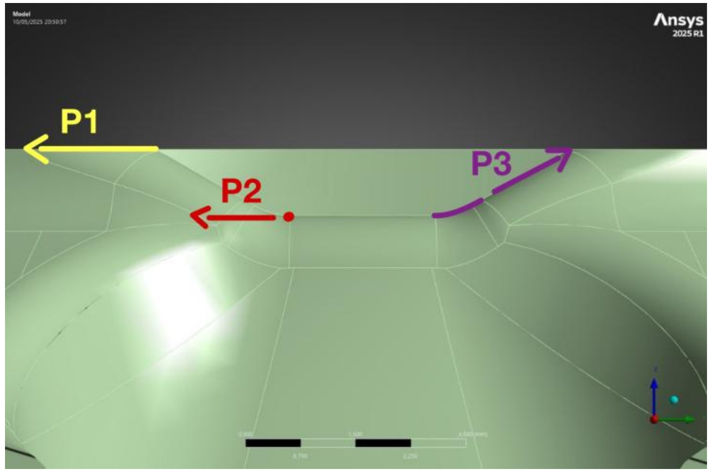




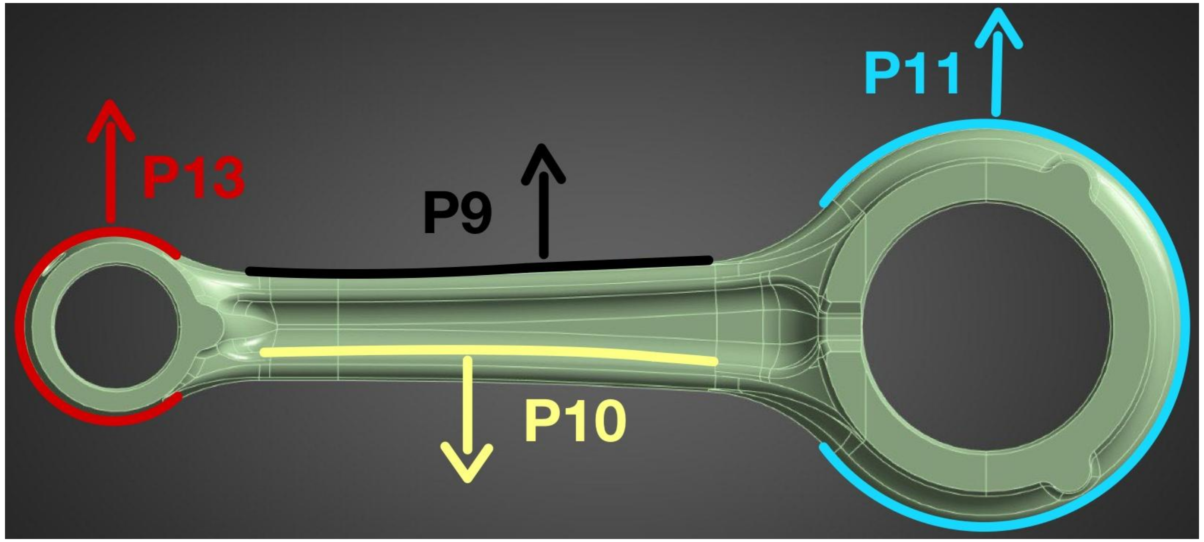
Mesh morphing

- 7 parameters:
  - 3 under the big eye





  - 2 on the connecting rod shank
  - 1 on the big eye
  - 1 on the small eye



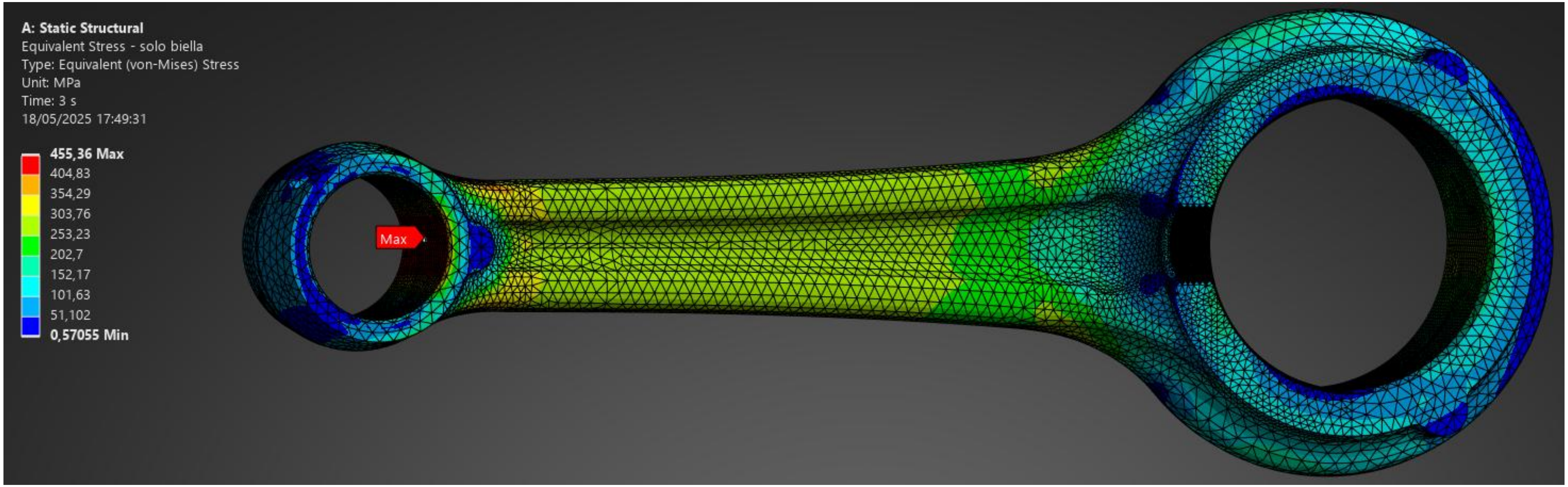
Optimization

- 103 DP generated with *Latin Hypercube Sampling* (DoE)
- 2 optimization campaigns :
  - First campaign:
    - Von Mises minimization on the connecting rod body
    - Maximum volume variation of ±40 mm3
    - Maximum variation of the centroid displacement of ±2 mm → Commands (APDL)
  - Second campaign:
    - Volume minimization
    - Maximum Von Mises stress below 551 MPa

Results of the first optimization

DP	P1	P2	P3	P9	P10	P11	P13
113	1.239	0.787	-0.087	1.102	0.781	0.995	0.954
119	1.218	0.765	-0.146	1.003	0.900	0.903	0.952

DP	σ_{VM} [MPa]	V_{tot} [mm^3]	$\Delta\sigma$ [MPa]	$\Delta\sigma$ [%]	ΔV [%]	Δx_G [mm]
113	455.4	18016.4	-95.6	-17.4	0.9	-0.6
119	542.0	14110.9	-9.0	-1.6	-21.0	4.4



Results of the second optimization

DP	P1	P2	P3	P9	P10	P11	P13
113	1.239	0.787	-0.087	1.102	0.781	0.995	0.954
119	1.218	0.765	-0.146	1.003	0.900	0.903	0.952

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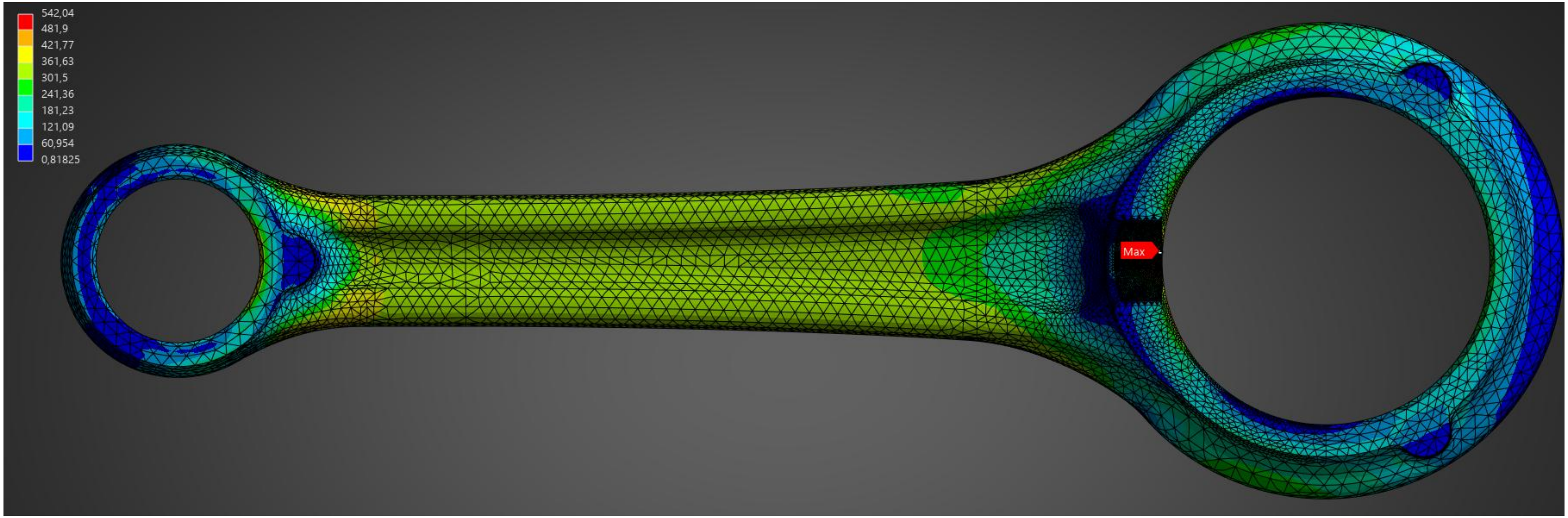


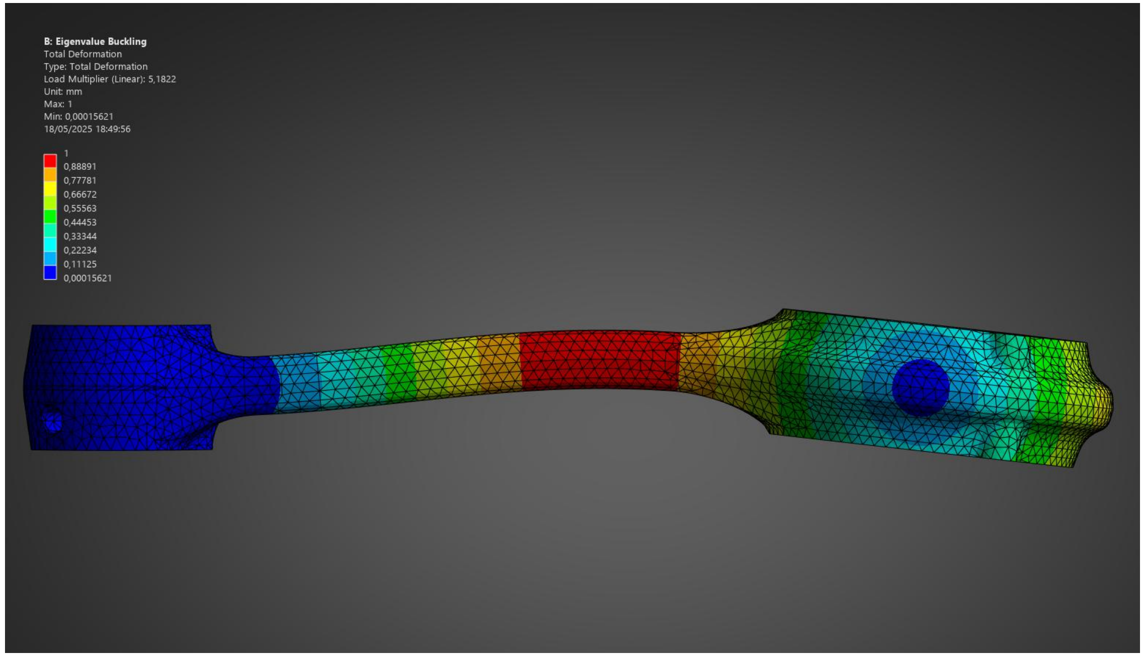
Dynamic verification

- With Power Surfacing, the solid geometry was regenerated and the following was recalculated:
  - Moment of inertia along the z-axis.

- Using MATLAB code, the reaction forces for DP119 were recalculated → variation of 1 MPa.

Buckling analysis

- Analysis with various constraint conditions
- Multiplicative coefficients of the loads always greater than one

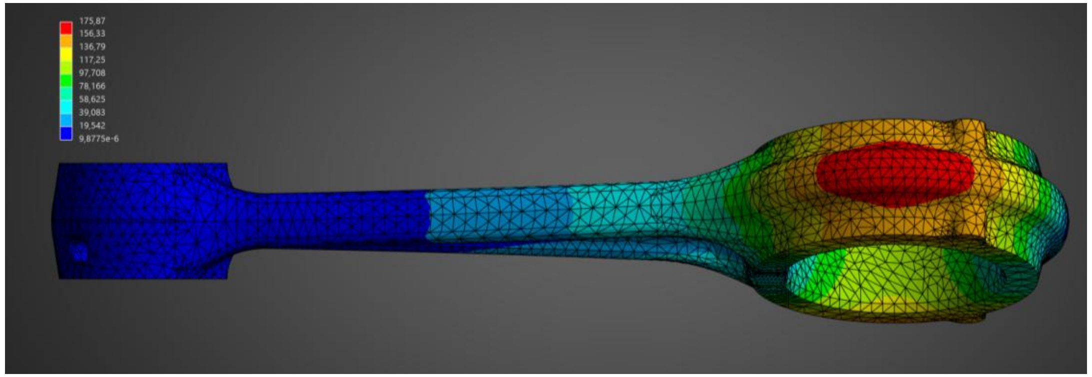


DP	Big eye	$\theta(^\circ)$	λ_1	λ_2
Baseline	Simple hinge	0	6.0127	14.437
113	Simple hinge	0	6.949	16.772
119	Simple hinge	0	4.630	12.696
Baseline	Simple hinge	-4.5	6.000	14.428
113	Simple hinge	-4.5	6.932	16.762
119	Simple hinge	-4.5	4.623	12.693
Baseline	Spherical hinge	-4.5	5.182	6.000
113	Spherical hinge	-4.5	6.248	6.933
119	Spherical hinge	-4.5	4.622	4.862

Modal analysis

- Analysis with various constraint conditions
- The first natural frequencies do not deviate much from the baseline results and are still greater than the crank frequency.

$$f_{\text{crank}} = \frac{10600}{60} = 176.67\,\text{Hz}$$



DP	Big eye	$\mathbf{f_{n1}}$ [Hz]	$\mathbf{f_{n2}}$ [Hz]
Baseline	Simple hinge	2423.00	6497.70
113	Simple hinge	2641.50	6401.00
119	Simple hinge	2349.10	6178.90
Δf_{nMAX} %		9.02	-4.91
Baseline	Spherical hinge	727.88	2073.50
113	Spherical hinge	860.99	2209.50
119	Spherical hinge	876.81	2242.50
Δf_{nMAX} %		-20.26	8.15

Reduced order model (ROM)

- Proper Orthogonal Decomposition (POD) ⟶ Singular Value Decomposition (SVD)
- SVD:

$$\mathbf{M}_{m\times n} = \mathbf{U}_{m\times j} \cdot \mathbf{\Sigma}_{j\times j} \cdot \mathbf{V^T}_{j\times n}$$

  - With matrix $\mathbf{M}$ having the snapshots of the training set as columns
  - $\mathbf{U}$ and $\mathbf{V}$ orthonormal matrices for which : $\mathbf{U}^T \cdot \mathbf{U} = \mathbf{V}^T \cdot \mathbf{V} = \mathbf{I}_{j\times j} \quad \mathbf{U} \cdot \mathbf{U}^T = \mathbf{I}_{m\times m}$
  - $\mathbf{\Sigma}$ diagonal matrix containing the singular values σ of the matrix $\mathbf{M}$

- Low-rank approximation of $\mathbf{M}$: $\mathbf{M}_r = \sum_{i=1}^{r} \sigma_i \mathbf{u}_i \mathbf{v}_i^T$

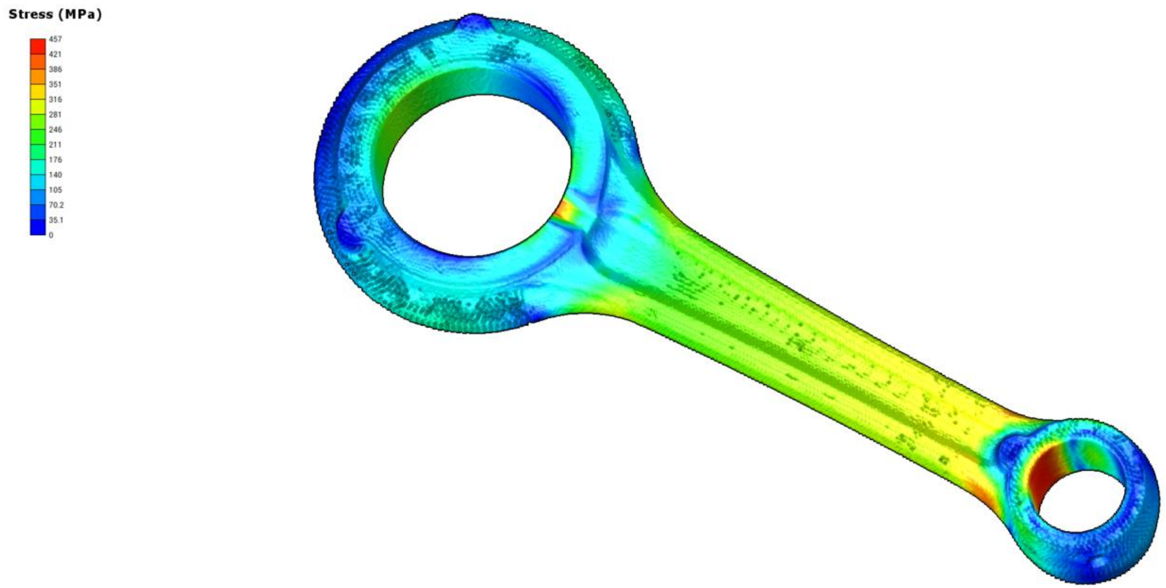
- The solution field can be approximated as a linear combination of the first *r* modes:

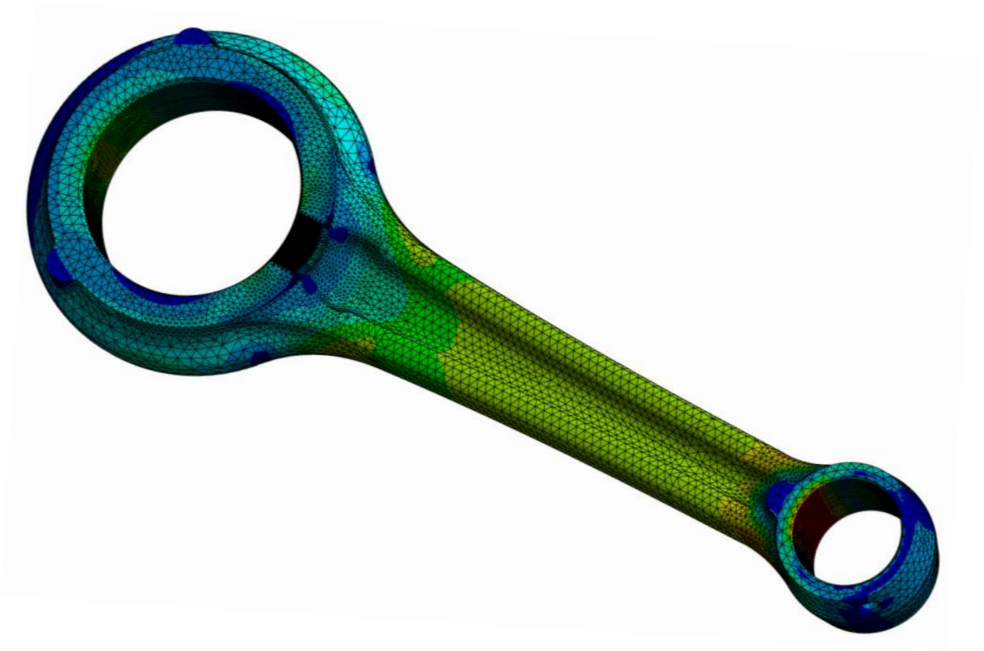
$$\mathbf{x} = \sum_{i=1}^{r} \alpha_i \mathbf{u_i}$$

ROM results

- 20 modes
- 80% training set, 20% validation set
- Maximum percentage error of the ROM: 7%

	σ_{VM} FEM (N)	σ_{VM} ROM (N)	$\Delta\sigma_{VM}$ [%]
DP113	455.36	456.52	-0.26
DP119	542.04	566.00	-4.42

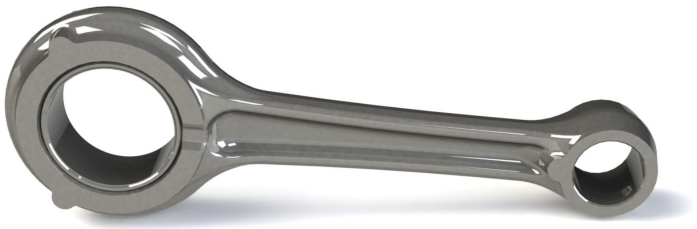




Conclusions and future developments

- **First optimization**: 17.4% reduction in maximum stresses
- **Second optimization**: 21% reduction in mass
- The components were lightened while maintaining structural reliability and preserving dynamic performance.

- A **multi-objective** optimization could be performed by identifying the Pareto front or by finding a compromise solution through interaction with the ROM.
- Future perspectives include the integration of the ROM model within **augmented reality** tools. This approach would enable direct and intuitive interaction with the structural behavior of the component.



Thank you for your attention

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