multibody simulation in fatigue design

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E 10153 a

- **loading**
  - load level
  - constant amplitude / variable amplitude
  - uniaxial / multiaxial
- **geometry**
  - load path
  - notch severity
  - local stress state
- **material**
  - basic properties
  - surface finish / manufacturing
  - residual stresses

parameters determining fatigue life

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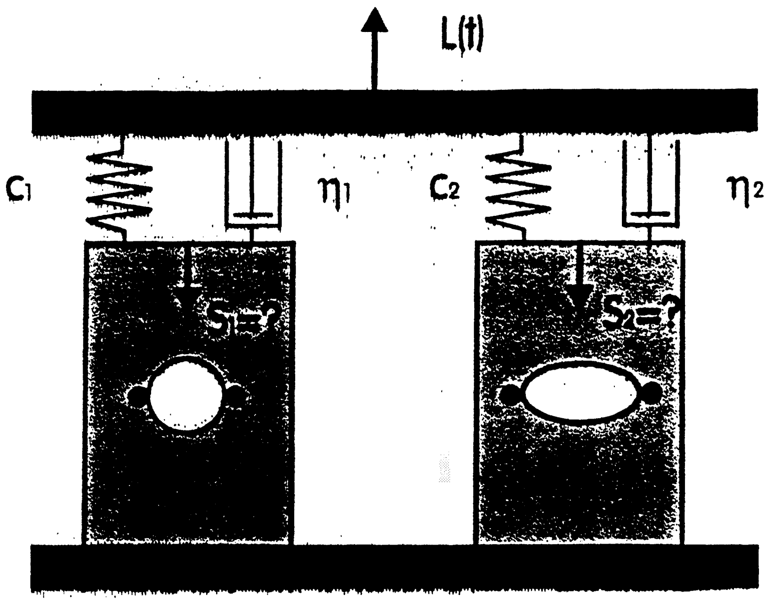

mild notch

severe notch

critical locations depend on load path **and** notch severity

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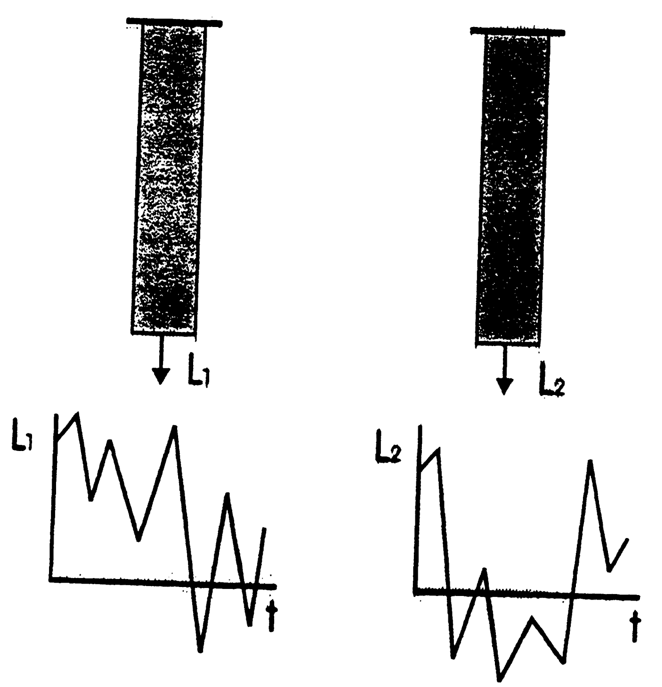

which is the more damaging loading: $L_1(t)$ or $L_2(t)$?

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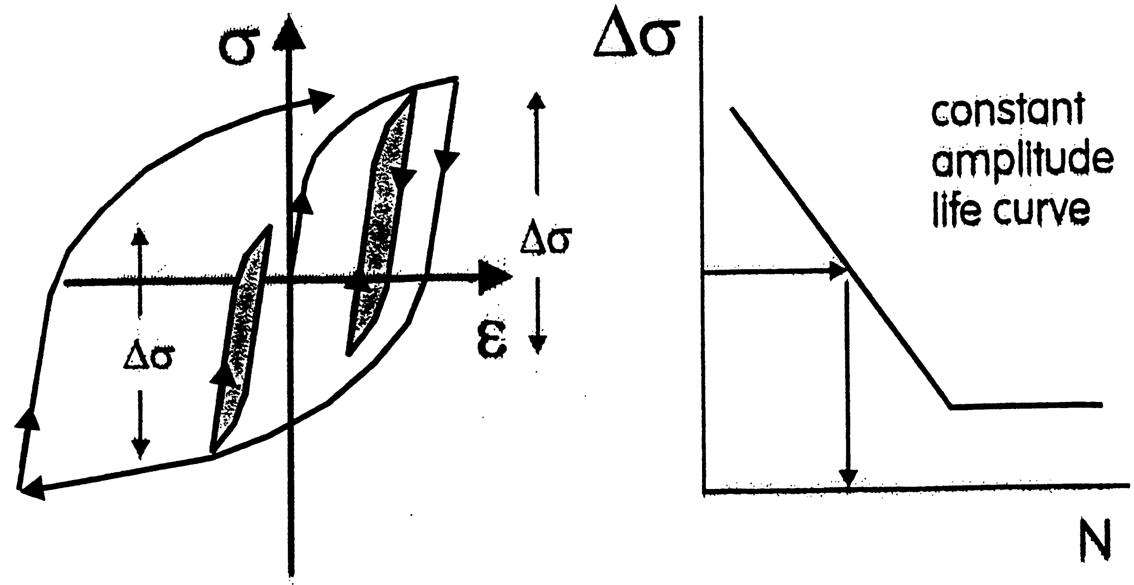

the closed hysteresis loop is the basic damage "event" used to determine the damage increment

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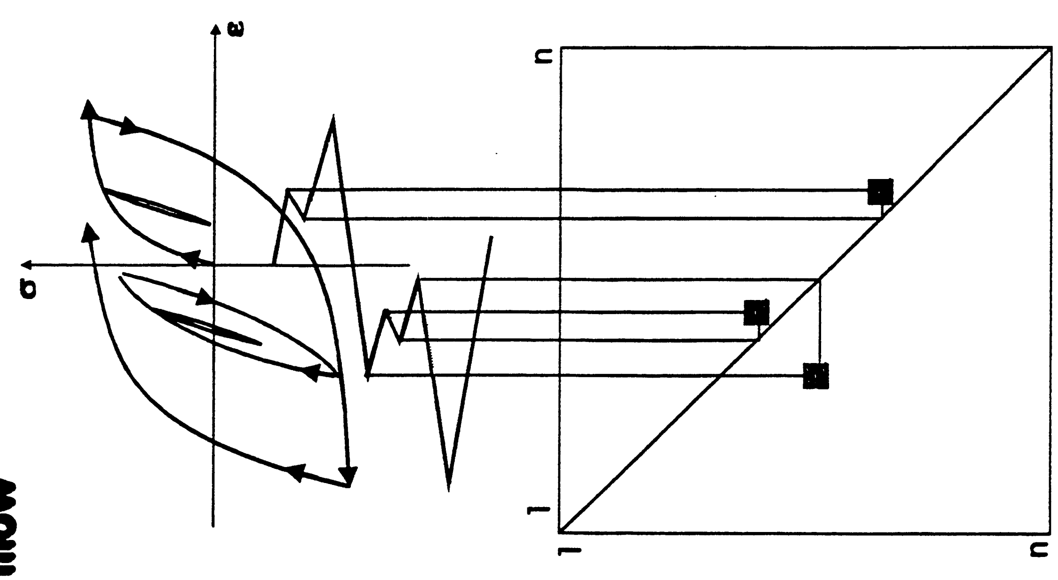
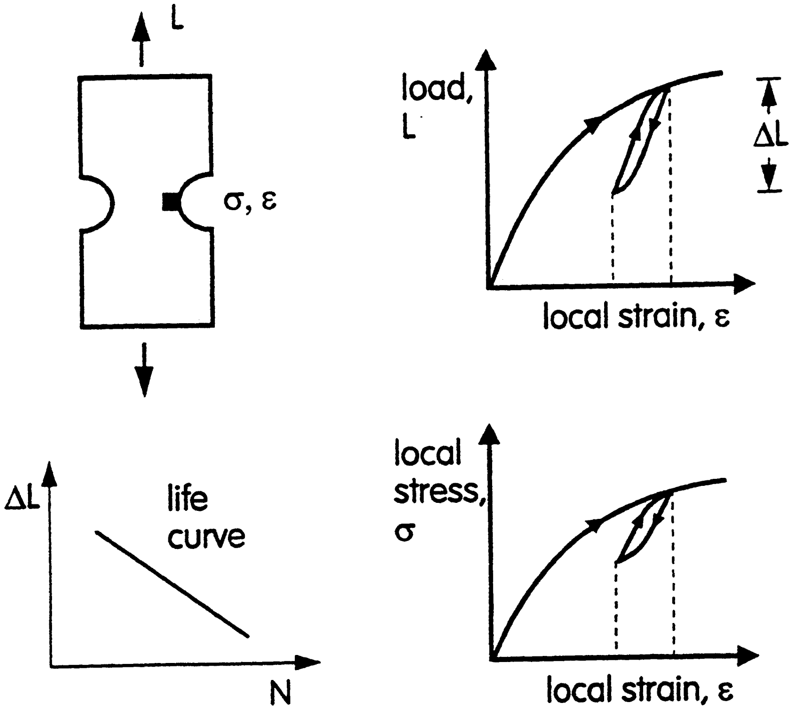
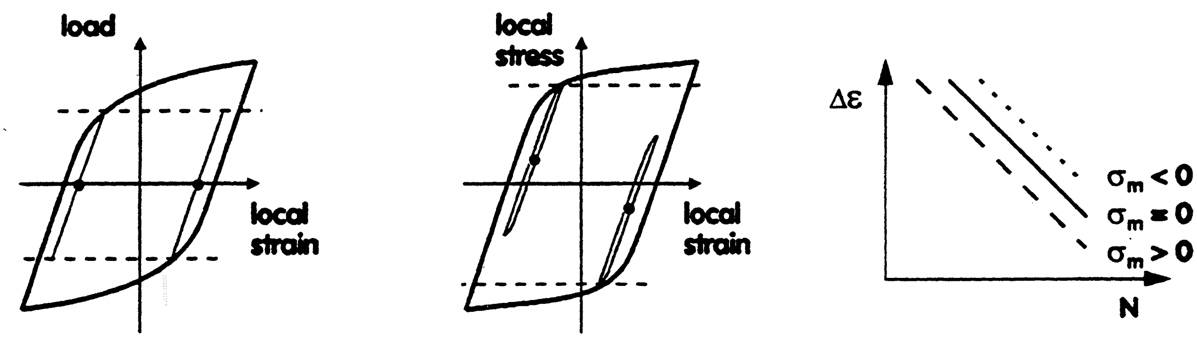
Rainflow





load hystereses
and
local hystereses
open and close
at the same time

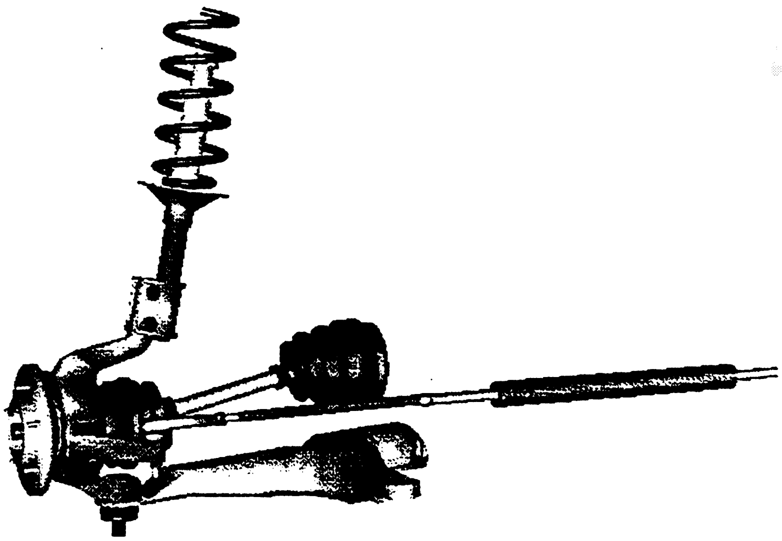


same mean load

different mean stress

mean stress effect on fatigue life

"from-to" rainflow counting gives the best estimate of local mean stress



example for [illegible] analysis

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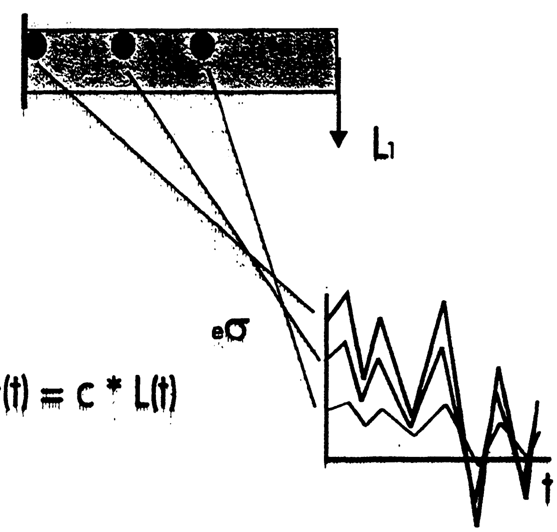

$$ {}_{e}\sigma(t) = c * L(t) $$

uniaxial case:
all pseudo stress histories are proportional - only the max(c) history is interesting

pseudo stress [illegible] analysis reduction (I)

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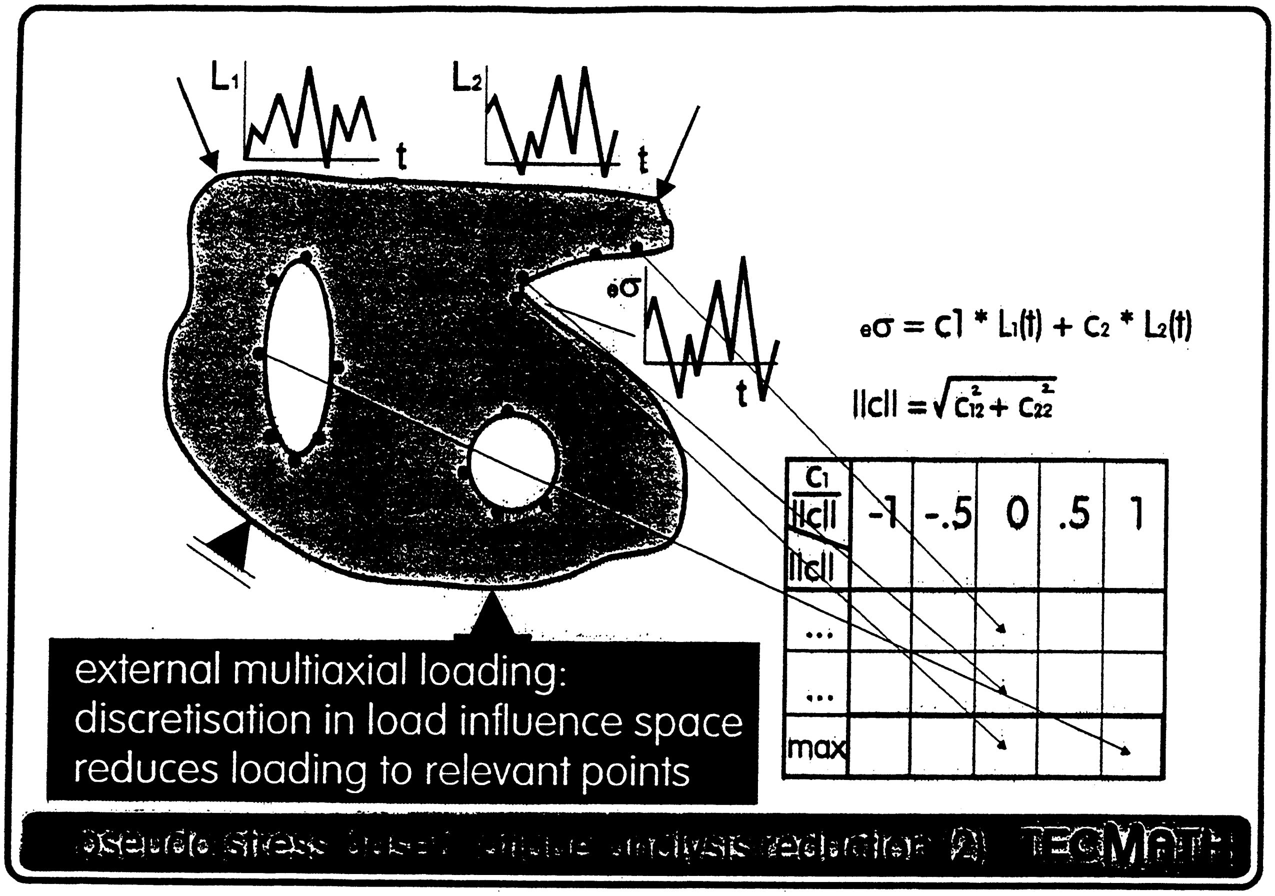
L1
t
L2
t
eσ
t
eσ = c1 * L1(t) + c2 * L2(t)
||c|| = √(c12² + c22²)
c1 / ||c||
-1
-.5
0
.5
1
||c||
...
...
max
external multiaxial loading:
discretisation in load influence space
reduces loading to relevant points
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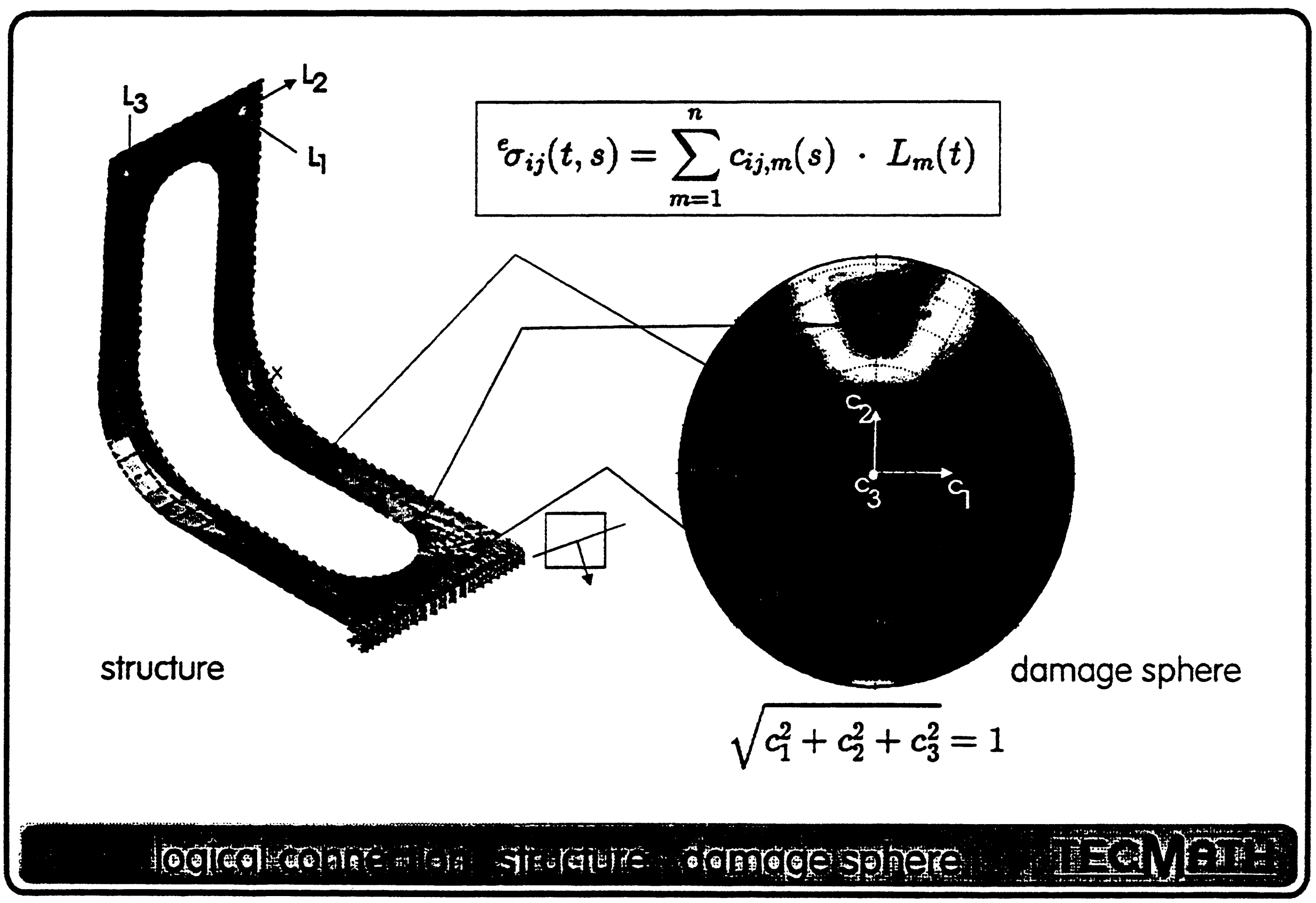
L3
L2
L1
$^{e}\sigma_{ij}(t,s) = \sum_{m=1}^{n} c_{ij,m}(s) \cdot L_m(t)$
c2
c1
c3
structure
damage sphere
$\sqrt{c_1^2 + c_2^2 + c_3^2} = 1$
structure damage sphere
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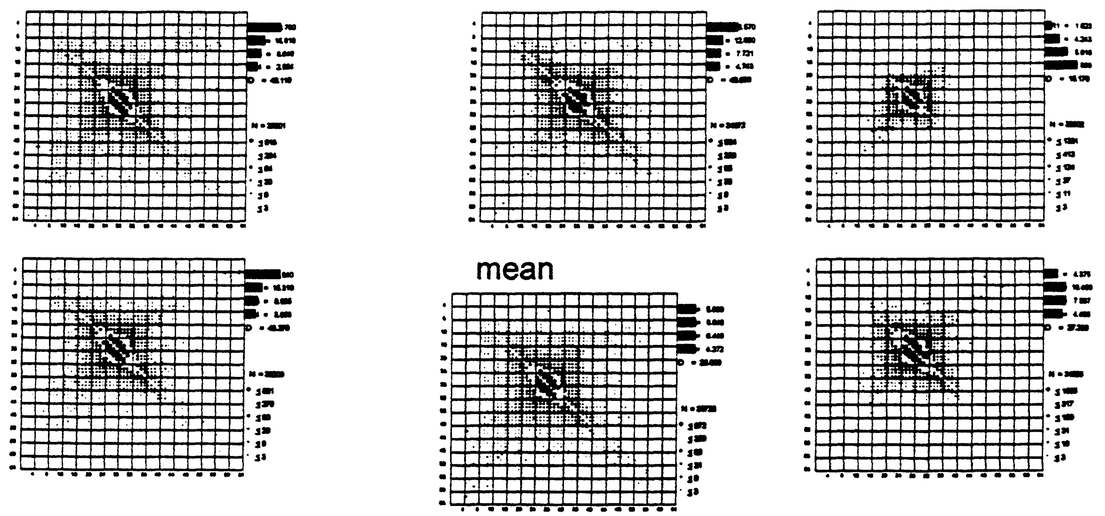
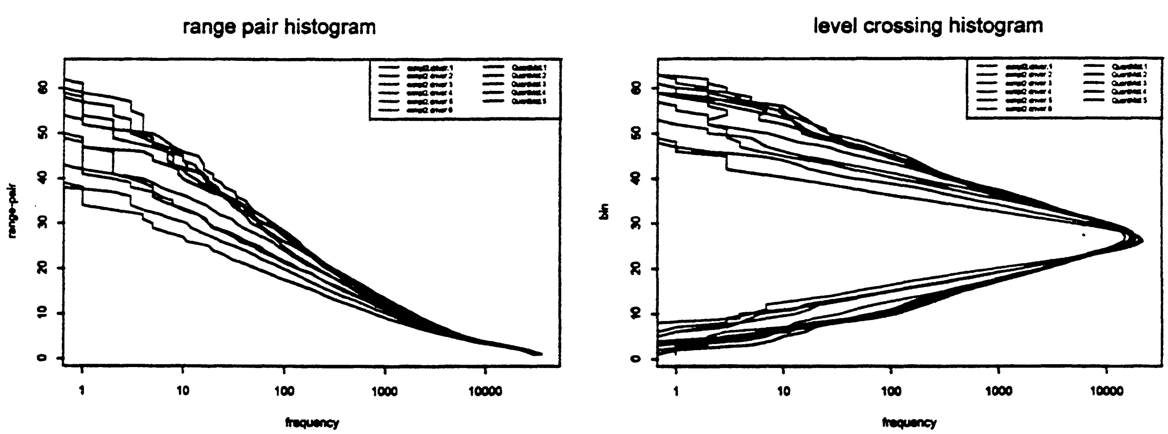
comparison of matrices

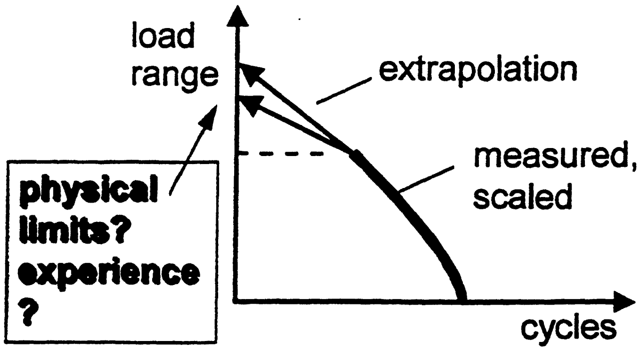
extreme matrices

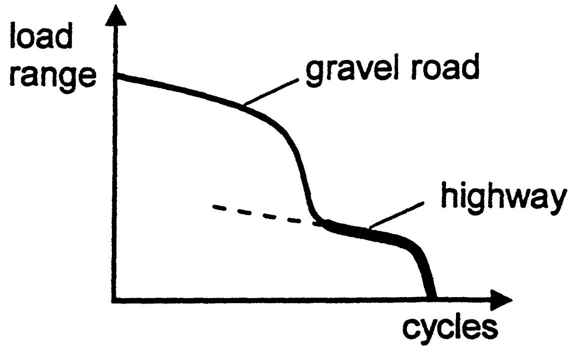
original matrices



comparison of the 1D loading spectra

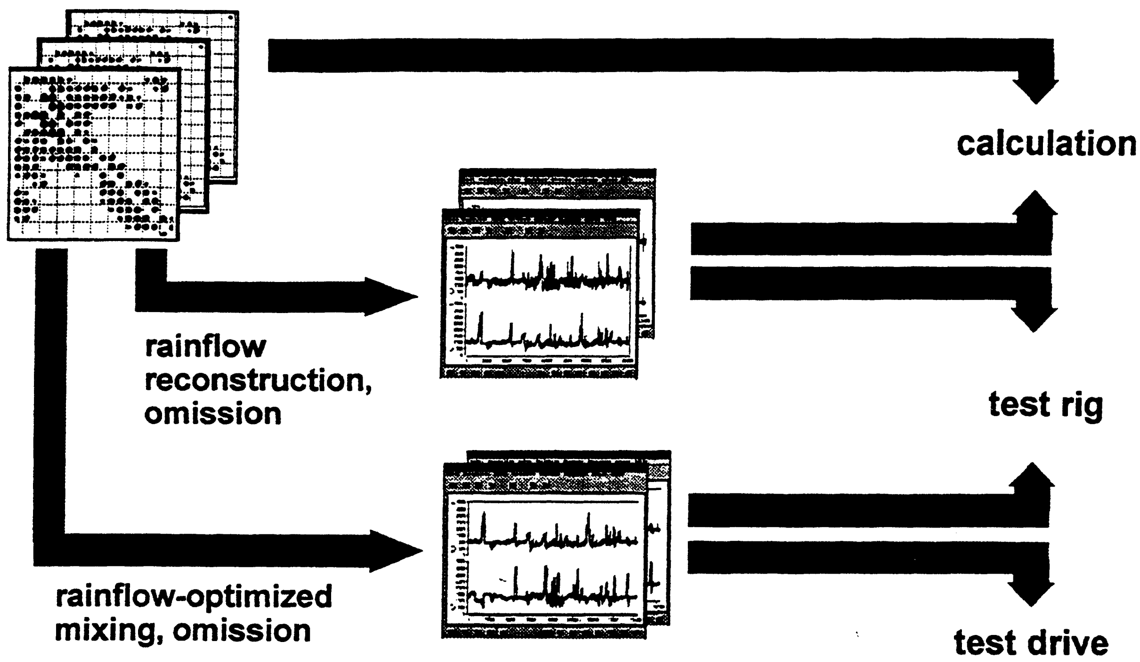






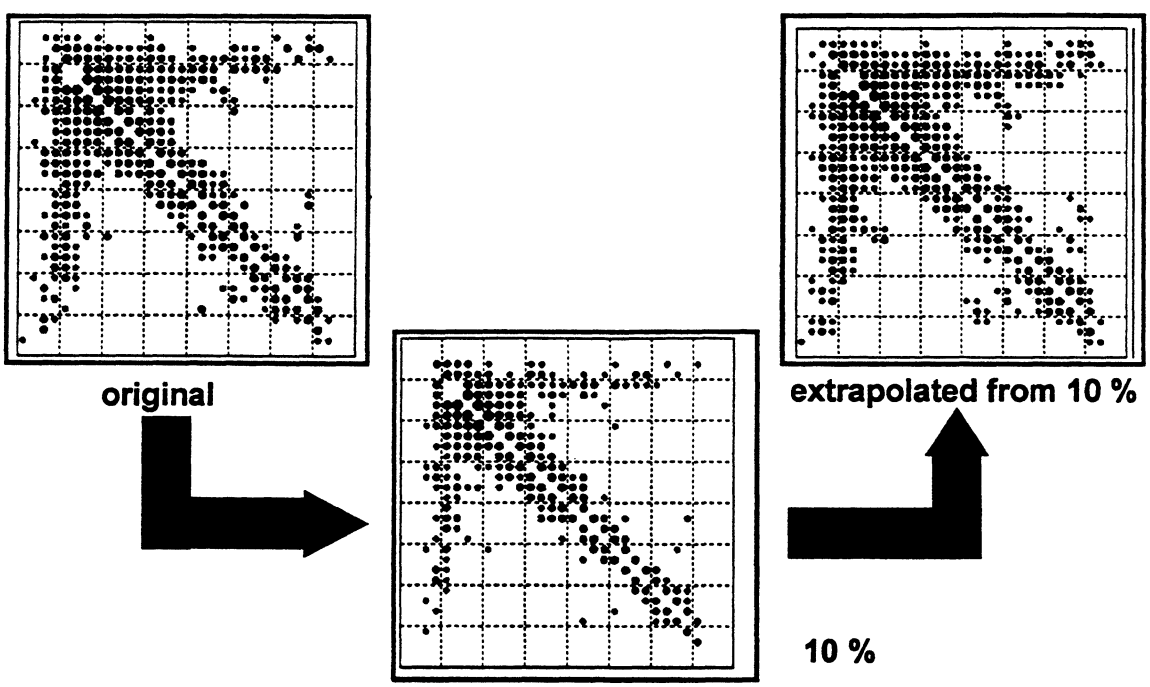
- extrapolation can be improved by knowledge of physical limits and customer behavior
- extrapolation will not predict different types of loading with sufficient accuracy

ideal service-loads

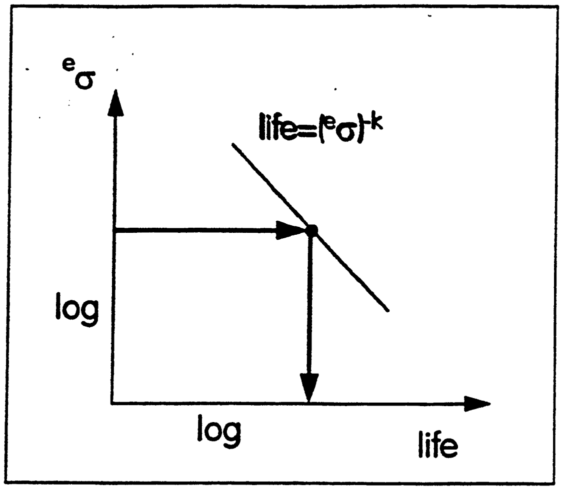


load analysis TECMATH

non-parametric, adaptive density estimation



extrapolation, verification, data validation TECMATH



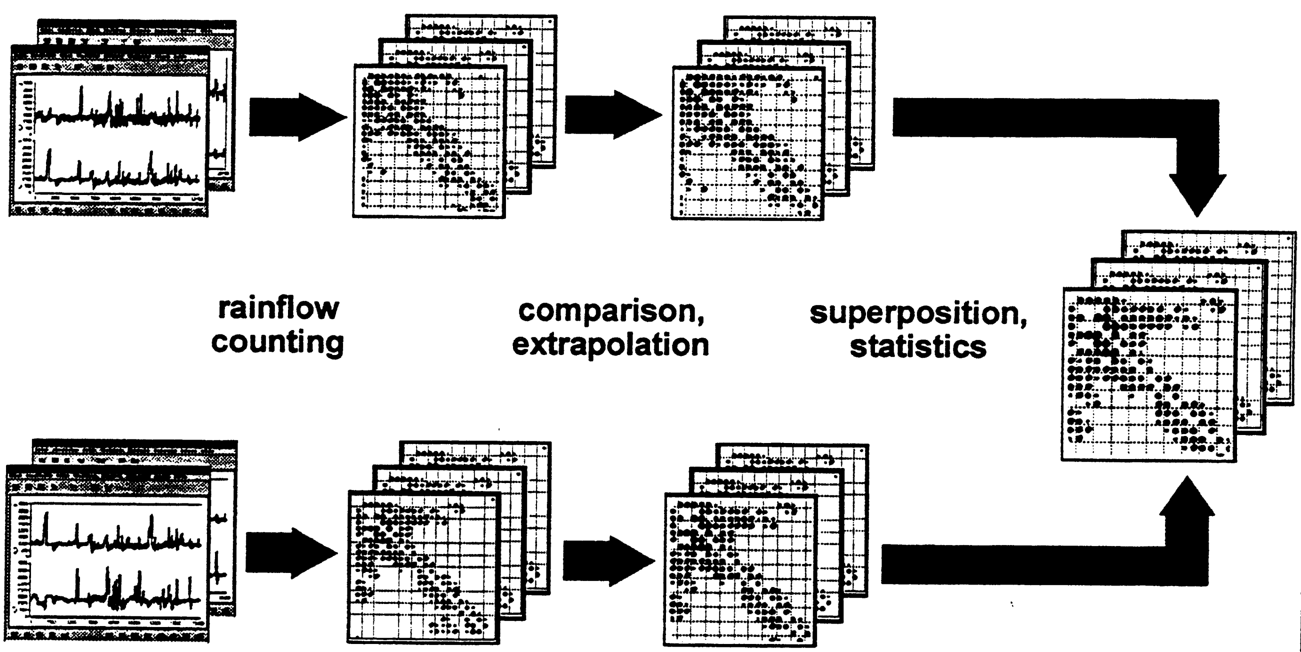
stress $^e\sigma$	life k=3	life k=5	life k=7
1	1	1	1
1,1	0,75	0,62	0,51
1,3	0,45	0,27	0,16
1,5	0,30	0,13	0,06
2,0	0,13	0,03	0,01

a (local) notch with $K_t = 2$
can increase the damage by a factor of 100

component damage and local notch effects

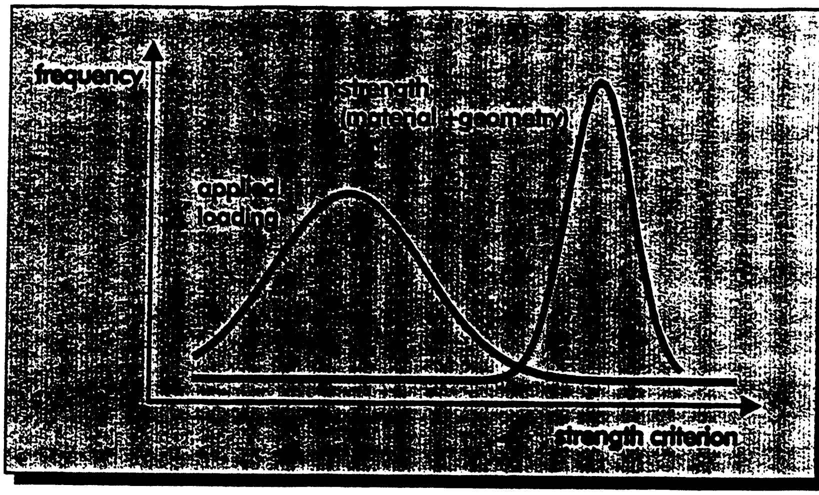
test drives:
- customers
- road types
- ...

ideal service-loads

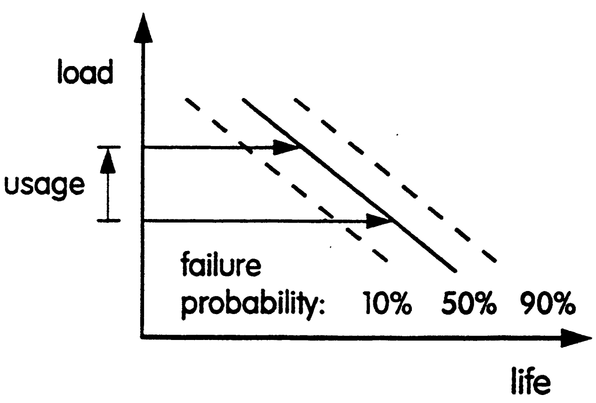


load analysis

$C_{applied} < C_{applicable}$



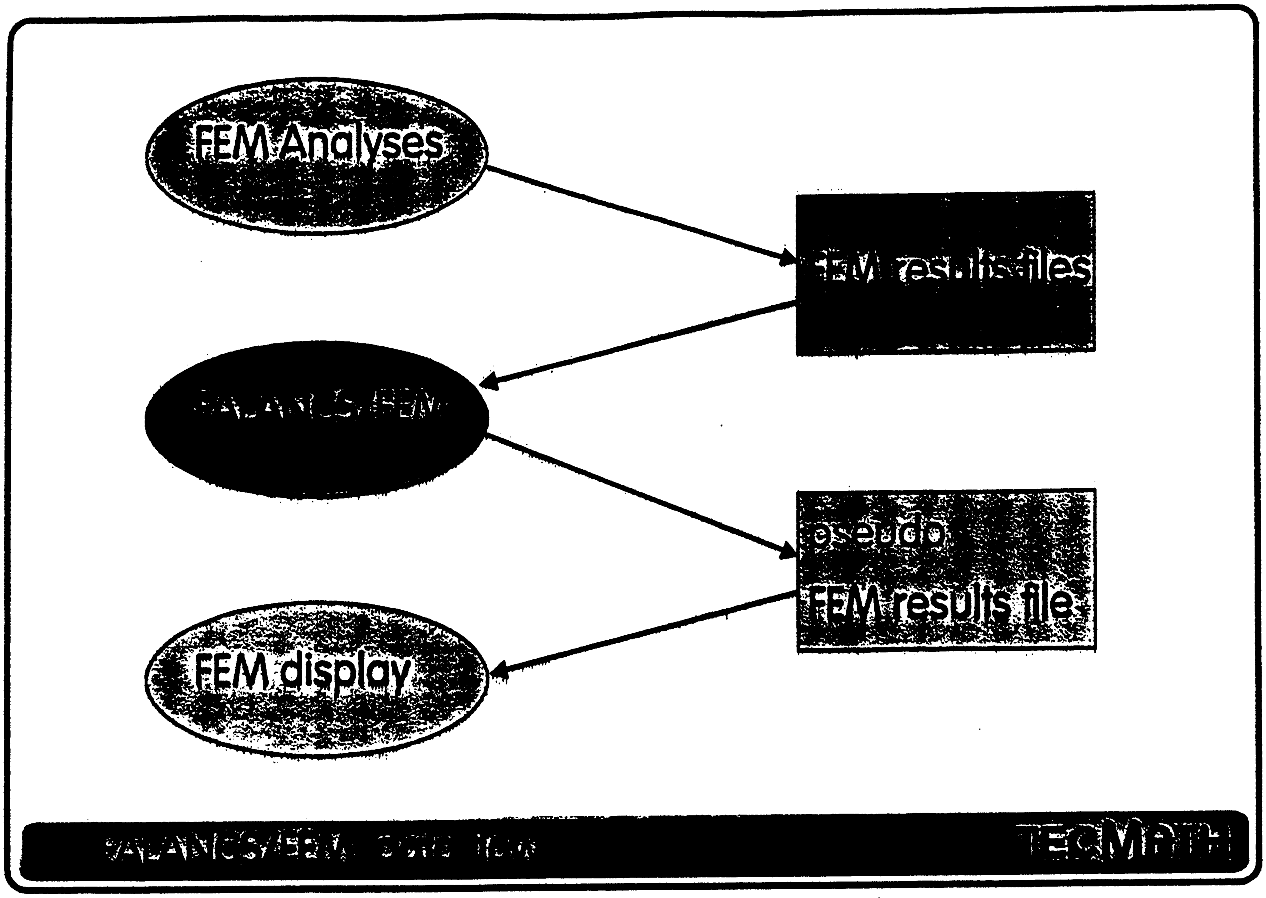
➜ scatter bands determine ideal fatigue design



typical ratios of
10% / 90% probability

geometry	1,02
material	
- controlled	1,15
- different welds	1,45
loads (car)	2,00

today, customer usage is the most important source of fatigue scatter


FEM Analyses
FEM results files
pseudo
FEM results file
FEM display

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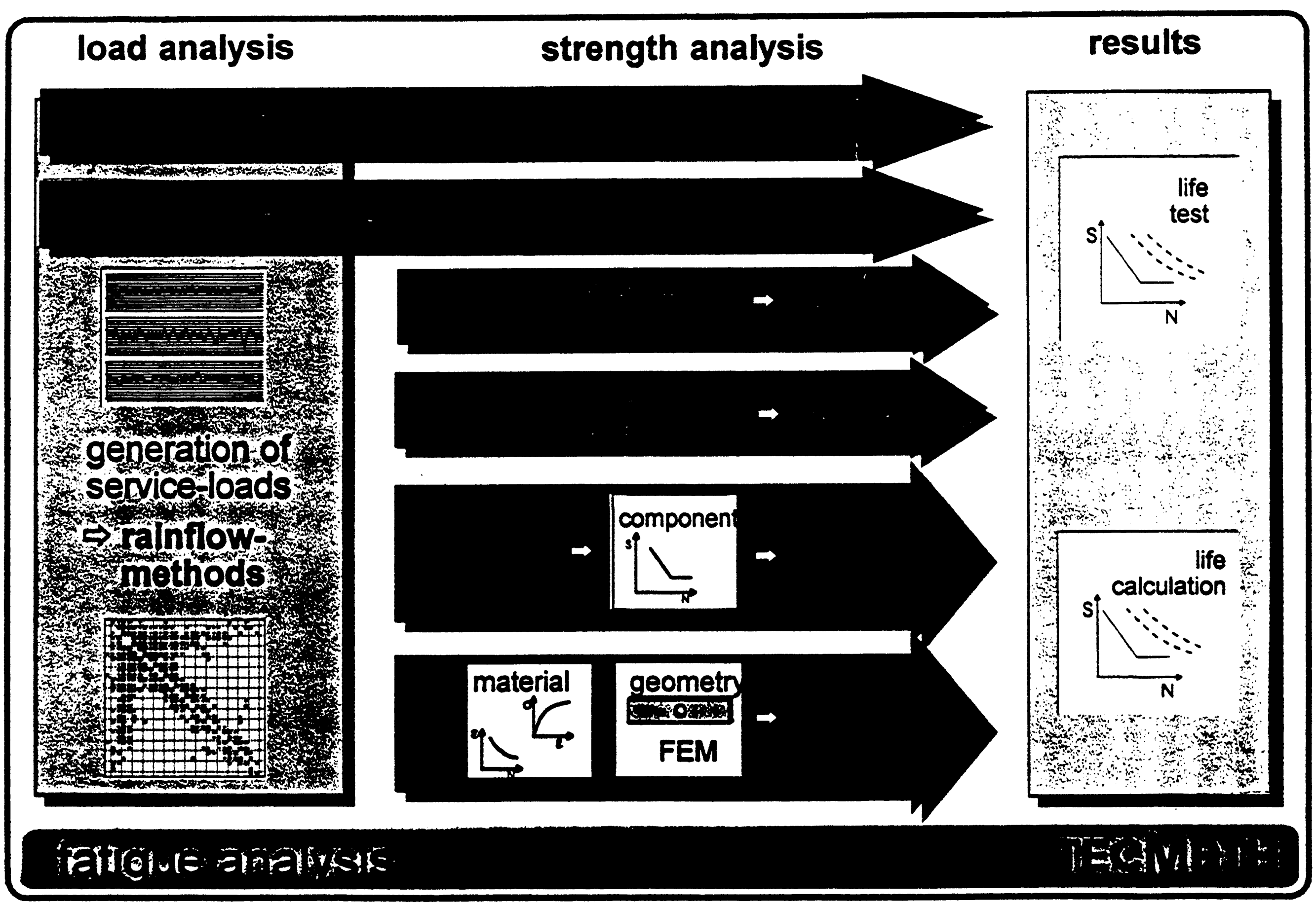

load analysis
strength analysis
results
life
test
S
N
generation of
service-loads
⇨ rainflow-
methods
component
material
geometry
FEM
life
calculation
S
N
fatigue analysis

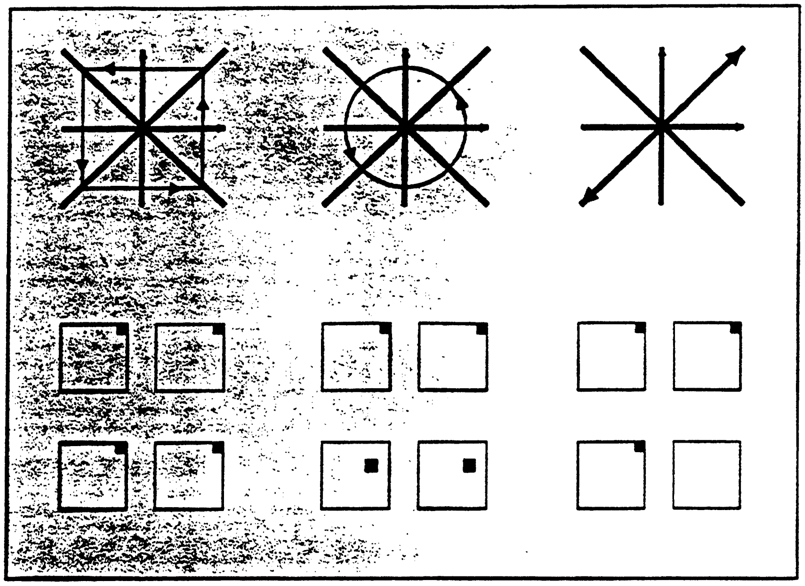
rainflow projection counting

load path

rainflow matrices

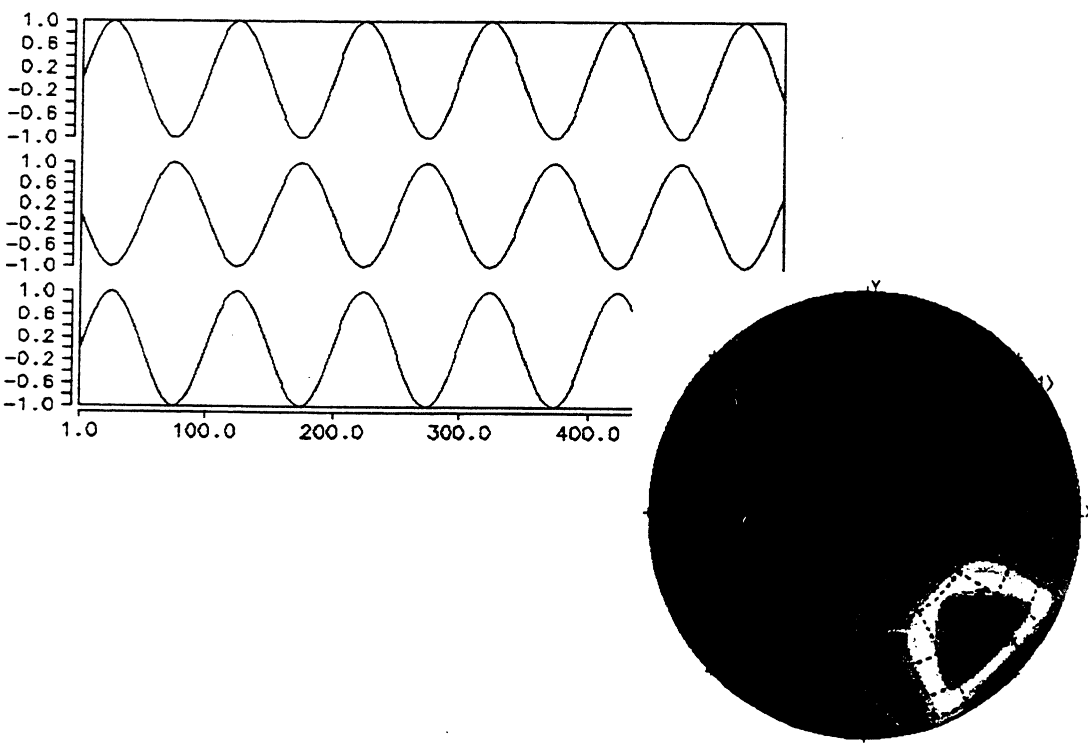
axial counting

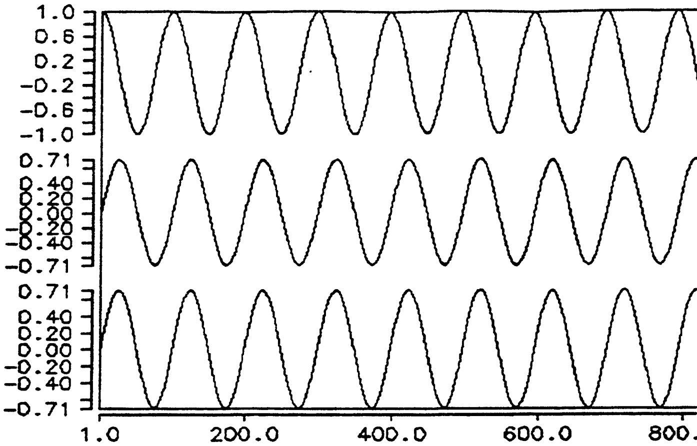
diagonal counting

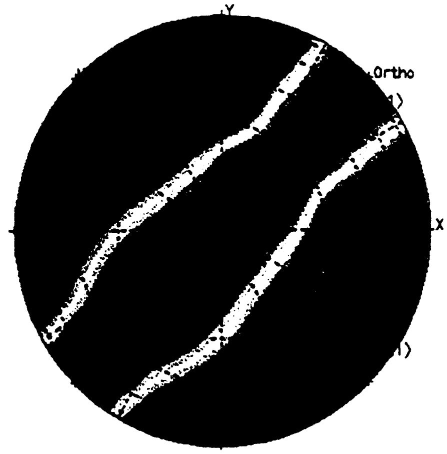


keeping the phase information in the rainflow matrices

RP counting: proportional loading

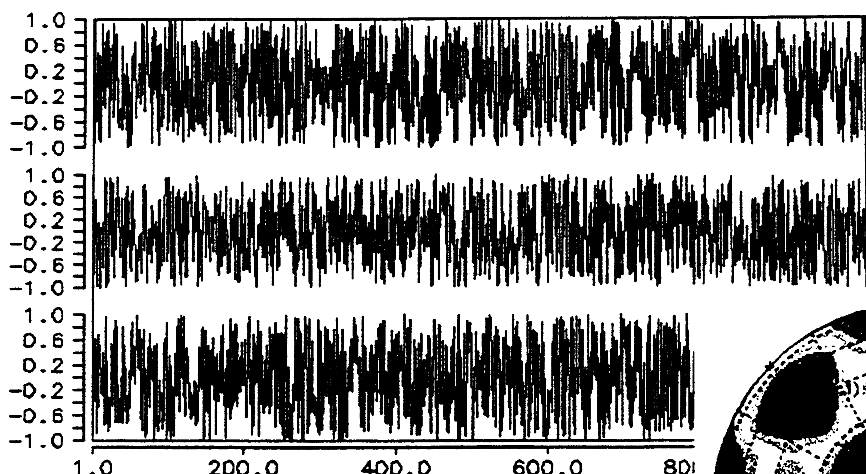


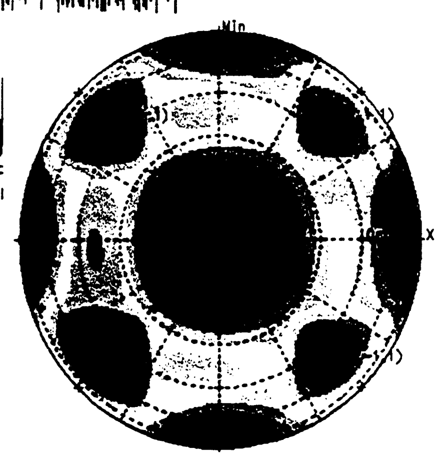




RP counting: loads with phase shift

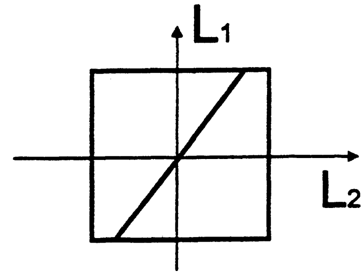
RP counting: equidistribution in 3D-box





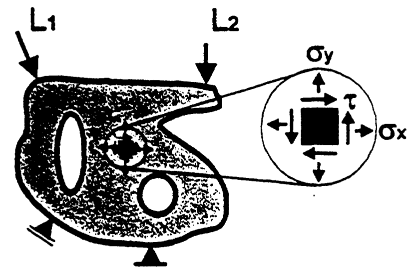
logical connection between projections in the phase diagram and pseudo stresses

load projections:



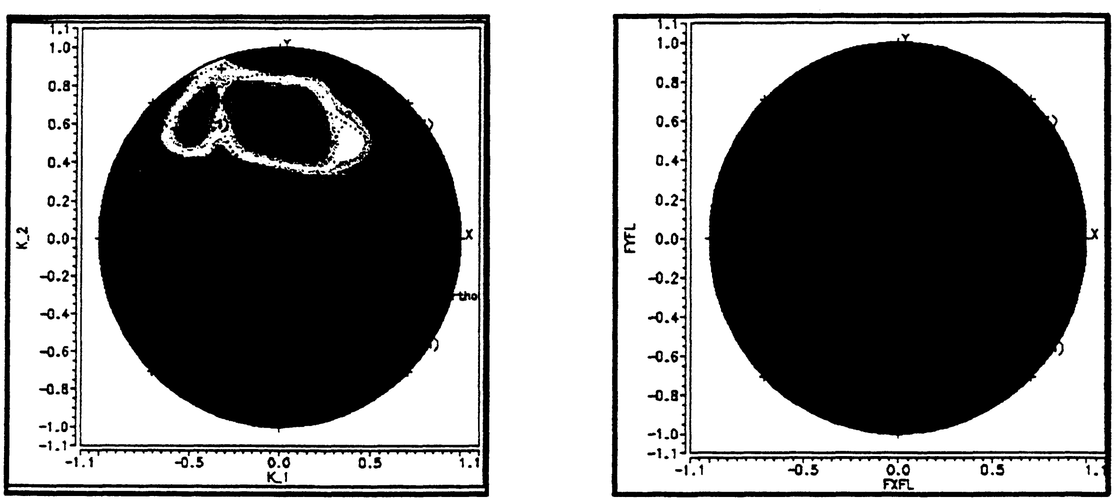
$$L_\xi(t) = d_1 * L_1(t) + d_2 * L_2(t)$$

pseudo stresses:



$${}_e\sigma_\xi(t) = c_1 * L_1(t) + c_2 * L_2(t)$$

similar equation, but different coefficients



before

after

load path optimisation

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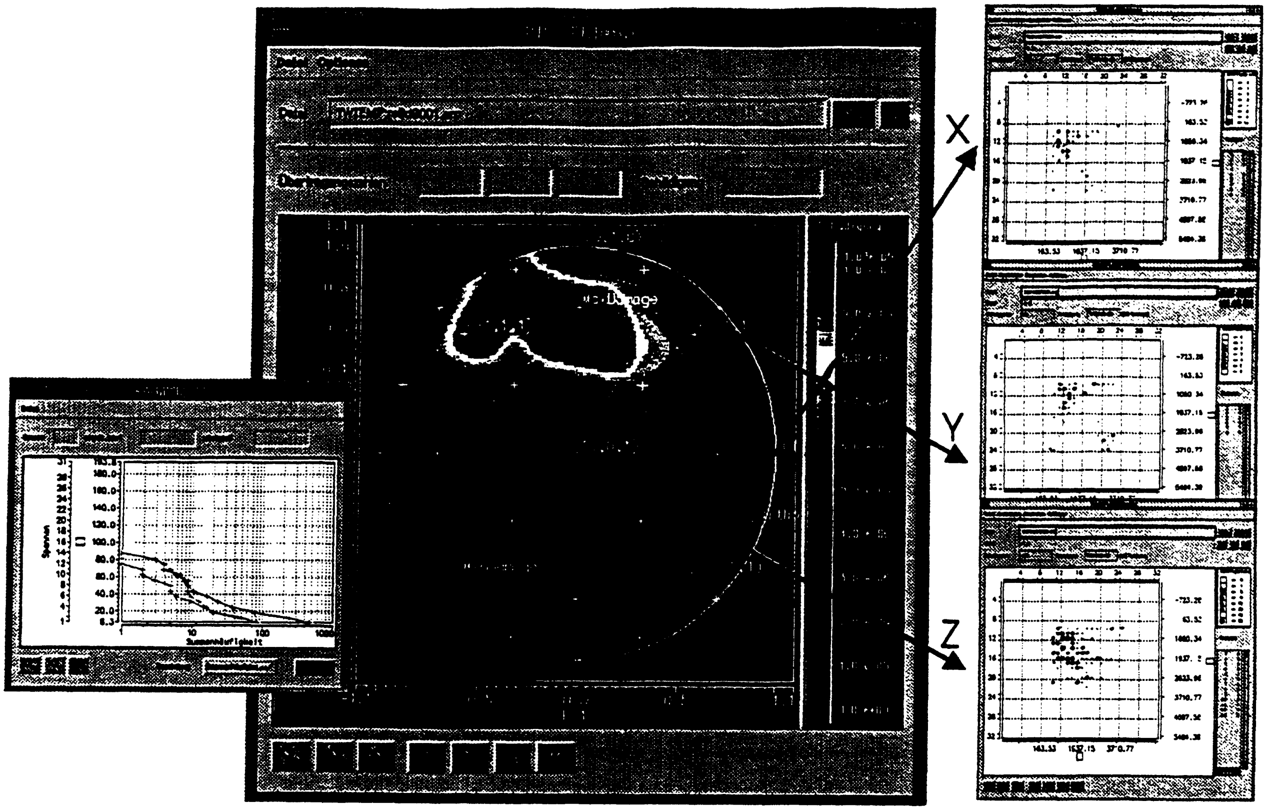
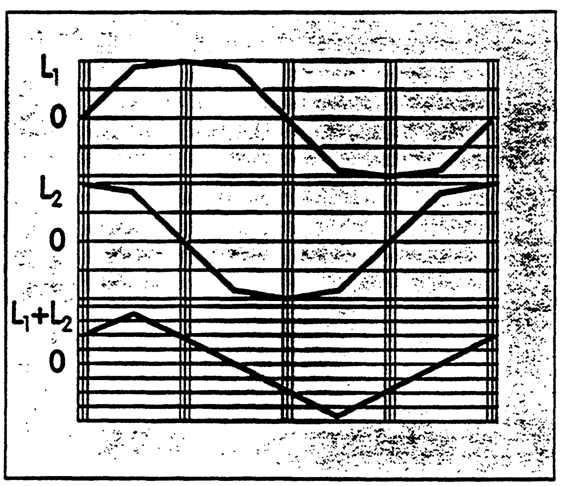
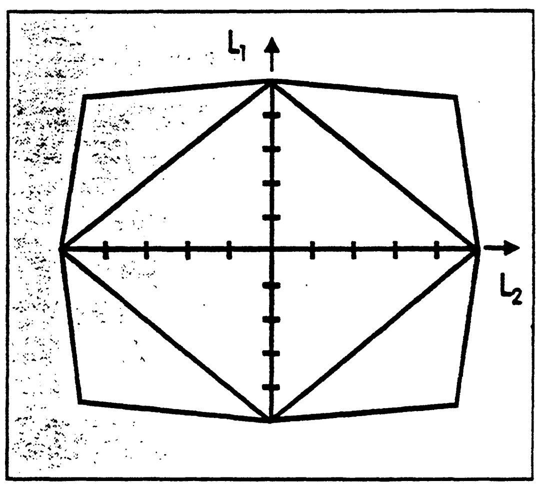
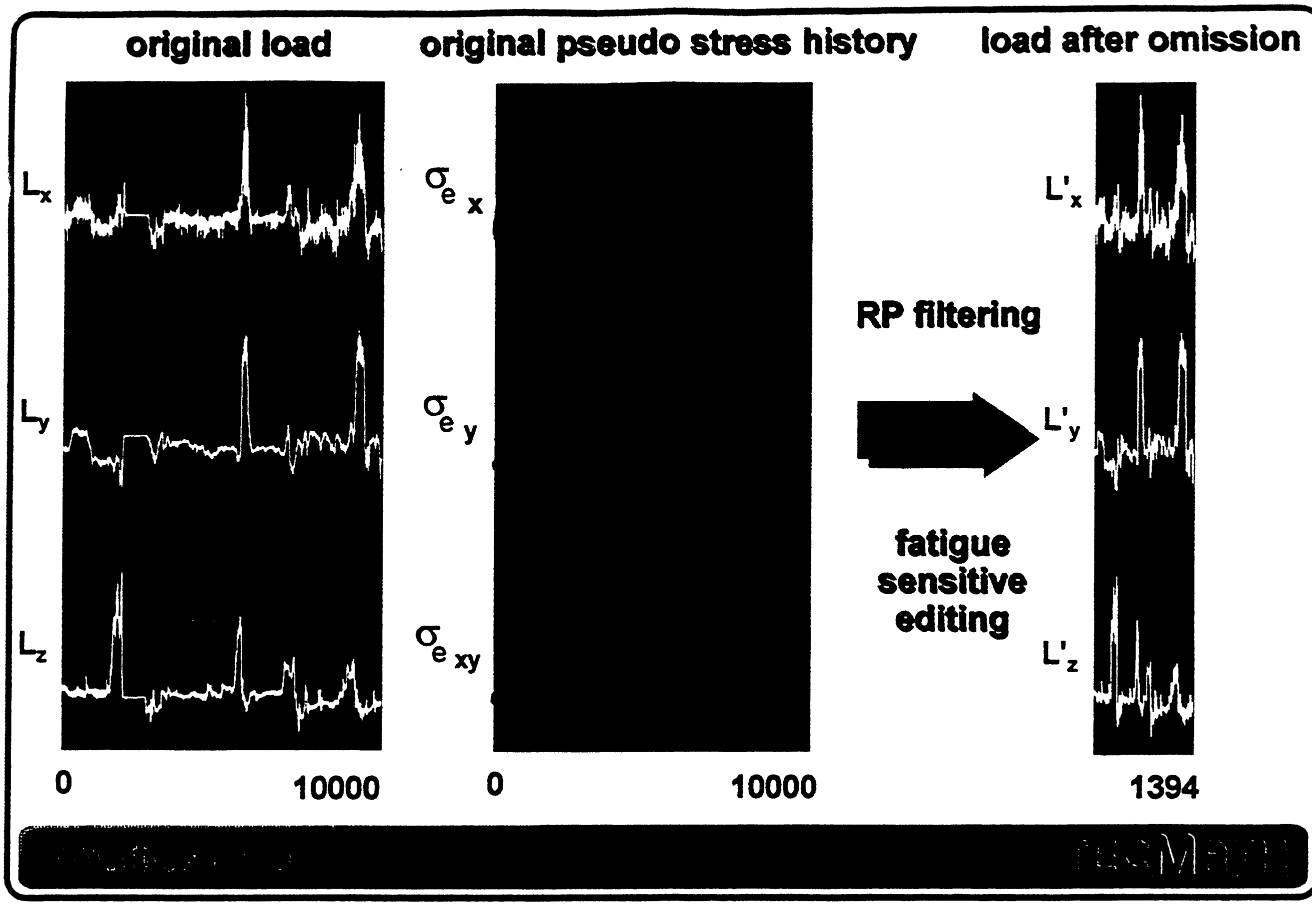




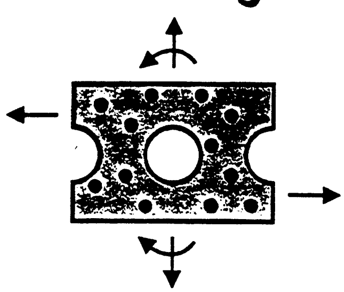


peak slicing (multiple channel peak/value extraction) changes the phase content



RP filtering	fatigue sensitive editing

RP filtering

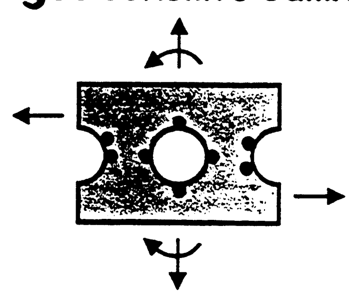


abstract locations (rainflow projections)

load level independent

➡ suitable for conservative first filtering before structural definition and analysis

fatigue sensitive editing



user defined locations

omission depends on load level

➡ further test time reduction when structure has been analysed by FEM

Structural 'MASING plus Memory' Model

material

- cyclic stress-strain curve $\varepsilon = g(\ \sigma\ )$
- MASING behaviour $\Delta\varepsilon \cdot \mathrm{sgn}(\Delta\sigma) = 2 \cdot g(\ |\Delta\sigma|/2\ )$
- memory

structure

- load notch-strain curve $\varepsilon = g(\ {}^{e}\sigma\ )$
- MASING behaviour $\Delta\varepsilon \cdot \mathrm{sgn}(\Delta {}^{e}\sigma) = 2 \cdot g(\ |\Delta {}^{e}\sigma|/2\ )$
- memory

standard notch analysis in unaxial fatigue

Local Pseudo Stress, Pseudo Strain

local stress (${}^{e}\sigma$) or strain (${}^{e}\varepsilon$)
at a specific site of the structure
computed by theory of elasticity

one load component, local stress state uniaxial

$${}^{e}\sigma(t) = K_t \cdot S(t) = c \cdot L(t)$$

K_t – stress concentration factor (non-dimensional)
S – arbitrarily definable nominal stress
c – dimensional proportionality constant
L – load: force, moment, stress, acceleration, etc.
t – time

general loading

$${}^{e}\sigma_{ij}(t) = \sum_{m=1}^{n} (c_{ij})_m \cdot L_m(t)$$

$\rightsquigarrow$ pseudo stress = specially defined nominal stress

Non-proportional Notch Analysis

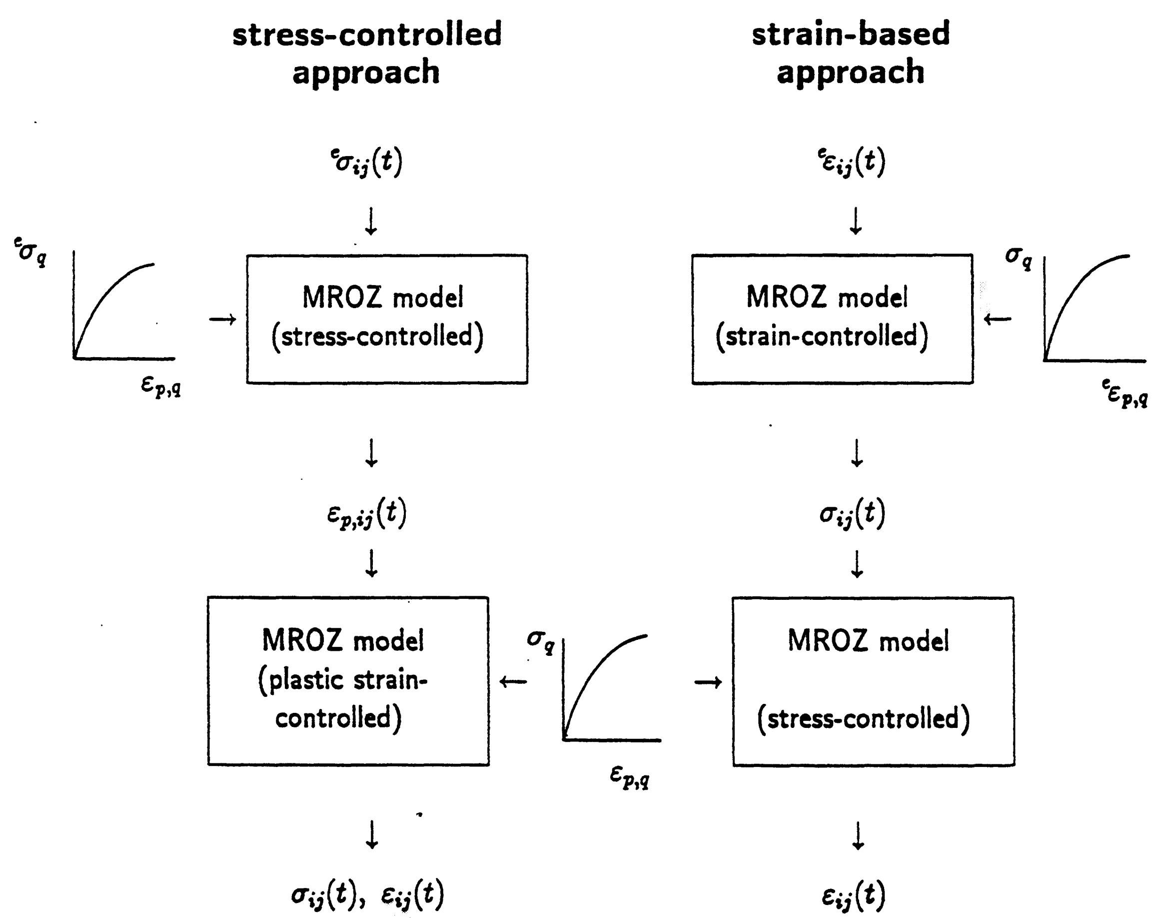
material

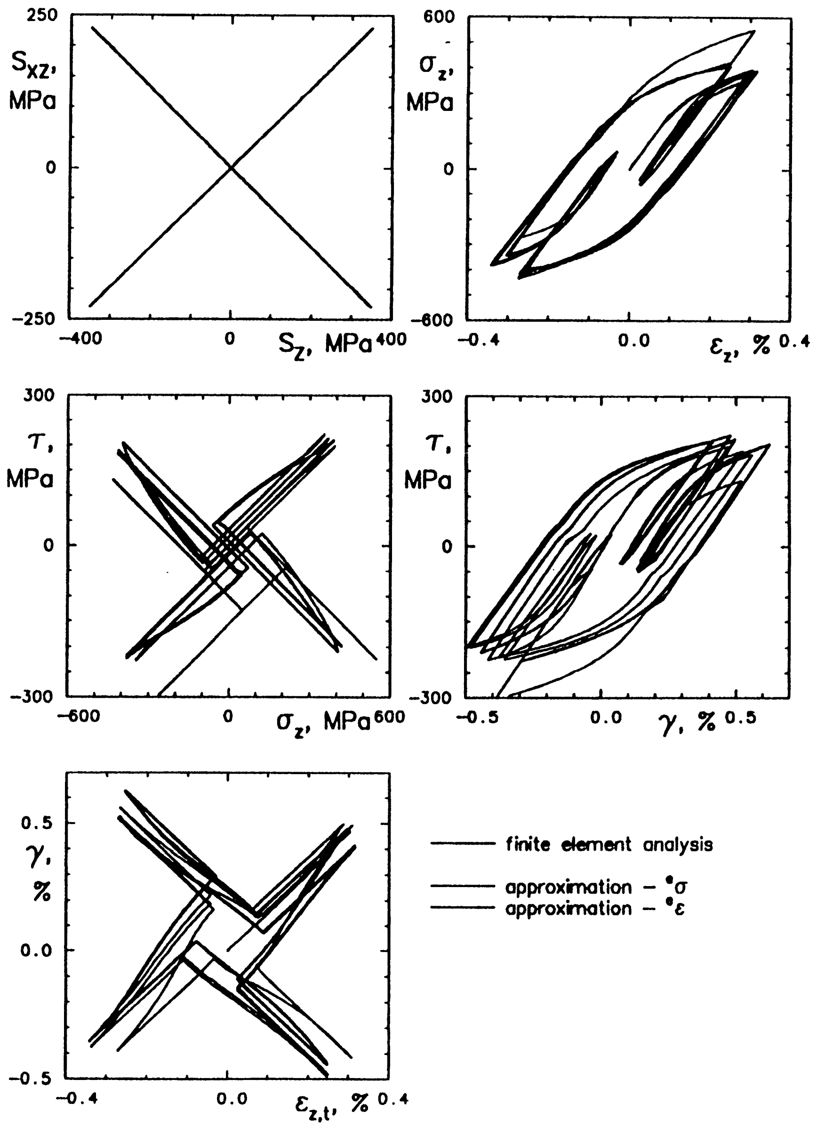
- cyclic stress-strain curve $\varepsilon_{p,q} = g(\sigma_q)$
- von MISES yield criterion, $\rightsquigarrow \sigma_q$
- MROZ model

structure

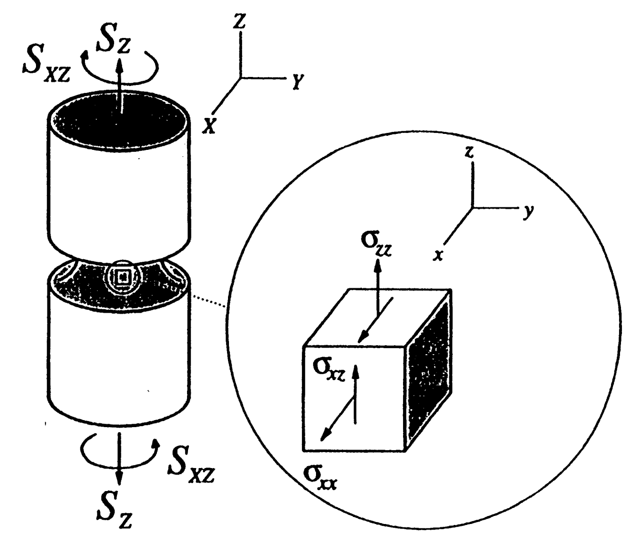
- load notch-strain curve $\varepsilon_{p,q} = g({}^e\sigma_q)$, ${}^e\varepsilon_{p,q} = g(\sigma_q)$
- von MISES yield criterion, $\rightsquigarrow {}^e\sigma_q$
- MROZ model

originally:
BARKEY, SOCIE, HSIA – anisotropic Y.C., nominal stress



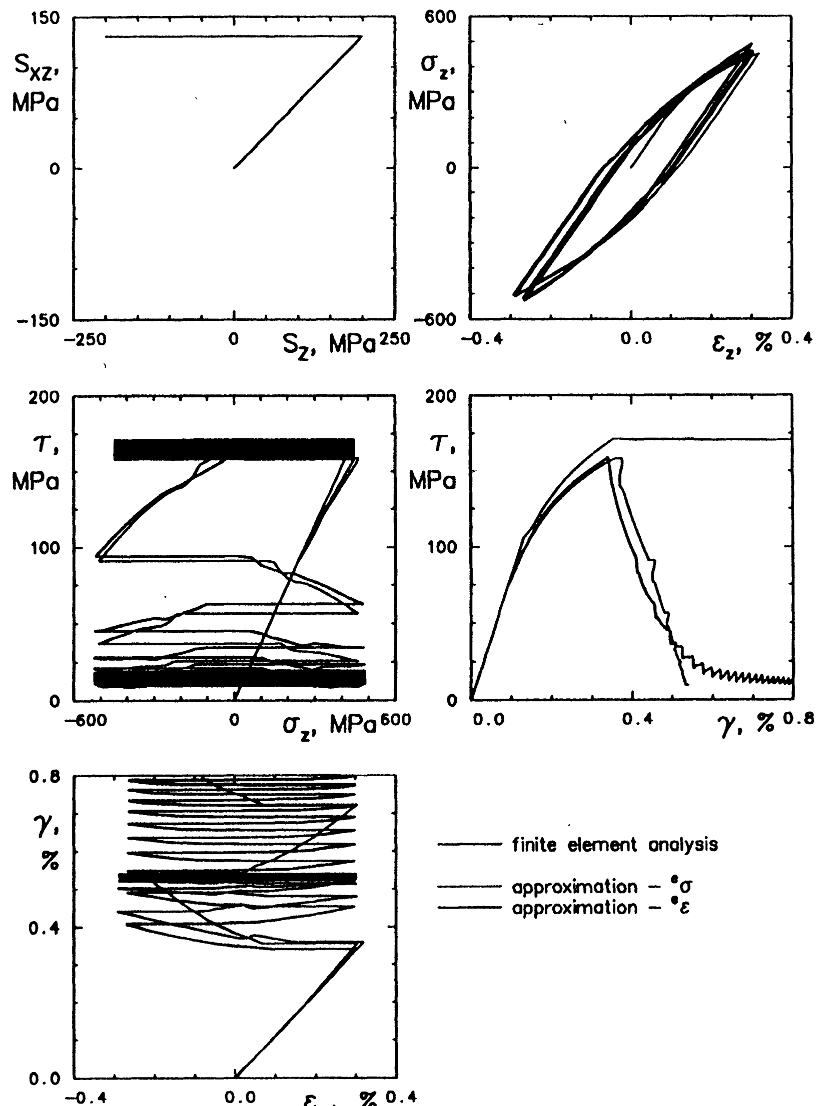


X path
(mild notch)

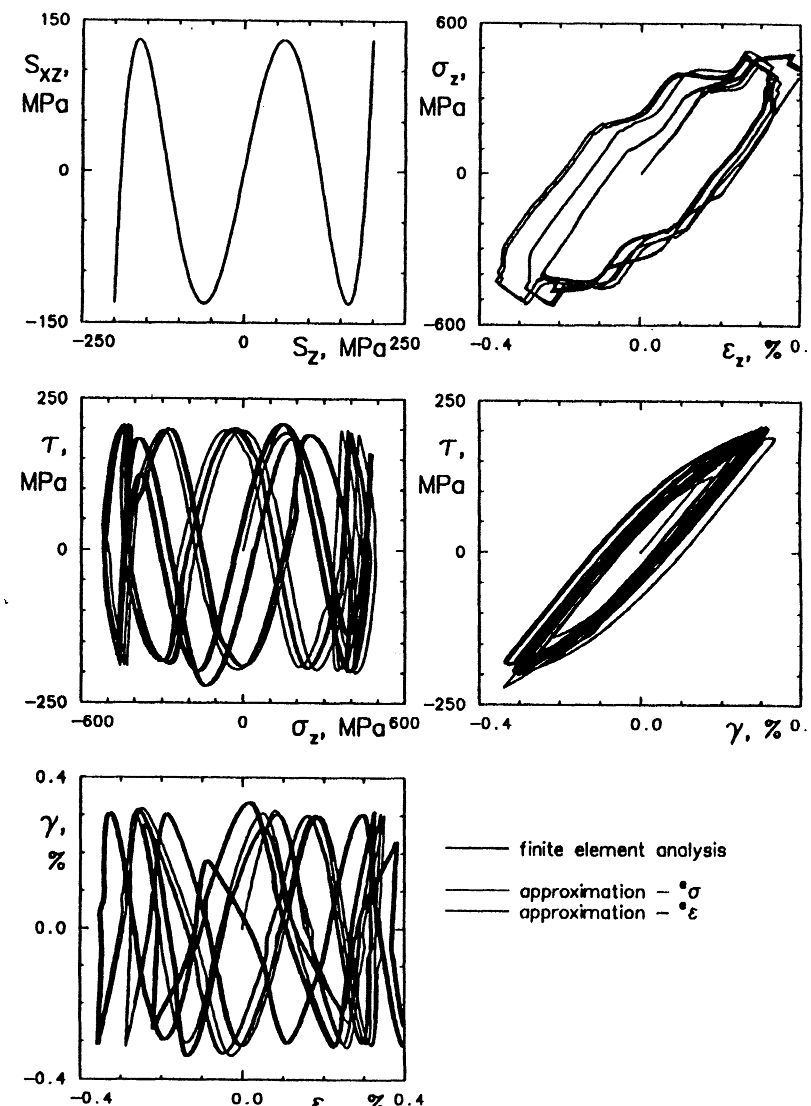


	mild	sharp
notch radius / net section diameter	1 : 2	1 : 40
axial stress concentration factor	1.40	2.92
torsional stress concentration factor	1.14	1.70

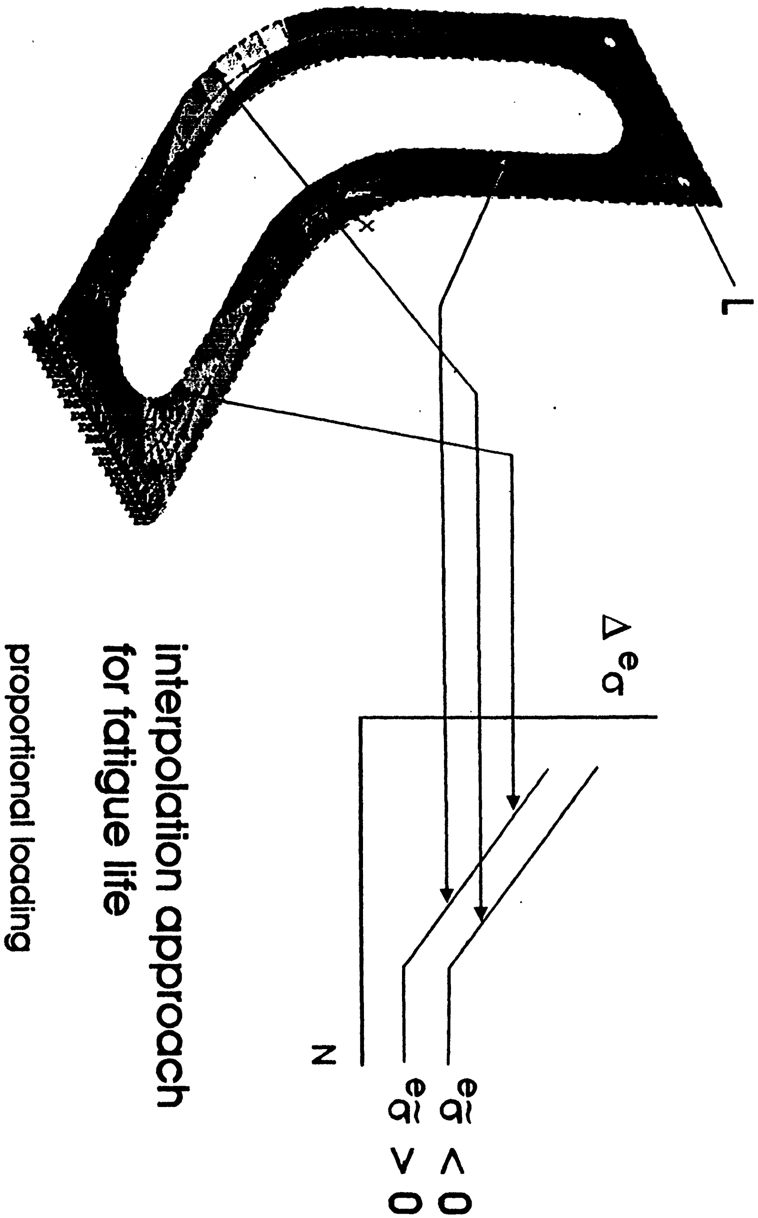
Example: notched round bar
axial and torsional loading



Constant torsion and fully reversed axial loading (sharp notch)



Sinusoidal loading, unequal frequency (sharp notch)



interpolation approach for fatigue life

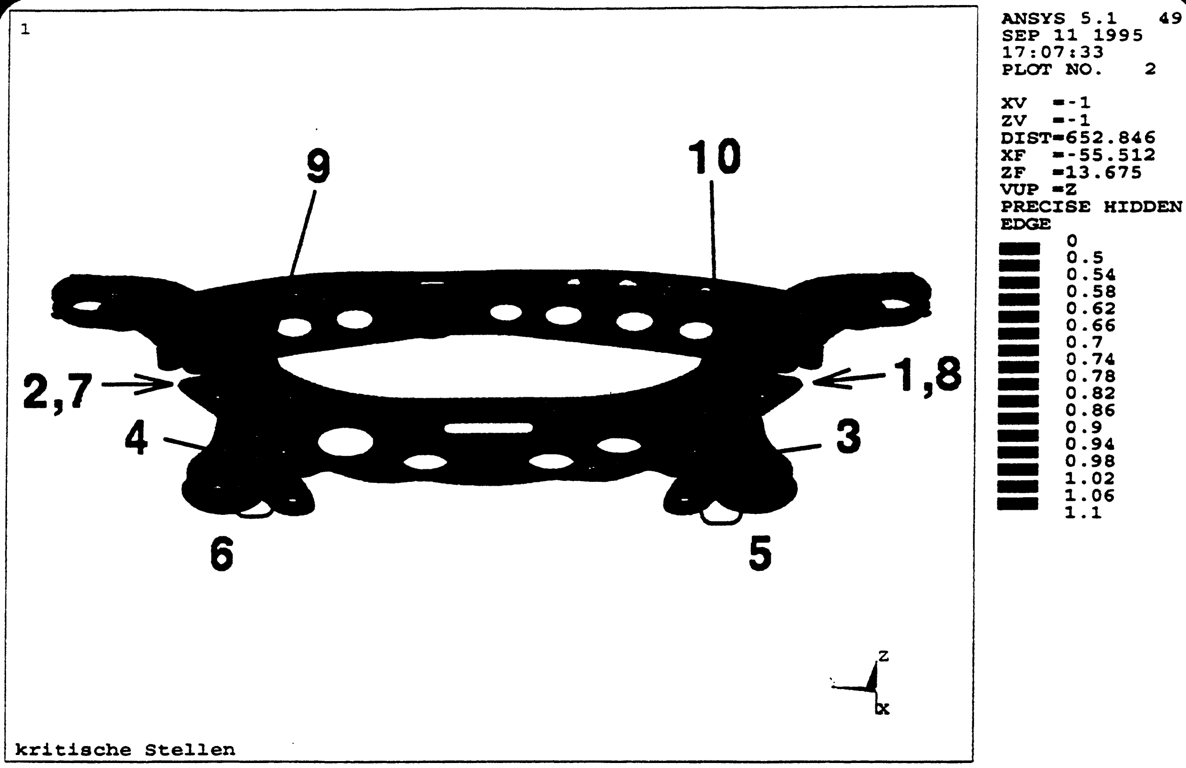
proportional loading
local uniaxial stress state

Advantages

- no limits on number of load components
- works with <u>any</u> monotonic load-notch strain estimation formula or elastic-plastic finite element analysis
- not limited to specific plasticity model
- well suited to FEM postprocessing

To Be Solved

- 'unbalanced' loading, ratchetting in plasticity model
- generalization for plastic limit loads
- non-stabilized response (cyclic hardening/softening, etc.)



Kritische Stellen

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17 *6 + 6 = 102 internal forces acting on FEM model

5 min of test track loading = 45000 samples per channel

shell elements (critical locations: top or bottom)

37000 nodes = 74000 possible crack initiation sites

18 (potentially) critical planes per crack initiation site

→ 1.3 million damage analyses

analysis of [illegible] series subframe TECMATH

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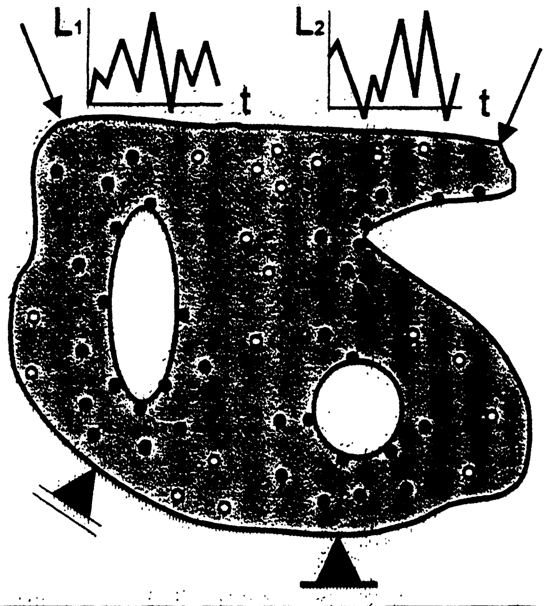

1. rainflow projection filtering based on load influence state determines short, medium, long history
2. determine maximum damage percentage elimininated by shortening histories
3. based on short history determine nodes which accumulate less damage than eliminated by shortening the history
4. repeat for medium length history

durability postprocessing for 1.3 million critical planes can be done in 30 + 30 minutes

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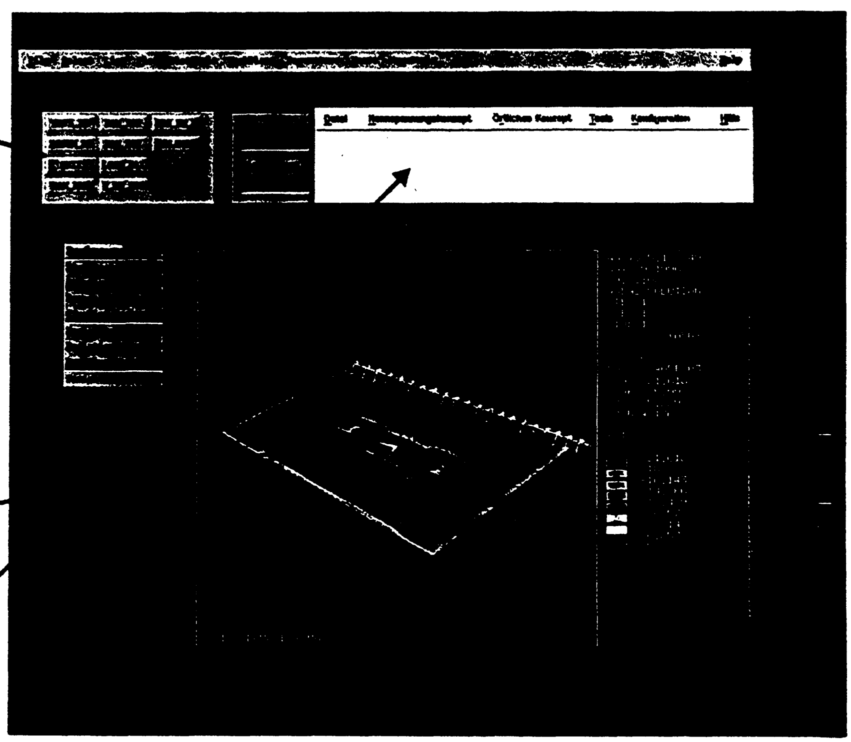
extended ANSYS tool bar
- start FALANCS
- display
  - damage top
  - damage bottom
  - damage top & bottom
  - "safety" factors



damage contours

"standard" FALANCS user interface

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