Assessment of Uncertainties in Life Prediction of Fatigue Crack Initiation in Rails – Influence of Residual Stresses From Manufacturing

Jonas W Ringsberg[1] **and B Lennart Josefson**[2]

Chalmers University of Technology
[1]Department of Shipping and Marine Technology
[2]Department of Applied Mechanics
Göteborg, SWEDEN

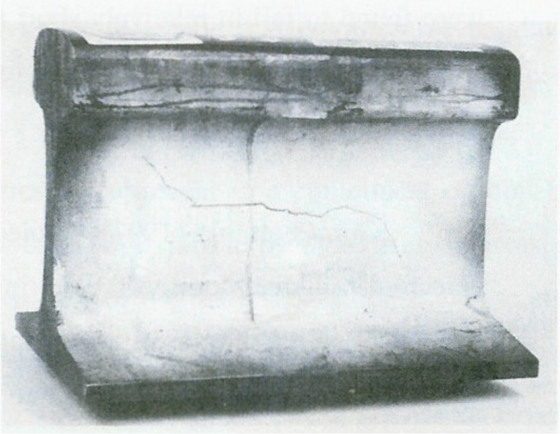
Outline of presentation

- Introduction and motivation for study
- Finite element models and analyses
- Fatigue analysis
- Statistical analysis
- Conclusions

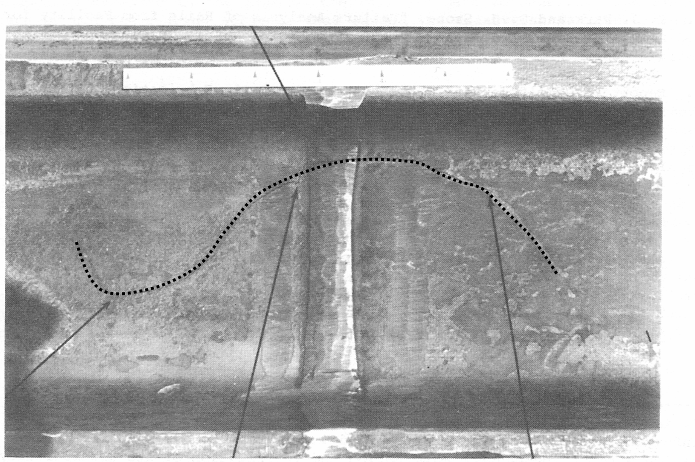
Introduction and motivation for study

- Modern rails are subject to a complex loading situation with high **local stresses** at the railhead during a wheel passage superposed with a **global bending stress** in the rail cross section.
  - *Hence, a material point near the rail's surface is subject to cyclic, fatigue loading with rotating principal stresses.*
- The manufacturing of rails may give rise to additional concern for fatigue cracks starting from defects in the weld zone.
  - *Failures at rail welds and growth of cracks starting in the weld zone have been studied in Mutton and Alvarez [2] and Beretta et al. [3].*
- A completed weld, a flash butt weld or a thermite weld, typically exhibits high tensile residual stresses in the web region.
  - *These stresses may increase the risk for fatigue failure as they are relatively unaffected by the subsequent resulting high local stresses at the railhead during wheel passages; see Skyttebol et al. [5].*

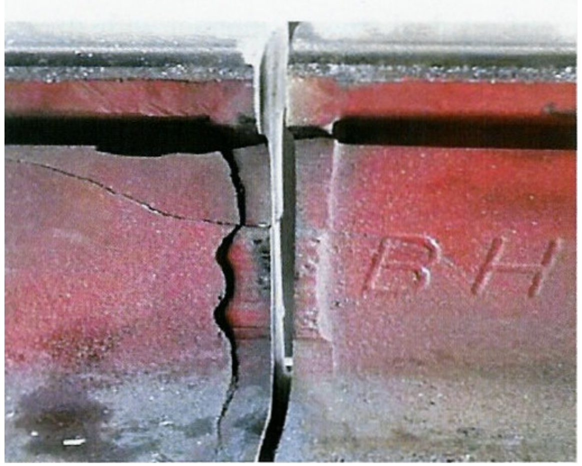
Introduction and motivation for study



S. Marich (1983)



D.E. Sonon (1980)



P.J. Mutton (2003)

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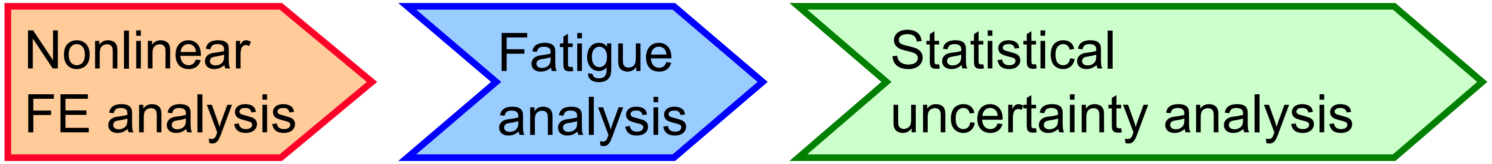
Introduction and motivation for study

- The influence of the **tensile residual stress level** (relative to the service stress level) with respect to the **risk for initiation of fatigue cracks** in the **web in the weld zone** of a rail is studied.



Nonlinear FE analysis

Fatigue analysis

Statistical uncertainty analysis

- Parameter variation in FE analysis:
  - *the welding residual stress distribution (shape) and magnitude,*
  - *the service load magnitude, and*
  - *the material parameters used in the fatigue life estimation.*
- Fatigue analysis:
  - *study of fatigue crack initiation using the Dang Van criterion.*
- Statistical uncertainty analysis:
  - *study of variances according to the Gauss approximation formula.*

Finite element models and analyses

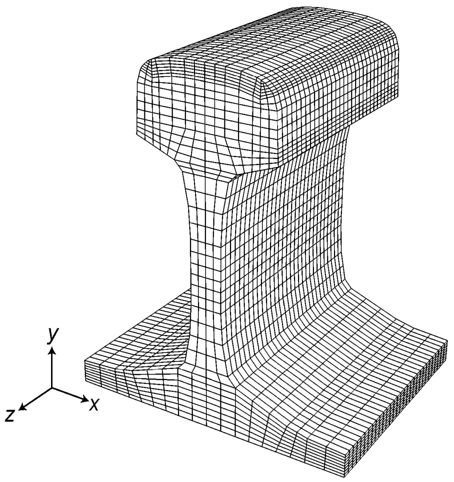
- Ringsberg et al. [9]: FE tool developed for the analysis of RCF of rails.
  - ***Track model:*** *track dynamics.*
  - ***Rail model:*** *local/detailed RCF analysis.*

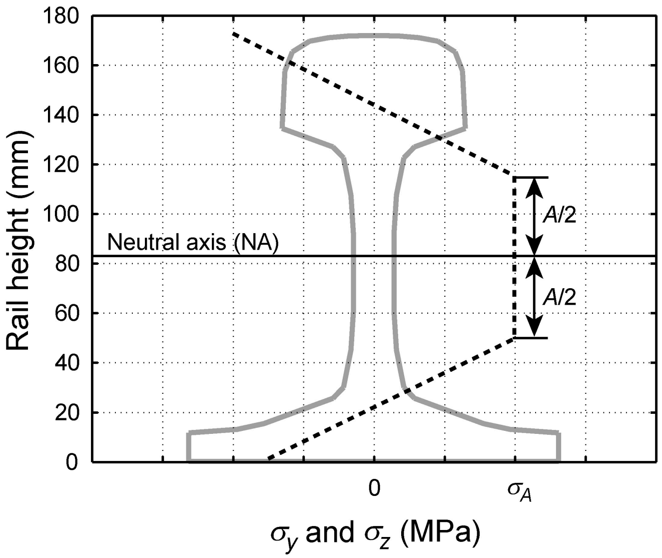
- The rail model is a 3D FE model made of 8-node brick elements.
  - *Elasto-plastic material behaviour of the steel grade 900A was modelled by a linear kinematic hardening model.*
  - *A Hertzian contact load distribution simulates a traveling wheel (normal and tangential loads).*
  - *An initial welding residual stress field representing a flash butt weld was introduced at the weld position.*

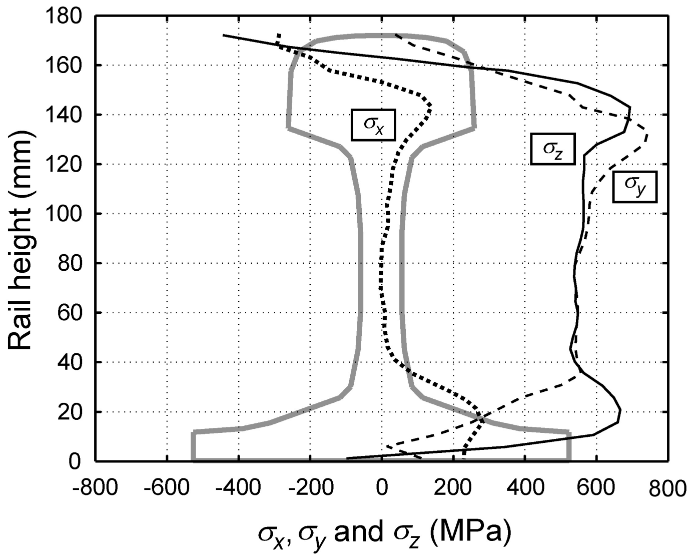
Finite element models and analyses

- Welding residual stress field:
  - *Equally large stress components in the vertical (y) and longitudinal (z) directions.*
  - *No stress in the lateral (x) direction.*

- The residual stress components were given a piece-wise linear shape:
  - *tensile magnitude σ_A in the web, and the extent of the tensile zone A.*
  - *This shape is a simplification of the stress fields determined numerically and experimentally by Skyttebol and Josefson [4] and by Tawfik [11].*



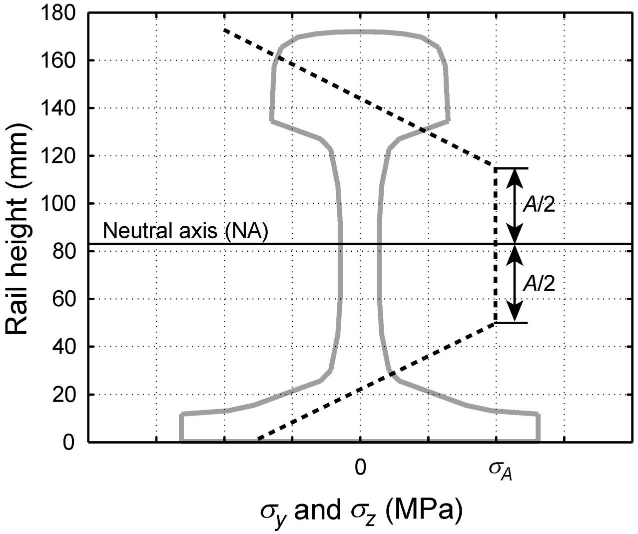




Finite element models and analyses

- Simulated service load situation:
  - *The heavy haul iron-ore line situated in the North of Sweden (“Malmbanan”).*
  - *10 wheel passages on the rail were simulated (elastic shakedown in the web).*

Axle load or *p* @ velocity (10^3 kg or MPa @ km/h)	σ_A (MPa)	*A* (mm)	τ_e (MPa)
5 or 720 @ 70	300	60	150
22.5 or 1280 @ 100	450	70	168
25 or 1320 @ 50	600	80	190
30 or 1410 @ 60			



Fatigue analysis

- The Dang Van criterion was used for evaluation of the results from the FE analyses.

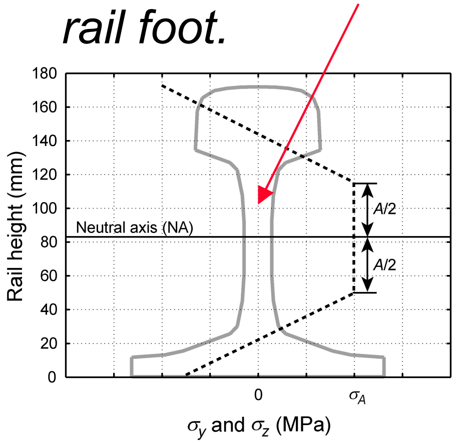
$$\tau_{\mathrm{a}}(t) + a_{\mathrm{DV}}\sigma_{\mathrm{h}}(t) > \tau_{\mathrm{e}}$$

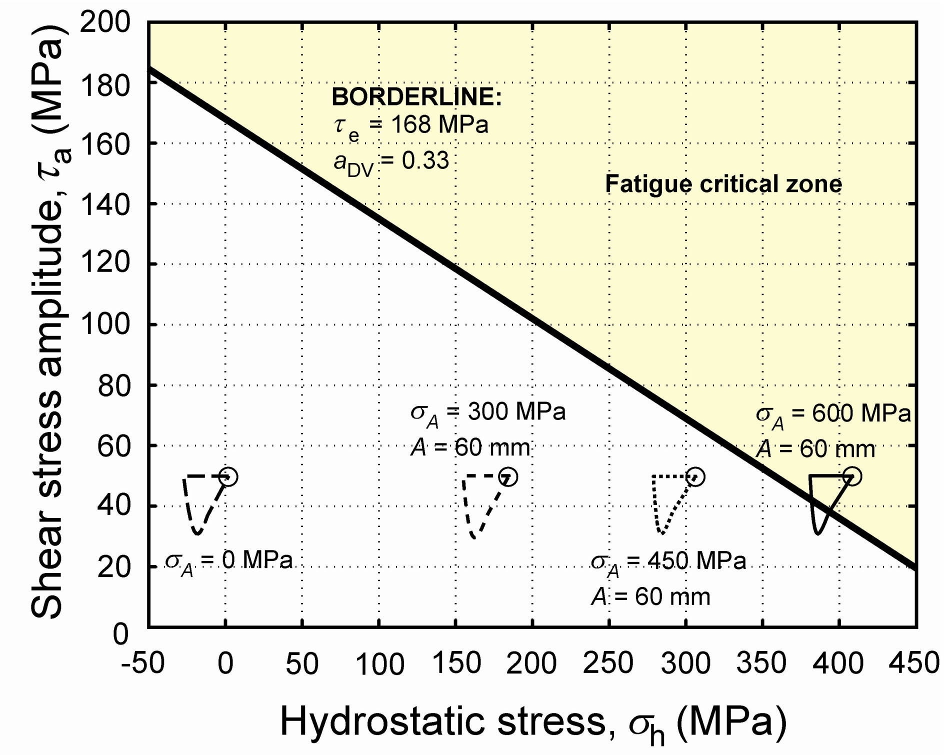
- $\tau_{\mathrm{a}}(t)$ is the shear stress “amplitude”,
  - *i.e. deviation from mid value during a stress cycle on a shear plane.*
- $\sigma_{\mathrm{h}}(t)$ is the **total hydrostatic stress** at elastic shakedown.
  - *It includes the history (residual stresses) from the welding, the global load and the contact load from the wheel passage.*
- τ_{e} and a_{DV} are material parameters obtained from two fatigue limit tests.

Fatigue analysis

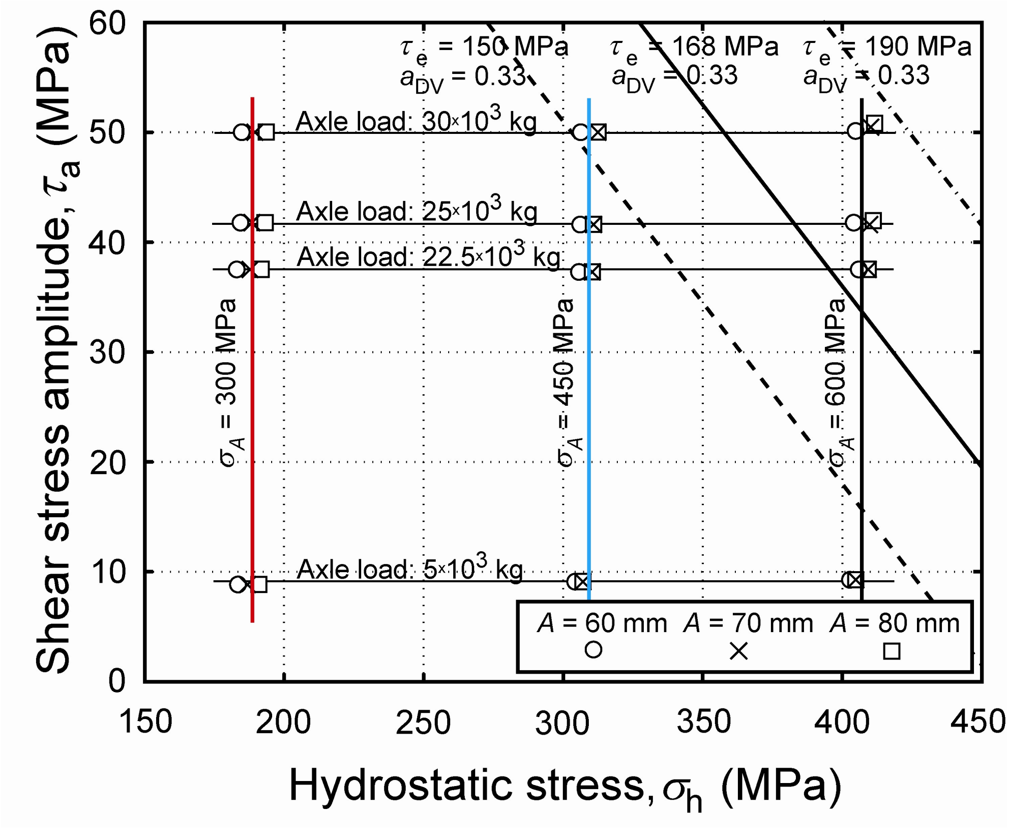
- For every material point considered in the fatigue analysis, a closed material response cycle (MRC) represented by $\tau_a(t)$ and $\sigma_h(t)$ is plotted in the Dang Van diagram.

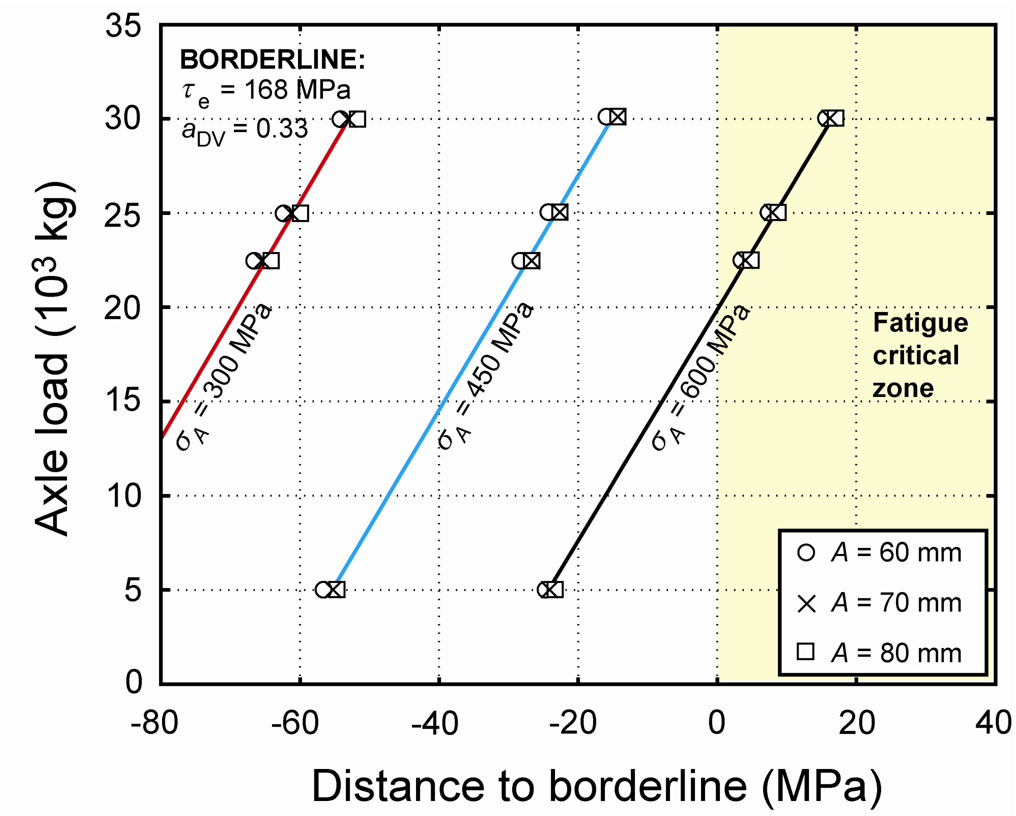
- Example in the figure:
  - *Axle load 30·10^3 kg.*
  - *Train speed 60 km/h.*
  - *Fatigue-critical point in the rail web region 100 mm from the rail foot.*





Fatigue analysis





Statistical analysis

- The accuracy in the fatigue crack initiation prediction depends on the uncertainties in:
    - *the residual stress shape and magnitude,*
    - *the service load,*
    - *the mechanical properties, and*
    - *the model errors.*
- The uncertainty was estimated here considering uncertainties in:
    - *the residual stress shape and magnitude,*
    - *the service load level (the maximum contact pressure), and*
    - *the fatigue limit.*
- The expectancies E[·] and variances Var(·) of the stochastic variables were obtained from references in the literature:
    - E[A] ≈ *60 mm and* Var(A) ≈ *302.*
    - E[σ_A] ≈ *360 MPa and* Var(σ_A) ≈ *1002.*
    - E[p] ≈ *1410 MPa and* Var(p) ≈ *2712.*
    - E[τ_e] ≈ *168 MPa and* Var(τ_e) ≈ *252.*

Statistical analysis

- Assume that σ_A, A, p and τ_e are stochastic variables one has for the difference ξ,

$$\xi = \log(\tau_e) - \log(\tau_a(t) + a_{DV}\sigma_h(t))$$

$$\mathrm{Var}(\xi) \approx \sum_{i=1}^{4}\left(\frac{\partial\xi}{\partial\log(X_i)}\right)^2 \mathrm{Var}(\log(X_i)) + 2\sum_{i<j}^{4}\frac{\partial\xi}{\partial\log(X_i)}\frac{\partial\xi}{\partial\log(X_j)}\mathrm{Cov}(\log(X_i),\log(X_j))$$

- The Gauss approximation formula gives:

$$\mathrm{Var}(\log(X_i)) = \mathrm{Var}(X_i)/\mathrm{E}[X_i]^2$$

- Requirement of a zero net longitudinal residual stress component in a vertical plane at the weld. The relation between the variables can be expressed as $\sigma_A \cdot A \approx$ constant which gives:

$$\mathrm{Cov}(\log(\sigma_A),\log(A)) = -\mathrm{Var}(\log(\sigma_A))$$

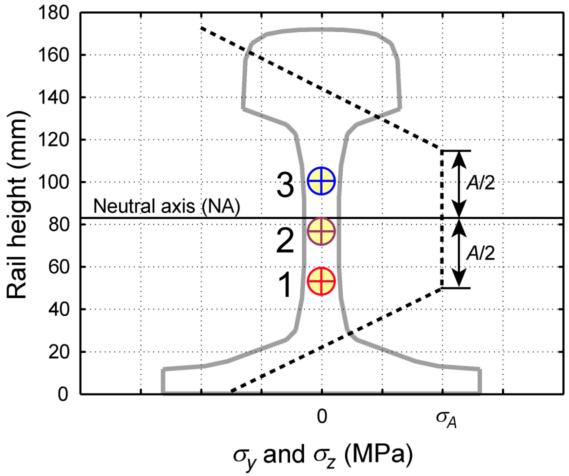
Statistical analysis

$$\tau_{\mathrm{a}}(t) + a_{\mathrm{DV}}\sigma_{\mathrm{h}}(t) > \tau_{\mathrm{e}}$$

$$\xi = \log(\tau_{\mathrm{e}}) - \log(\tau_{\mathrm{a}}(t) + a_{\mathrm{DV}}\sigma_{\mathrm{h}}(t))$$

$$\mathrm{Var}(\xi) \approx \sum_{i=1}^{4}\left(\frac{\partial\xi}{\partial\log(X_i)}\right)^2 \mathrm{Var}(\log(X_i)) + 2\sum_{i<j}^{4}\frac{\partial\xi}{\partial\log(X_i)}\frac{\partial\xi}{\partial\log(X_j)}\mathrm{Cov}(\log(X_i),\log(X_j))$$

	Position 1: d_y = 53 mm	Position 2: d_y = 76 mm	Position 3: d_y = 100 mm
σ_A: residual stress level	761	646	749
A: extent of tensile residual stress	1121	24	36
τ_e: fatigue parameter	625	625	625
p: (maximum) contact pressure	112159	171179	280363
The “covariance term”	-1027	-137	-183
Var(ξ)	**113640**	**172336**	**281590**



The uncertainty in the risk for initiation of fatigue cracks is dominated by the uncertainty in the contact load level.

Conclusions

- The representation of the welding residual stress field was simplified compared with similar investigations.
  - *It was deemed satisfactory for a quantitative investigation.*

- The fatigue analysis showed that:
  - *the presence of welding residual stresses increases the risk for fatigue crack initiation, and*
  - *the higher the magnitude of the stresses (σ_A) the larger is this risk for fatigue failure.*

- The statistical analysis showed that:
  - *the contact load, p, had the greatest influence on* Var(ξ),
  - *the welding residual stress magnitude, σ_A, was the second most influencing parameter,*
  - *the fatigue parameter, τ_e, was the third most influencing parameter,*
  - *followed by the welding residual stress distribution, A.*