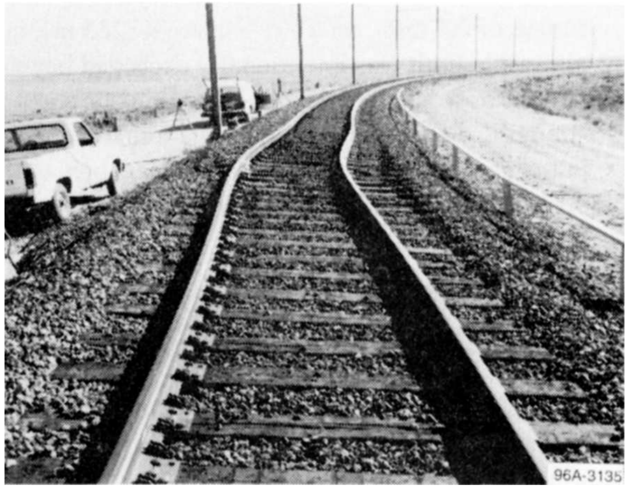
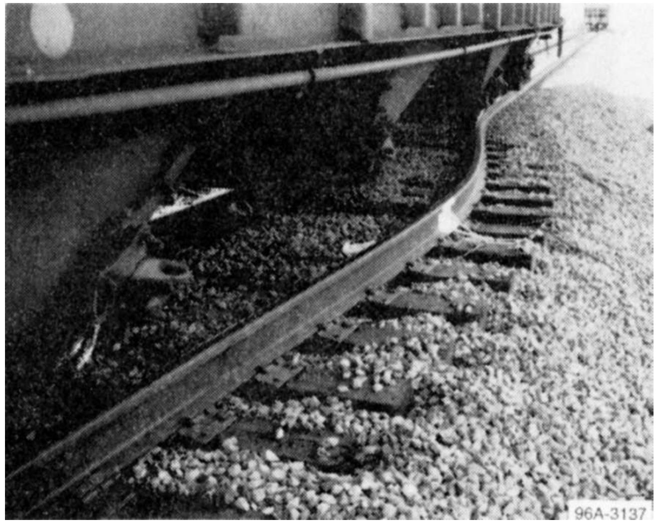
Contribution of Ultrasonic Rail Stress Analysis to Track Maintenance





Source: A. Kish 1996

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Phone: +49 (0)681 / 9302 – 3840
Email: eckhardt.schneider@izfp. fraunhofer.de

Fraunhofer IZFP

Fraunhofer at a Glance

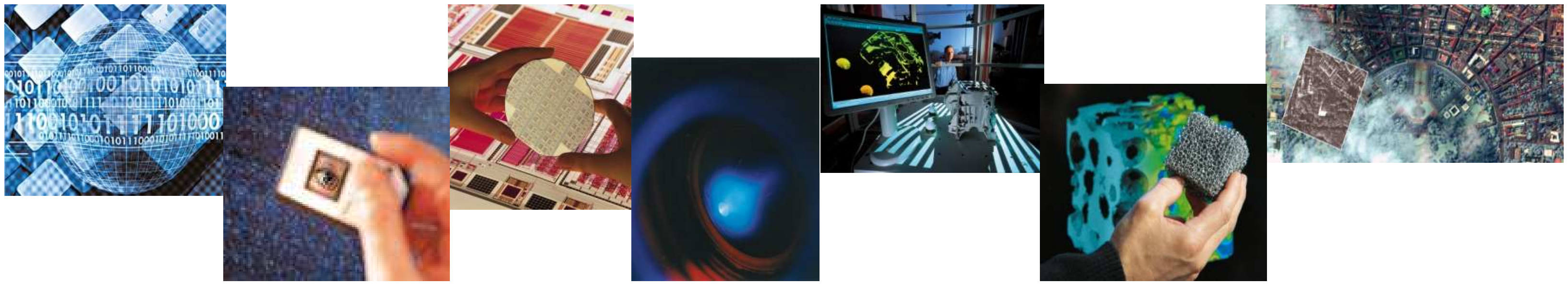
60 Institutes

17 000 employees

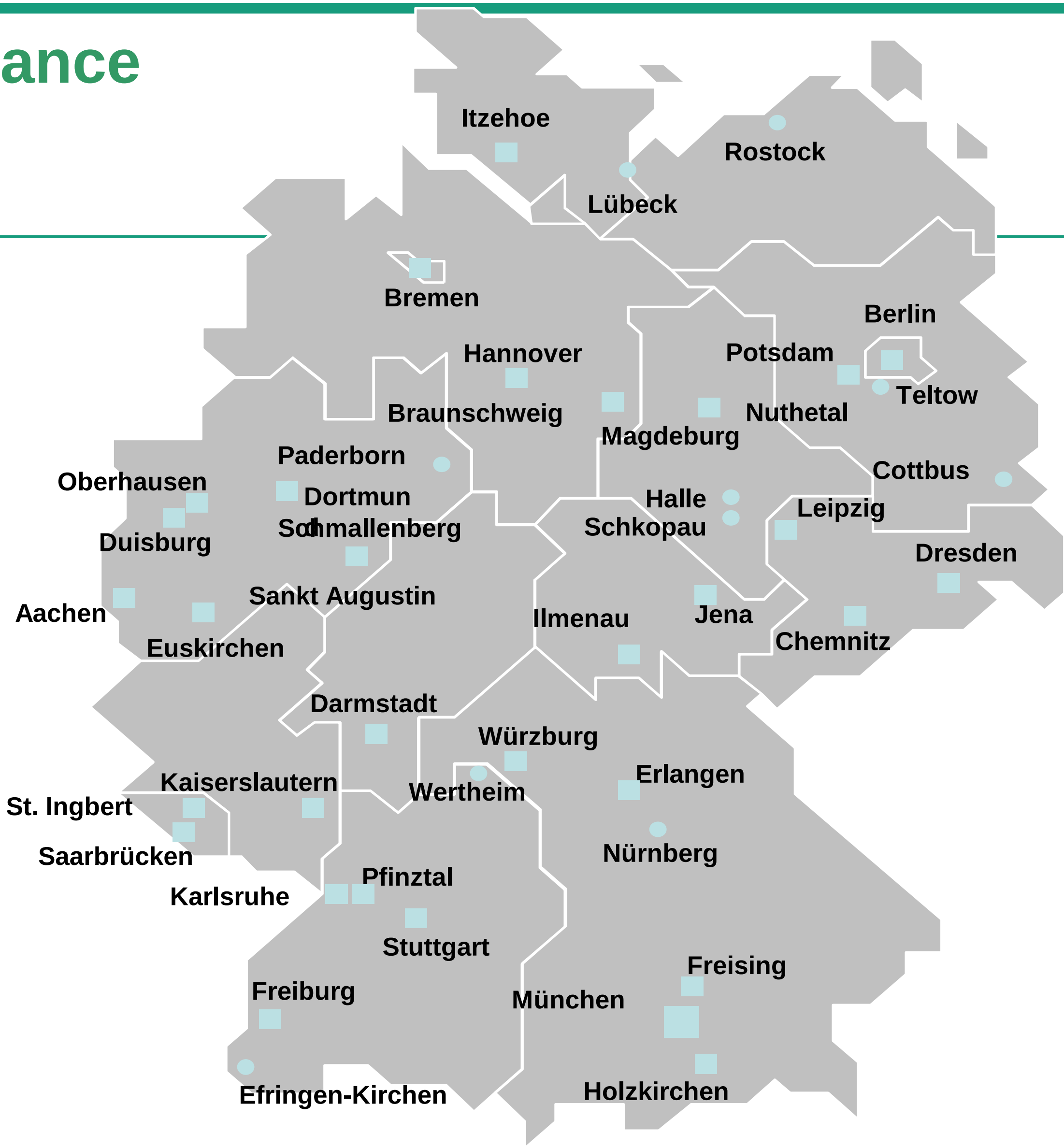
about €1,6 billion
research budget

7 Groups

- Information and Communication Technology
- Life Sciences
- Materials and Components
- Microelectronics
- Production
- Surface Technology and Photonics
- *Defense and Security*



Fraunhofer at a Glance



IZFP at a Glance

Saarbrücken

Dresden

Methods and Techniques

Ultrasonic, Eddy Current, Electromagnetics, Micromagnetics, Microwave, x-ray-Radio-scopie, Tomo-, Laminography, Atomic-Force-Mikroscopy, Thermography, Acoustic Emission, Nuclear Magnetic Resonance

Employees

120 Scientists and engineers

12 Technicians & 29 supporting personnel

130 PhD and Diploma students, Research assistants Guest Scientists

Finances

23 Mio €, from which

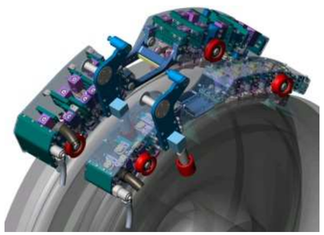
11,8 Mio € by orders from industry

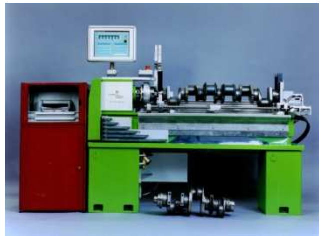
Fraunhofer IZFP

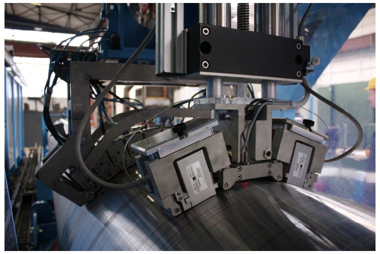
IZFP at a Glance

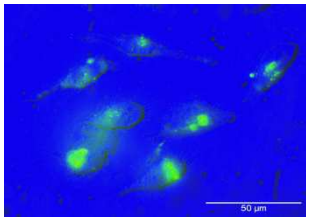
Business Units

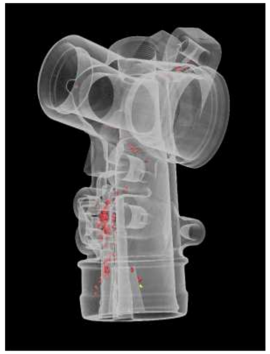
Railway	SB
Automotive	SB
Aviation, Aerospace	DD
Metal Production, Processing	SB
Plant, Installation	SB
Power Plant, Power Line	SB
Piping Systems, Pipelines	SB
Electronics and Micro-Nano-Systems	DD
Environment, Life Sciences	DD





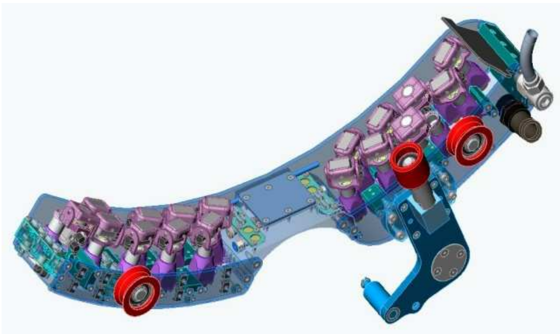


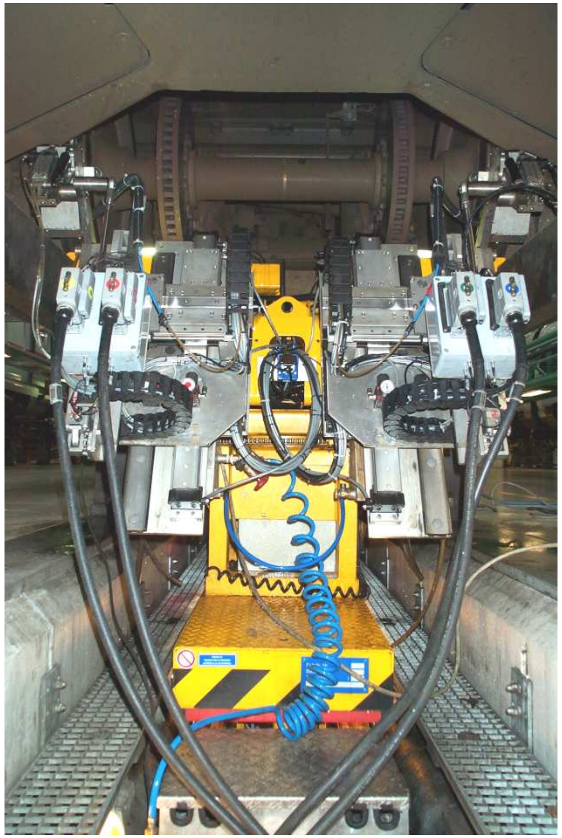


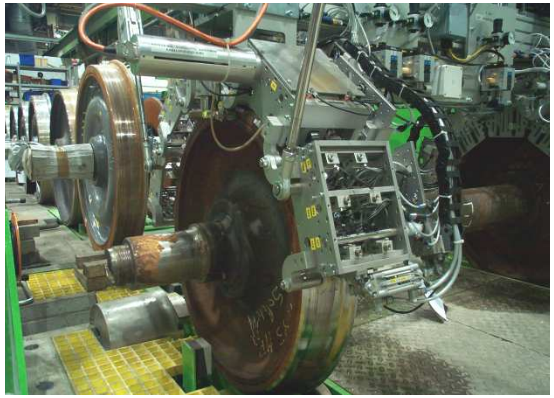


IZFP Developments for Railroads

Automated systems AURA and UFPE to detect defects in wheels



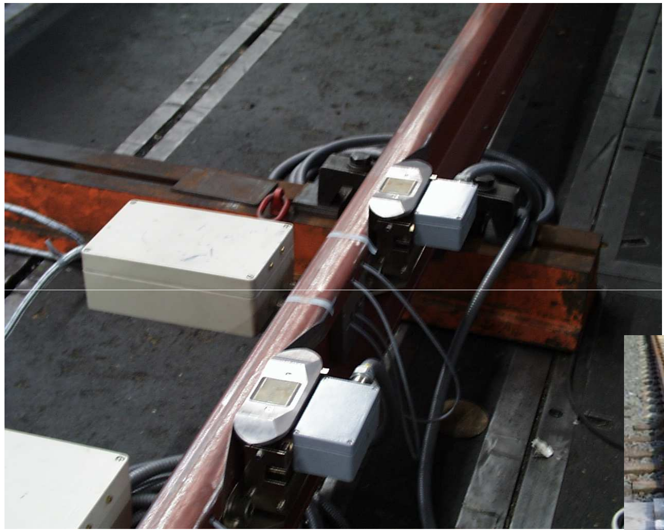


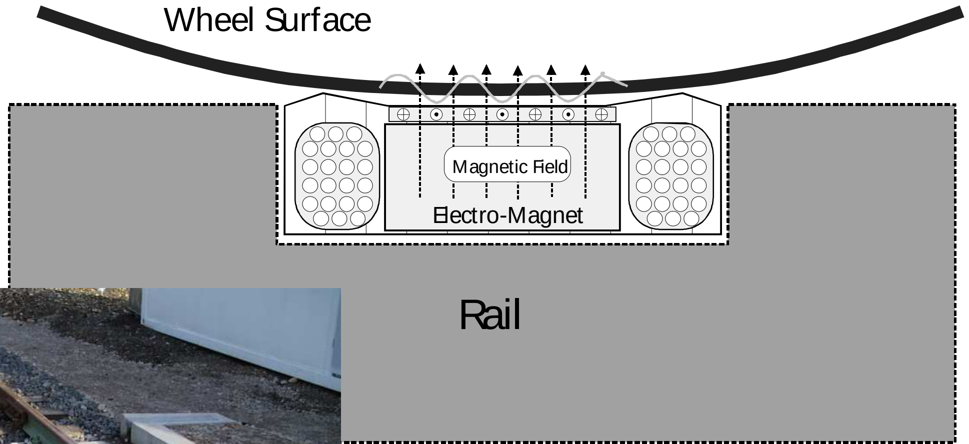


IZFP Developments for Railroads

Automated system AUROPA to detect defects in wheels

EMAT Sensors in the rail, Train speed 15 km/h to be increased till up to 30 Km/h





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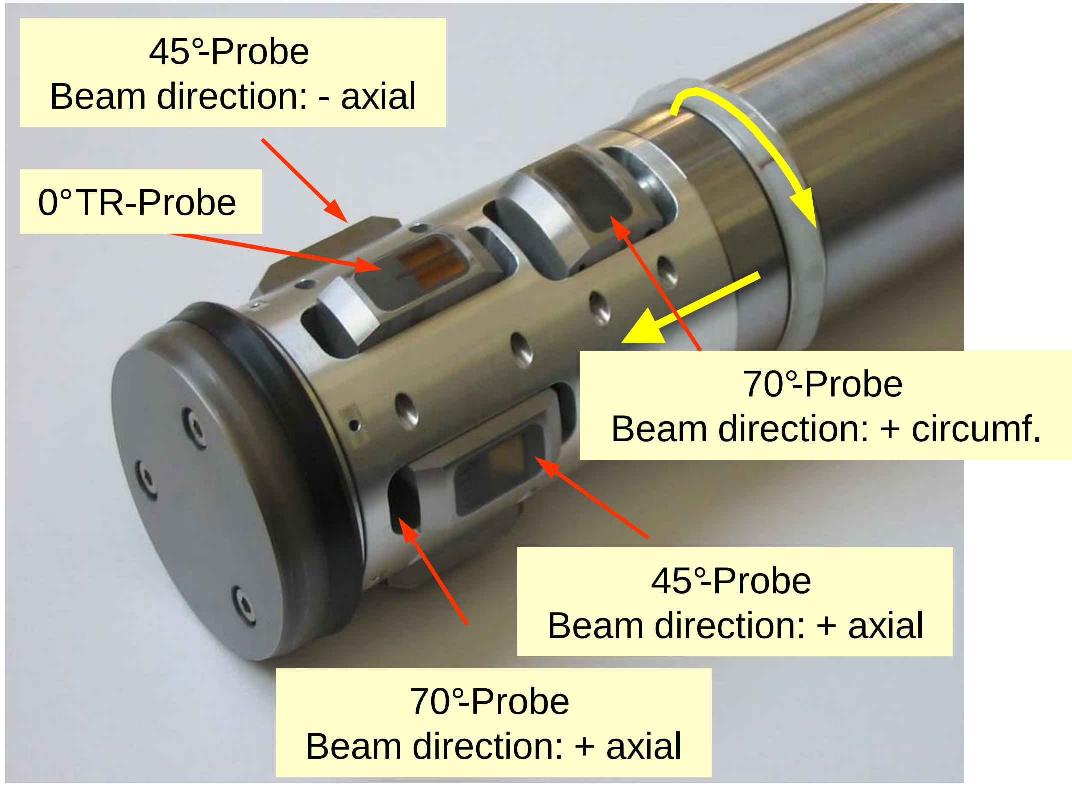
IZFP Developments for Railroads

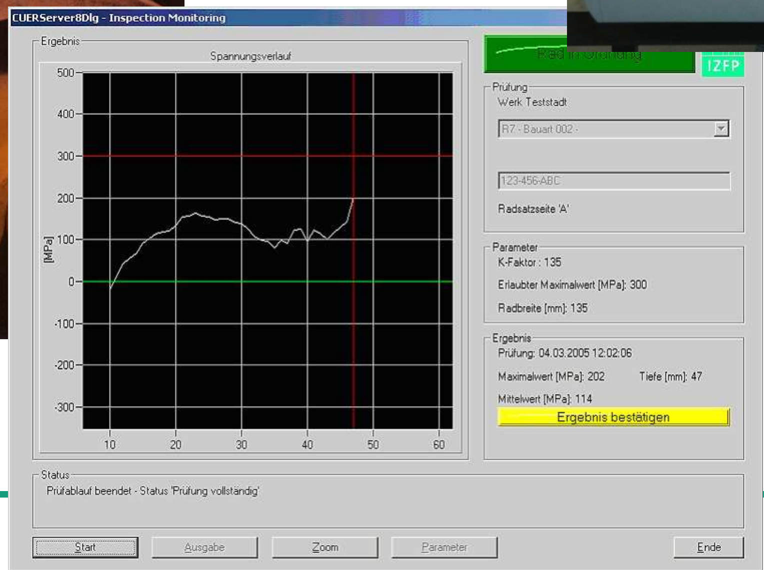
Automated systems to detect defects in axles

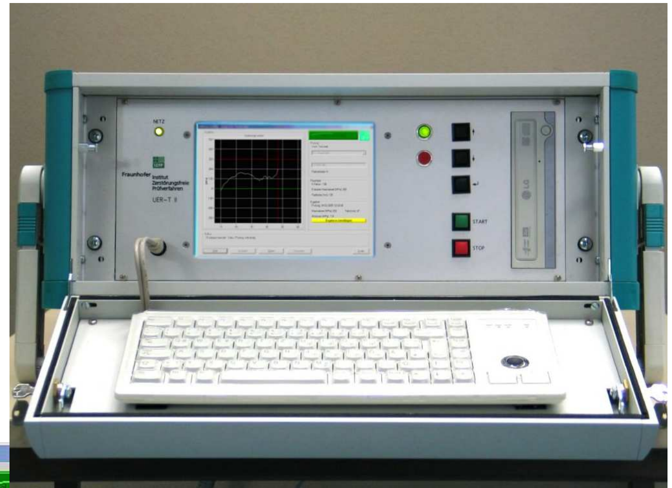
Probe Head Module for Bore Hole Ø 60 mm



IZFP Developments for Railroads

Automated system UER to evaluate the stress state of the rim of railroad wheels





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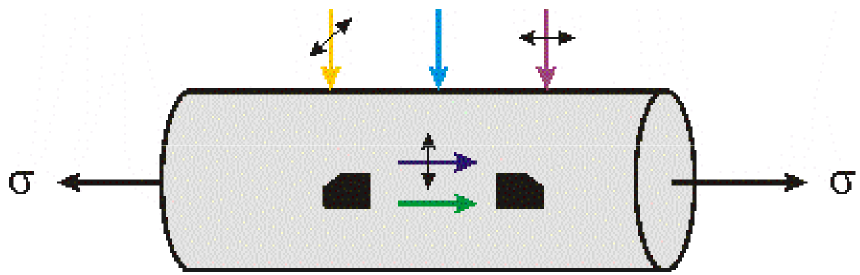
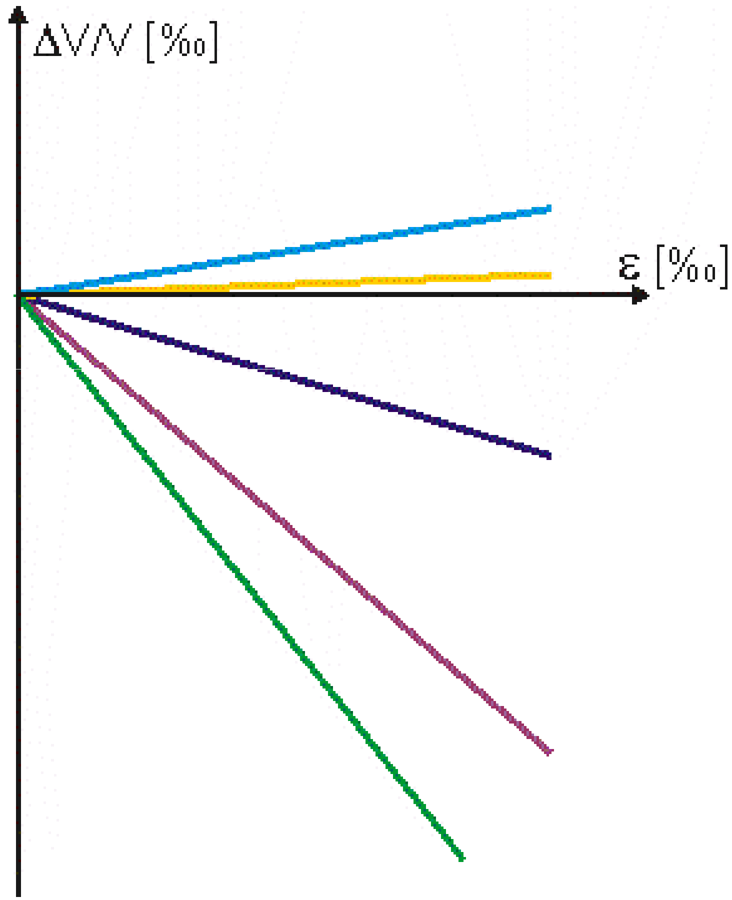
Ultrasonic Techniques to Evaluate Stress States

The acousto-elastic effect





The strain state influences the propagation velocities of ultrasonic waves.
The size of the acousto-elastic effect depends on the directions of wave propagation and vibration

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Ultrasonic Techniques to Evaluate Stress States

Influence of strain or stress state on the longitudinal wave velocity

$$\rho_0 v^2_{ii} = \rho v^2_L + (2l + \lambda)(\varepsilon_i + \varepsilon_j + \varepsilon_k) + (4m + 4\lambda + 10\mu)\,\varepsilon_i$$

Approximation:	$2v_L = v_{ii} + v_L$
Hook's Law:	$\varepsilon_i = 1/E\,[\sigma_i - \nu\,(\sigma_j + \sigma_k)]$
Young's Modul:	$E = \mu\,(3\lambda + 2\mu)\,/\,(\lambda + \mu)$
Poisson ratio:	$\nu = \lambda/2\,(\lambda + \mu)$

$$\frac{v_{ii} - v_L}{v_L} = \frac{t_L - t_{ii}}{t_{ii}} = \frac{A}{C}\cdot\sigma_i + \frac{B}{C}\left(\sigma_j + \sigma_k\right)$$

$A = 2\,(\lambda+\mu)\,(4m+5\lambda+10\mu+2l) - 2\lambda\,(2l+\lambda)$

$B = 2\,(2l+\lambda)\,(\lambda+\mu) - \lambda\,(2l+\lambda) - \lambda\,(4m+5\lambda+10\mu+2l)$

$C = 4\mu\,(\lambda+2\mu)\,(3\lambda+2\mu)$

Ultrasonic Techniques to Evaluate Stress States

Influence of strain or stress state on the shear wave velocity

$\rho_0 v^2_{ij} = \mu + (\lambda + m)(\varepsilon_i + \varepsilon_j + \varepsilon_k) + 4\mu\,\varepsilon_i + 2\mu\,\varepsilon_j - 0{,}5n\,\varepsilon_k$

Approximation: $2v_T = v_{ij} + v_T$

Hookes Law: $\varepsilon_i = 1/E\,[\sigma_i - \nu\,(\sigma_j + \sigma_k)]$

E – Youngs Modulus: $E = \mu\,(3\lambda + 2\mu) / (\lambda + \mu)$

Poisson - Ratio: $\nu = \lambda/2\,(\lambda + \mu)$

$$\frac{v_{ij} - v_T}{v_T} = \frac{t_T - t_{ij}}{t_{ij}} = \frac{D}{K}\cdot\sigma_i + \frac{H}{K}\cdot\sigma_j + \frac{F}{K}\cdot\sigma_k$$

$D = 2\,(\lambda+\mu)\,(\lambda+m+4\mu) - \lambda\,(2\lambda+2m+2\mu-0{,}5n)$

$H = 2\,(\lambda+\mu)\,(\lambda+m+2\mu) - \lambda\,(2\lambda+2m+4\mu-0{,}5n)$

$F = 2\,(\lambda+\mu)\,(\lambda+m-0{,}5n) - \lambda\,(2\lambda+2m+6\mu)$

$K = 4\mu^2\,(3\lambda+2\mu)$

$$\frac{v_{ij} - v_{ik}}{v_{ik}} = \frac{t_{ik} - t_{ij}}{t_{ij}} = \frac{(4\mu + n)}{8\mu^2}\,(\sigma_j - \sigma_k)$$

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Situation and Task

Very typical distribution of the stress component σ $_{Length}$ along height of new rail

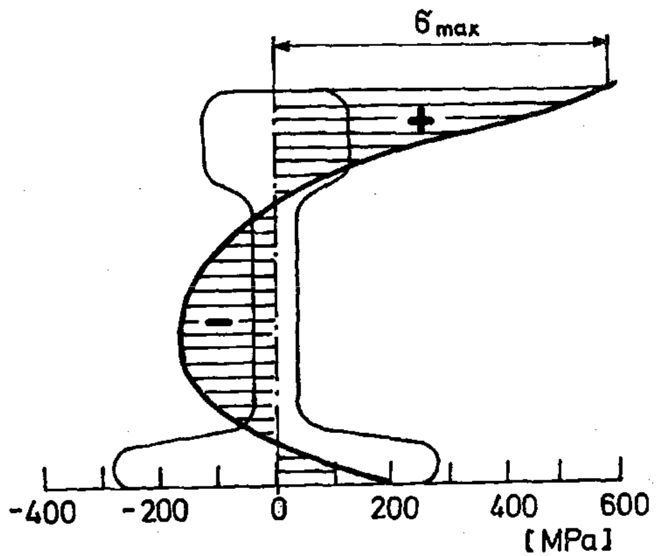

Fig.2. Distribution of longitudinal residual stress in a cross-section of a rail.

Source: A. Brokowski, J. Deputat, WCNDT, 1985

Typical result:

+ Tensile stress in the head
+ Compressive stress in web
+ Tensile stress in foot area
+ stress distribution mainly influenced by roller straightening condition

Situation and Task

Assumption

* residual stress averages to zero at any length position
* rail has neutral temperature during final welding

Result

=> there is no stress, except stress σ_{Length} induced by temperature change

Request

! Evaluation of temperature induced stress
! Evaluation of neutral temperature or stress free temperature

Problem

- Measurements covering the cross section are at least time consuming
- Strain or stress states superimpose each other, independent of origin

- There is no reliable non destructive technique to evaluate or check the neutral temperature except during bedding and final welding

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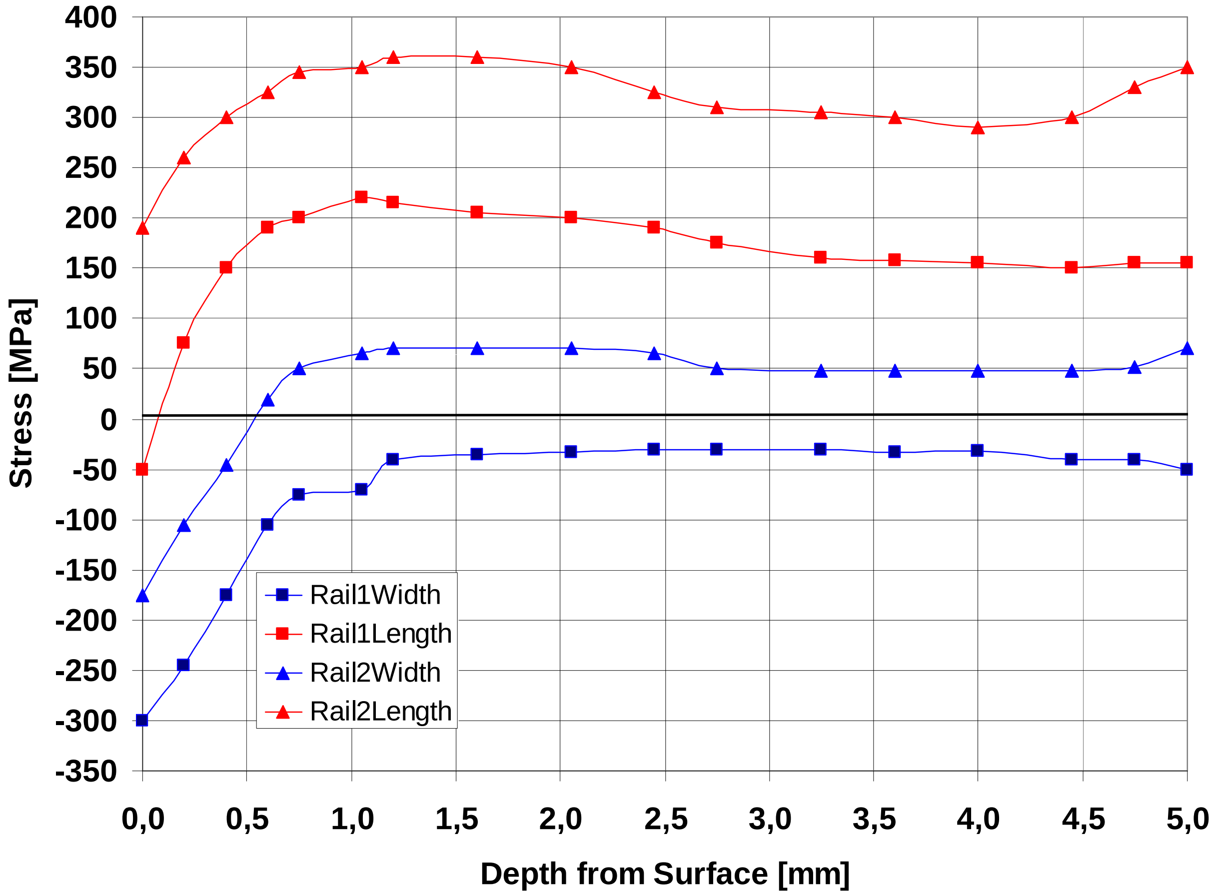
Stress State of Tread Area of New Rails

Results of destructive ring-core-technique; MPA Stuttgart



Principal result:

+ One dimensional stress state
+ Principal stress along width negligible
+ Tensile stress along length, mainly due to roller straightening

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Ultrasonic Approaches and Systems

DEBRO-approach and system of the Polish Academy of Science, Warsaw

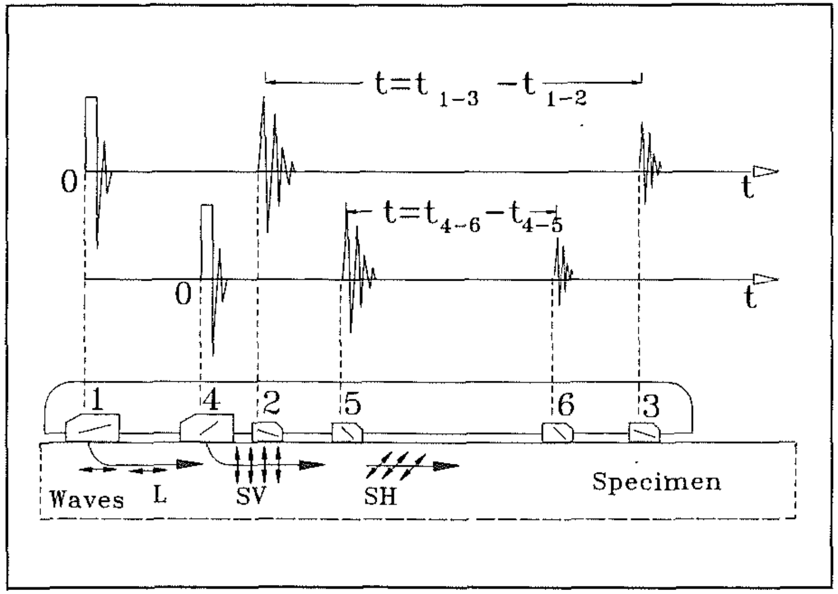


Fig. 2. Layout of ultrasonic transducers to measure the difference in travel times of subsurface ultrasonic longitudinal waves (1 – transmitter, 2, 3 – receivers); and transverse waves (4 – transmitters, 5, 6 – receivers). Relevant pulses are shown above.

Source: J. Deputat; ACUSTICA 79 (1993) 161-169

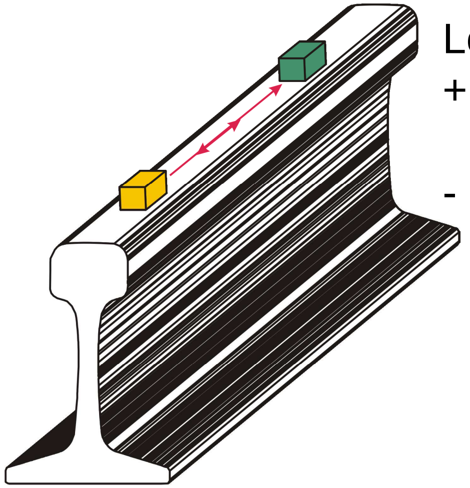
Idea

The same stress state influences the velocities of ultrasonic waves differently in size and sign, depending on the propagation and vibration direction with respect to the principal stresses

Use of different wave types to discriminate e.g. the microstructural influences

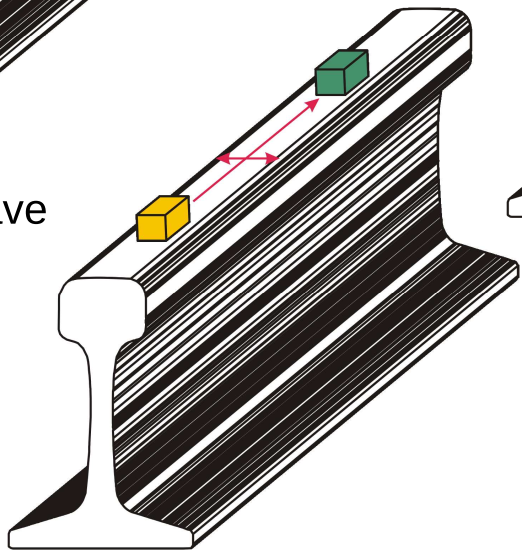
Ultrasonic Approaches and Systems

Different possibilities of ultrasonic applications, tested by IZFP

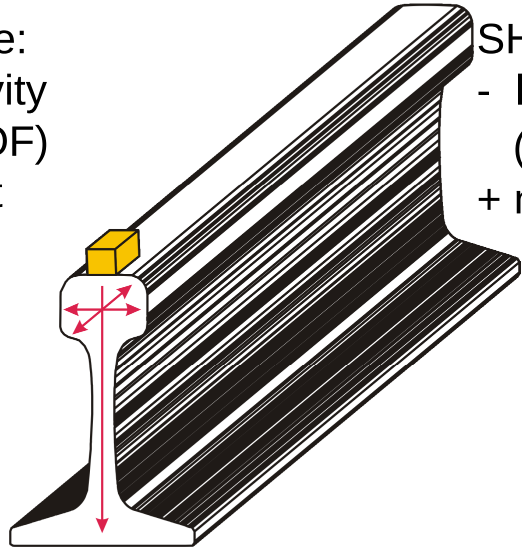


Longitudinal wave:
+ highest sensitivity (80MPa / ‰ TOF)
- needs couplant (water, oil, gel)

Longitudinal wave

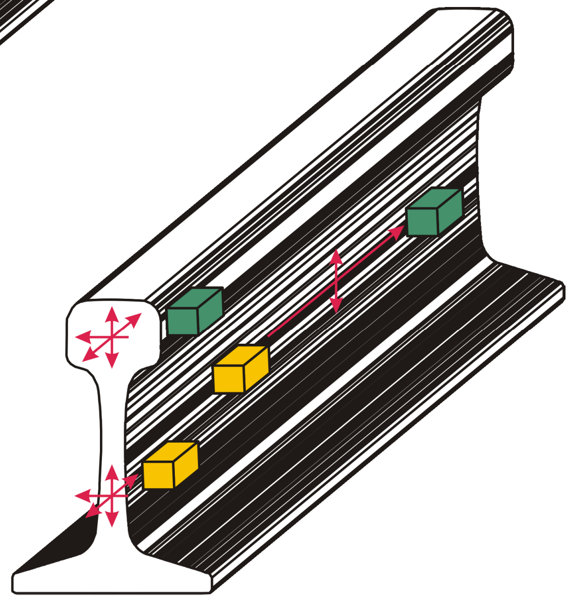


SHo wave



Linearly polarized shear waves

SHo and shear wave:
- lower sensitivity (150MPa/ ‰)
+ needs no couplant



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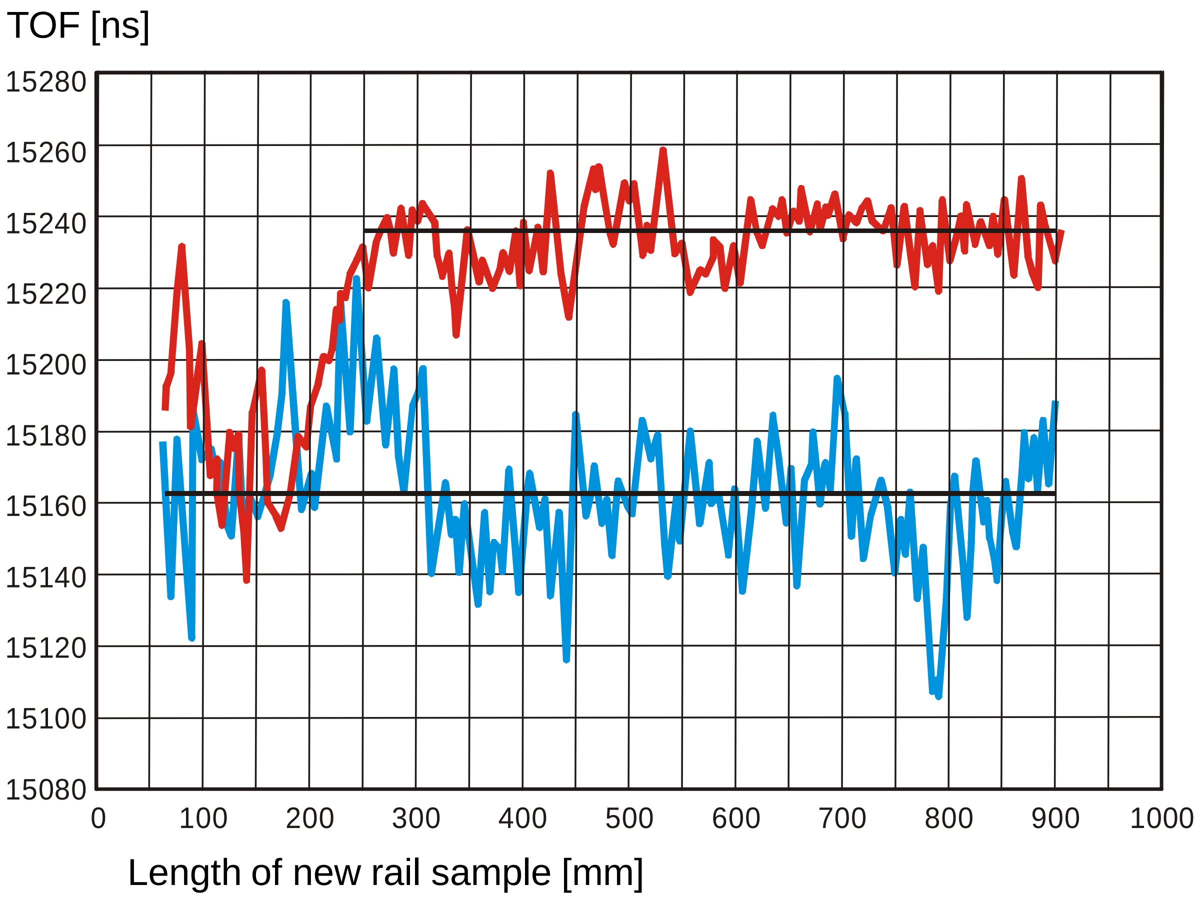
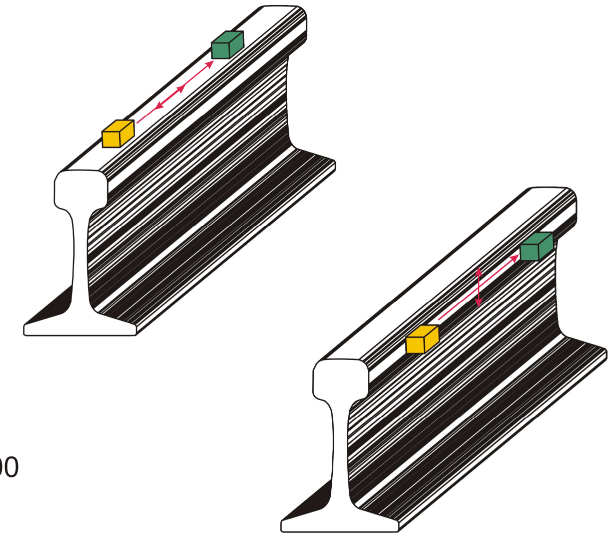
Ultrasonic Approaches and Systems

Time-of-flight (TOF) of a longitudinal wave propagating between transmitter and receiver probe with fixed distance, penetration depth about 3 mm



Rail sample is
partly roller straightened

ultrasound propagates
-> tread (red)
-> outside of head (blue)



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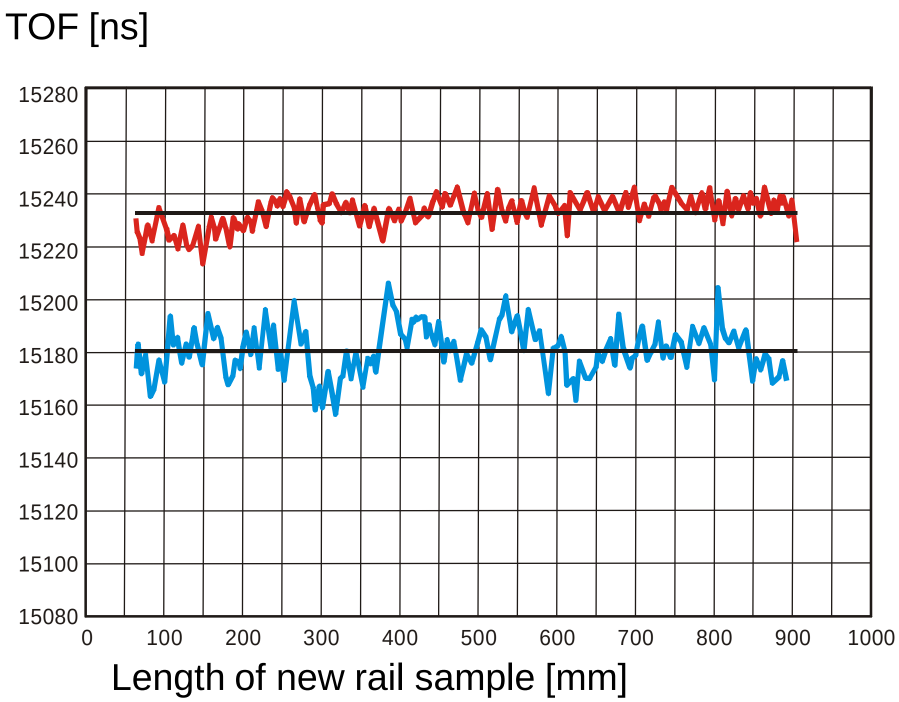
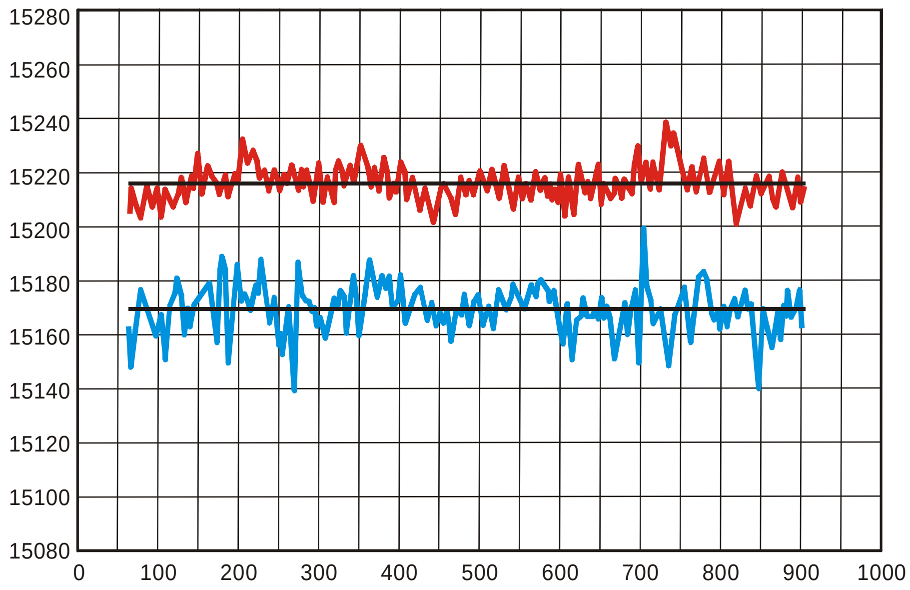
Ultrasonic Approaches and Systems

Time-of-flight (TOF) of a longitudinal wave propagating between transmitter and receiver probe with fixed distance, penetration depth about 3 mm

Continuous measurement of time-of-flight along length of new rail samples 5, 2; Sound propagates the tread (red) and the outer side of rail head (blue)





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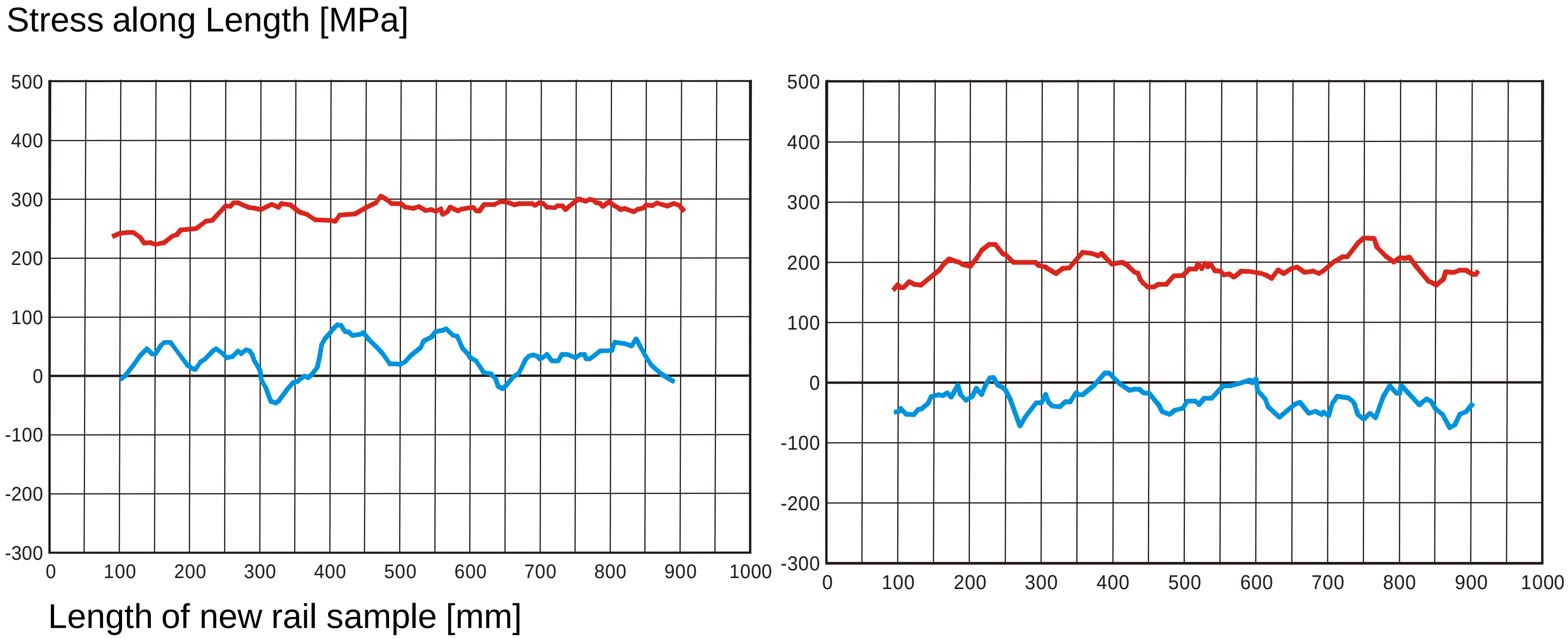
Ultrasonic Approaches and Systems

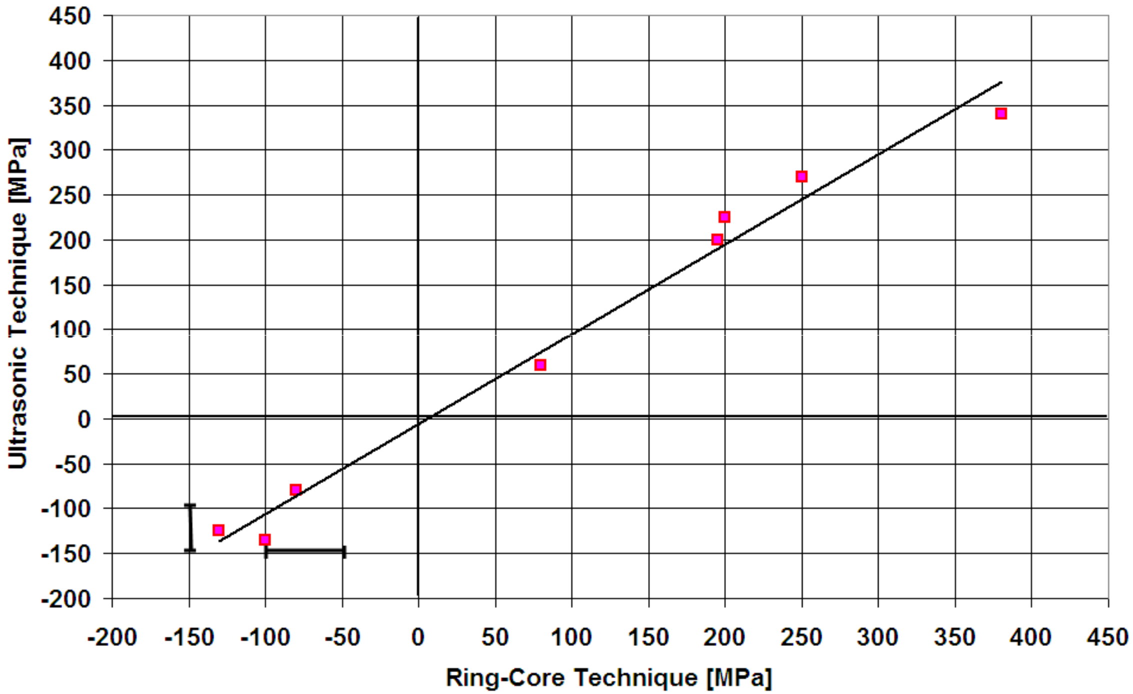
Results of ultrasonic stress analysis

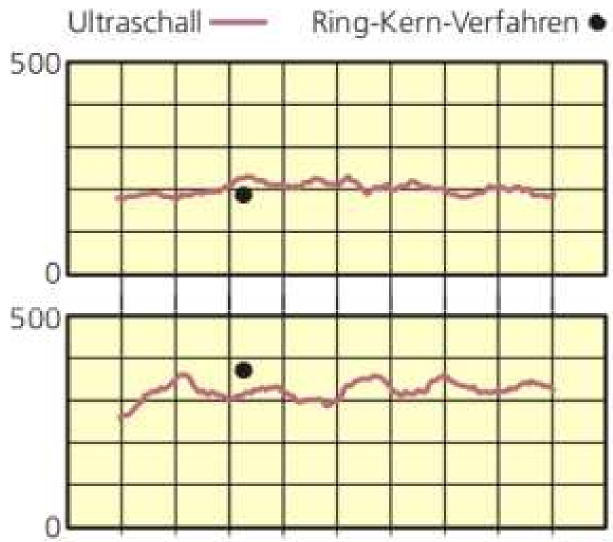
Stress along length of new rail sample 5 and 2;
σ_{Length} in tread area (red) and σ_{Length} in outer side of rail head (blue)



Ultrasonic Evaluation of Stress State of New Rails

Comparison of ultrasonic and ring-core results of stress analysis





In order to avoid errors caused by local inhomogeneities of the material, the stress results should be averaged along a certain part of rail length

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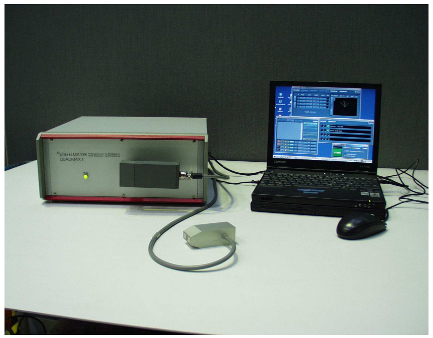
Ultrasonic Evaluation of Stress State of New Rails

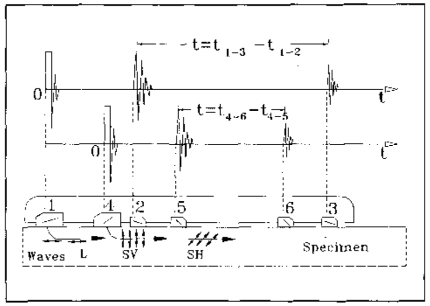
State

+ There is a quasi one dimensional stress state in new rails with the major stress component σ_{Length} along the length of rail
+ The stress state varies at different positions along the length of the rail mainly because of influences of straightening and cooling conditions
+ Different ultrasonic and micromagnetic techniques are available to evaluate the stress σ_{Length} along the length

UES



3MA



DEBRO Stress Meter

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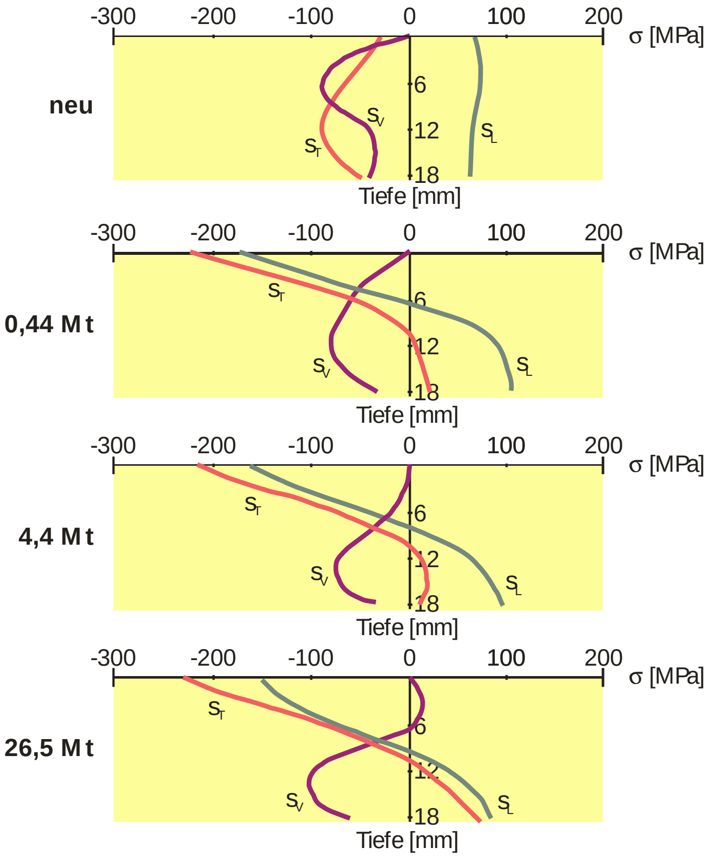
Situation concerning Rails in the Track

Very typical distribution of the stress component σ_{Length} along height of used rail



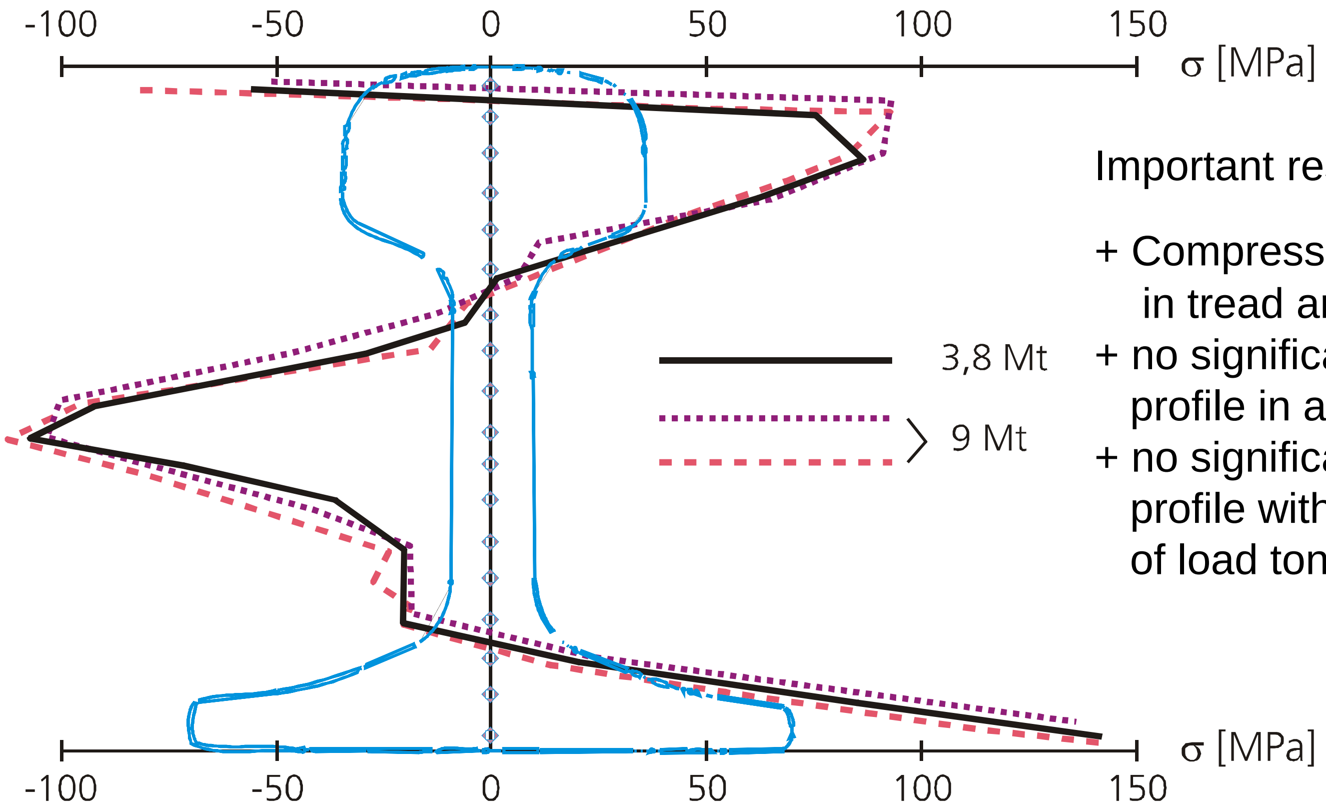
Source: P.R. Cheesewright: A Critical Review of Residual Stress Measurement in Rails, British Railway Board, Technical Note, TN STM 15, 1980

Important result:

+ Compressive stress σ_{Length} (blue, S_L) in tread area
+ Compressive stress σ_{Width} (red, S_T) in tread area
+ Stress σ_{Width} larger in size than stress σ_{Length}
+ no significant change of stress profiles with increasing load tons (threshold at about 0.5 Mt)

Situation and Task, concerning Rails in the Track

Very typical distribution of the stress component σ $_{Length}$ along height of used rail



Important result:

+ Compressive stress σ_{Length} in tread area
+ no significant change of stress profile in area of web and food
+ no significant change of stress profile with increasing number of load tons

Source: ORE Bericht D 156 / RP 4, 1987

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Situation and Task, concerning Rails in the Track

Very typical distribution of the stress component σ $_{\text{Length}}$ along height of used rail

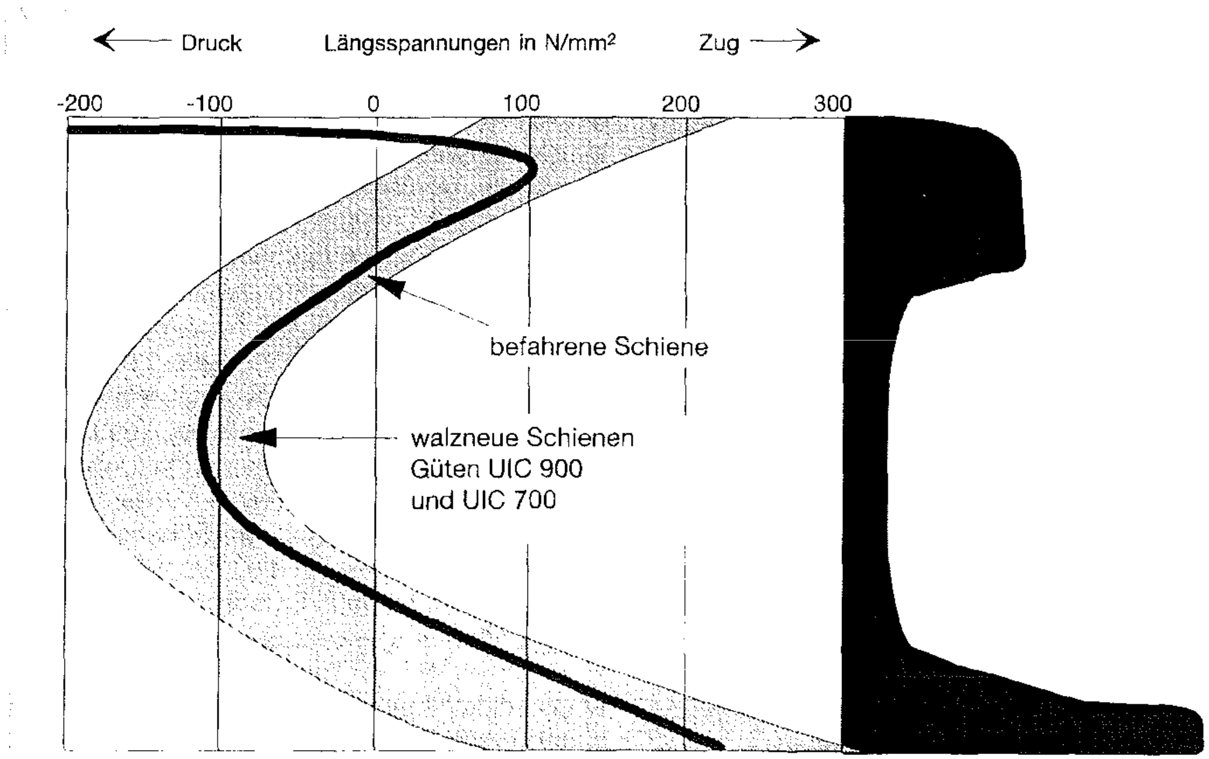
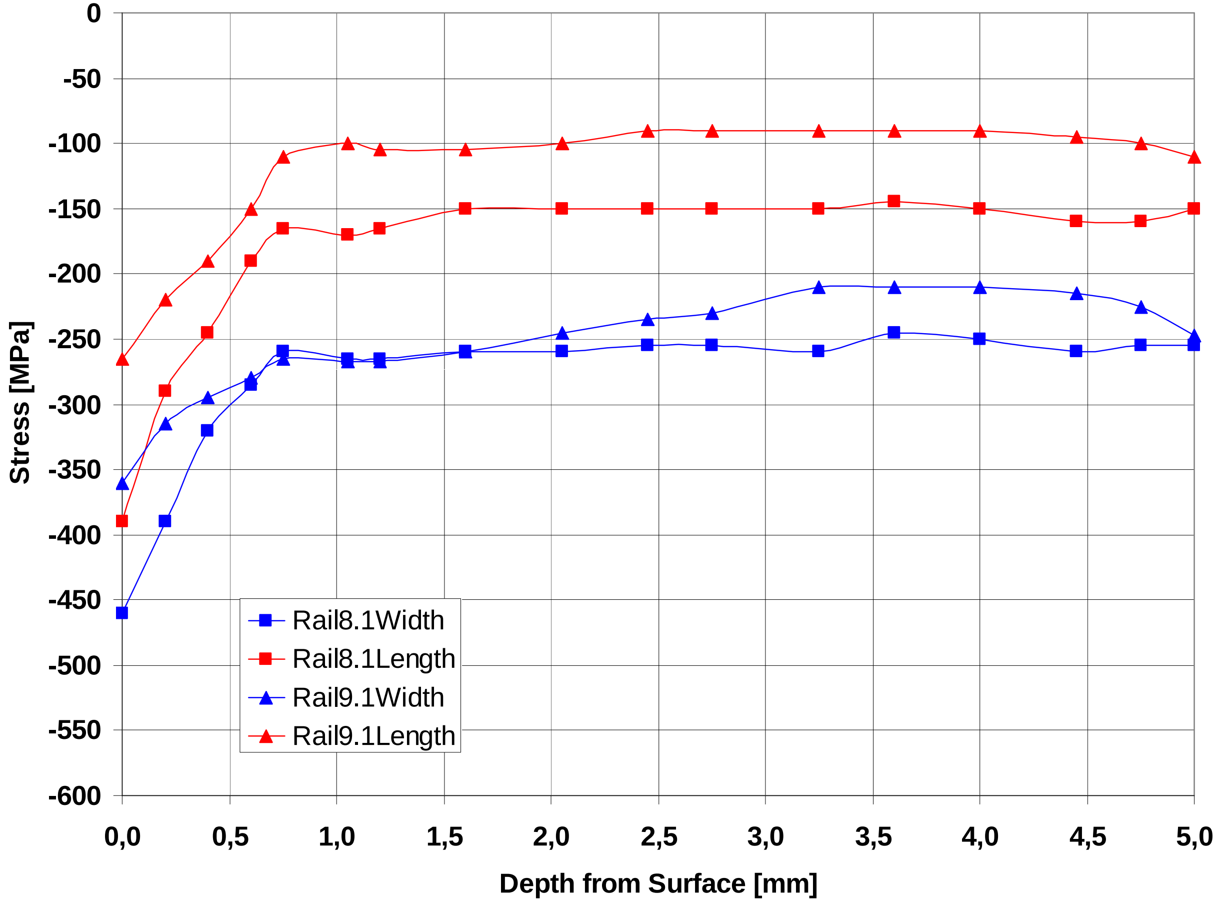


Bild 1: Eigenspannungen in walzneuen Schienen und in einer befahrenen Schiene

Source: E. Jericho; ETR 46 Heft 10 (1997) 663-666

Stress State of Used Rails, Cut from the Track

Results of destructive ring-core-technique; MPA Stuttgart



Principal result:

+ Two dimensional stress state
+ Principal stresses along length <u>and</u> width
+ Compressive stresses
+ Stress along width usually larger in size than stress along length

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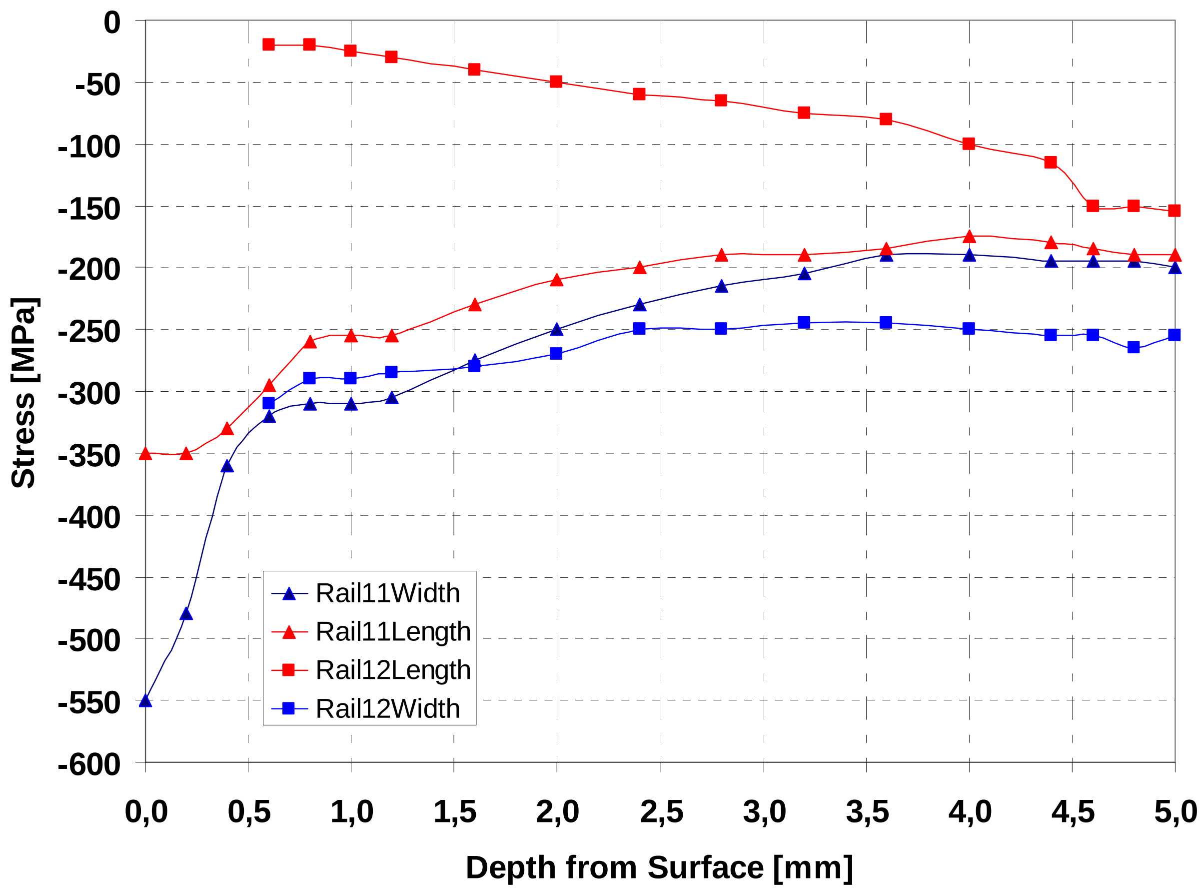
Stress State of Used Rails

Results of destructive ring-core-technique; MPA Stuttgart



Principal result:

+ Two dimensional stress state
+ Principal stresses along length and width
+ Compressive stresses
+ Stress along width usually larger in size than stress along length

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Situation and Task concerning Stress Analysis in the Track

Assumption

* residual stress averages to zero at any length position / not important
* rail has neutral temperature during final welding

Result

=> there is no stress, except stress induced by temperature change / not true

Request

! Evaluation of temperature induced stress / will not be sufficient to prevent
! Evaluation of neutral temperature / buckling or cracking

Problem

not meaningful
- Measurements covering the cross section are ~~at least time consuming~~
- Strain or stress states superimpose each other, independent of origin

=> A new approach is needed

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Approach

IZFP suggestion

* Evaluation of total stress state of tread (σ_{Width} and σ_{Length}) caused by
- manufacturing (residual stress; cross section, different along length), by
- bedding (elastic and anelastic local deformations, cross section), by
- welding (very local, cross section), by
- traffic (long ranged stress influence, similar in a range of a few meters, tread area only), by
- temperature changes (long ranged, tens of meters, cross section)

* Measurement of rail temperature
- Evaluation of temperature induce stress using thermal expansion coefficient and temperature base of 20℃;
- Evaluation of Stress state of treat caused by manufacturing, bedding, welding and traffic

* Model buckling safety based on stored energy (stress state), rail size, tie type, track curvature, etc. as suggested by e.g. A. Kish, G. Samavedam, D. Read

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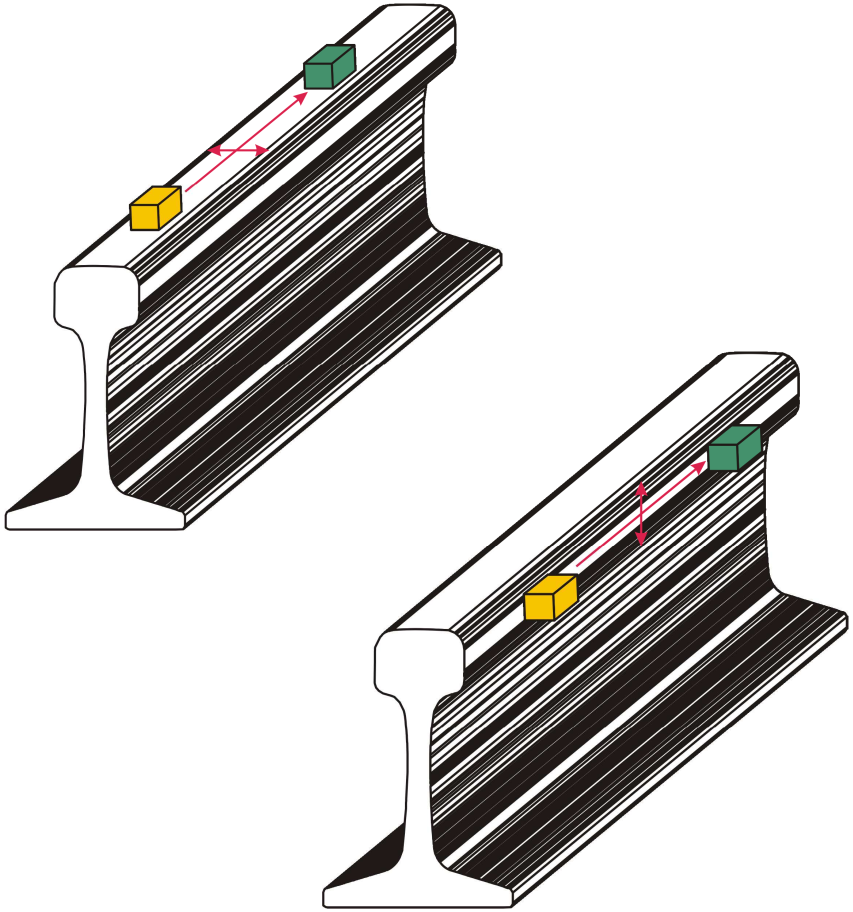
Ultrasonic Approach

IZFP suggestion



* Measurement of SHo time-of-flight (TOF) in treat area (influence of σ_{Width} and σ_{Length} plus microstructure)
* Measurement of SHo TOF on outer side of head (influence of microstructure)
* Measurement of rail temperature
* Evaluation of stress state of tread (influence of σ_{Width} and σ_{Length})
* Model buckling safety based on
  stored energy (stress state) and
  tie type
  track curvature
  etc as suggested by e.g. A. Kish, G. Samavedam, D. Read

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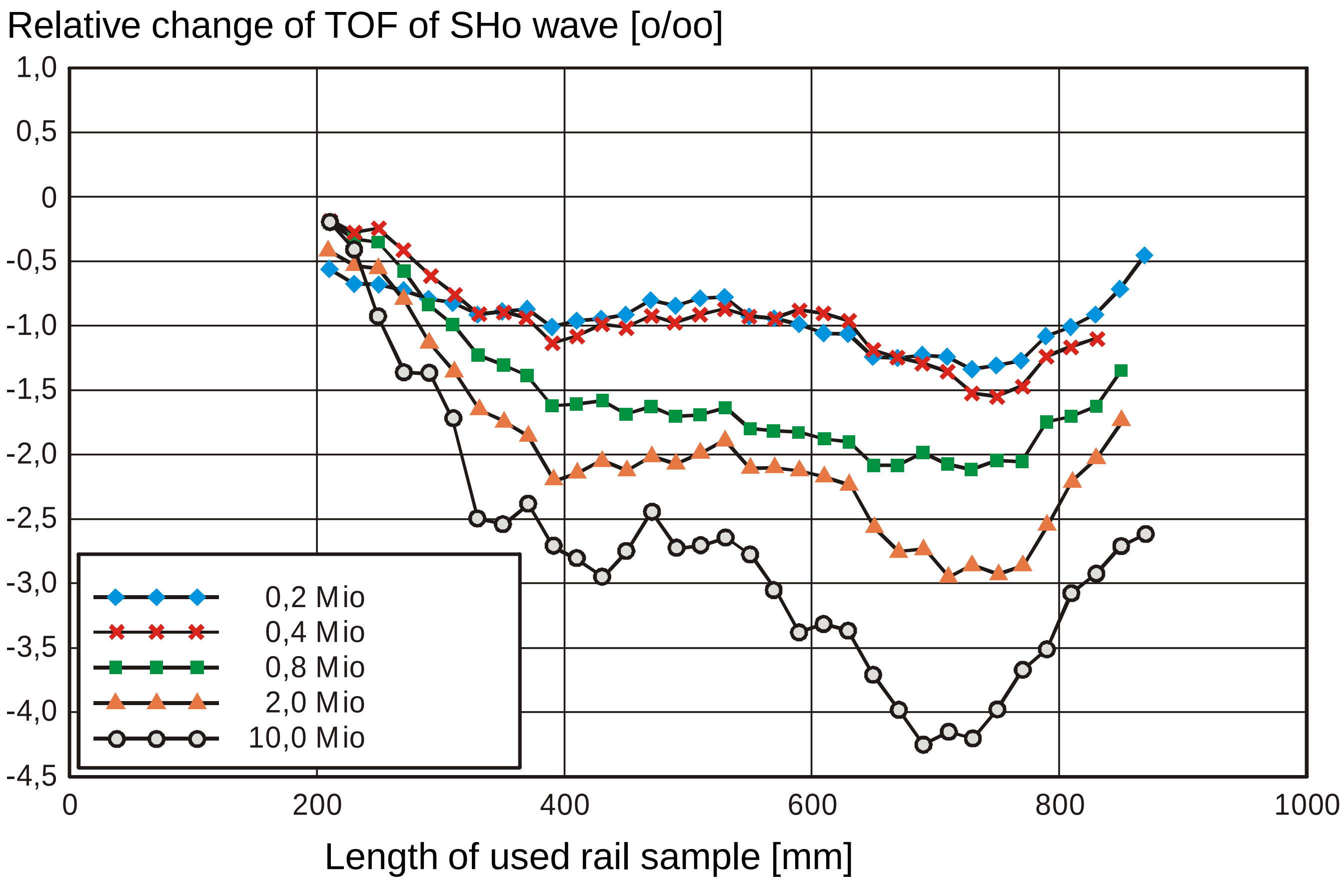
Ultrasonic Evaluation of Stress State of Used Rails

Time-of-flight (TOF) of a SHo wave propagating between transmitter and receiver probe with fixed distance vs load tons applied in a over-rolling-test stand



SHo wave propagates the tread in a surface layer of about 6 mm of thickness

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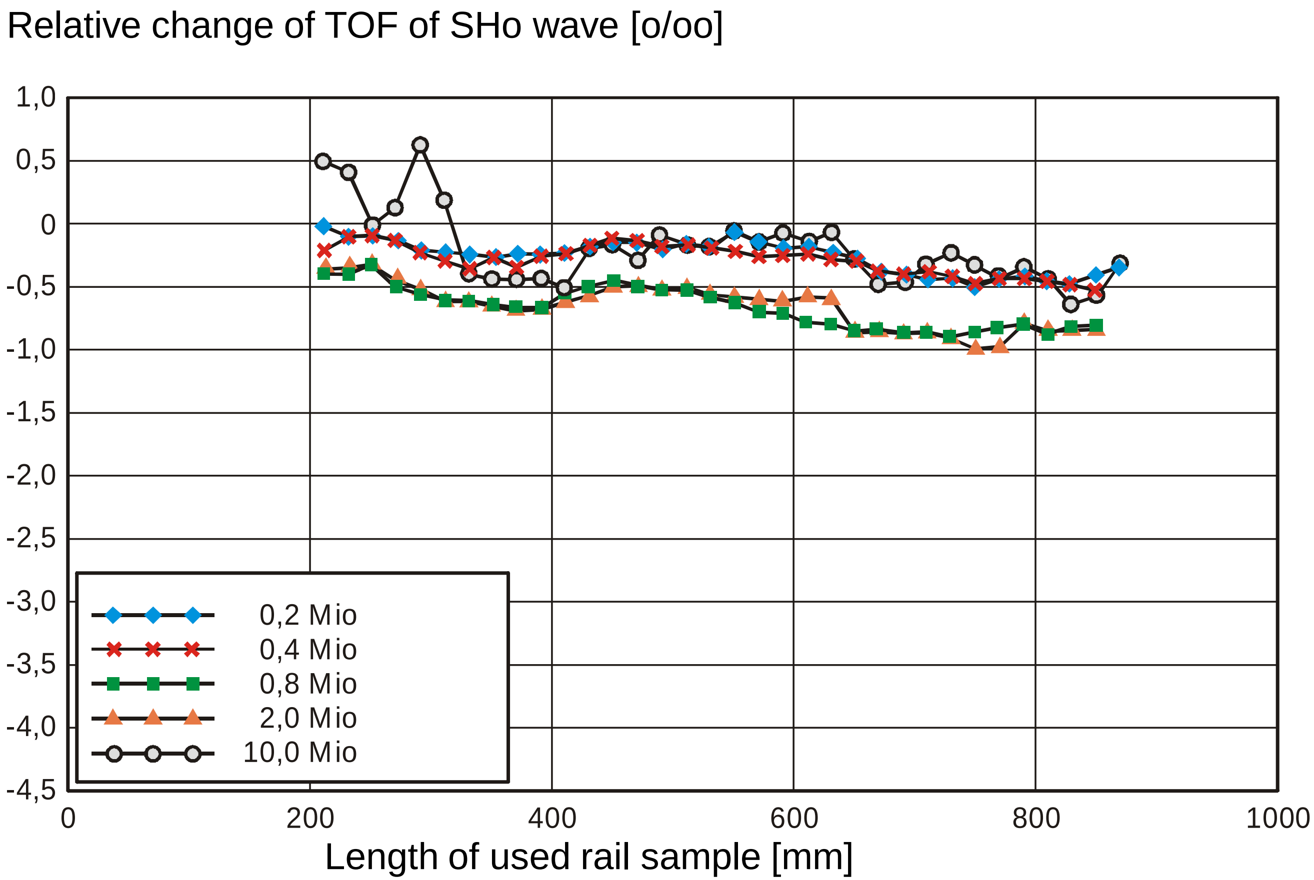
Ultrasonic Evaluation of Stress State of Used Rails

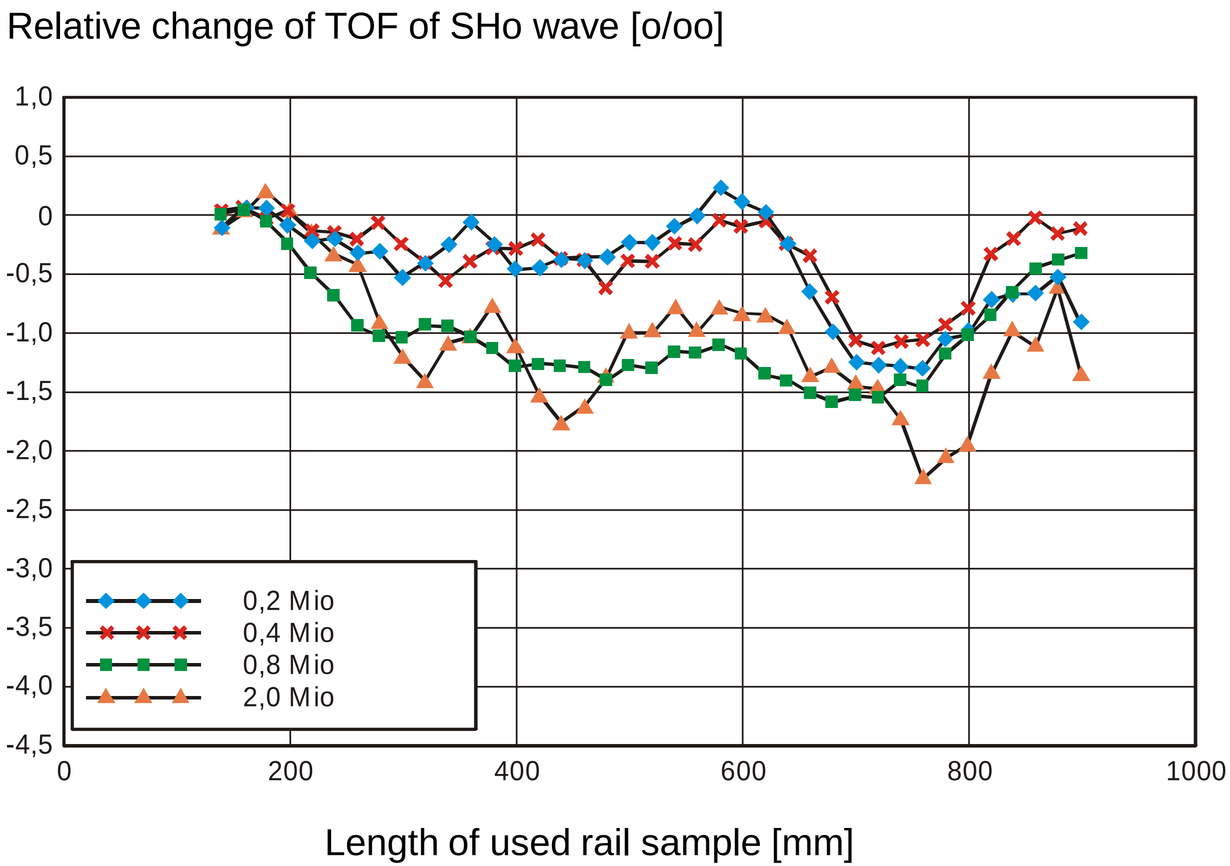
Time-of-flight (TOF) of a SHo wave propagating between transmitter and receiver probe with fixed distance vs load tons applied in a over-rolling-test stand



SHo wave propagates the outer side of the rail head in a surface layer of about 4 mm of thickness

Ultrasonic Evaluation of Stress State of Used Rails

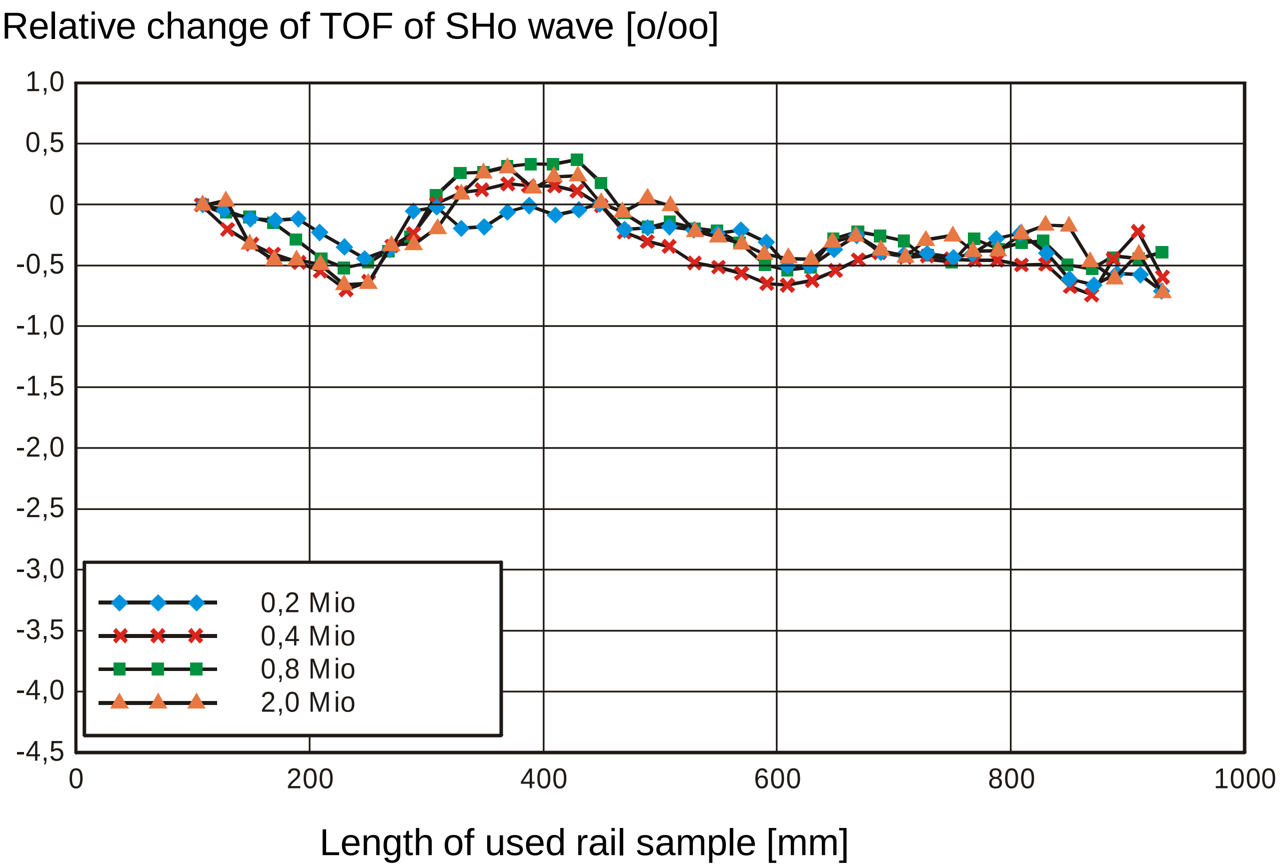
Time-of-flight (TOF) of a SHo wave propagating between transmitter and receiver probe with fixed distance vs load tons applied in a over-rolling-test stand



SHo wave propagates the tread of the rail head in a surface layer of about 6 mm of thickness

Ultrasonic Evaluation of Stress State of Used Rails

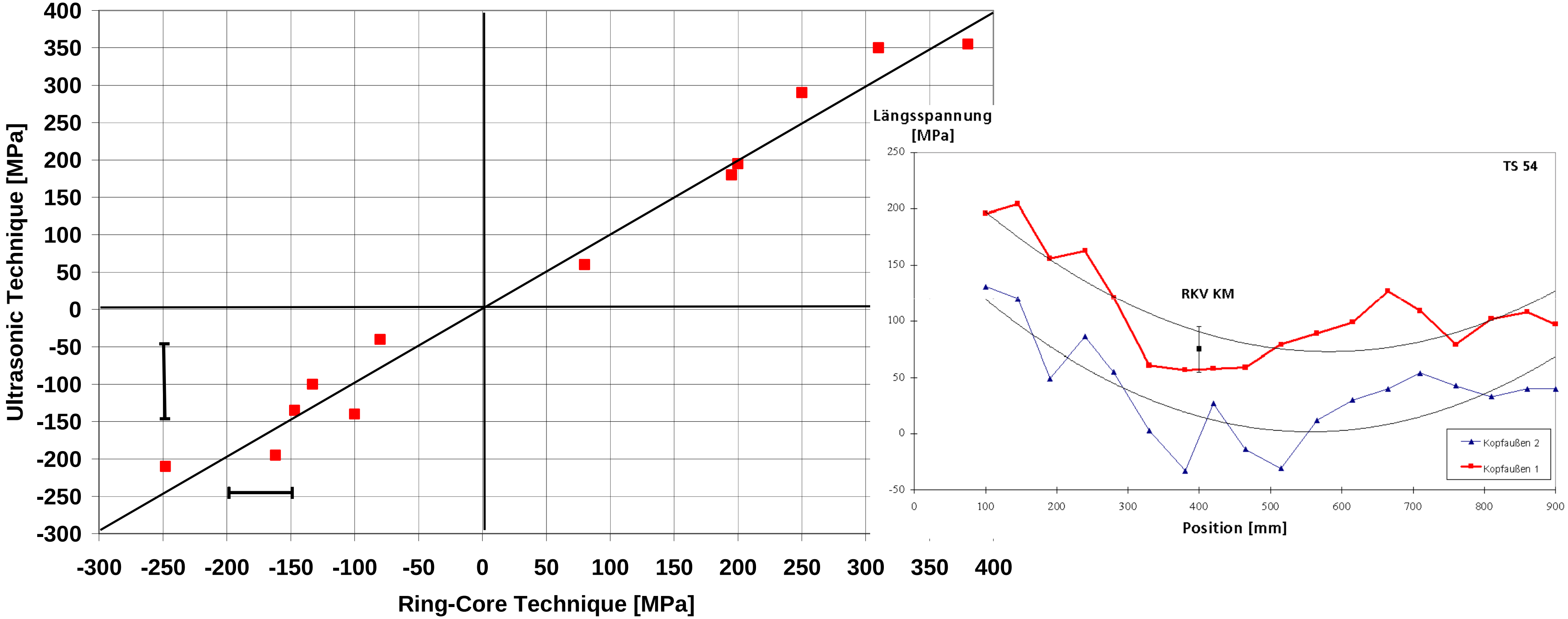
Time-of-flight (TOF) of a SHo wave propagating between transmitter and receiver probe with fixed distance vs load tons applied in a over-rolling-test stand



SHo wave propagates the outer side of the rail head in a surface layer of about 4 mm of thickness

Ultrasonic Evaluation of Stress State of Used Rails

Comparison of ultrasonic and ring-core results of samples of new and used rails



In order to avoid errors caused by local inhomogeneities of the material, the stress results should be averaged along a certain part of rail length

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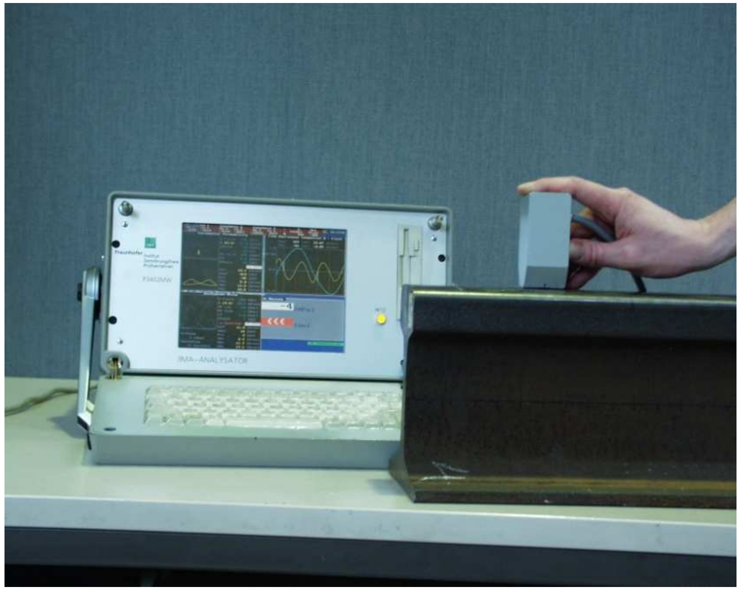
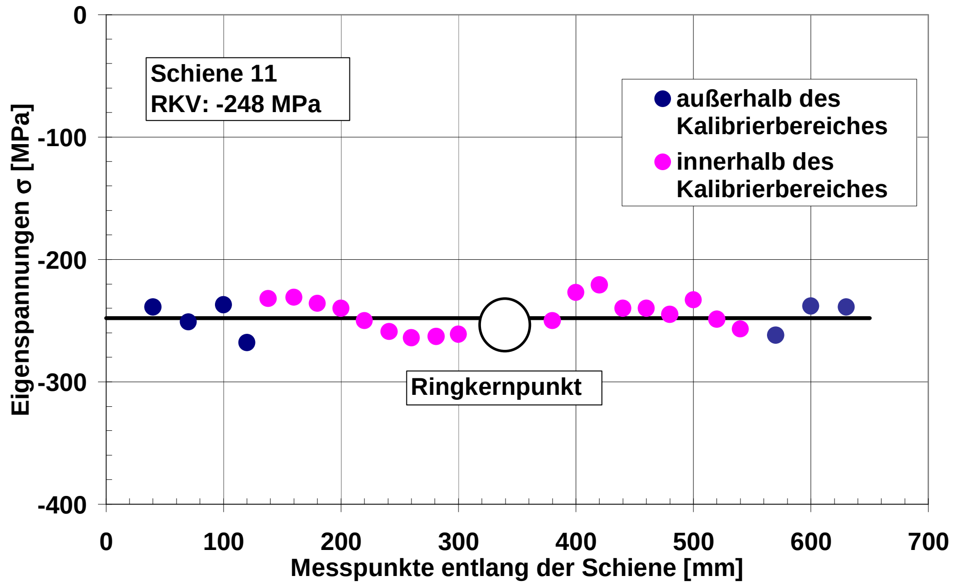
MicroMagnetic Evaluation of Stress State of Used Rails

3MA system was calibrated using the ring-core result of -248 MPa and taking reference values in the vicinity of the ring-core measuring point (pink).





After calibration, the 3MA system was used to evaluate the stress σ_{Length} in the tread at other measuring positions (blue).

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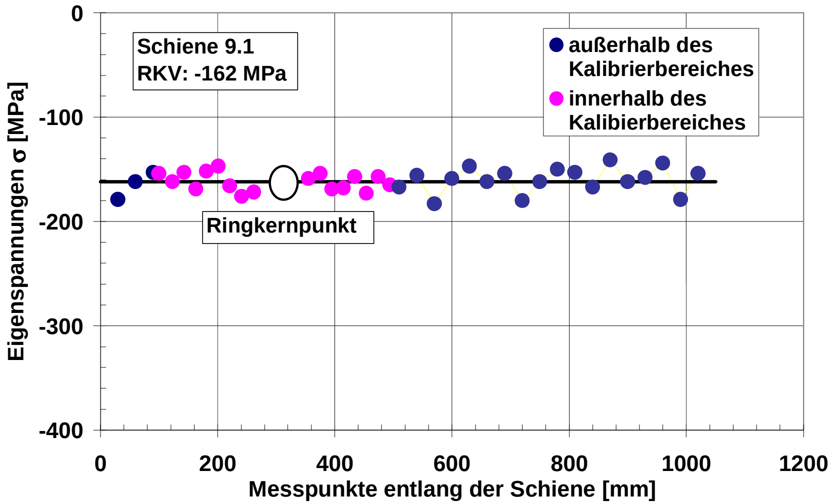
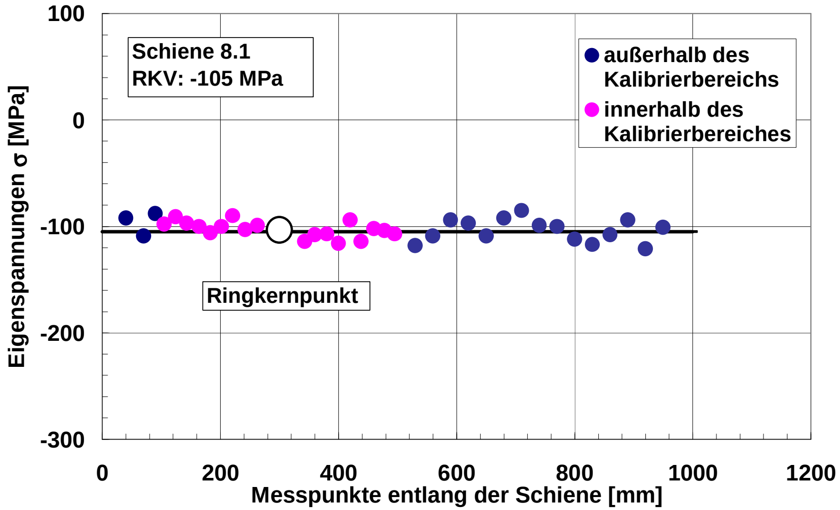
MicroMagnetic Evaluation of Stress State of Used Rails

3MA system was calibrated using the ring-core results of -168 MPa (left), -105 MPa (right) and taking reference values in the vicinities, respectively (pink).

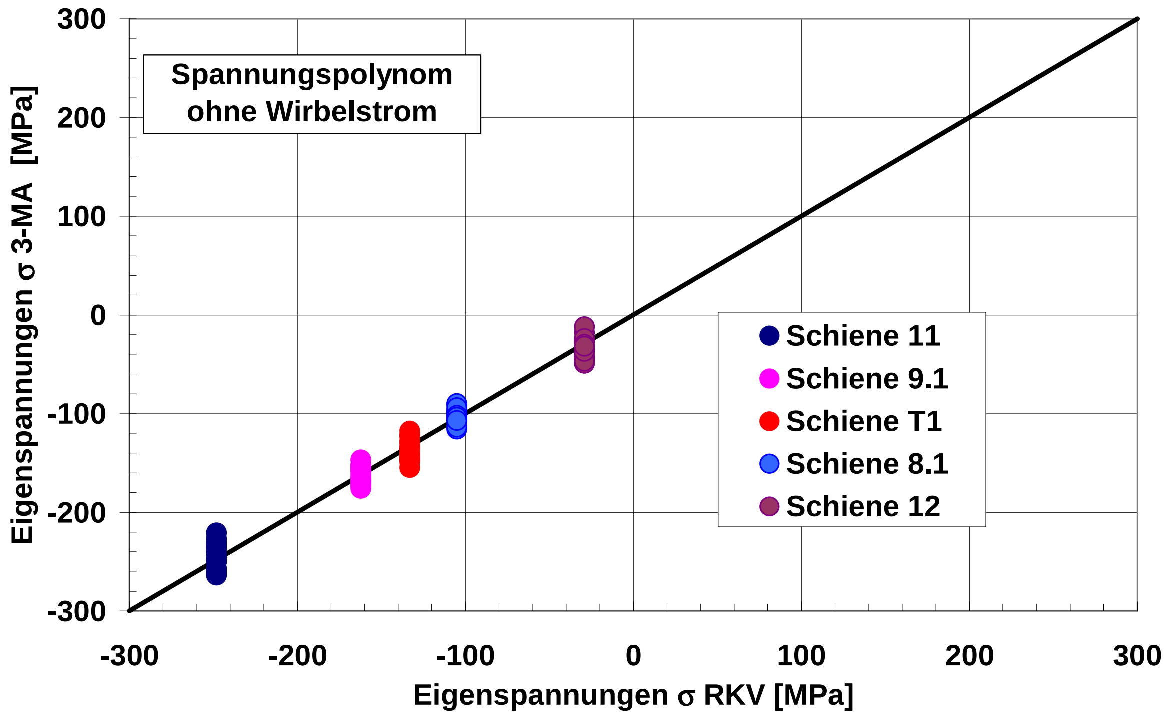




After calibration, the 3MA system was used to evaluate the stress σ_{Length} in the tread at other measuring positions (blue).

MicroMagnetic Evaluation of Stress State of Used Rails

3MA system was calibrated using the ring-core results of all the individual rails and taking reference values in the vicinities, respectively.



Using the one calibration function, the stress values σ_{Length} in the tread of the 5 samples of used rails are evaluated.

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Approach to Evaluate Stress States of Rails in the Track

IZFP suggestion

* Measurement of rail temperature

Influence of temperature

1) Linear expansion coefficient $\alpha_{Fe} = 12{,}1 \times 10^{-6}$ / °K and
Youngs-Modulus of 210 GPa
=> Temp Change of 10°C causes a change of stress σ_{Length} of about 25 MPa
2) Ultrasonic velocities decrease linearly with increasing material temperature
=> Temp Change of 10°C causes a relative velocity change of about 1.2 ‰

and also the acousto-elastic effect causes a change of the shear wave velocity:
=> about 150 MPa cause a change of 1.2 ‰

=> rail temperature has to be measured with an accuracy of at least ± 1°C

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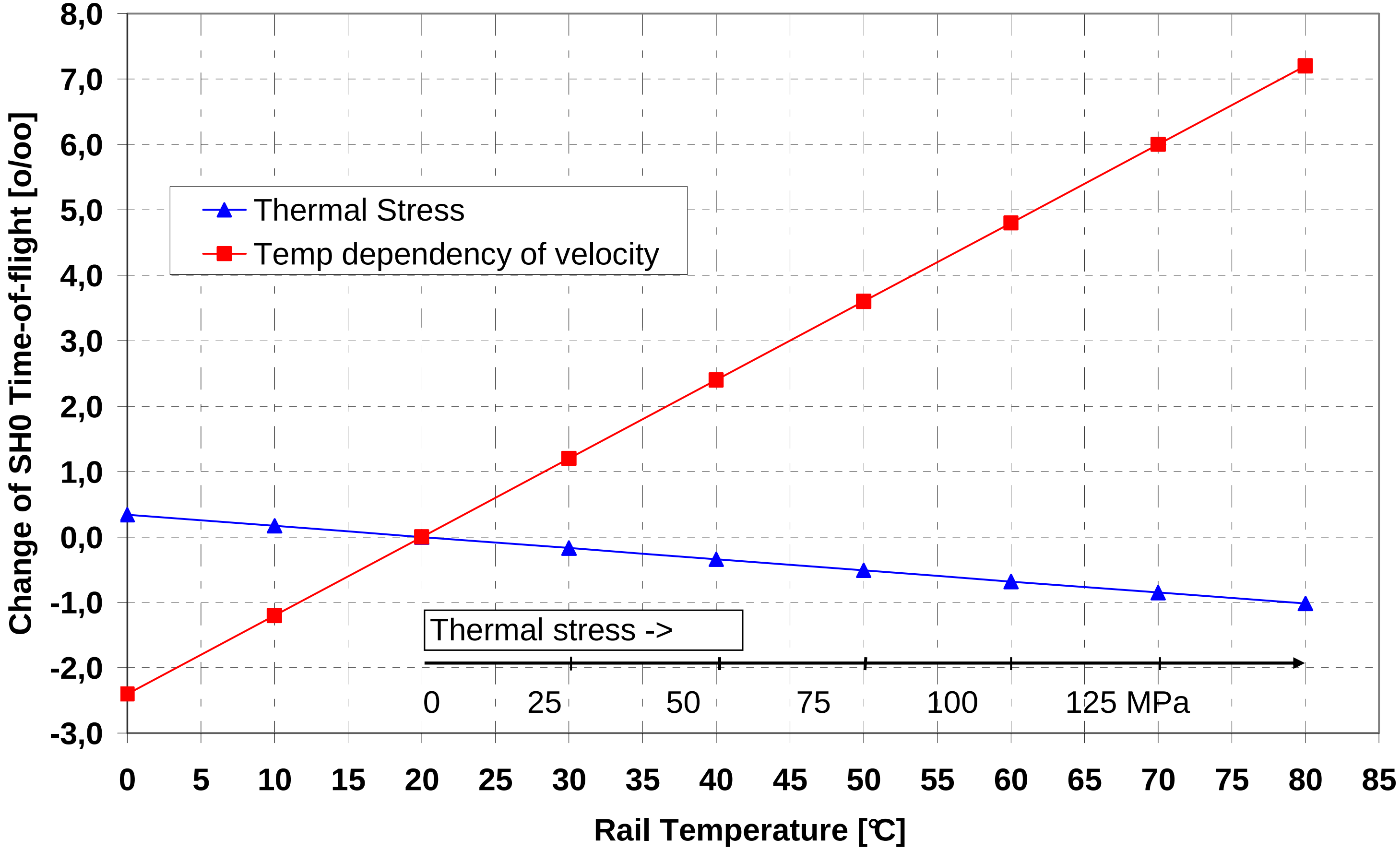
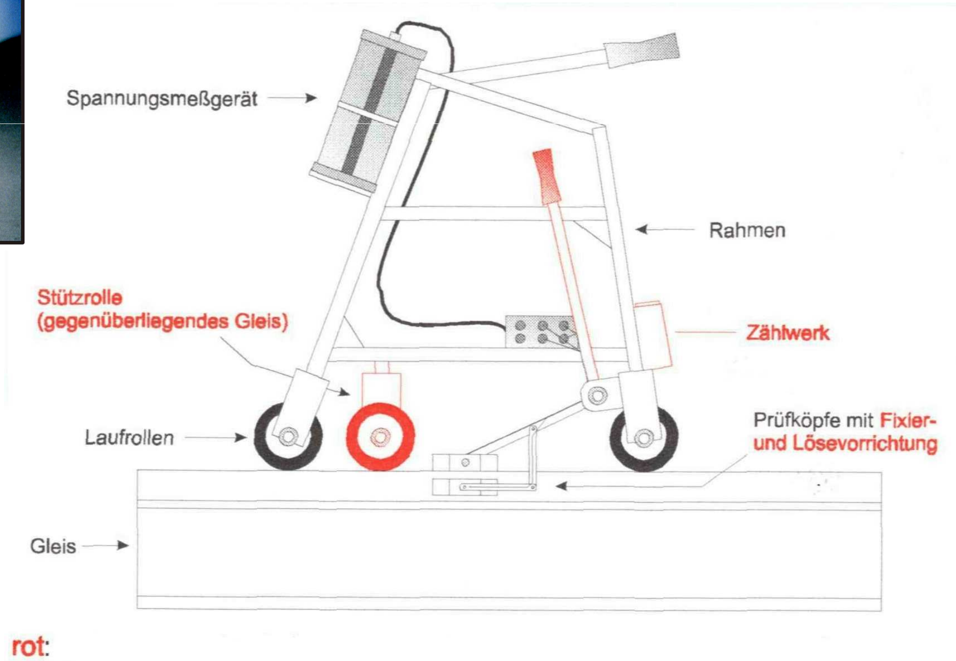
Approach

Influence of rail temperature on TOF of SHo wave, due to thermally induced stress (blue) and due to temperature dependence of sound velocity (red)



Ultrasonic System for Stress Analysis on Rails

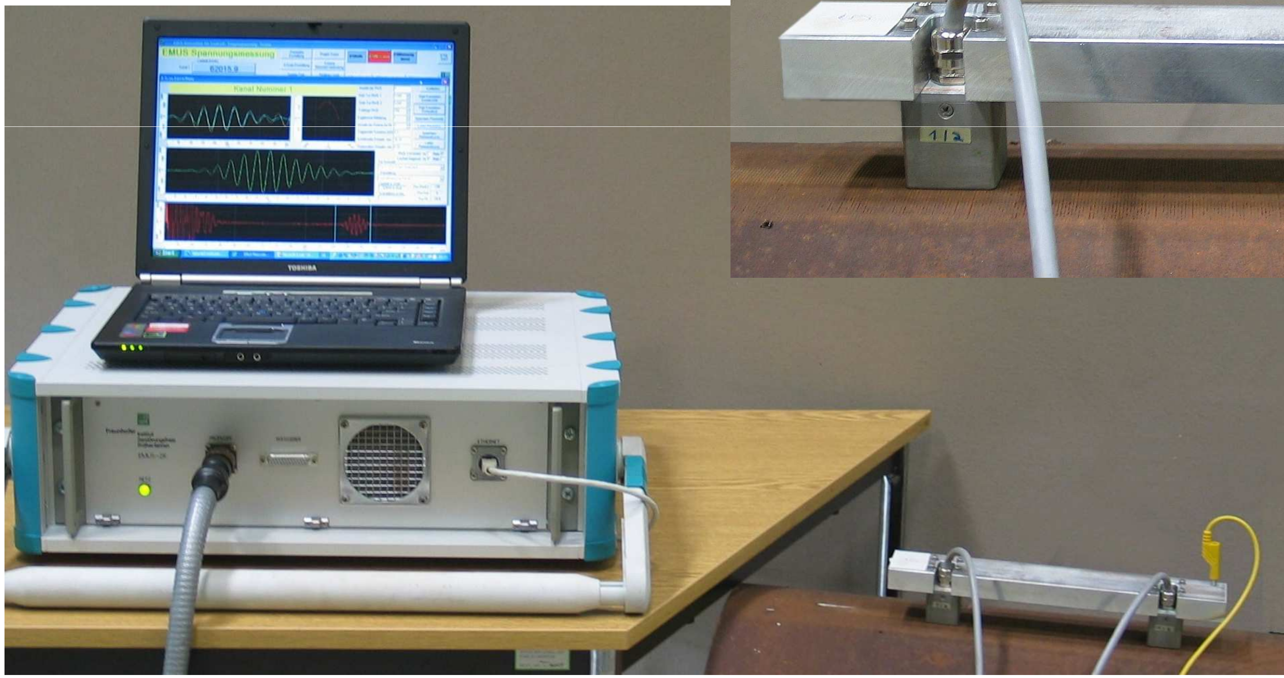
IZFP Version UES; 1997; mounted on cart by DB



Ultrasonic System for Stress Analysis

IZFP system, 2008

EMAT Transmitter-receiver
unit for shear waves →
SHo mode



EMAT Frontend und
PC for
data acquisition,
visualization, and
evaluation
←

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Ultrasonic System for Stress Analysis

IZFP system, 2008

A-Scan (bottom), measured signal (yellow) and reference signal (blue), curve of correlation function (center) and max value of correlation function (top)

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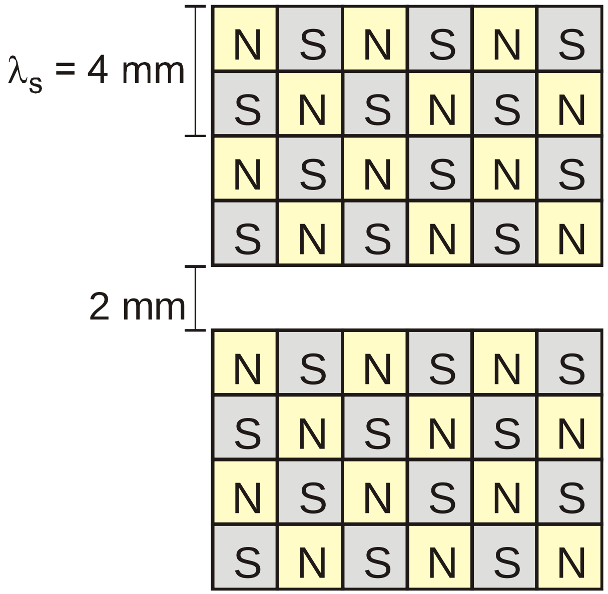
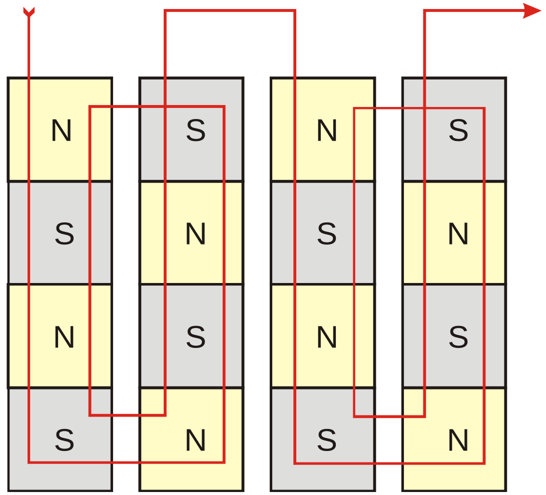
Ultrasonic Transducer for Stress Analysis

IZFP EMAT´s for SHo wave



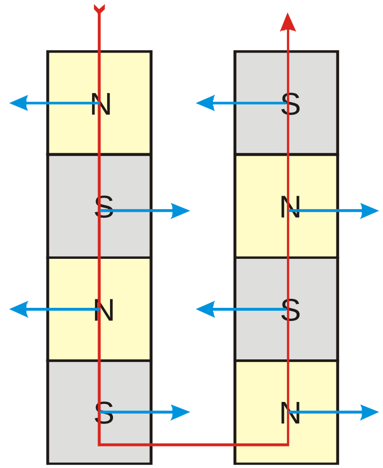
EMAT SHo Transducer

Arrangement of permanent magnets
View towards the food of transducer



Sketch of coil

and current (red)



Resulting forces on

metallic lattice

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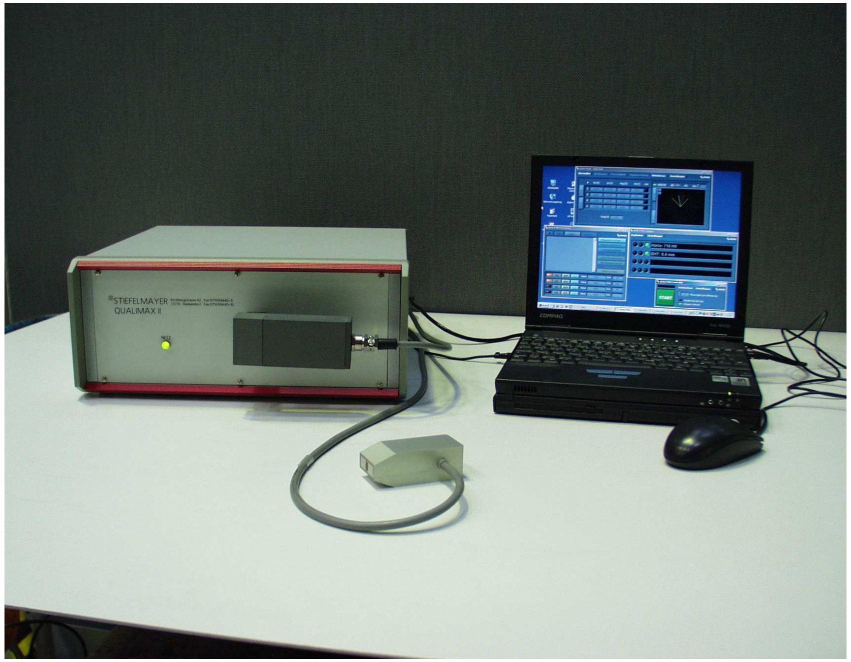
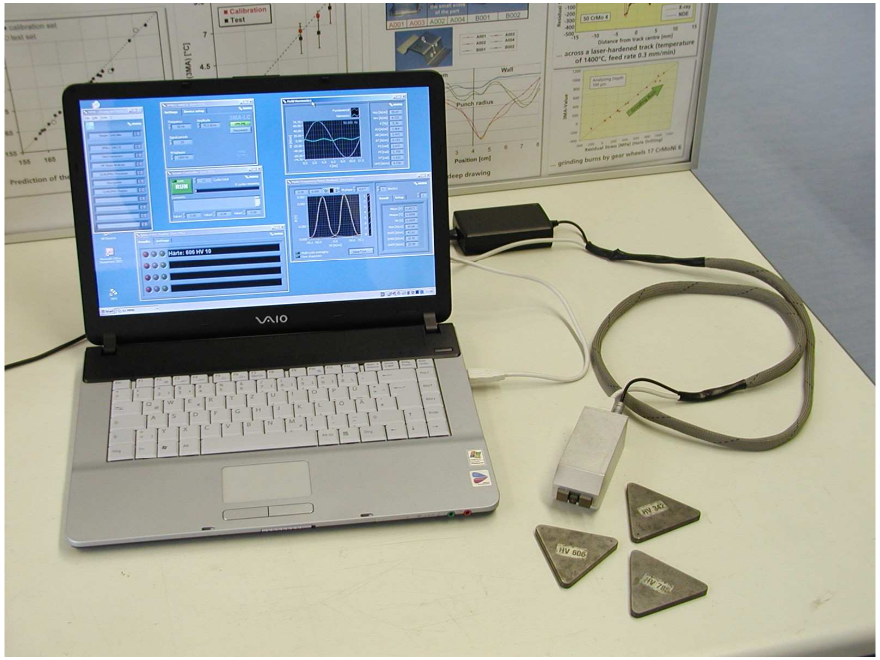
MicroMagnetic 3MA and MicroMach System

Electromagnetic, micromagnetic, magneto-elastic material properties are measured and correlated to e.g. with Stress, Rp0,2, Rm, Hardness, Depth





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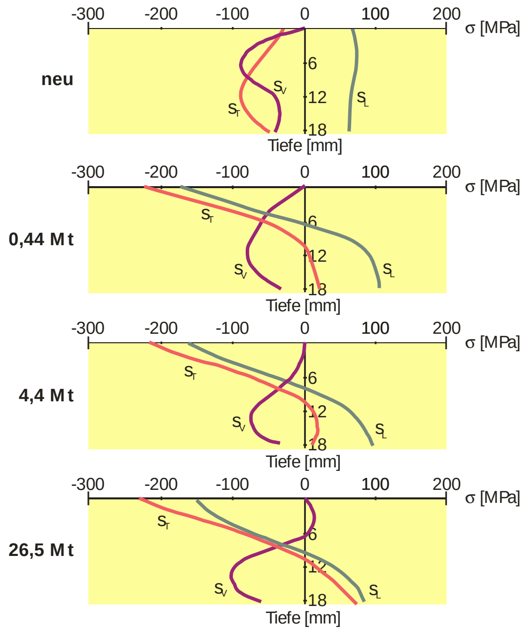
Contribution of Ultrasonic Rail Stress Analysis to Track Maintenance

State

1) The concept:
   - measuring the total stress state of the tread,
   - separate the thermally induced stress by measurements of the rail temperature,
   - use the mean value of stress results, measured at different tread positions along at least two tie spaces in order to minimize the influence of structural inhomogeneities

   needs to be discussed in detail and accepted.

2) Ultrasonic systems are developed. The EMAT sensors need to be built for the stress analysis according to the mentioned concept.
   It is recommended to perform measurements at individual fixed positions rather than continuously along the length.

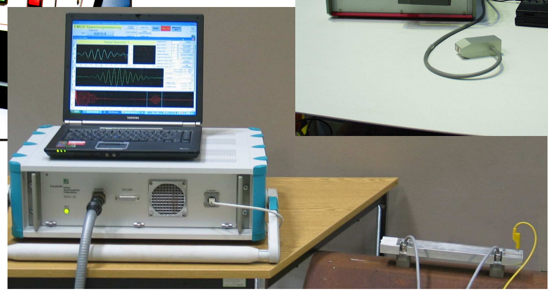


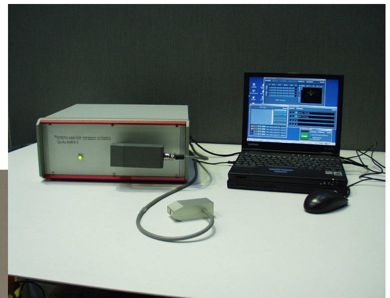
Contribution of Ultrasonic Rail Stress Analysis to Track Maintenance

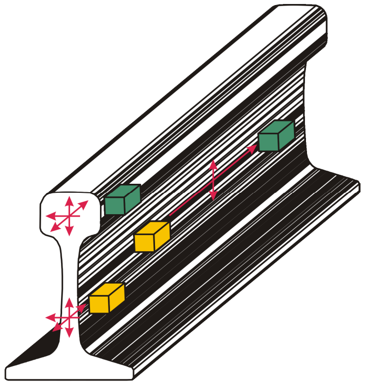
State

3) It will be possible to monitor
   - the stress state and its changes with the traffic load;
   - the stress state and change in the entrance/exit area of tunnels and bridges
   - the stress state of switches and its change
   - the stress state of the track in the vicinity of underpasses

   It will be possible to
   - measure and monitor the temperature of the bulk of the rail,
     using a EMAT shear wave sensor as shown.







Contribution of Ultrasonic Rail Stress Analysis to Track Maintenance

State

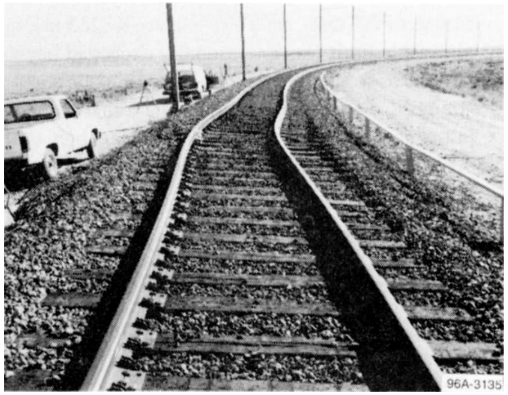
4) It seems to be feasible

- to integrate the EMAT Transmitter – Receiver SHo sensors into the head of rail, similarly to the AUROPA sensors as shown in the figure,

- to monitor the dynamic change of stress state, taking advantage of the measuring rate of the ultrasonic TOF measurement of 50 Hz

- to improve existing models for track buckling and uplift using the knowledge of the stress state of the track section

- to develop a model for the characterization of the roadbed condition based on measurements of rail strain/stress state and dynamic changes



Source: A. Kish 1996

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