STRUCTURALLY CONSTRAINED AERODYNAMIC ADJOINT OPTIMISATION OF HIGHLY LOADED COMPRESSOR BLADES

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Motivation

Objective - optimisation methodology for highly loaded compressor blades to increase their efficiency while maintaining an acceptable value of maximum stress

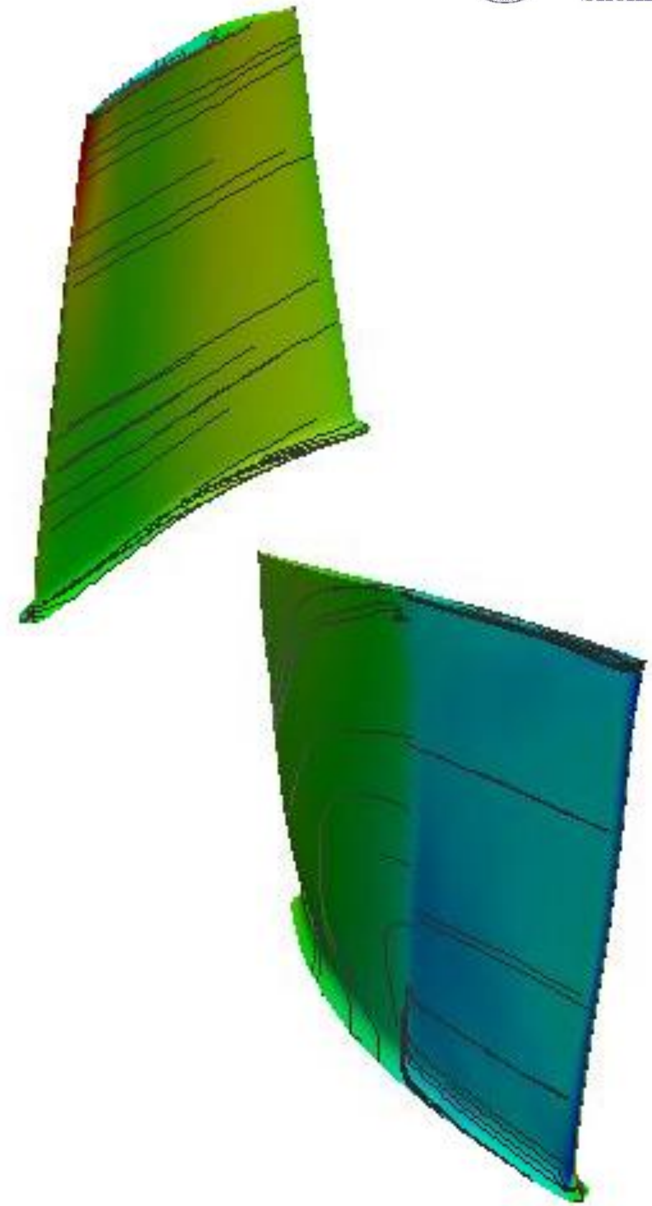
Novelty - coupling an adjoint-based aerodynamic optimisation with a response surface based model for constraining the maximum stress on the blade

Context - designing highly loaded transonic compressor blades

- challenging task
- driven by several disciplines
- lower costs and much shorter design time scales
- multidisciplinary optimisation

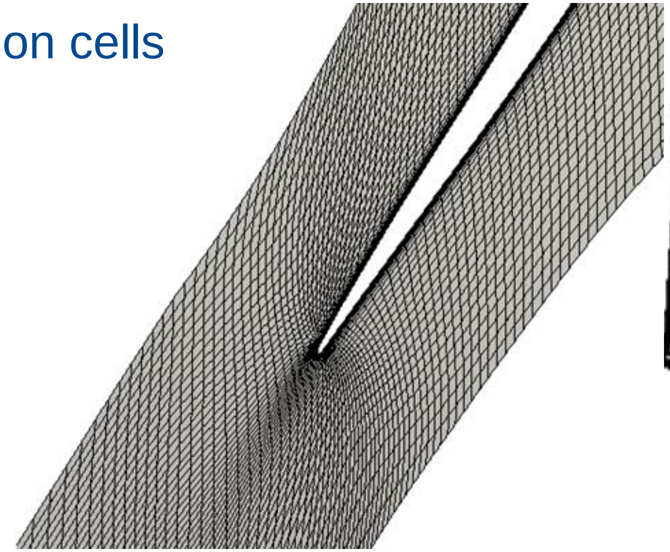
Case studied

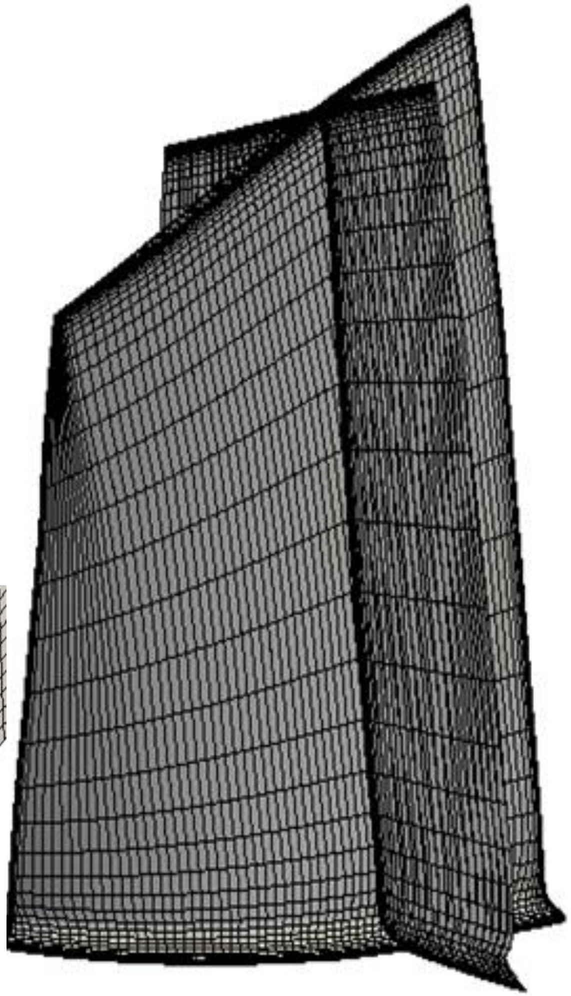
- **NASA Rotor 37**
  - well-documented in the literature
  - good test case in optimisation problems as it poses several challenges
    - highly separated flow
    - shock waves and interaction with the boundary layer
    - large tip-leakage vortex



Methods and tools

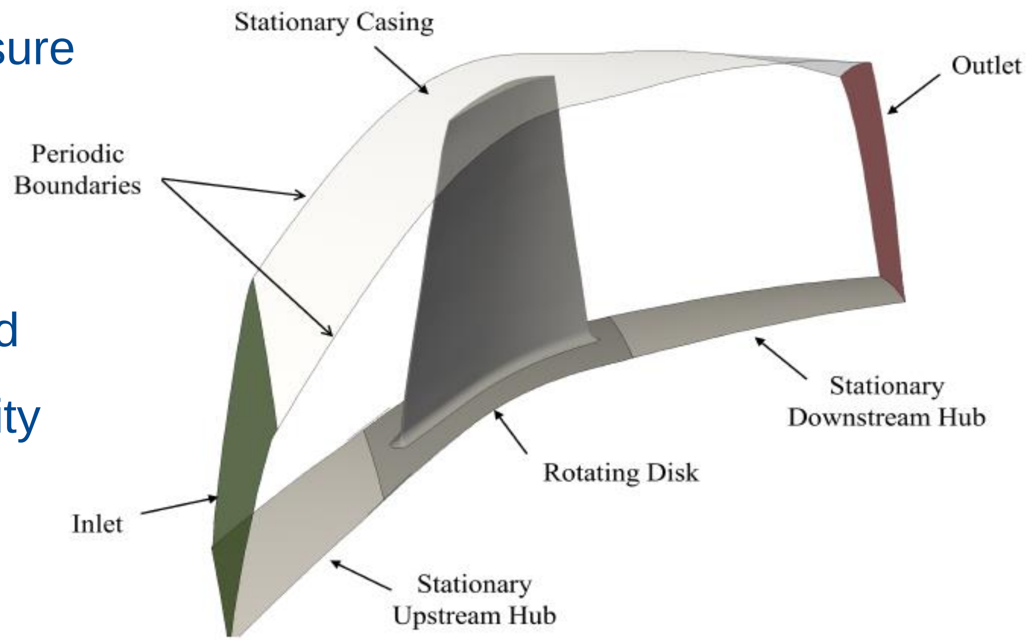
- **Mesh**
  - In-house software PADRAM
  - Multi-block structured grids
  - $y^+ \sim O(1)$
  - For optimisation purpose a relatively "coarse mesh" is used - approximately 600,000 cells
  - Usual size: 2 to 4 million cells





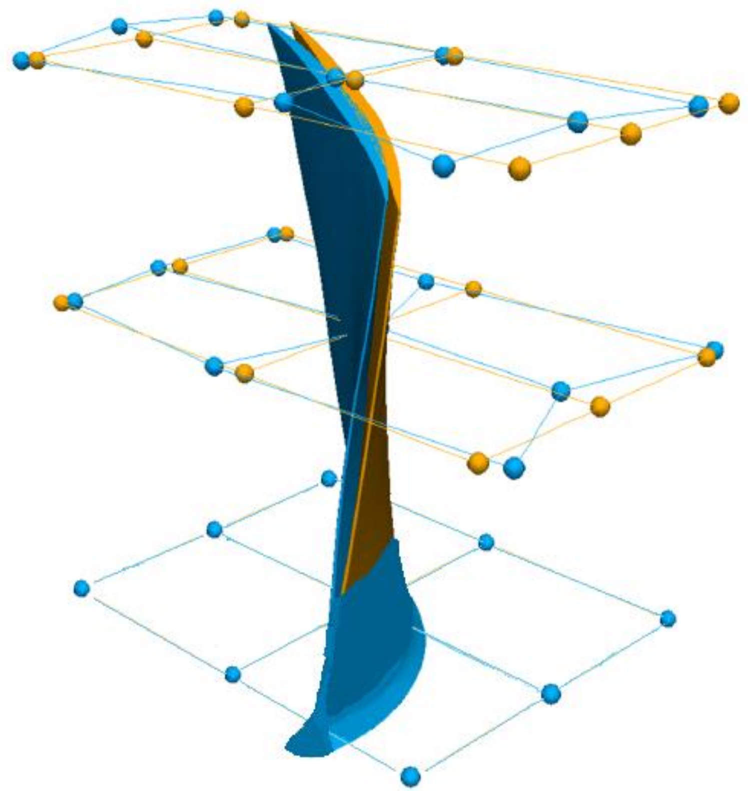
Methods and tools

- **CFD setup**
  - In-house Rolls-Royce code, Hydra
  - Inlet boundary conditions:
    - radial distribution of total pressure and temperature
  - Outlet boundary condition:
    - circumferentially mixed-out and radially mass-averaged capacity
  - Adiabatic viscous walls
  - Rotational speed: 1800 rad/s
  - Turbulence model: Spalart-Allmaras



Methods and tools

- **Geometry parametrisation**
  - FFD - free-form deformation approach
  - Control points of the volume represent the design parameters
  - A one-to-one correspondence
  - Better shaping flexibility
  - Control points have no apparent physical meaning
  - FFD grid dimension: 3x3x2
  - 36 design parameters

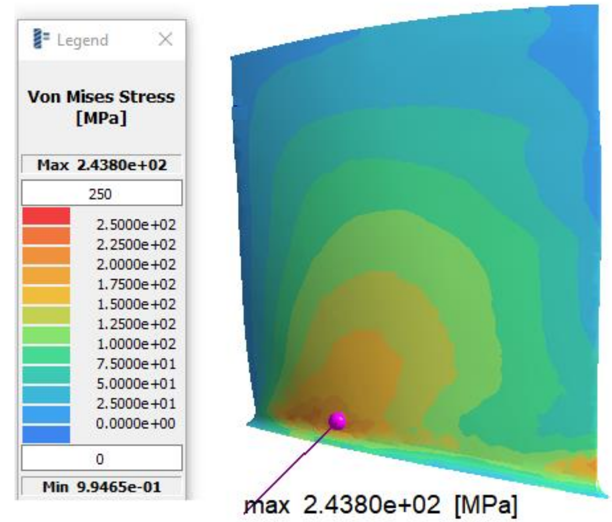


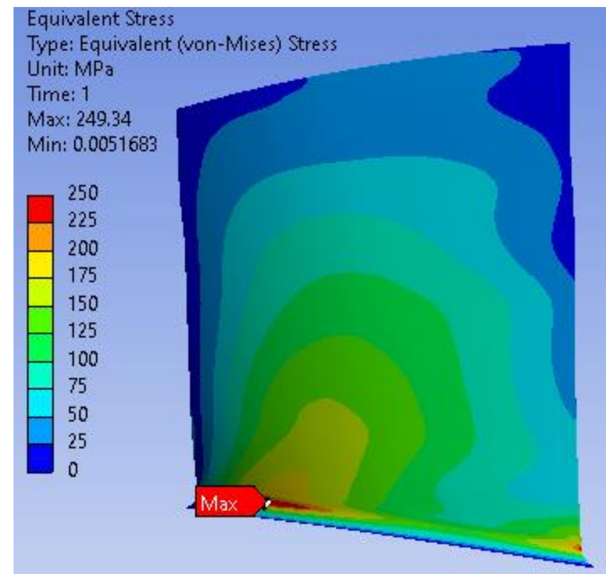
Methods and tools

- **Adjoint method**
  - Discrete approach
  - Implemented in Hydra Adjoint
  - The computational cost does not depend on the number of design variables, but only on the objective function
  - From a single adjoint solution, the sensitivity with respect to many design parameters is computed
  - The adjoint solver is coupled with the primal flow solver

Methods and tools

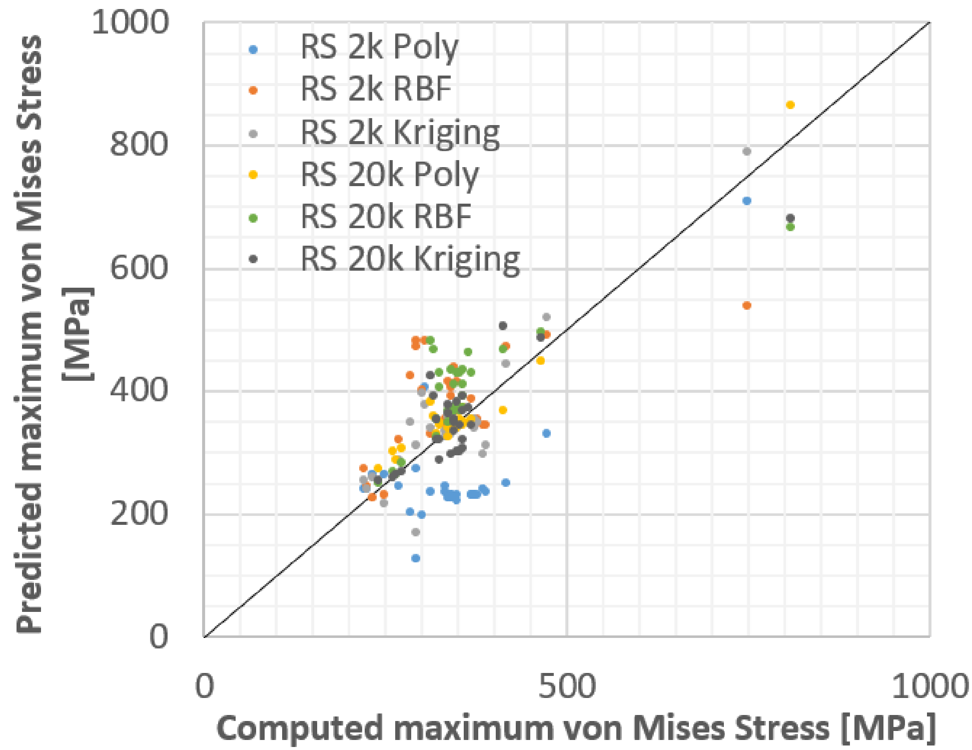
- **Stress analysis**
  - Fixed hub section
  - Centrifugal load; pressure load to be added in subsequent developments
  - Maximum von Mises stress
  - Solid titanium alloy, yield strength of 710 MPa
  - Response surface generated beforehand
  - SimSolid software used for the structural analysis
    - a fast, meshless tool
  - 2.2% relative difference in maximum stress compared to Ansys Mechanical for datum geometry
  - Simsolid is 10 times faster than ANSYS FE analysis

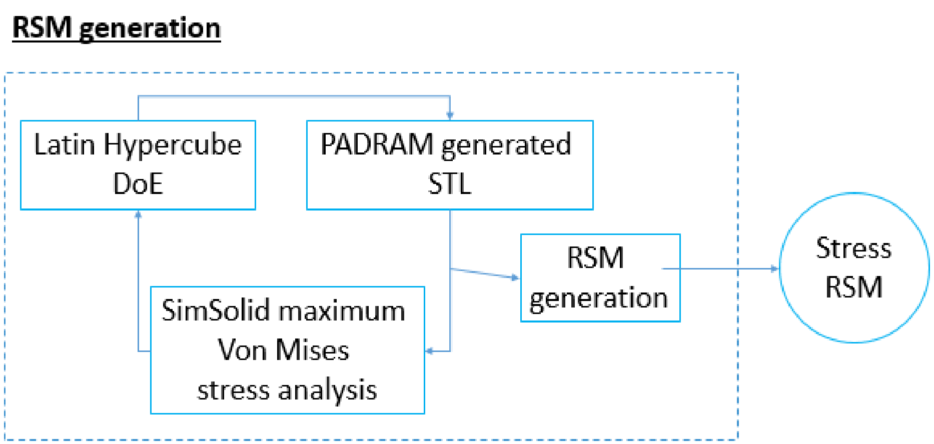




Methods and tools

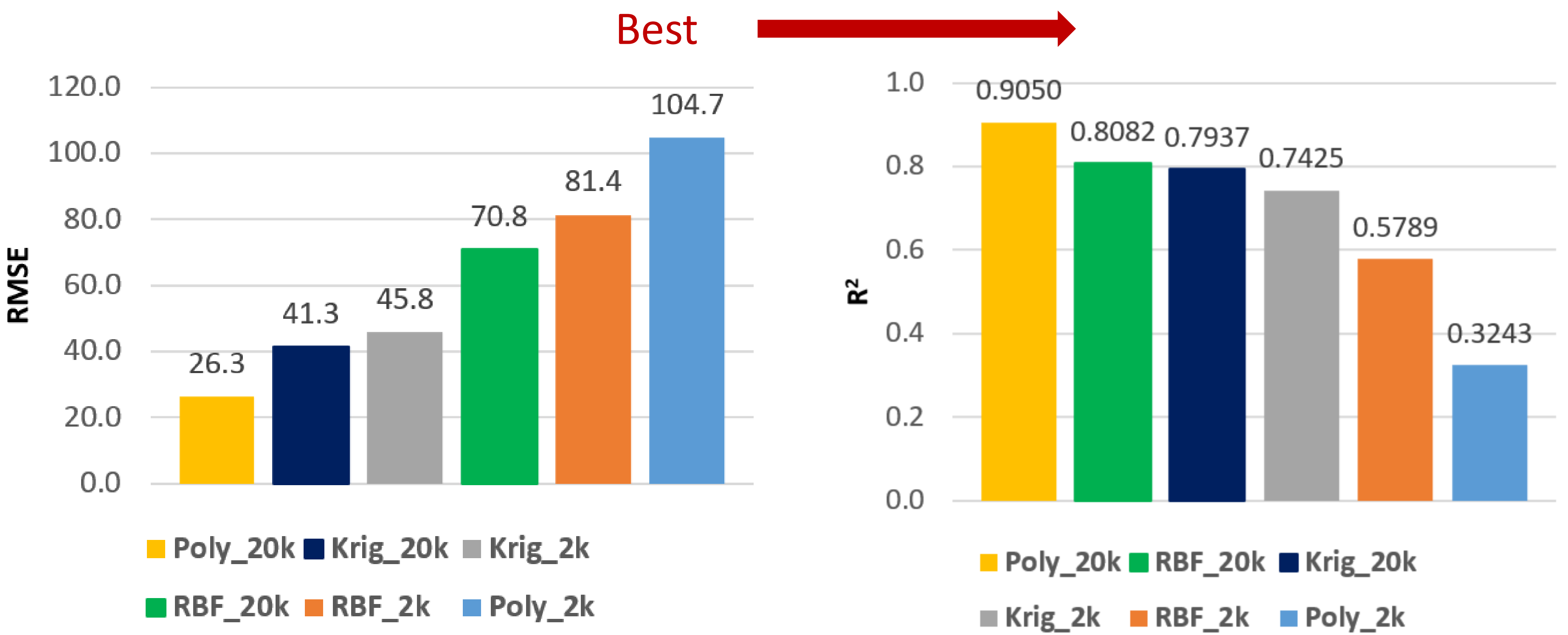
- **Stress Response Surface (RS)**
  - Design of Experiments:
    - Latin Hypercube
  - Two different DoE sizes:
    - 2k, 20k
  - Different RS methods:
    - Polynomial, Kriging, Radial Basis Function





Methods and tools

- **Stress response surface**
  - Root Mean Square Error (RMSE) and coefficient of determination (R2)
  - Sampling: 30 geometries from the unconstrained optimisation process



Methods and tools

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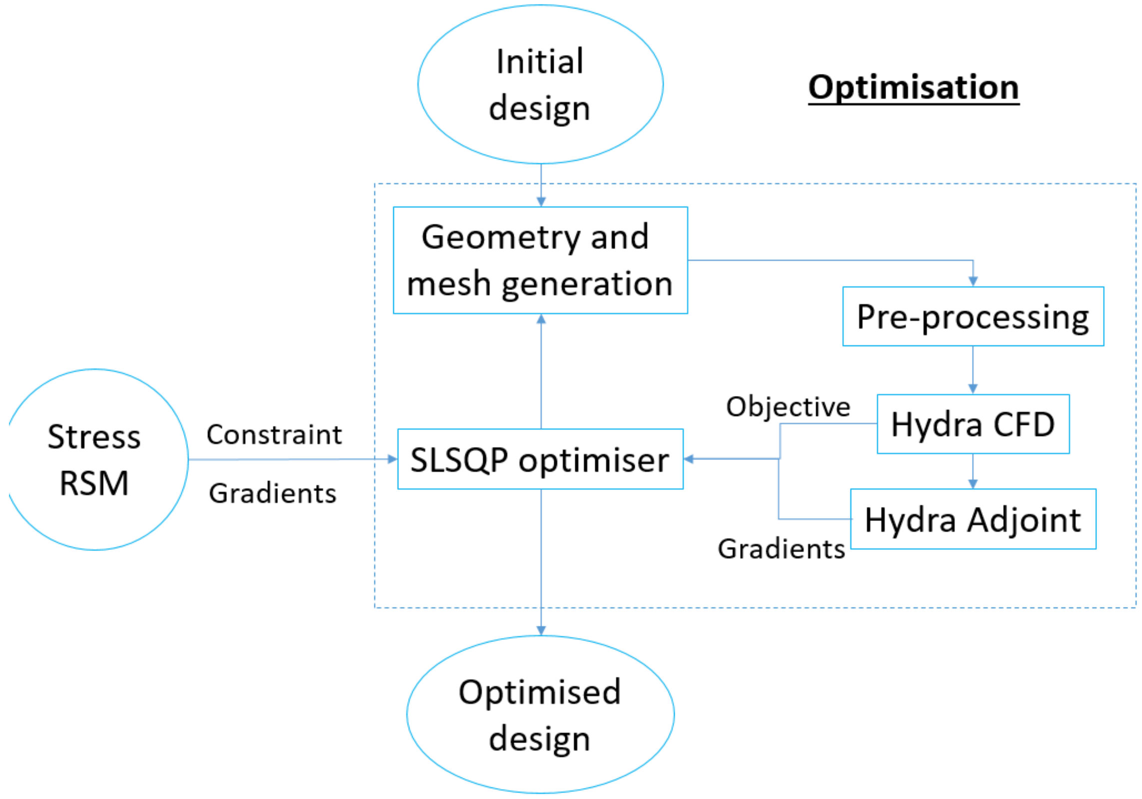
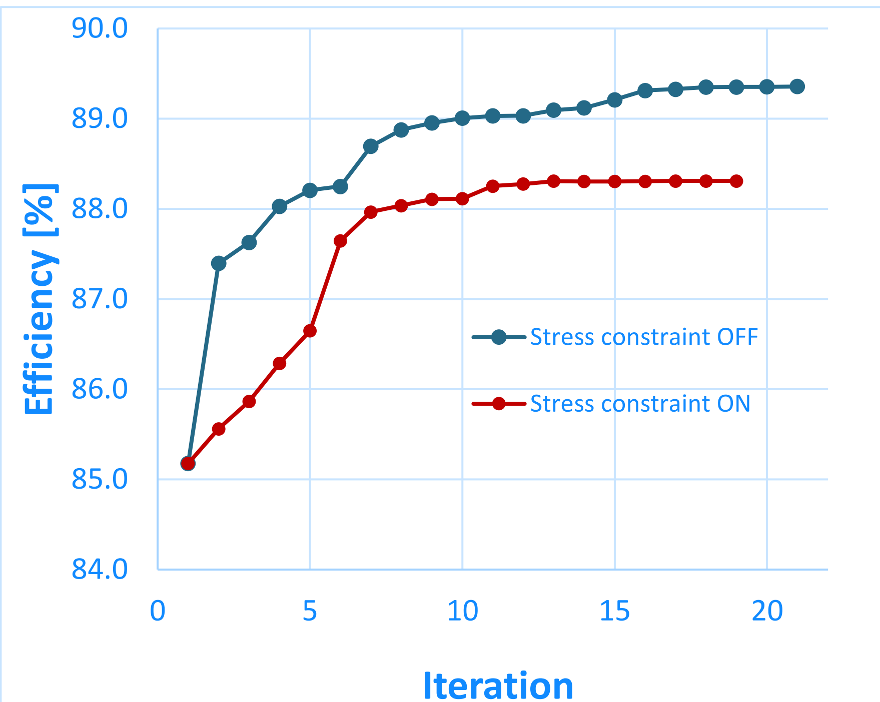
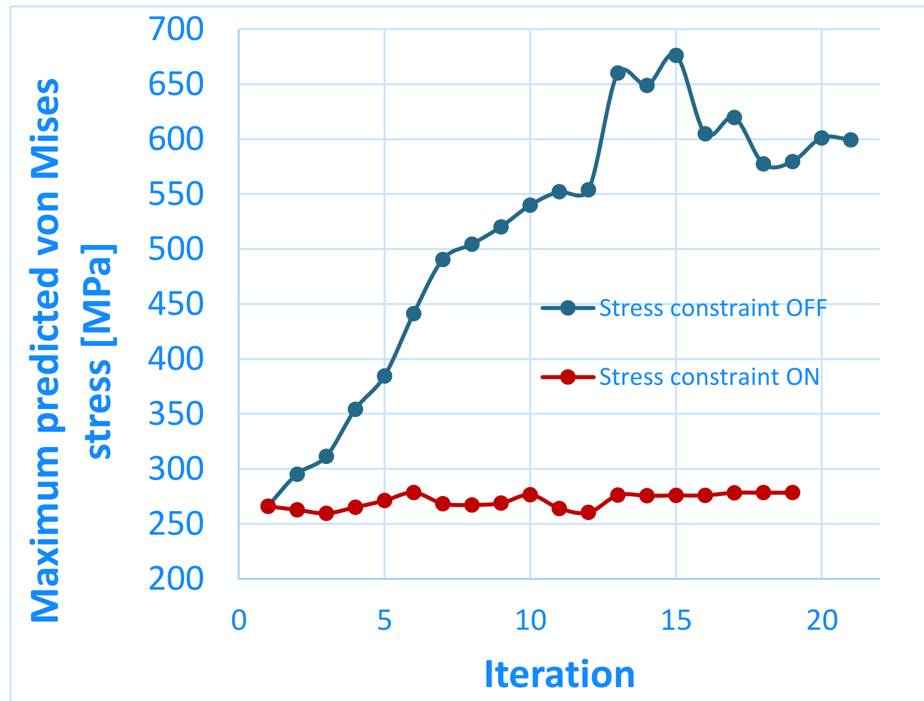
- **Optimisation process**
  - Python - Sequential Least SQuares Programming (SLSQP) algorithm
  - Workflow diagram:



Results and discussion

- **Optimisation results**
  - Unconstrained and stress constrained optimisation histories for R37
  - The maximum stress was successfully constrained to the datum value, but with a cost on the efficiency benefit

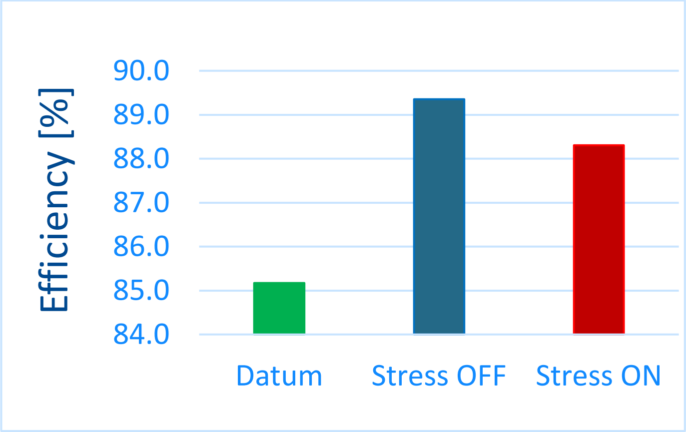


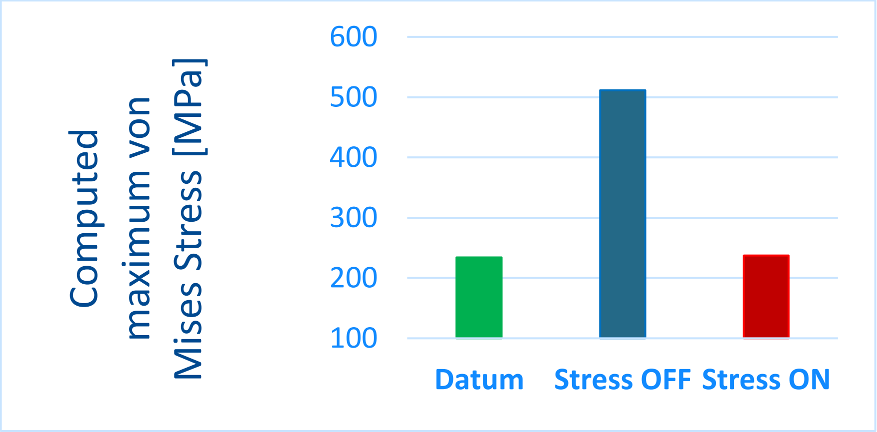


Results and discussion

- **Optimisation results**

Geometry	Efficiency [%]	Computed maximum von Mises stress [MPa]
Datum	85.18	243.8
Optimal with no stress constraint	89.36	511.8
Optimal with stress constraint	88.3	238.1

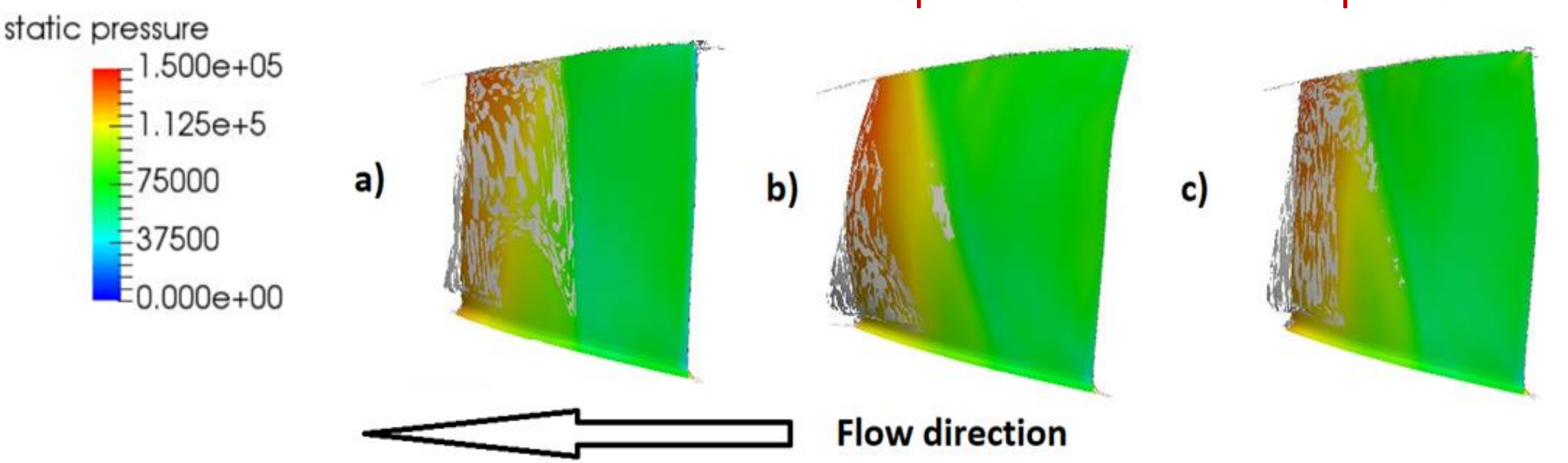




Results and discussion

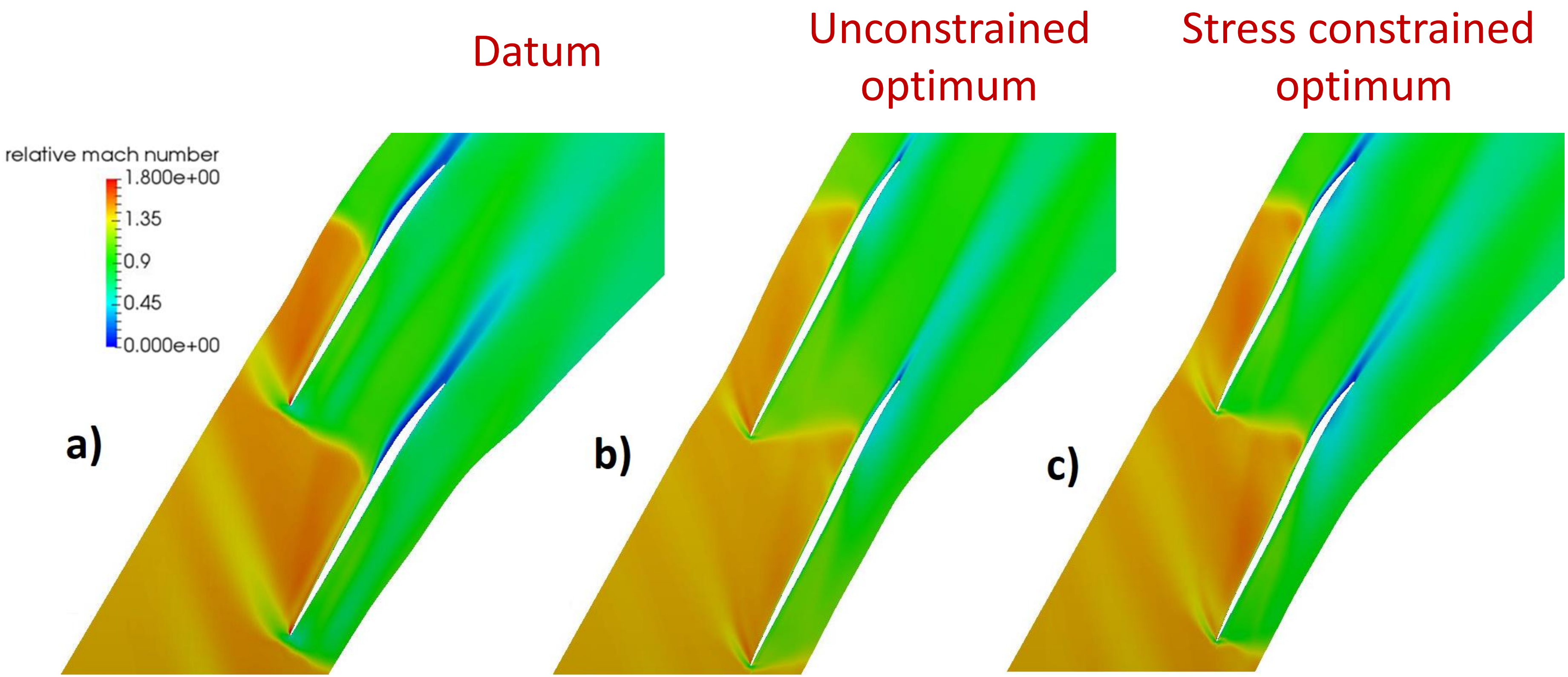
- **Optimal geometry flow features**
  - The pressure distribution on the suction side
  - IsoVolume of zero axial velocity, indicative of where the shock induced flow separation starts, in grey

Datum | Unconstrained optimum | Stress constrained optimum



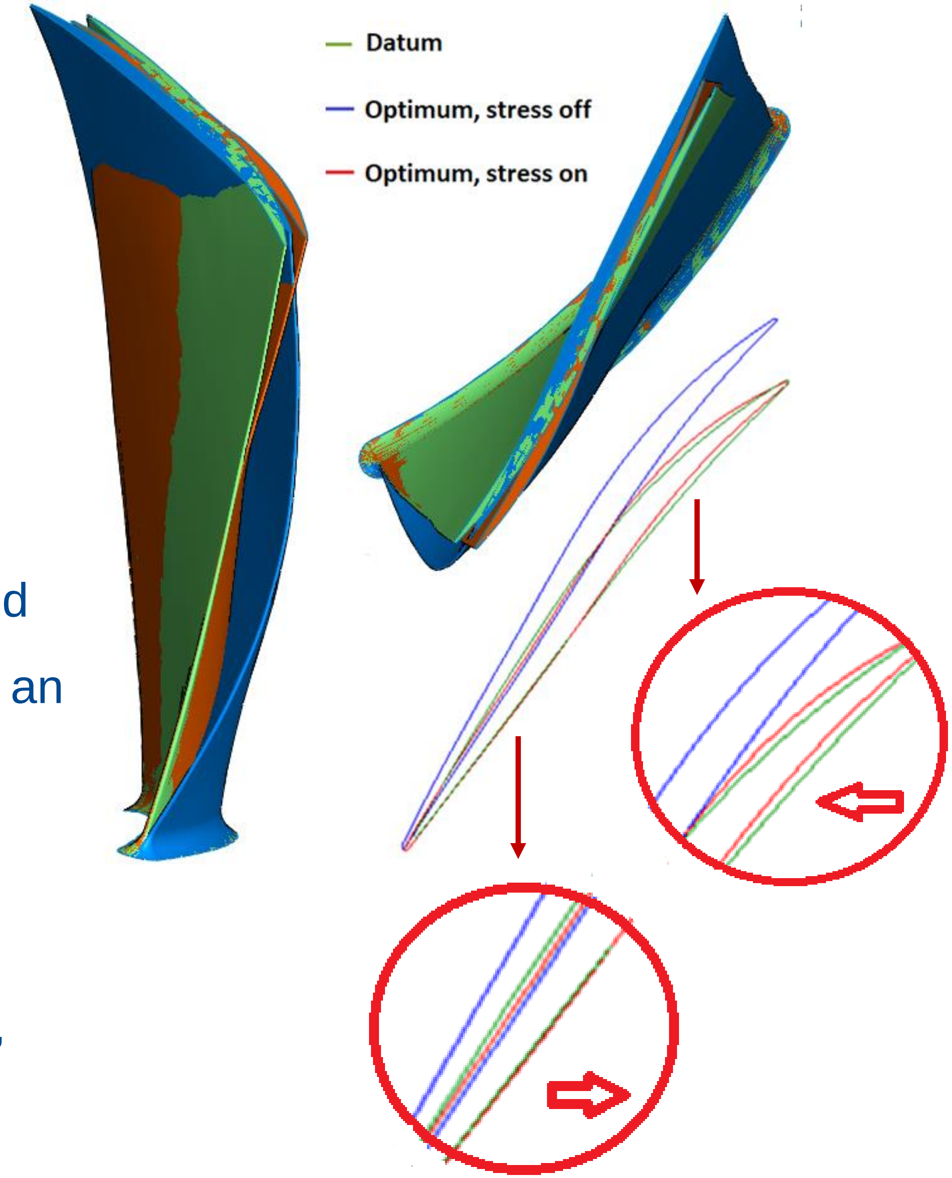
Results and discussion

- **Optimal geometry flow features**
  - Relative Mach number distribution near the tip



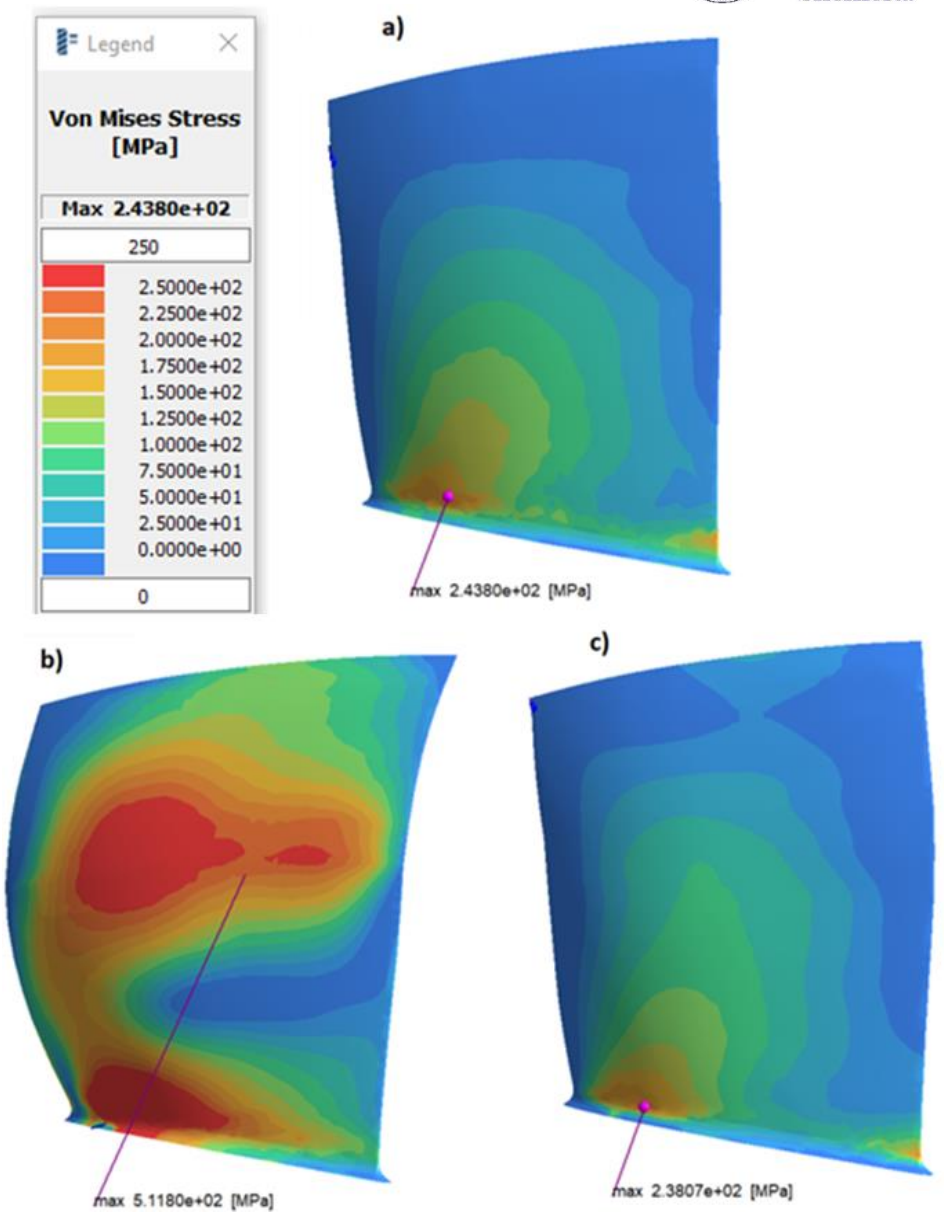
Results and discussion

- **Optimal geometry comparison**
  - 3D blades
  - The corresponding blade profiles superimposed, at mid-span
  - Lean introduced
  - Both optimal geometries (constrained and unconstrained) have developed an s-shape of the airfoil
    - more pronounced for the unconstrained optimum
    - causes a "pre-compression ramp"



Results and discussion

- **Optimal geometry stress distribution**
  - Optimal geometry with stress constraint has a similar stress distribution to the datum
  - The unconstrained optimum geometry blade lean causes a stress increase



Conclusion

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- A response surface based stress constraint has been introduced in the efficiency optimisation of compressors using adjoint method
- Without a structural constraint, the maximum stress on the blade increases drastically, to more than double the datum value
- **Although some of the potential efficiency gain was sacrificed in the favour of structural integrity, the tool successfully improved the Rotor 37 efficiency by over 3%, while maintaining the maximum von Mises stress under the datum value**
- The methodology can be extended to other turbomachinery applications for aerodynamic optimisations with structural constraints at low computational costs while using a large number of design parameters

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