Stress mitigation of a thermal engine head block using the bioinspired BGM-FEM method

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Introduction

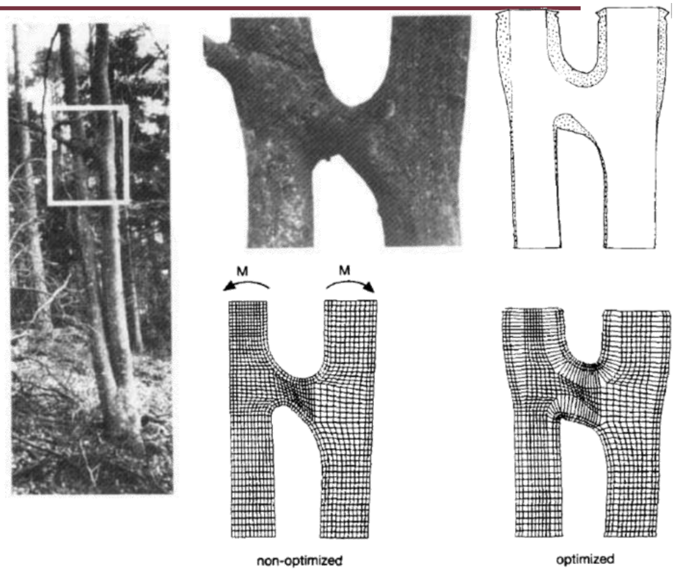
- The design and development of engine head blocks for internal combustion engines (ICE) demands meticulous attention to both the thermal and structural aspects
- extreme operating conditions, including high temperatures, pressure differentials, and mechanical stresses
- To address these challenges and enhance the design process, the integration of thermo-structural simulation techniques has become indispensable
- Advanced simulation techniques that not only integrate thermal and structural analysis, but also optimisation methods, have become essential tools for engineers

Introduction

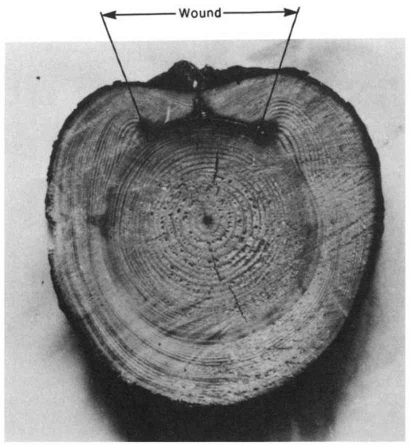
- In this work a novel procedure for the thermo-structural optimization of engine head blocks is presented, using the Biological Growth Method (BGM) in combination with RBF mesh morphing
- Simulations were carried in the framework of the ANSYS Mechanical FEA solver, using as RBF morpher the commercial tool RBF Morph
- By mimicking the growth processes observed in biological organisms, the BGM provides an innovative approach to optimize the design of engine head blocks
- The RBF mesh morphing technique complements the BGM by enabling seamless morphing and manipulation of the finite element mesh, facilitating the design iteration process in a fully automatic and evolutive fashion

BGM background

- BGM approach is based on the observation that biological structures growth is driven by local level of stress.
- Bones and trees' trunks are able to adapt the shape to mitigate the stress level due to external loads.
- The process is driven by stress value at surfaces. Material can be added or removed according to local values.
- Was proposed by Mattheck & Burkhardt in 1990*



Reduction of maximum stresses 56 %



*Mattheck C., Burkhardt S., 1990. A new method of structural shape optimization based on biological growth. Int. J. Fatigue 12(3):185-190.

BGM background

- The BGM idea is that surface growth can be expressed as a linear law with respect to a given threshold value:

$$\dot{\varepsilon} = k\left(\sigma_{Mises} - \sigma_{ref}\right)$$

- Waldman and Heller* refined this first approach proposing a multi peak one:

$$d_i^j = \left(\frac{\sigma_i^j - \sigma_i^{th}}{\sigma_i^{th}}\right) \cdot s \cdot c\,, \qquad \sigma_i^{th} = max(\sigma_i^j) \text{ if } \sigma_i^j > 0 \quad \text{or} \quad \sigma_i^{th} = min(\sigma_i^j) \text{ if } \sigma_i^j < 0$$

- In RBF Morph ANSYS Workbench ACT extension a different implementation is present and different stress types can be used to modify the surface shape:

$$S_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} \cdot d$$

Stress/strain type	Equation	Stress/strain type	Equation
von Mises stress		Stress intensity	
Maximum principal stress		Maximum Shear stress	
Minimum principal stress		Eqv. plastic strain	

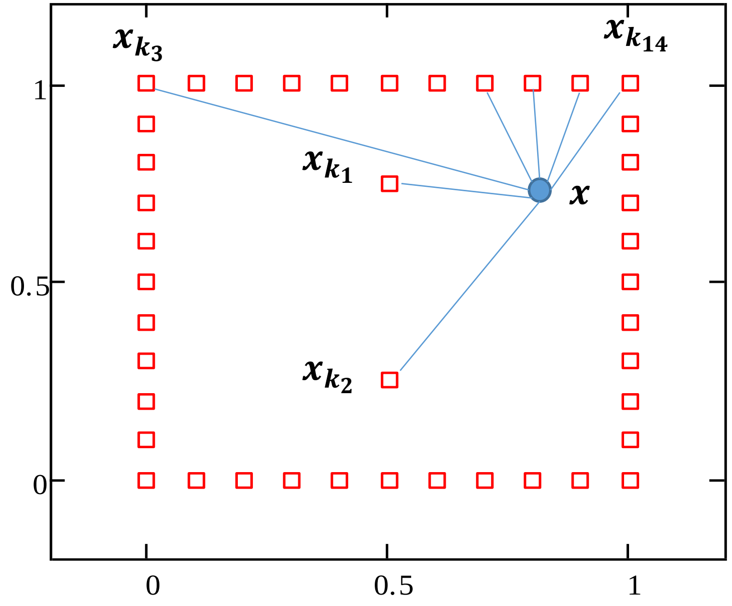
*Waldman W., Heller M., 2015. Shape optimization of holes in loaded plates by minimization of multiple stress peaks, Defence Science and Technology Organisation Fisherman Bend, Australia, Aerospace Div, http://www.dtic.mil/docs/citations/ADA618562.

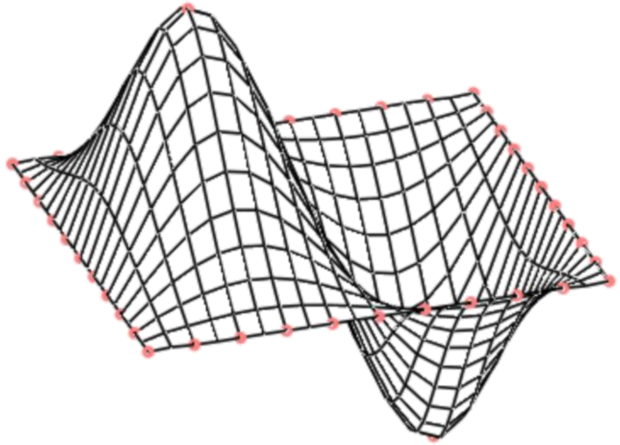
RBF background

- RBFs are a mathematical tool capable to **interpolate** in a generic point in the space a function **known** in a discrete set of points (**source points**).
- The interpolating function is composed by a **radial basis** and by a **polynomial**:

$$s(\boldsymbol{x}) = \underbrace{\sum_{i=1}^{N} \gamma_i \varphi\left(\left\|\boldsymbol{x}-\boldsymbol{x}_{k_i}\right\|\right)}_{\text{radial basis}} + \underbrace{h(\boldsymbol{x})}_{\text{polynomial}}$$

where $\left\|\boldsymbol{x}-\boldsymbol{x}_{k_i}\right\|$ is the distance from the i-th source point.





RBF background

- If evaluated on the source points, the interpolating function gives exactly the input values:

$$\begin{aligned} s(\boldsymbol{x}_{k_i}) &= g_i \\ h(\boldsymbol{x}_{k_i}) &= 0 \end{aligned} \qquad 1 \le i \le N$$

- The RBF problem (evaluation of coefficients γ and β) is associated to the solution of the linear system, in which M is the interpolation matrix, P is a constraint matrix, g is the vector of known values on the source points:

$$\begin{bmatrix} \mathbf{M} & \mathbf{P} \\ \mathbf{P}^{\mathrm{T}} & 0 \end{bmatrix} \begin{pmatrix} \boldsymbol{\gamma} \\ \boldsymbol{\beta} \end{pmatrix} = \begin{pmatrix} \boldsymbol{g} \\ 0 \end{pmatrix} \qquad M_{ij} = \varphi\left(\boldsymbol{x}_{k_i} - \boldsymbol{x}_{k_j}\right) \qquad 1 \le i, j \le N \qquad \mathbf{P} = \begin{bmatrix} 1 & x_{k_1} & y_{k_1} & z_{k_1} \\ 1 & x_{k_2} & y_{k_2} & z_{k_2} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{k_N} & y_{k_N} & z_{k_N} \end{bmatrix}$$

RBF background

- Once solved the RBF problem each displacement component is interpolated:

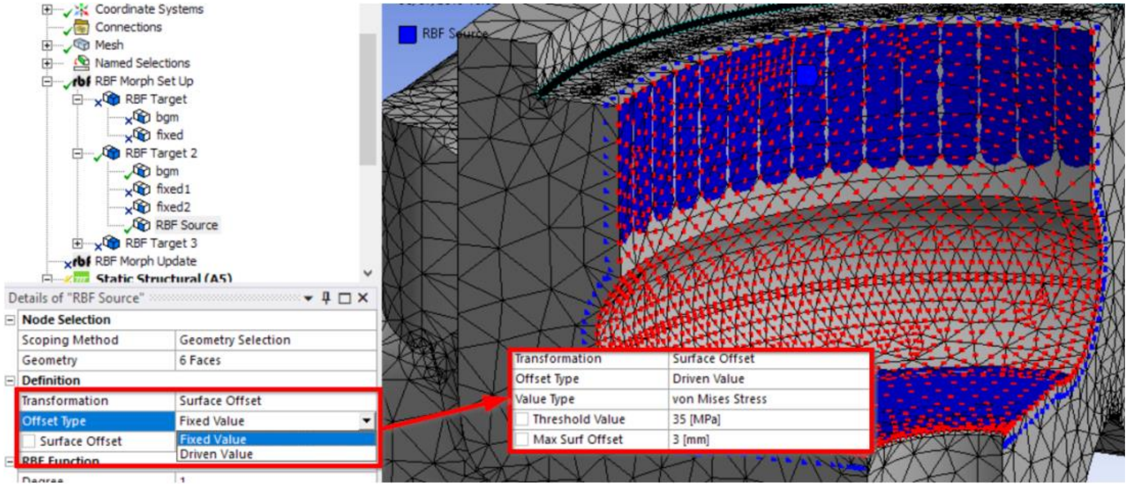
$$\begin{cases} s_x(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ s_y(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\ s_z(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z \end{cases}$$

- Several different radial function (kernel) can be employed:

RBF	φ(r)	RBF	φ(r)
Spline type (Rn)	r^n, *n odd*	Inverse multiquadratic (IMQ)	$\frac{1}{\sqrt{1+r^2}}$
Thin plate spline	$r^n \log(r)$ *n even*	Inverse quadratic (IQ)	$\frac{1}{1+r^2}$
Multiquadratic (MQ)	$\sqrt{1+r^2}$	Gaussian (GS)	e^{-r^2}

Automatic surface sculpting

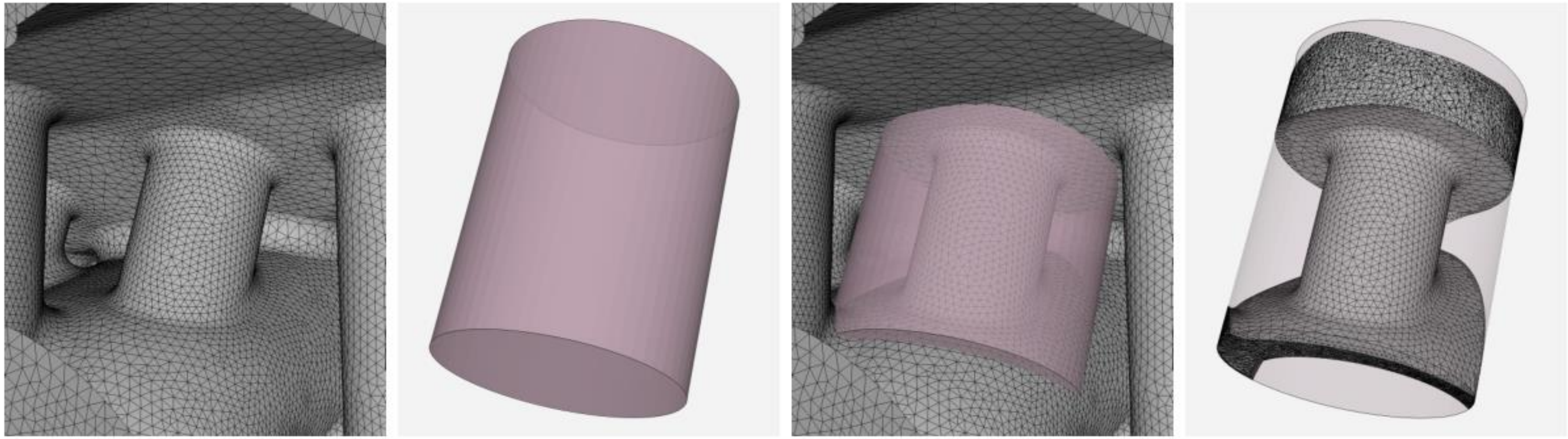
- Automatic optimization is accomplished connecting BGM data from numerical simulation to the mesh morphing tool.
- Offset Surface shape modification allows to define for each node a displacement according to the local normal direction.
- When using BGM data, the intensity of the displacement is defined according to BGM stress data, considering the threshold stress value σ_th and the d maximum displacement.



$$S_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} \cdot d$$

RBF-BGM setup for engine head optimisation

- Acting on the mesh morphing setup, it is possible to confine the deformation process to a specific portion of the domain: the computational burden is reduced, acting only in the area interested by optimization
- Useful approach for confined flows problems (cylinder head): the complex geometries with internal ducts make difficult the selection of the surfaces to be sculpted and those to be kept fixed



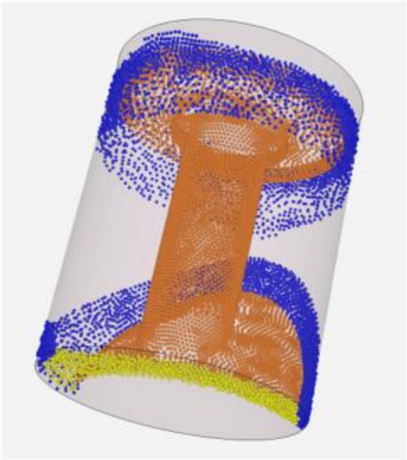
RBF-BGM setup for engine head optimisation

- Being a meshless method, RBFs require the definition of a displacement field prescribed at points. To automatically build the complete problem the setup is split in two fields:
  - Moving set → prescribing displacements on the nodes designated to undergo movement
  - Fixed set → defining the nodes for which the displacement must be kept to zero
- Being an evolutionary optimization, the first is computed at each step with a new evaluation while the latter is always maintained the same
- Fixed set extracted from the baseline mesh just once, on the baseline

RBF-BGM setup : Moving set

(a)

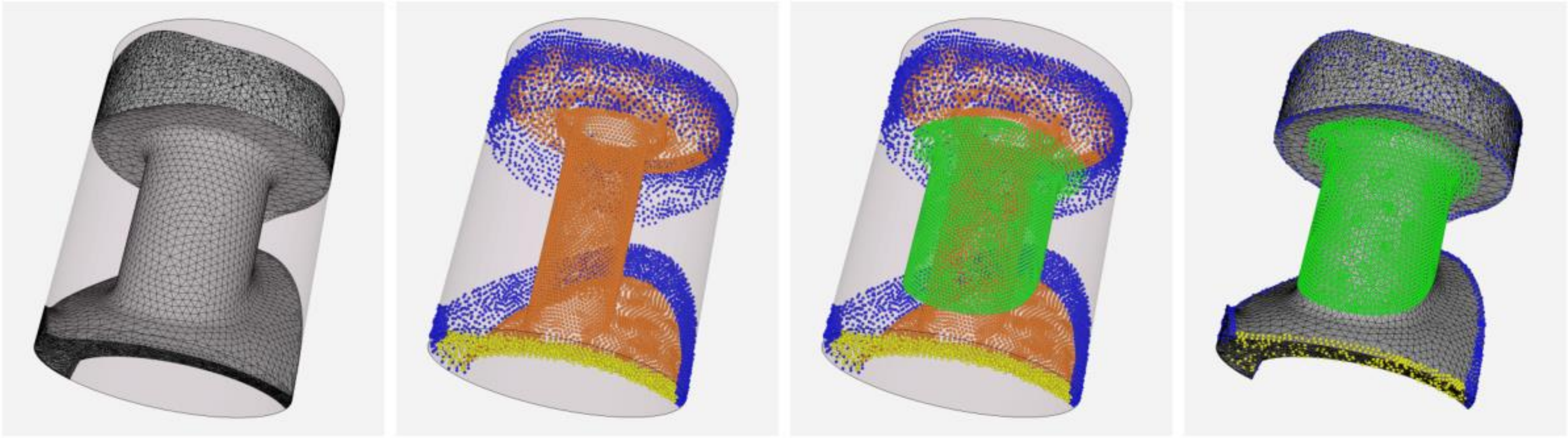
(b)



(c)

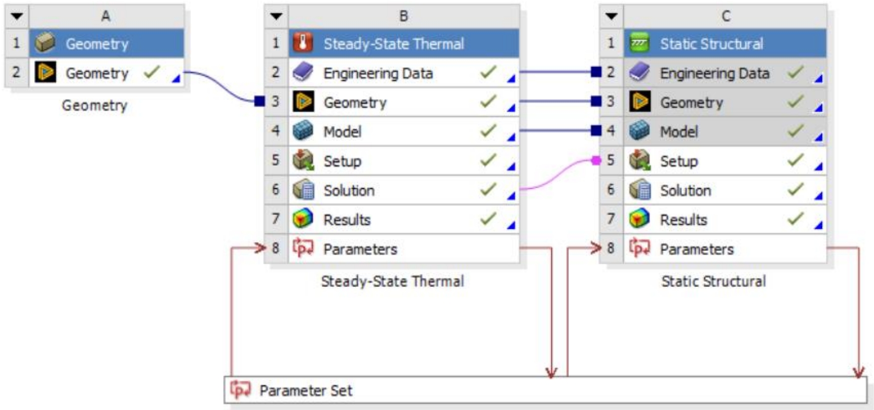
RBF-BGM setup : Complete setup

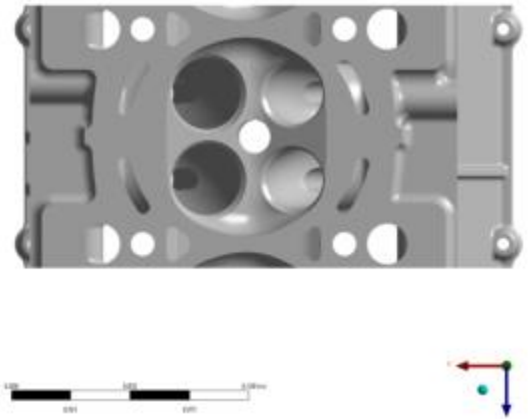
- All the nodes inside the domain that are not part of the fixed or the moving sets are left free to deform, smoothly blending between the two.

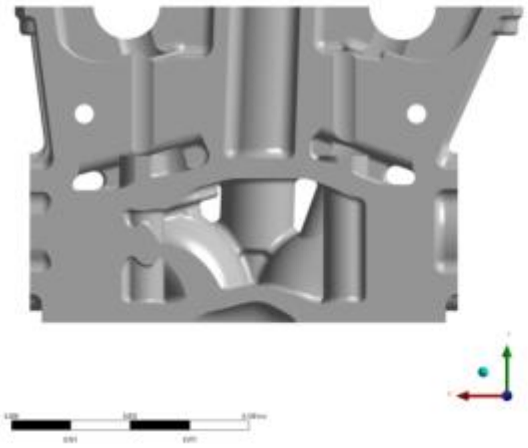


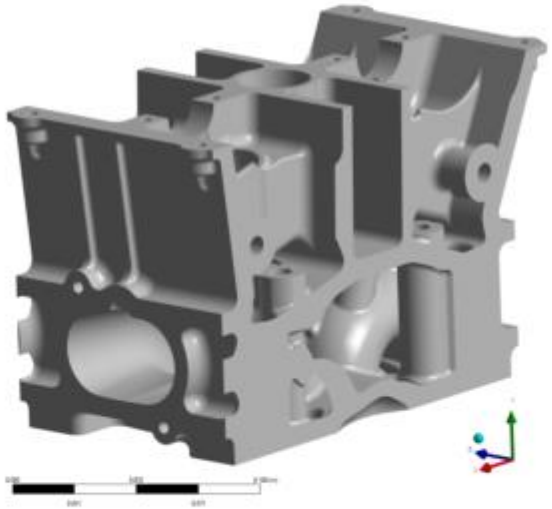
Generic engine head problem

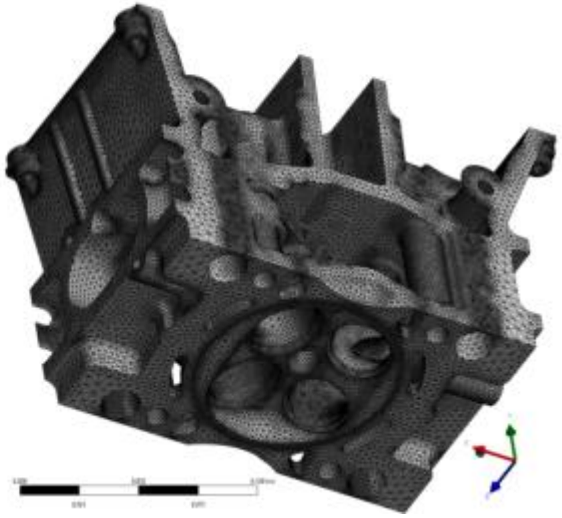
- The method was applied to a very generic model of engine head. To simplify the problem only the domain around a single cylinder was considered
- 2.9 Mill. nodes and 1.9 Mill. parabolic tetrahedral elements.



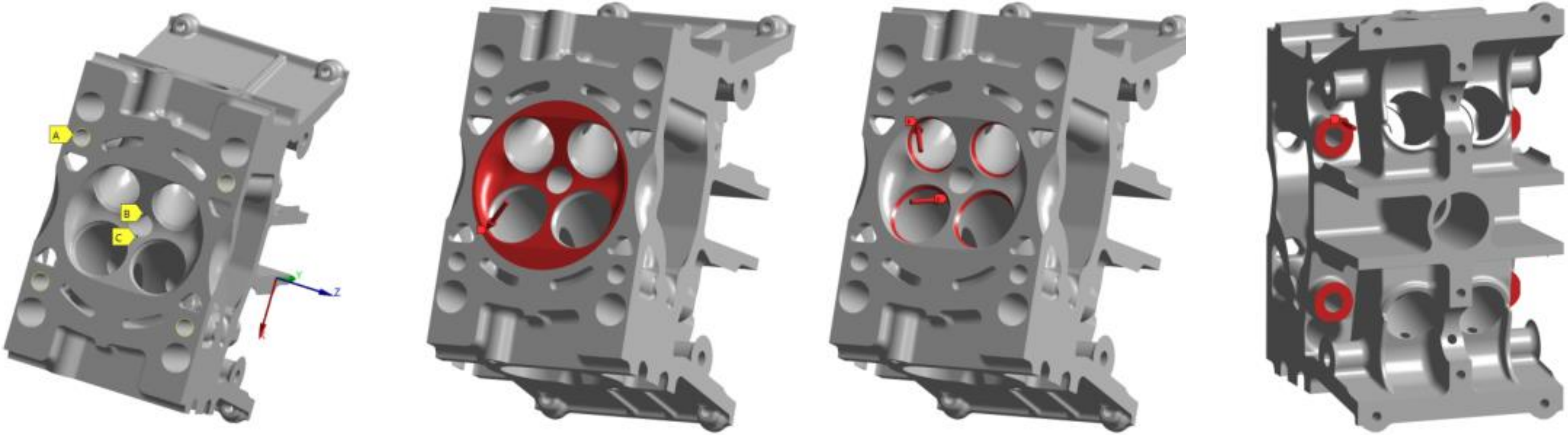






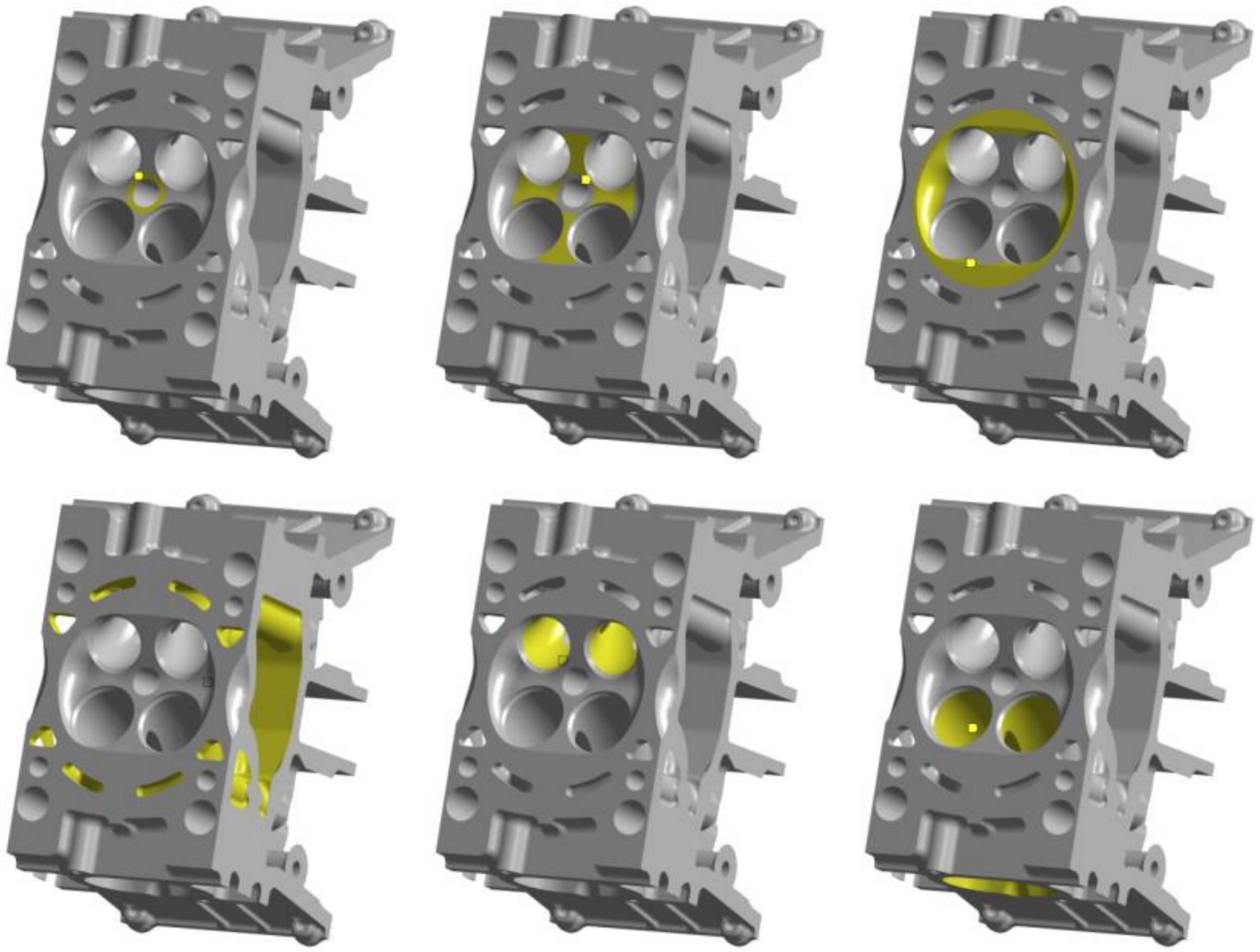


Generic engine head problem - structural BC



- edges A of the head stud holes constrained along the Y direction
- point B along X and Z and point C along Y
- pressures defined on the combustion side of the cylinder head and on the valve seats using different values for the exhaust and for the intake valves
- Pressure on the bolts of the head struts

Generic engine head problem - thermal BC



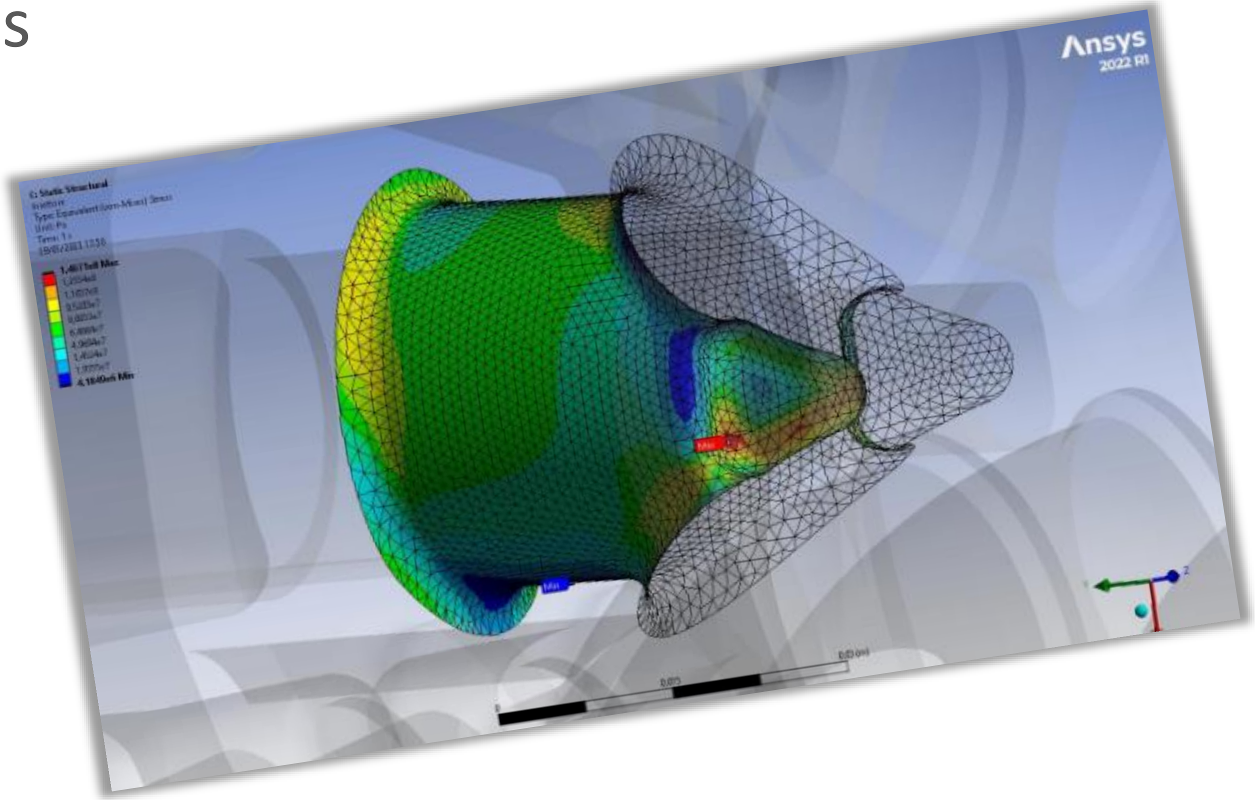
- convection boundary conditions applied to the combustion side
- three concentric areas defined with different values
- Convective boundary conditions to the water jackets
- Convective boundary conditions to the exhaust and intake ducts

Generic engine head problem – baseline results

- aluminium alloy (AlSi7MgCu0.5) $\sigma_y = 200\ MPa$
- Three areas of the domain were optimized, near the injector seat, the exhaust and the intake ducts

Injector seat

$\sigma_{VM\_MAX} = 140\ MPa$



Generic engine head problem – baseline results

- aluminium alloy (AlSi7MgCu0.5) $\sigma_y = 200\ MPa$
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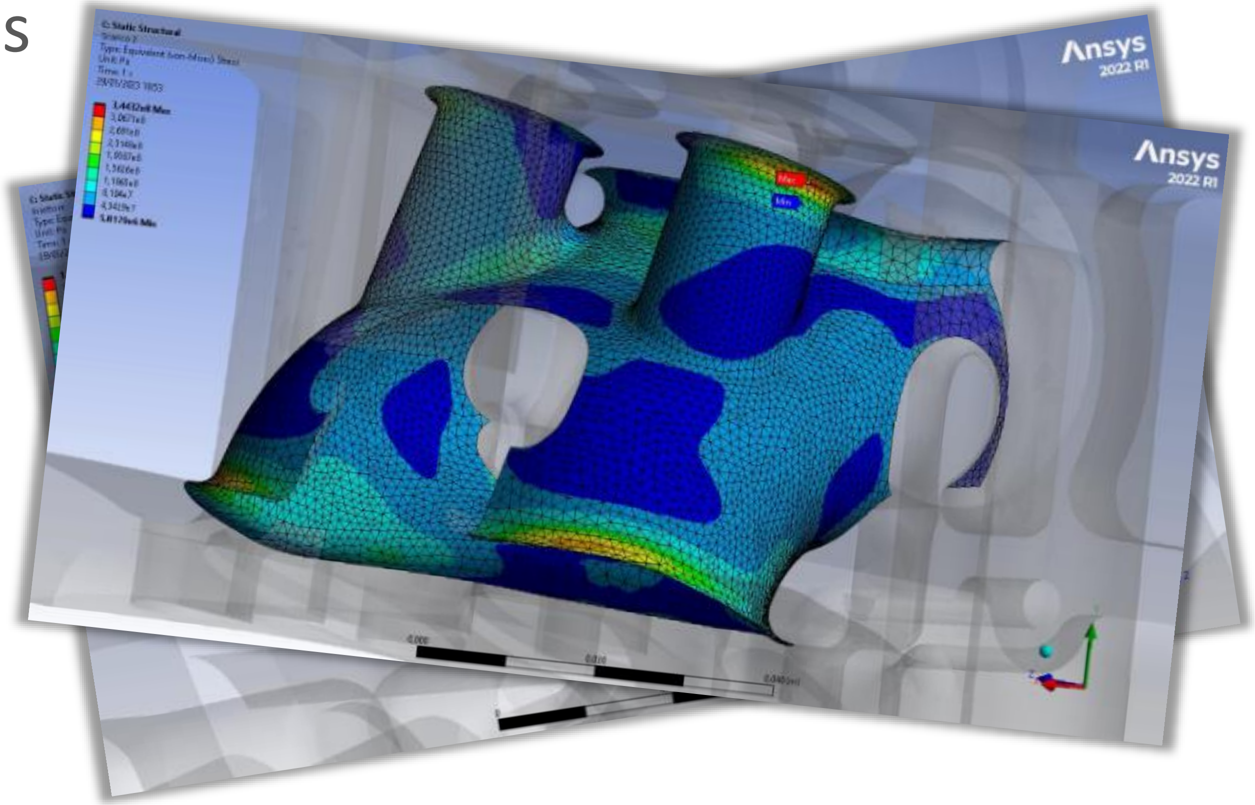
Exhaust duct

$\sigma_{VM\_MAX} = 344\ MPa$

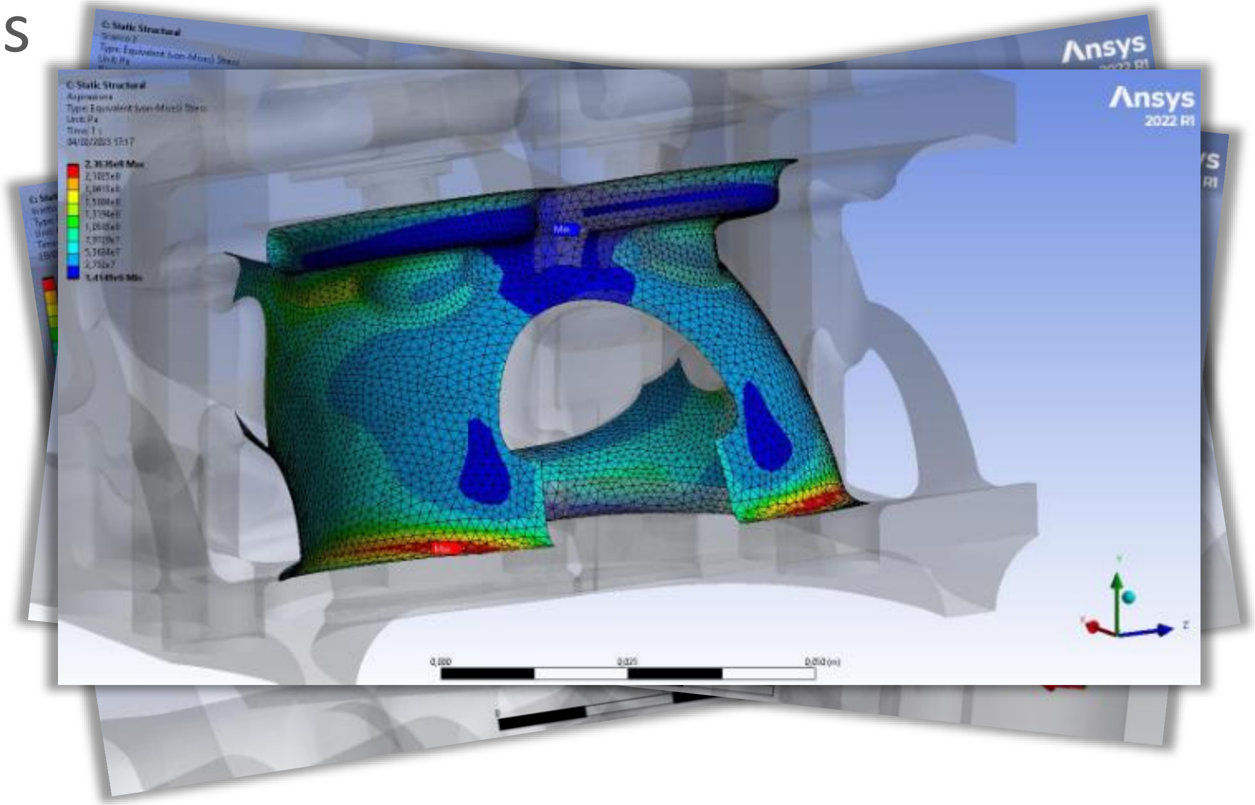


Generic engine head problem – baseline results

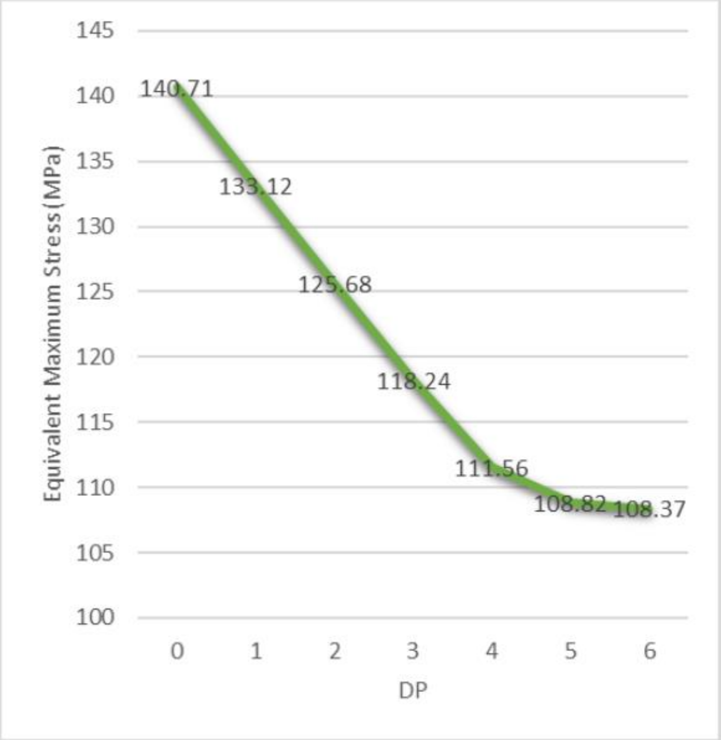
- aluminium alloy (AlSi7MgCu0.5) $\sigma_y = 200\ MPa$
- Three areas of the domain were optimized, near the injector seat, the exhaust and the intake ducts

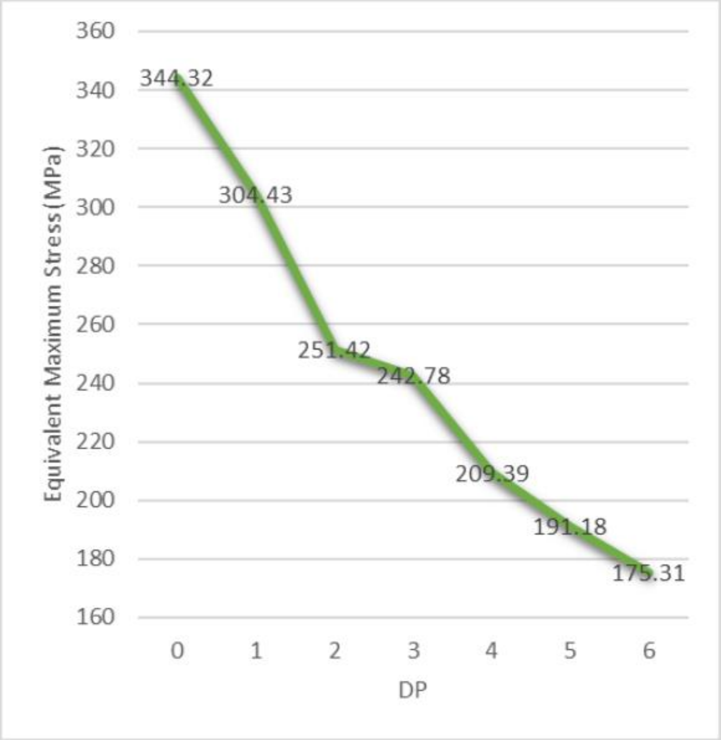
Intake duct

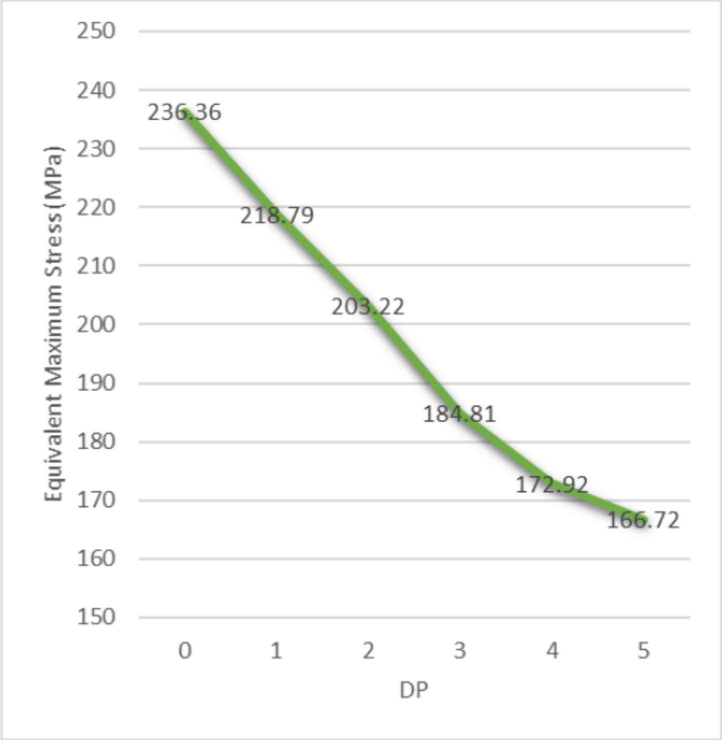
$\sigma_{VM\_MAX} = 236\ MPa$



Generic engine head problem – Optimisation results

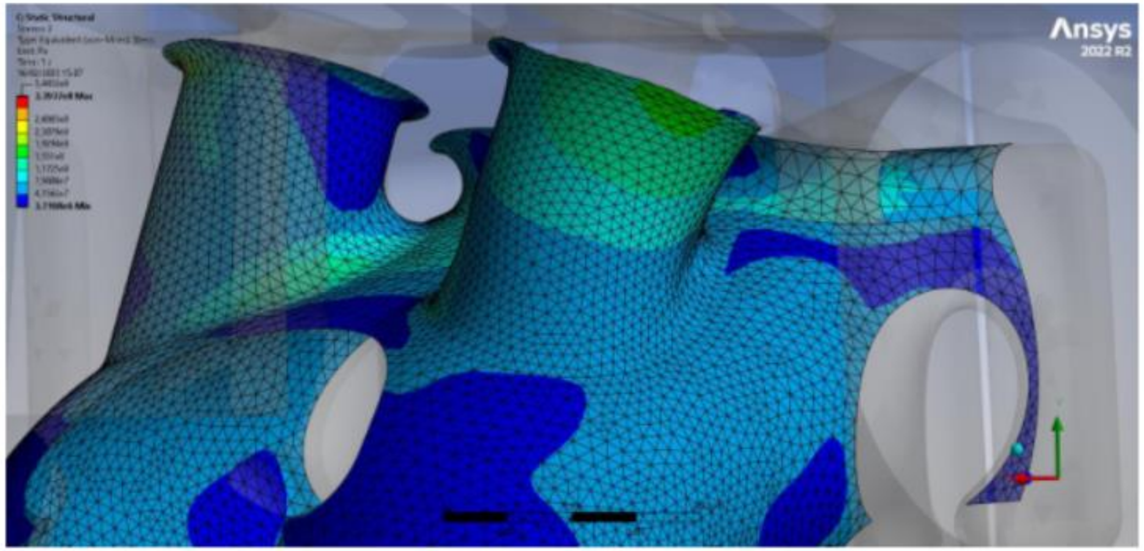


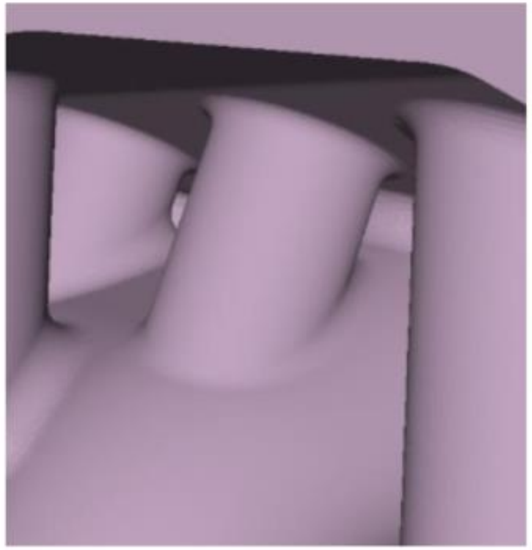


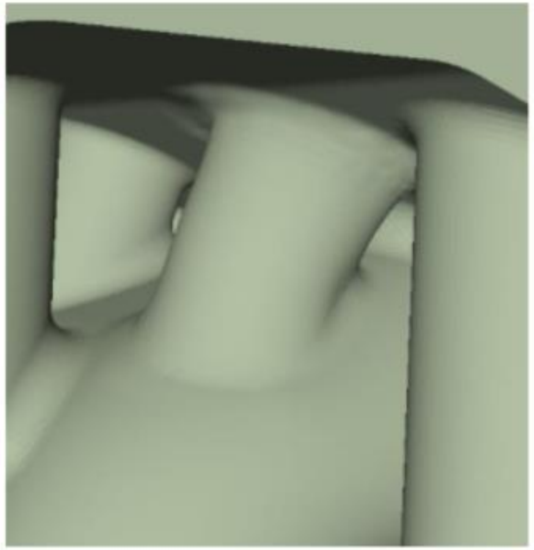


district	σ_{th}	d [mm]	σ_{max} baseline [MPa]	σ_{max} optimized [MPa]	reduction
Injection hole	0	0.5	140.71	108.37	25.5%
Exhaust ducts	58	1	344.32	175.31	49%
Intake ducts	0	0.5	236.36	166.72	29.5%

Generic engine head problem – Optimisation results

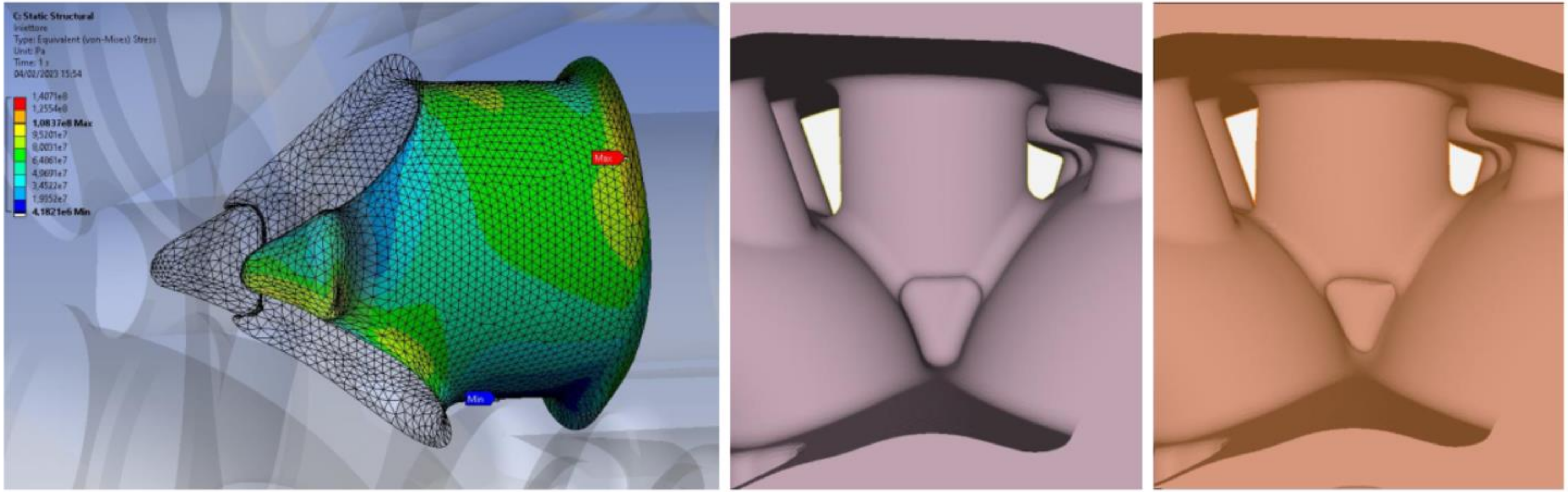






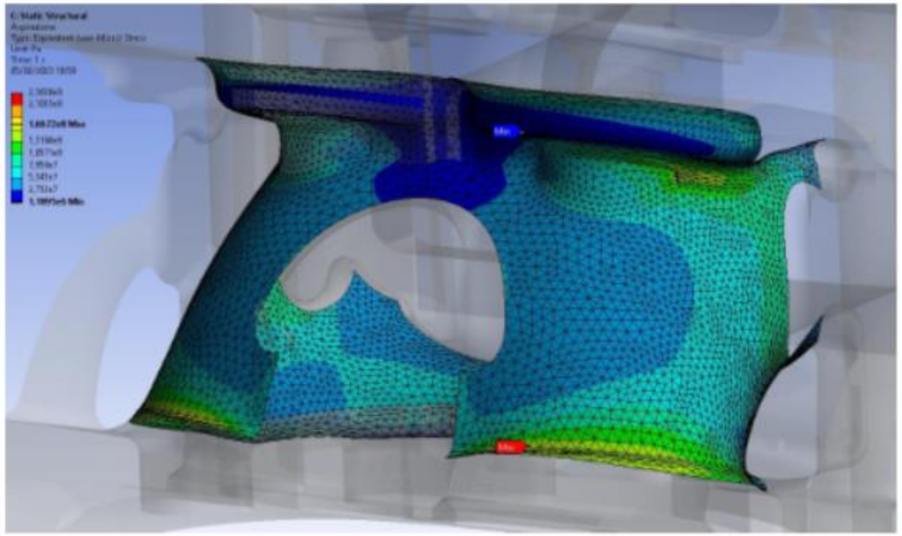
- Von Mises stress for the optimized exhaust duct

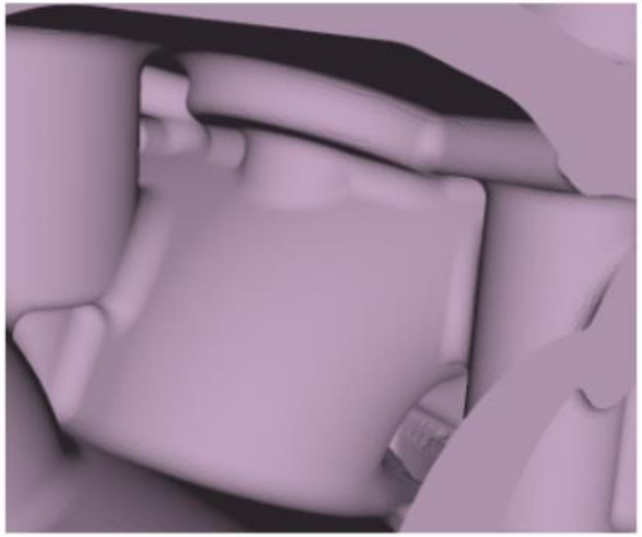
Generic engine head problem – Optimisation results



- Von Mises stress for the optimized injection seat

Generic engine head problem – Optimisation results

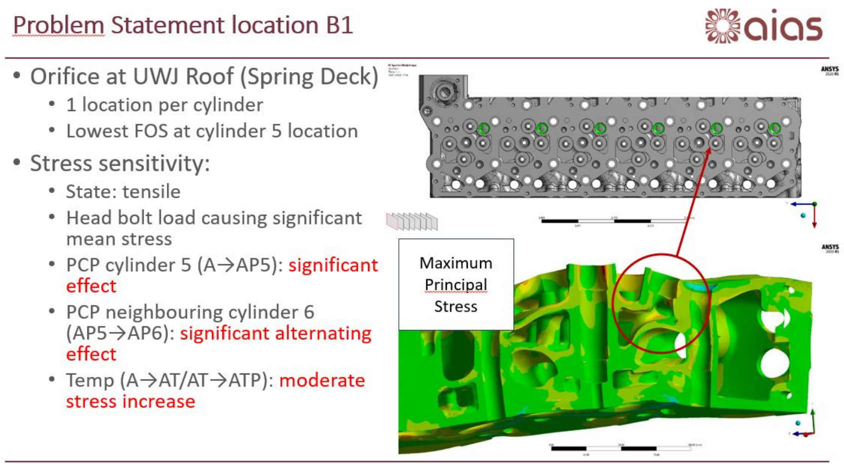


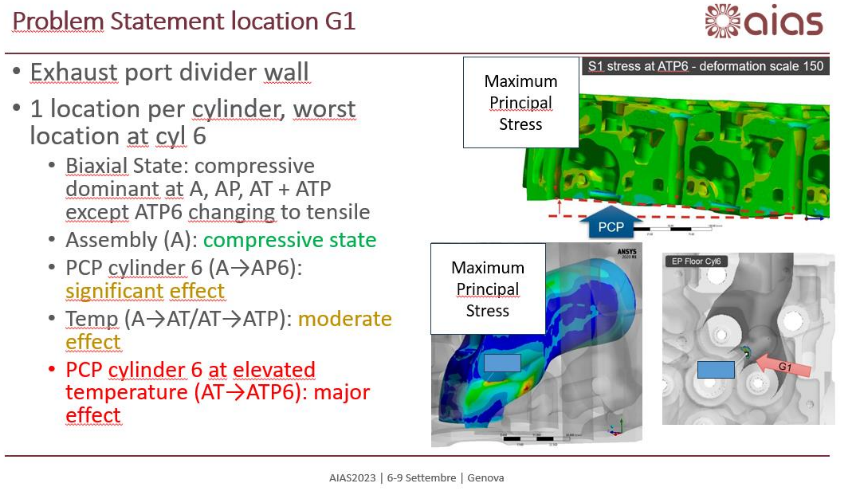


- Von Mises stress for the optimized intake ducts

Industrial case: Project Background

- Cylinder head FEA and Fatigue Analysis
- FEA → Analysis recommendations → design changes → new FEA
- 7 design and analysis iterations had been carried out
- **The Problem**
- Turnaround time per iteration ~ 1…2 weeks, often longer (Block-Gasket-Head assembly model)
- Slow improvements made at 2 locations (B1 and G1)



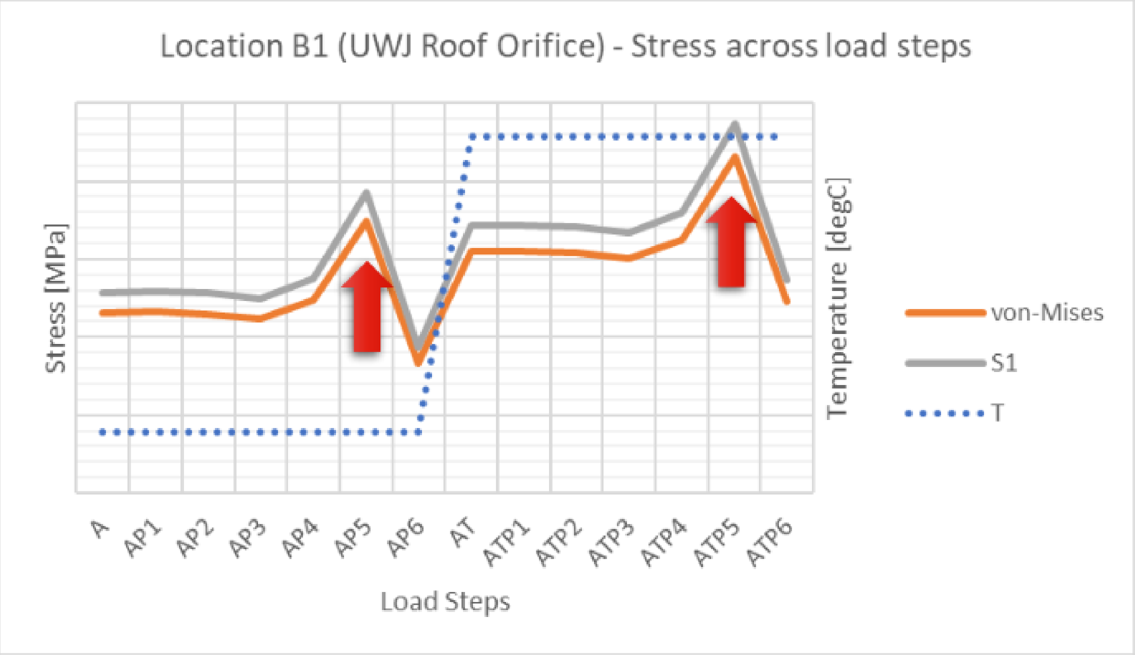


Industrial case: Project Background

- Cylinder head FEA and Fatigue Analysis
- **The Solution**
- BGM was employed to speed up the design process
- Benefits of using BGM shape optimisation:
  - Final morphed mesh was exported and used as guideline for redesign
  - Good understanding of limitations of the design before introducing major topology changes
  - Fast turnaround due to one-time model set-up and automated design point progression (all changes occurring on existing mesh and FE-model, cut's out CAD level changes and FE model updating)

Problem Statement location B1

- Orifice at UWJ Roof (Spring Deck)
  - 1 location per cylinder
  - Lowest FOS at cylinder 5 location
- Stress sensitivity:
  - State: tensile
  - Head bolt load causing significant mean stress
  - Peak Combustion Pressure cylinder 5 (A→AP5): significant effect
  - PCP neighbouring cylinder 6 (AP5→AP6): significant alternating effect
  - Temp (A→AT/AT→ATP): moderate stress increase



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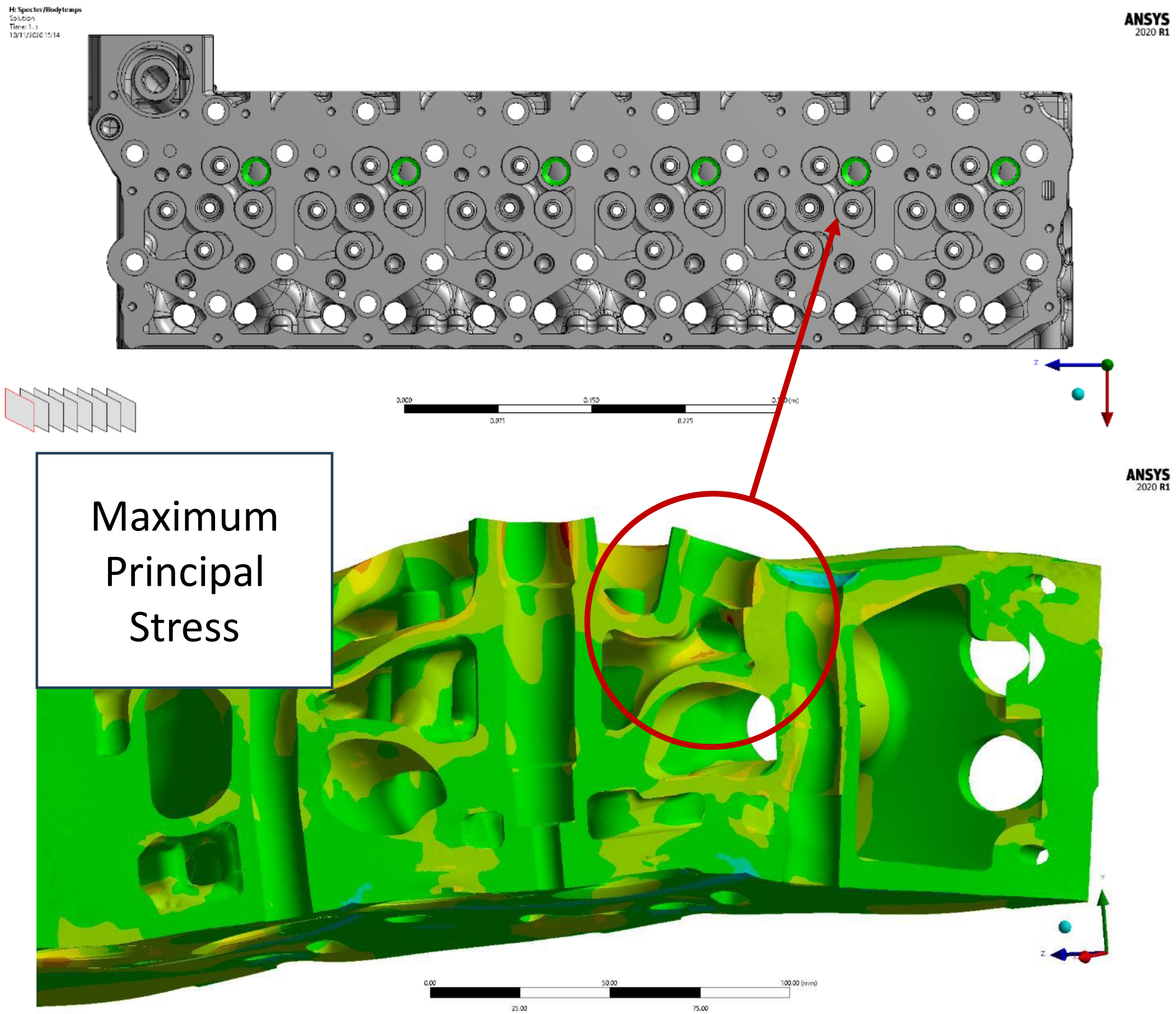
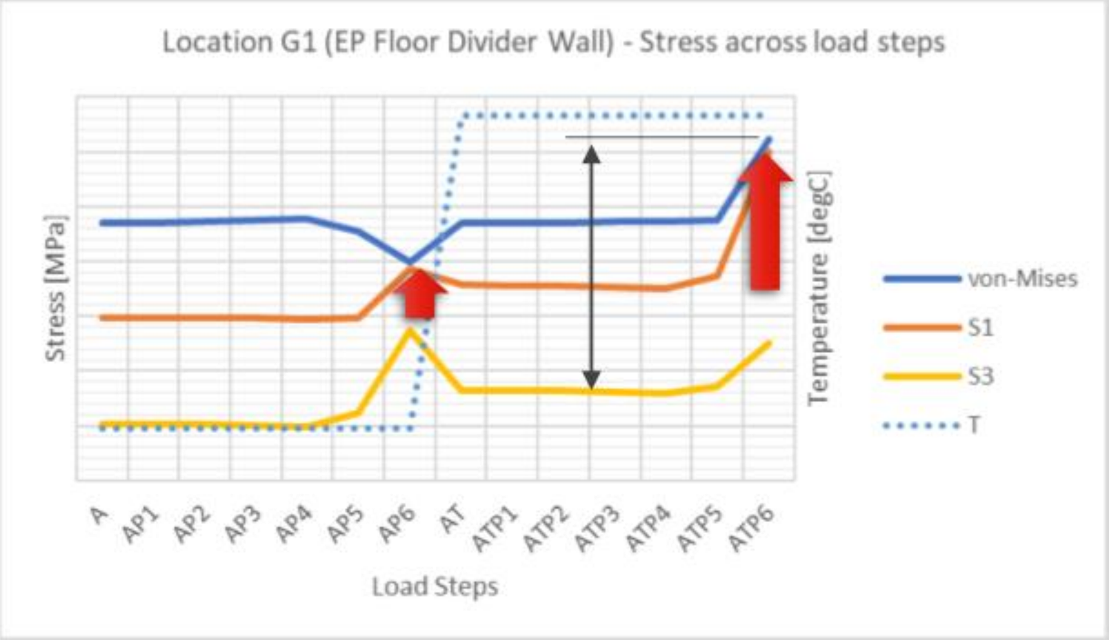


Problem Statement location G1

- Exhaust port divider wall
- 1 location per cylinder, worst location at cyl 6
  - Biaxial State: compressive dominant at A, AP, AT + ATP except ATP6 changing to tensile
  - Assembly (A): compressive state
  - PCP cylinder 6 (A→AP6): significant effect
  - Temp (A→AT/AT→ATP): moderate effect
  - PCP cylinder 6 at elevated temperature (AT→ATP6): major effect



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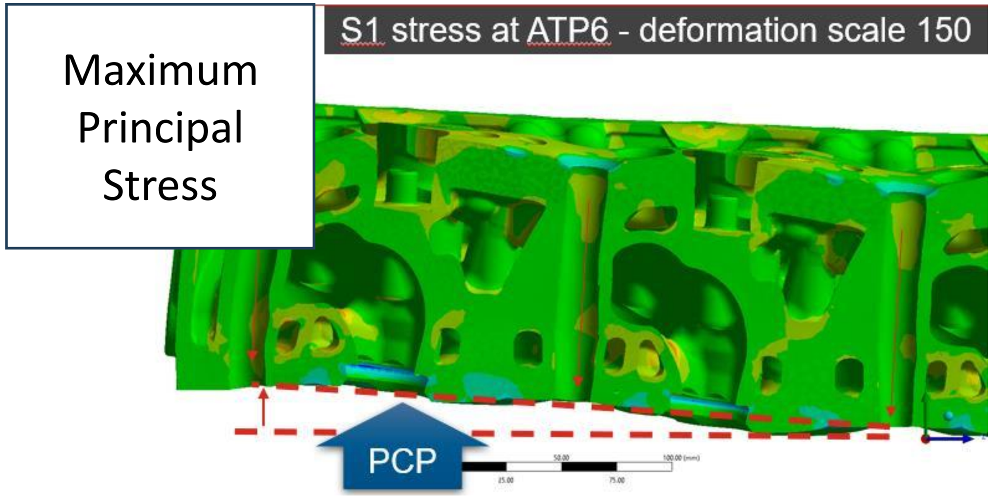
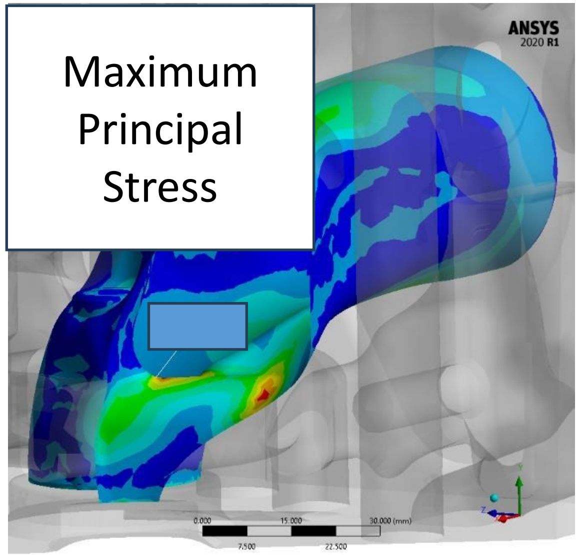
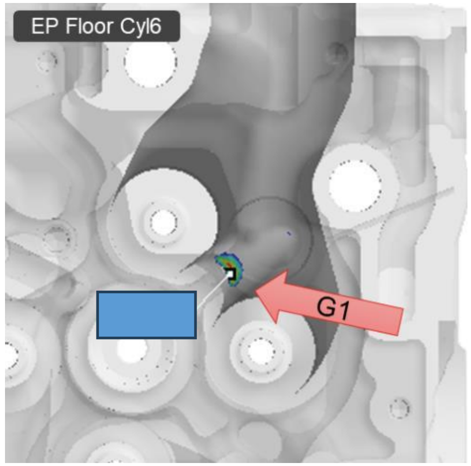


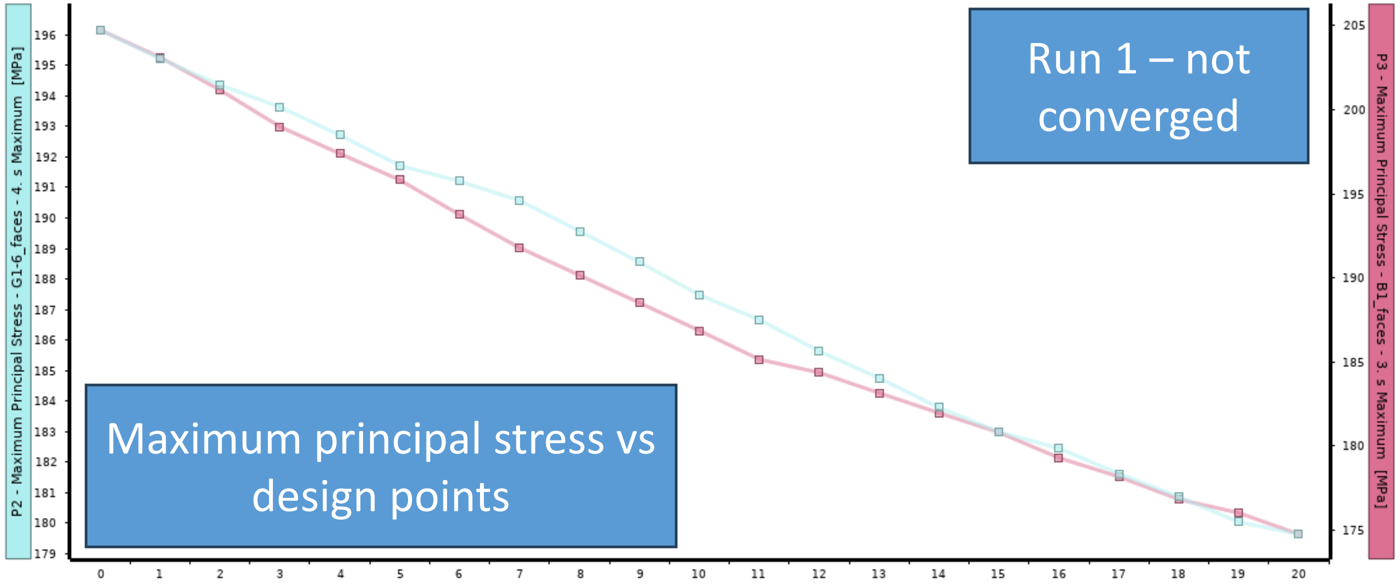


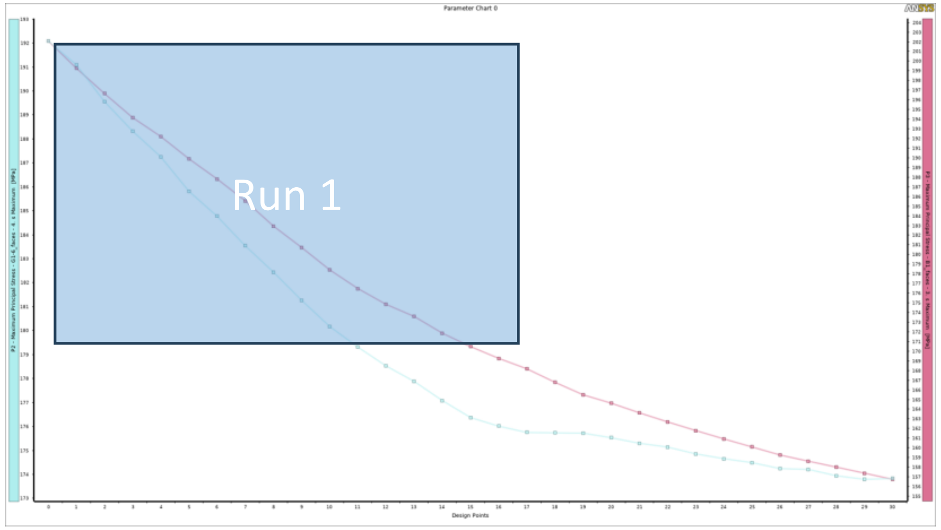


Shape optimisation at EP6 (G1) and UWJ5 (B1)

- Optimisation method: RBF Morph – Biological Growth Method
- Design points: 20
- Criteria: Highest maximum principal stress at design regions

Run 2 with 30 design points and tweaked settings

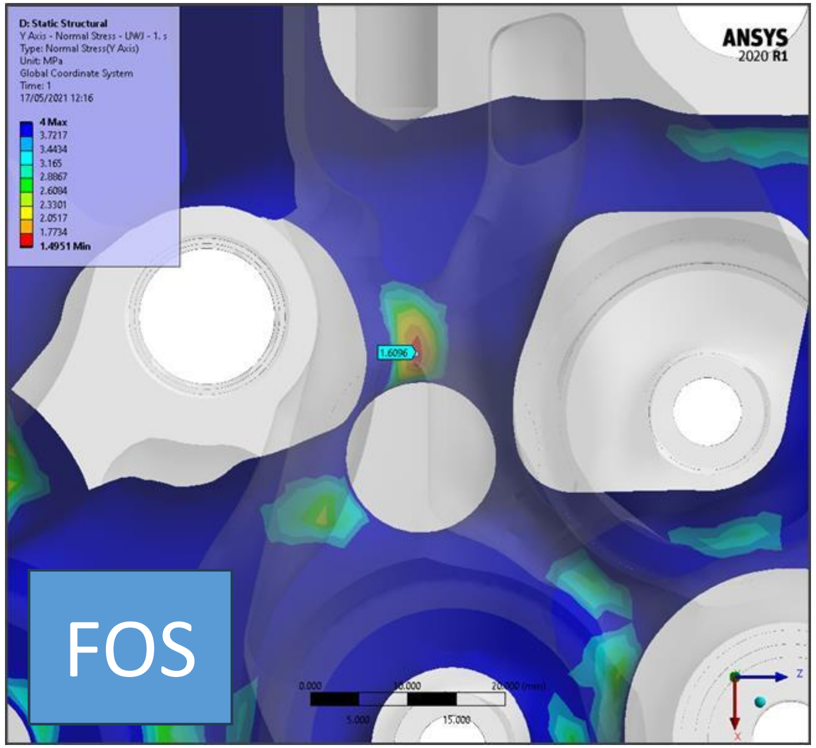




B1 optimisation

Design point 0 - Baseline

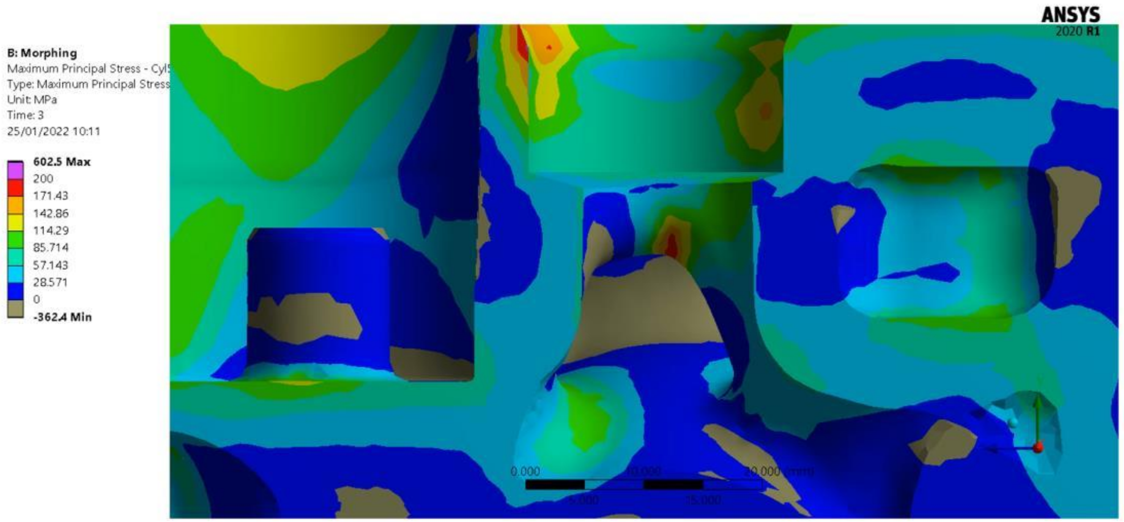
- Max principal stress: 205 MPa
- FOS: 1.42



Design point 20

- Max principal stress: 175 MPa (-14.6%)
- FOS: 1.61 (+13.4%)

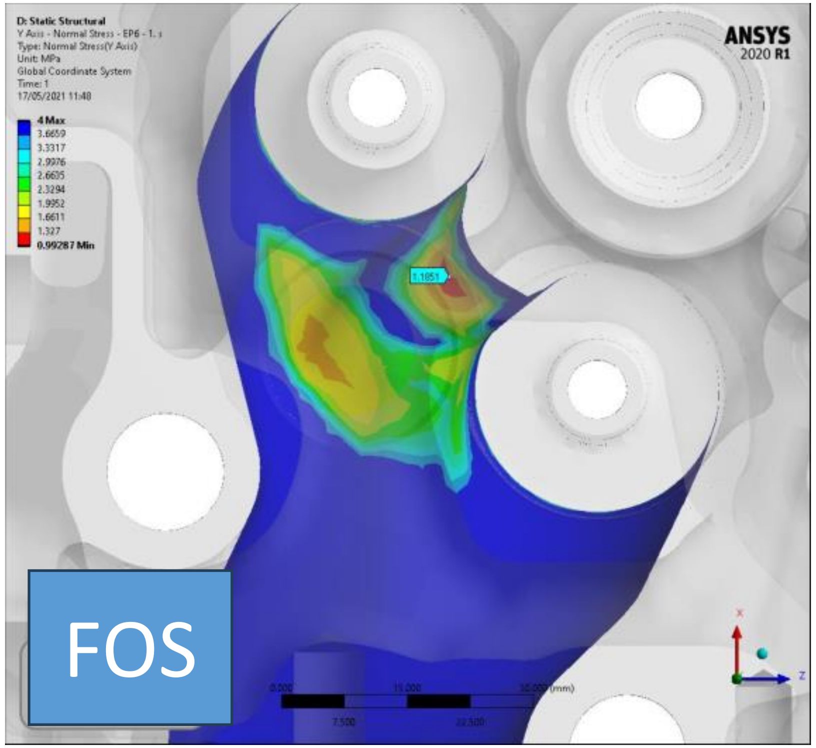
Maximum Principal Stress - Cyl5 B1-5-side



G1 optimisation

Design point 0 - Baseline

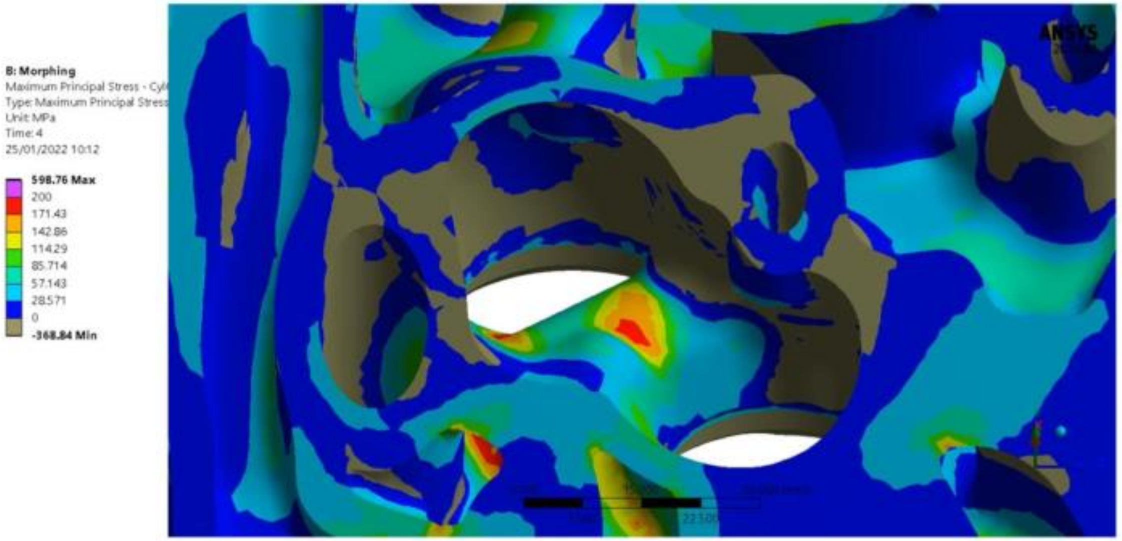
- Max principal stress: 196 MPa
- FOS: 1.09



Design point 20

- Max principal stress: 180 MPa (-8.1%)
- FOS: 1.19 (+9.2%)

Maximum Principal Stress - Cyl6 G1-6-side



Conclusions

- A methodology to perform automatic shape optimization via surface sculpting on a combustion engine cylinder head assembly model was presented.
- Iterations typically carried out manually since the complex casting topology makes geometry parameterisation near impossible
- The methodology was developed using Ansys Workbench and the RBF Morph ACT extensions, using a mixed setup using fixed and moving sets
- Improvements in terms of FOS and stress reduction were obtained for two cases: a generic cylinder head and an industrial case
- Speed up of the optimisation workflow via an automated solution

Thank you very much for your interest!

Stress mitigation of a thermal engine head block using the bioinspired BGM-FEM method

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