Robustness optimization of welded structure to minimized mass and target fatigue life using RAMDO

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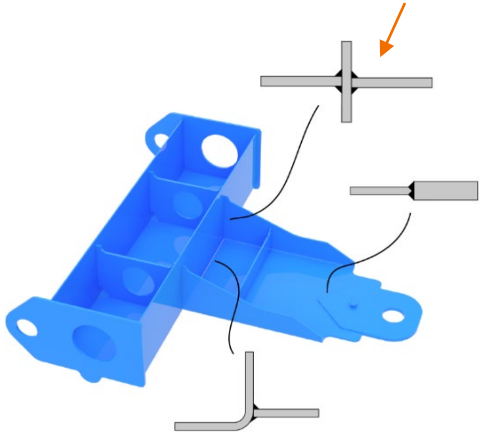
Introduction

- Our motivation for robustness optimization is, that
  - decreasing mass of vehicles enables energy efficiency and decreasing CO2 emissions.
  - and the quality variation affecting fatigue strength can be considered in lightweight design.
- As the weight of the welded structure is minimized, the stress levels at the welds tend to increase, and the fatigue strength of welds becomes the bottleneck in design.
- In general, weld quality has significant effect on fatigue strength of welds.
- We used robustness optimization to
  - minimize the weight of a mock-up structure
  - and to meet the required reliability of 95% for fatigue life, while considering the variation in manufacturing quality.

The mock-up structure and the studied welds

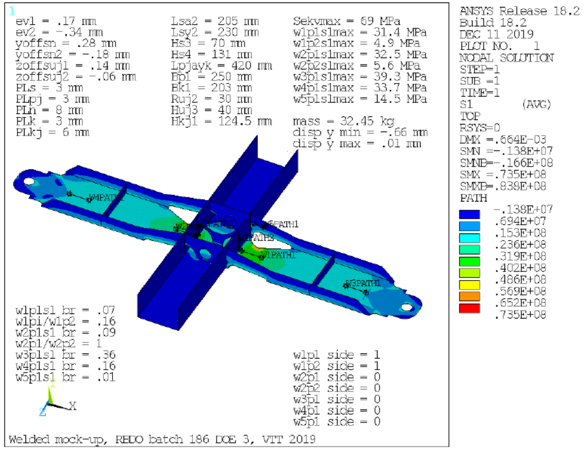
- The welded connections of an industrial target structure are studied using a mock-up structure.
- Two mock-up structures were designed, one for manufacturing and another for structural optimization.
- Parametric FE-models were created for both the structure and the studied weld.



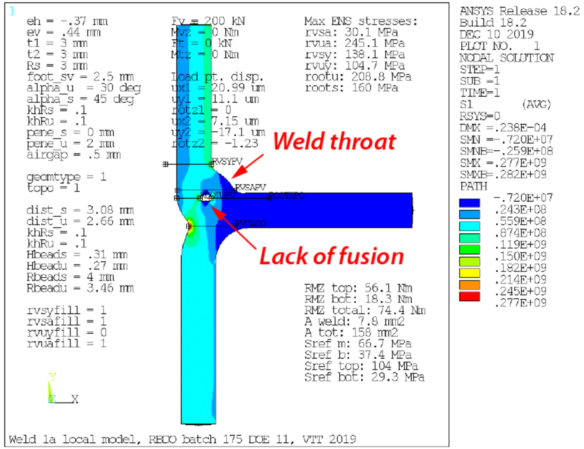
Mock-up structure for measuring the manufacturing quality

Thin plates, structural steel (S355)
Plate at thicknesses 4, 6 and 8 mm.
MAG welding, weld class C.

Global model of welded structure mockup



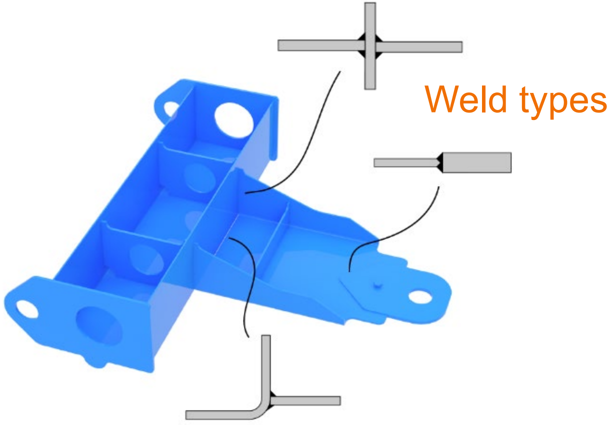
Local model of weld 1a



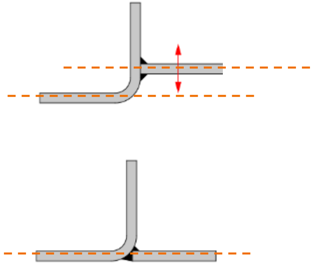
Mock-up structure for fatigue design and optimization

Manufacturing and measurements

- Two 10 piece series of mock-up structures were manufactured.
- By two manufacturers, at typical quality definitions for welding.
- Misalignments at welds were measured using coordinate measuring machine (CMM).

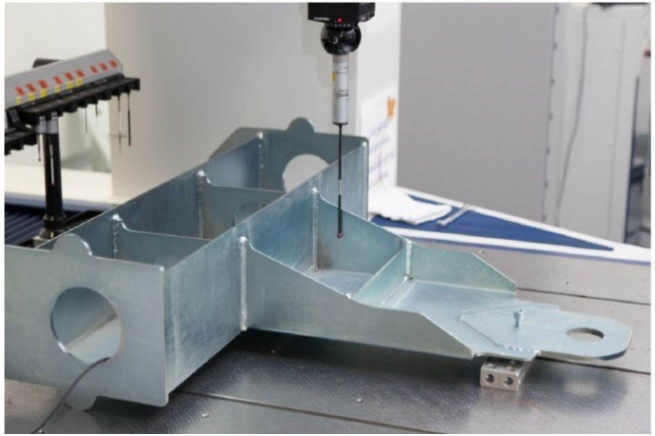


Misalignment



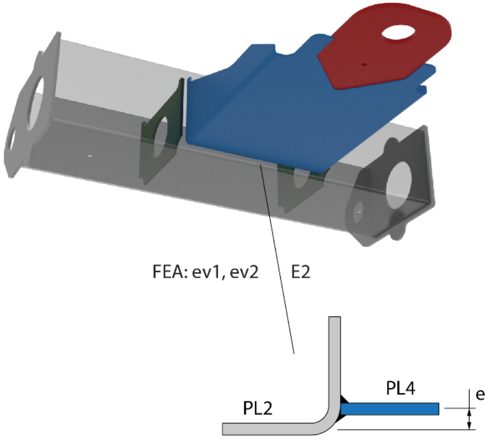
Perfect alignment

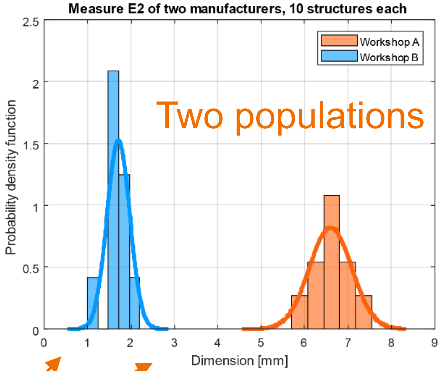
Coordinate measuring machine (CMM)

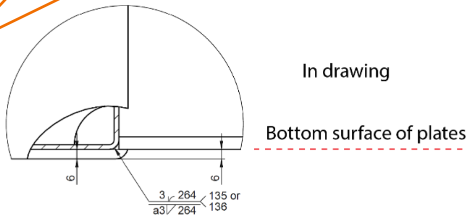


The measured misalignments at welds

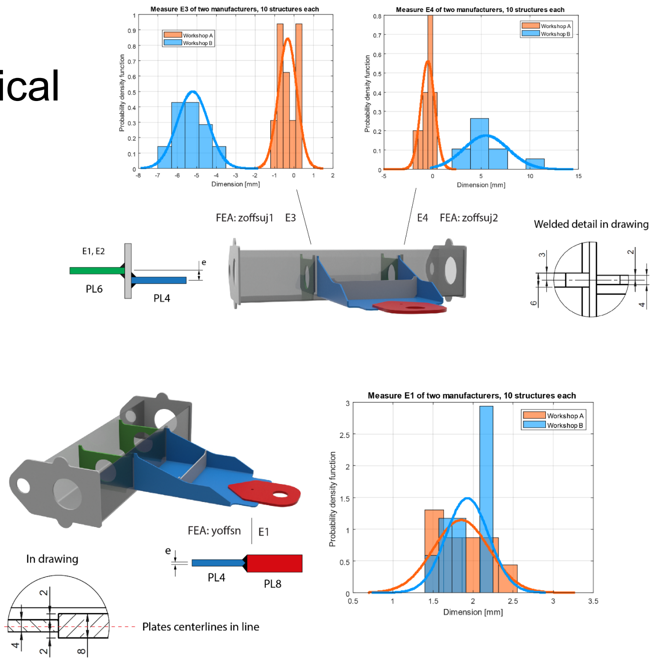
- The measured misalignments are represented as statistical distributions as inputs for reliability based design optimization (RBDO).
- Two manufacturers show as two populations in the statistical distributions.







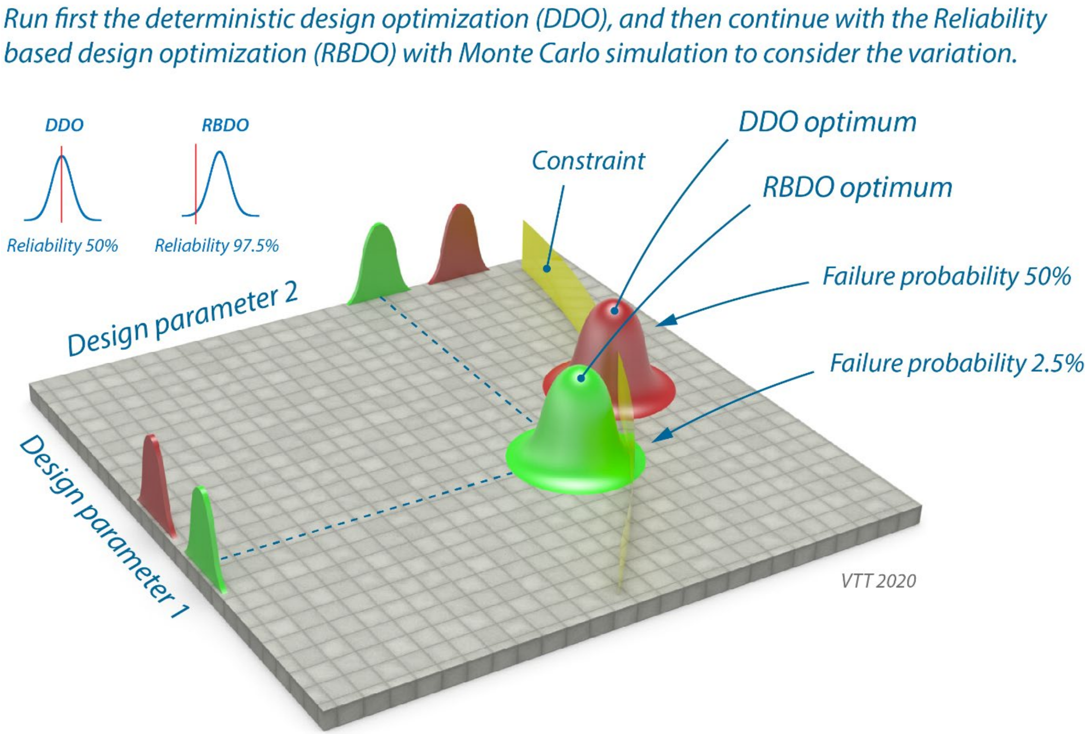
Weld studied in optimization (offsets were removed in current RBDO study)



Other measured welds

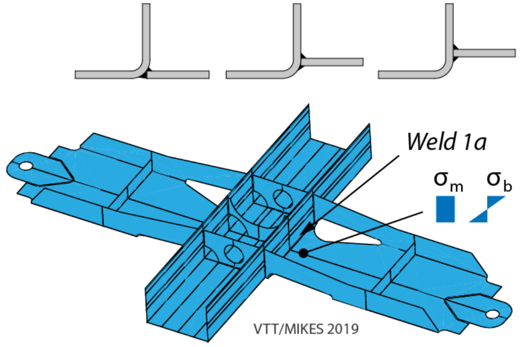
Reliability based design optimization (RBDO)

- 1st step - Traditional optimization.
- 2nd step - Continue with reliability based optimization
  - Find optimum that meets the target reliability, for example 95% survival probability.
  - Surrogate modelling and Monte Carlo simulation are carried out using RAMDO software.

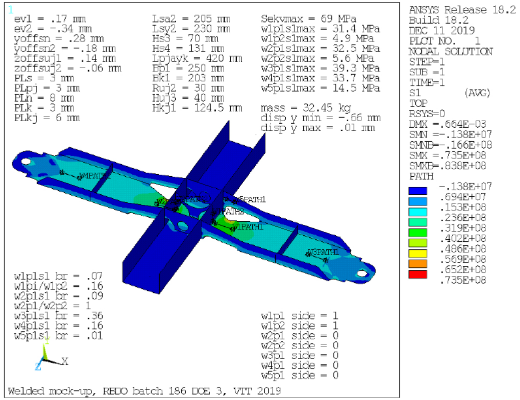


Optimization problem formulation

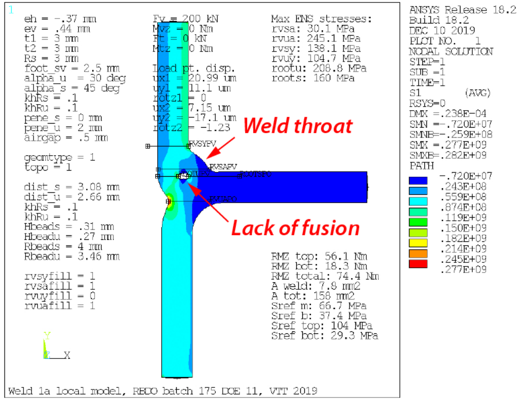
- Minimize mass
- Subject to constraints
  - Fatigue life ≥ 5 million cycles, and target reliability of 95%
  - Max stress ≤ limit value
  - Max displacement ≤ limit value
- At random parameters
  - Misalignments ± 0.5 mm … ± 1.0 mm
  - Lack of weld penetration 0…1 mm
    - As POD-curve
- And random design variables
  - Main dimensions
  - Plate thicknesses
  - Weld throat thickness



Global model of welded structure mockup

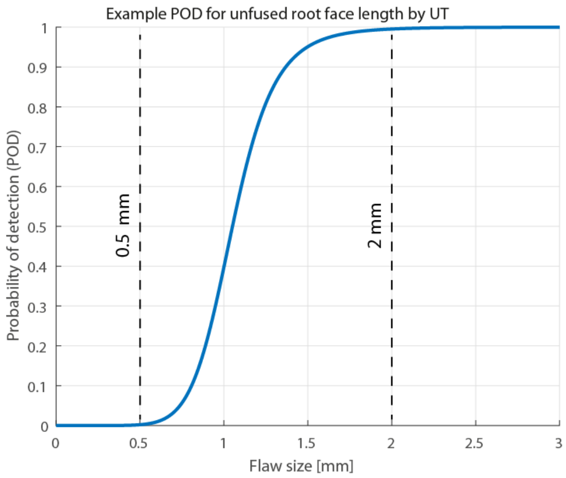


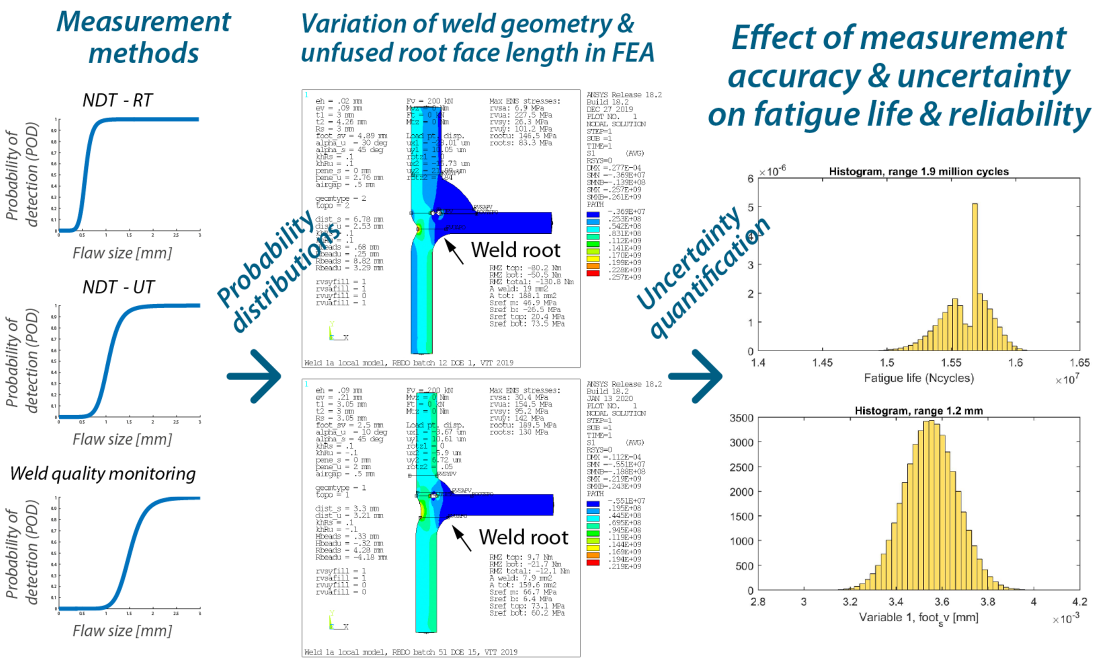
Local model of weld 1a



Using Probability of Detection (POD) curves

- POD curves represent the uncertainty of NDT methods.
- Here applied to weld penetration.
- POD curve is used after differentiation as input in the RBDO workflow.

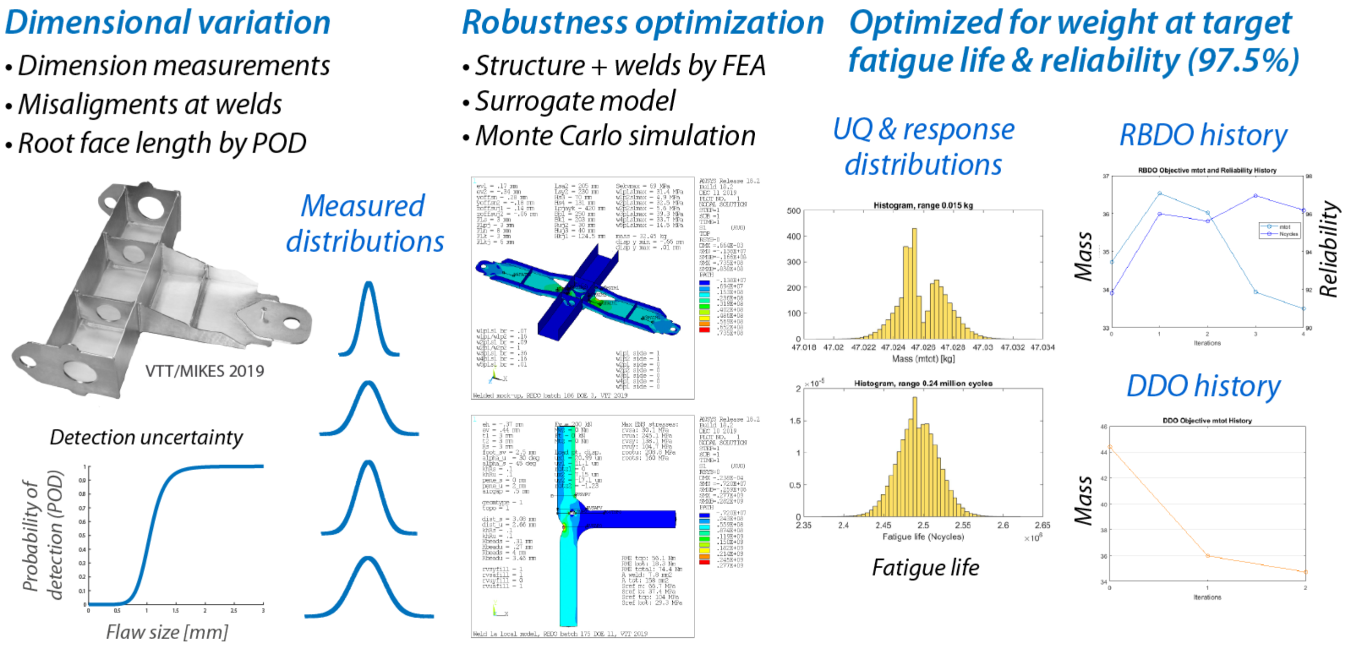




Compare different inspection methods

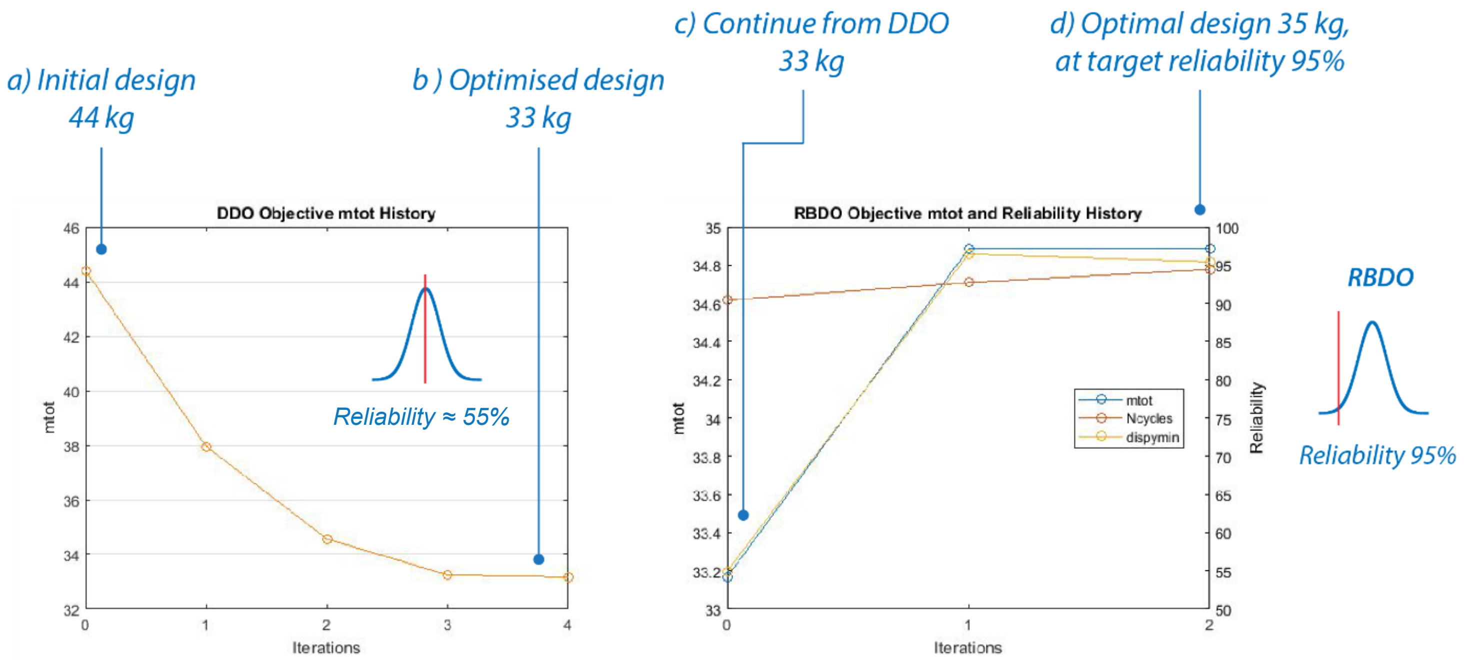
Robustness optimization workflow

- Statistical distributions as inputs to RBDO
  - Misalignments (CMM), weld penetration (POD-curve), and dimensional tolerances.
- RAMDO running FEA macros via MATLAB.
- Two level FE-models for the structure and the weld.



Optimization history

- Mass of initial design 44 kg is reduced to 33 kg after DDO, at reliability of 55%.
- Then after RBDO the optimum with mass of 35 kg and 95% reliability is found.



Deterministic design optimization (DDO) Reliability based design optimization (RBDO)

Effect of weld quality levels in optimization

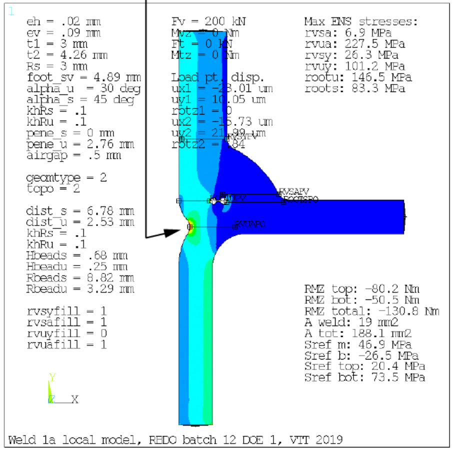
- Weld quality level affects the possible weight reduction of the structure.
- Limiting the constraint of transition angle to smooth values in optimization leads to a lighter structure.
- In engineering practice this would be equivalent to increasing the weld quality class.
- The optimization results agree with the engineering experience.

Sharp notch at weld toe as 'Bottleneck'

Abrupt transition at outside lower weld toe

Optimization 1

Lower weld quality class



Bigger mass at optimum

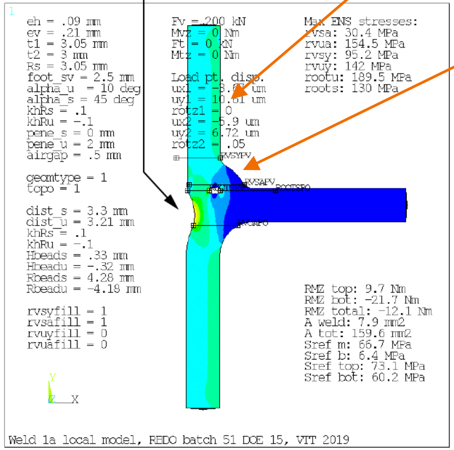
Smooth transition at outside lower weld toe

Thinner plate

Smaller weld

Optimization 2

Higher weld quality class



Smaller mass at optimum

Summary

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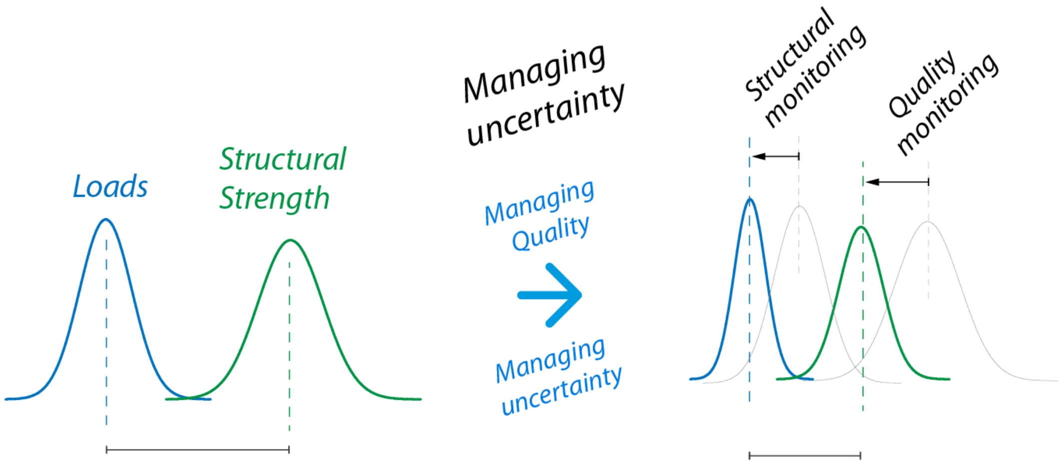
- Weld quality criteria can be linked to fatigue life in reliability based design optimization.
- The two level FE-modelling allows for efficient optimization of welded structures.
- About 25% decrease in mass was achieved with the example structure, and the required reliability of 95% was met for the fatigue life, while considering the measured variation in manufacturing quality.
- As user experience, the learning curve with RAMDO was short.
  - The connection between RAMDO, MATLAB and the FEA-software was easy to implement.
  - RAMDO can be easily connected to any software that can be scripted and started from command line.

Future thoughts

- The 1) increasing amount of available measured data, 2) modern software and 3) efficient computers enable use of reliability based approaches in engineering design.
  - The Big Data and monitoring trends increase the available information of loads, material defects, and manufacturing quality variation.
  - The increasing amount of available measured data improves reliability of case specific load distribution and structural strength distribution.
- The future plan is to apply robust design methods to actual industrial structures.



High safety factor & heavy structures

Considering reliability enables lighter structures

Thank You!

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