2. Kolloquium – GRK 2075
“Modelle für die Beschreibung der Zustandsänderung bei Alterung von Baustoffen und Tragwerken”

Testing for model-specific deterioration indicators - Versuche für modellspezifische Schädigungsindikatoren

Prof. Dr.-Ing. Steffen Anders

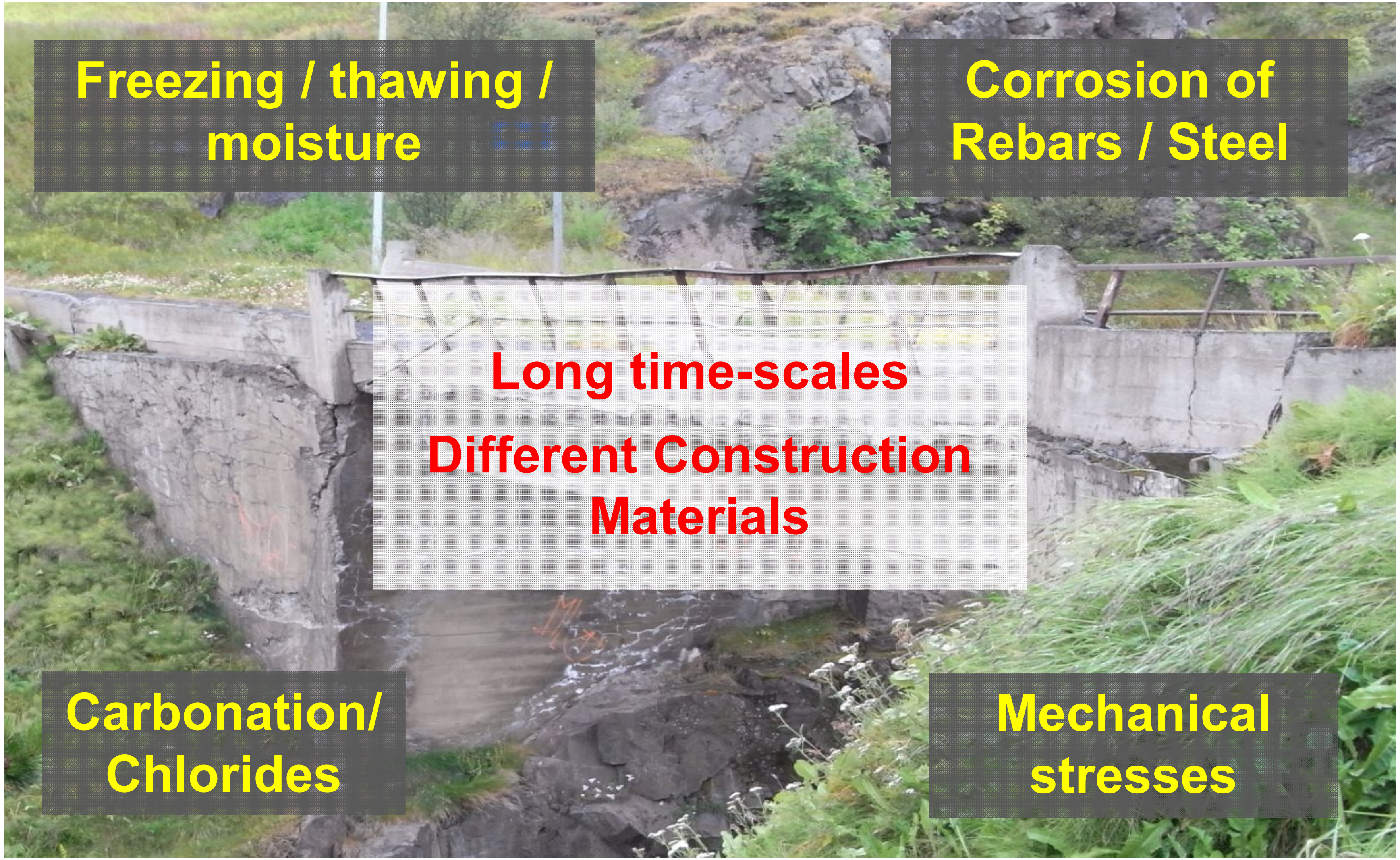
Institut für Konstruktiven Ingenieurbau – Werkstoffe im Bauwesen
Bergische Universität Wuppertal

BERGISCHE UNIVERSITÄT WUPPERTAL

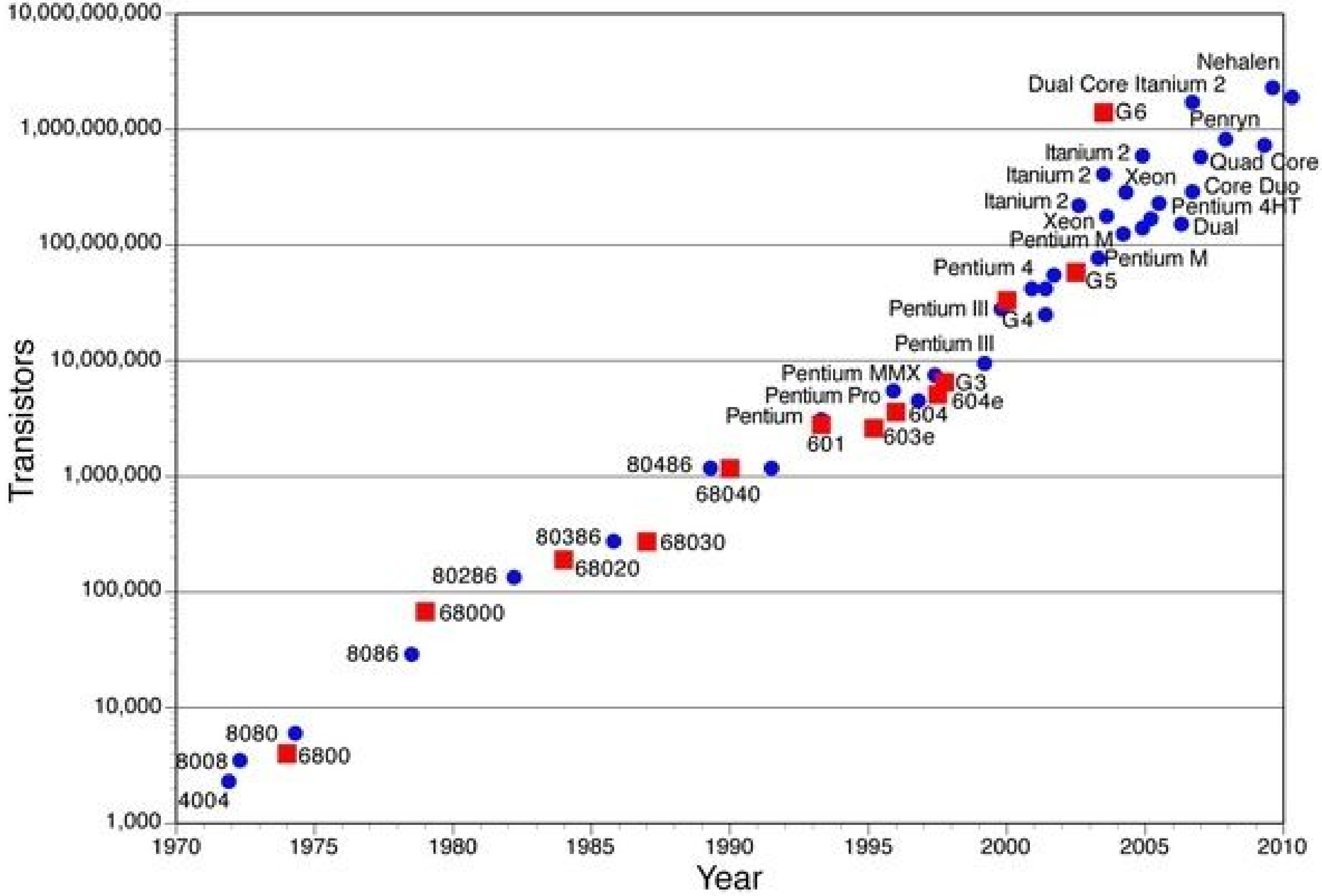
Contents

- ***Introduction***
- **Definition and Requirements**
- **Deterioration Process Analyses**
- **Quantification of deterioration**
- **Calibration of Material Models**
- **Summary**

Deterioration is wide a subject…



Comlexity of models has increase with speed of calculation



BERGISCHE UNIVERSITÄT WUPPERTAL

Let's choose Concrete in Fatigue as an example

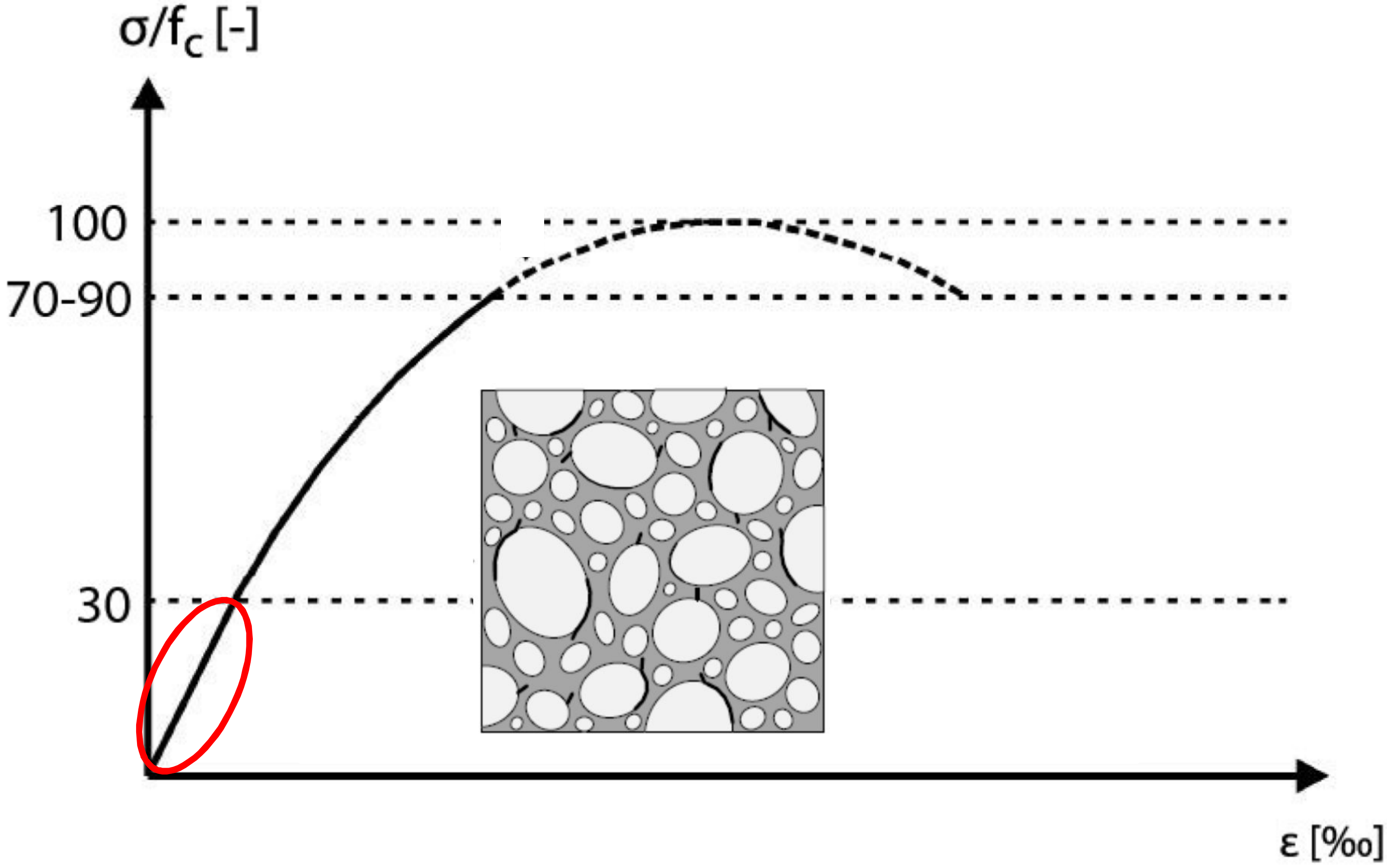
Why concrete? Concrete …

- … shows *distinct heterogeneity* on meso- and micro-scale,
- … is highly *non-linear* due to micro-cracking,
- … shows *visco-elastic* and *visco-plastic* behavior,
- … is *susceptible to durability related expositions* due to its capillary porosity (for additional deterioration).

Why Fatigue / cyclic loading…?

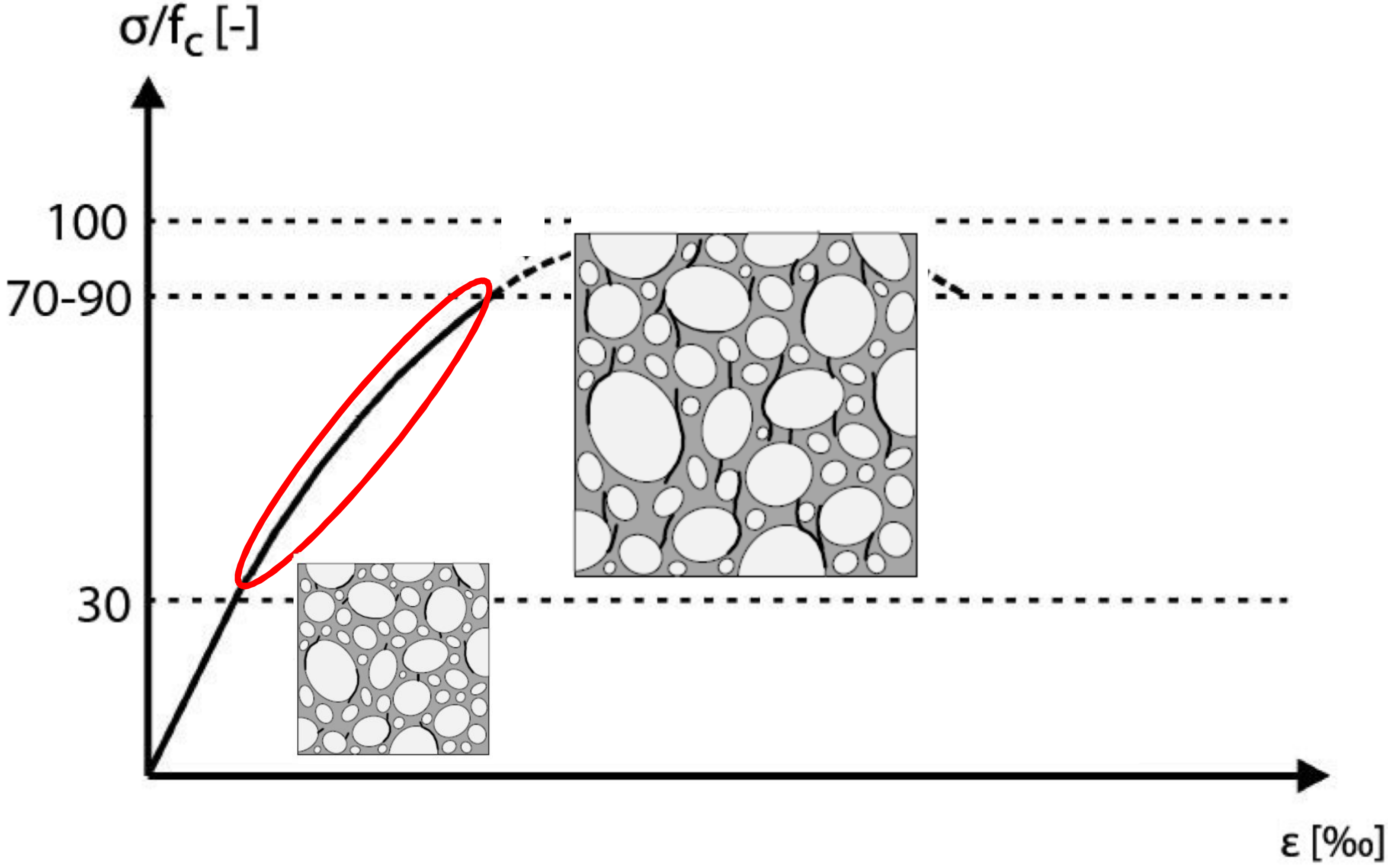
- … evolution of deterioration is crucial for modelling,
- … cyclic tests are needed for calibrations of complex models.

Deterioration development of concrete

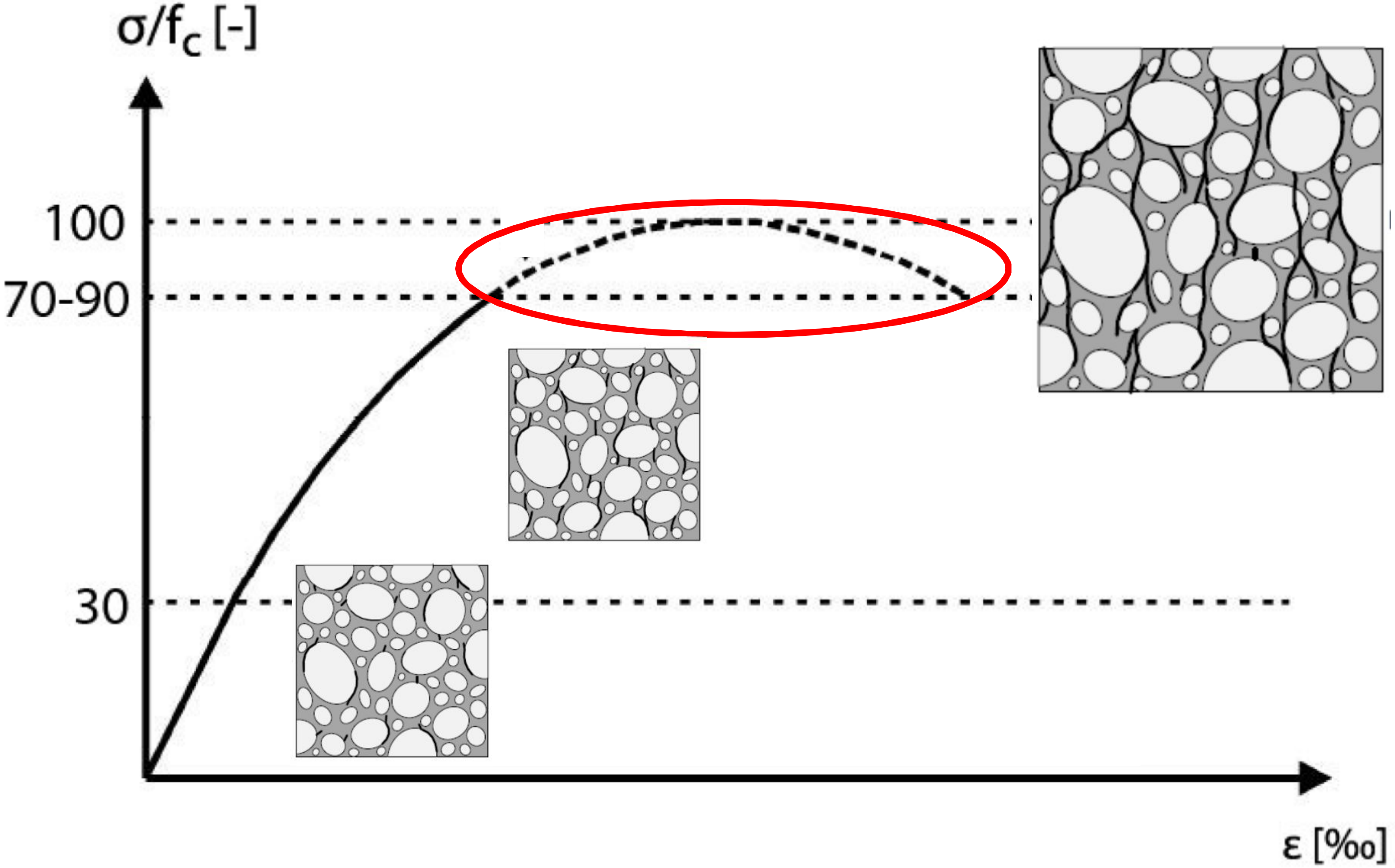


BERGISCHE UNIVERSITÄT WUPPERTAL

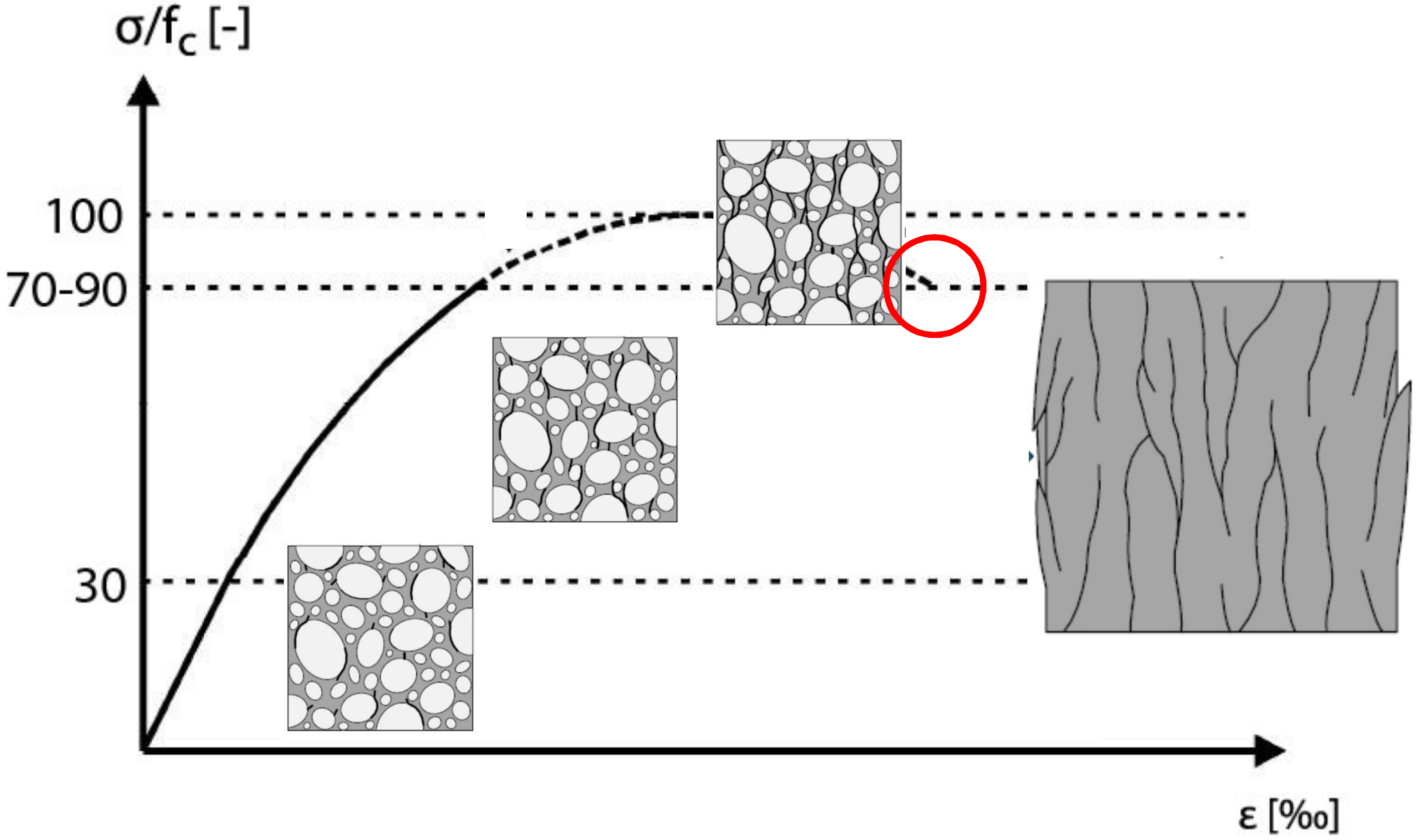
Deterioration development of concrete



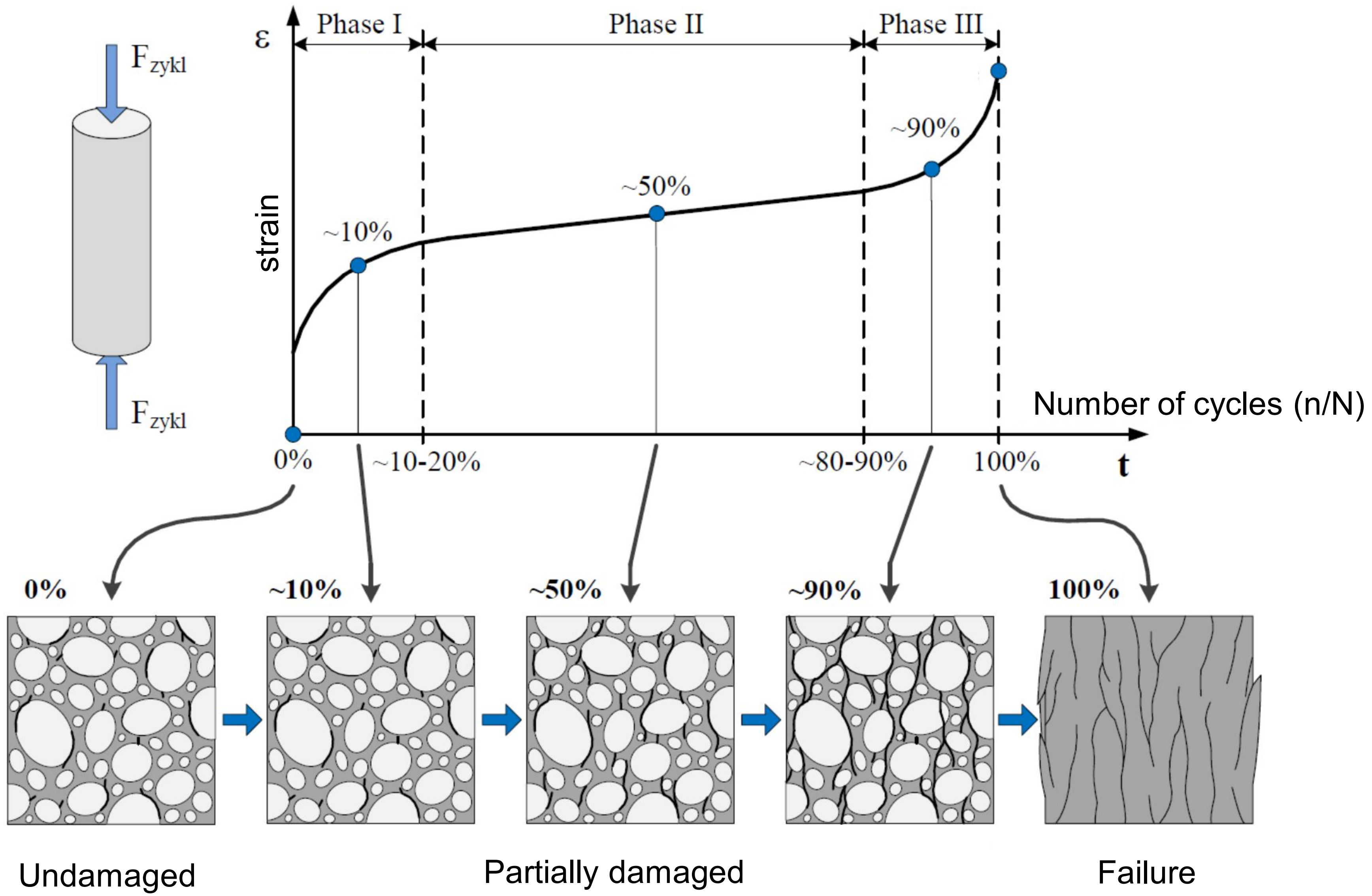
Deterioration development of concrete



Deterioration development of concrete



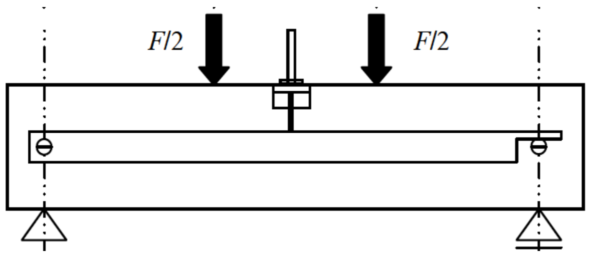
Deterioration development of concrete



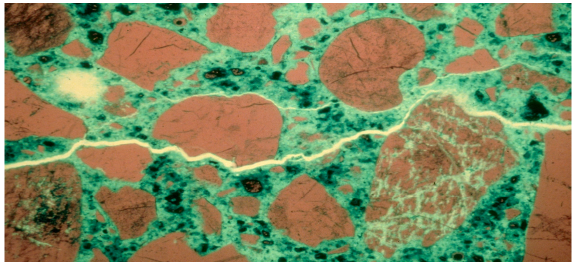
Acc.to. Thiele, 2013

Effects of deterioration depend on the scale…

Structural Level:
Increasing deformations / spalling phenomena



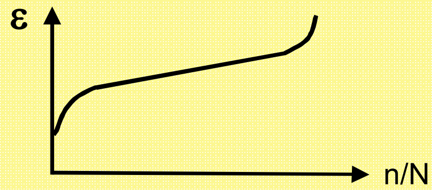
Material (Macro-) Level:
Increasing deformations / loss of stiffness / macro-cracking



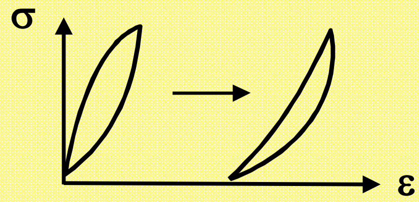
Material (Meso-) Level:
development of load-induced micro-cracks (oriented cracks) durability-induced (non-oriented cracks)

Aims of Deterioration Indicators

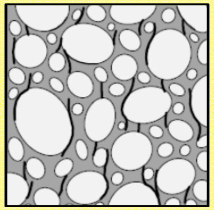
Long-term behavior
(macro-level)



Short-term behavior
(macro-level)



Meso-scale



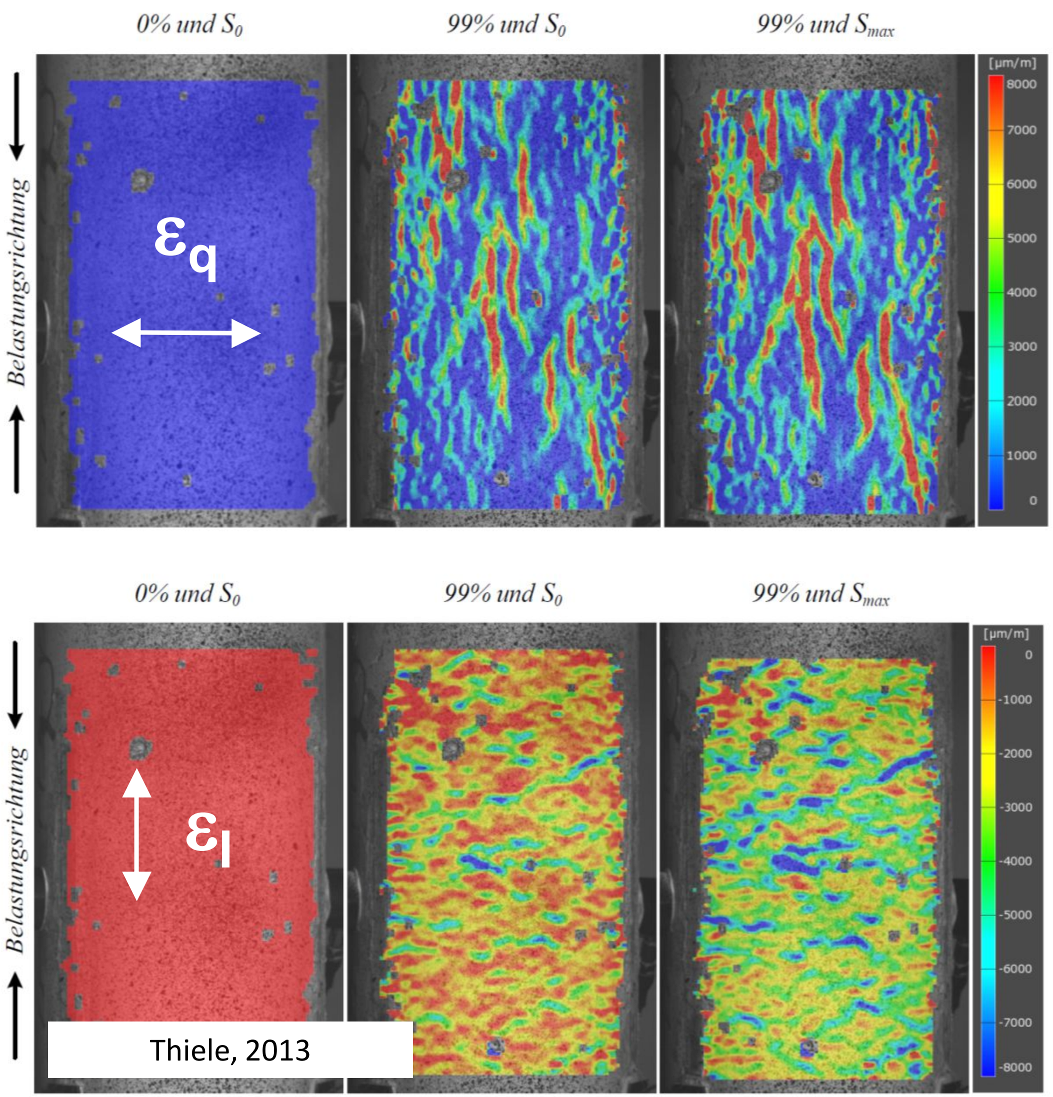
Deterioration
Process Analyses

Quantification of
deterioration

Prognosis of
deterioration *evolution*

Contents

Aramis-Optical System for Strain-measurements

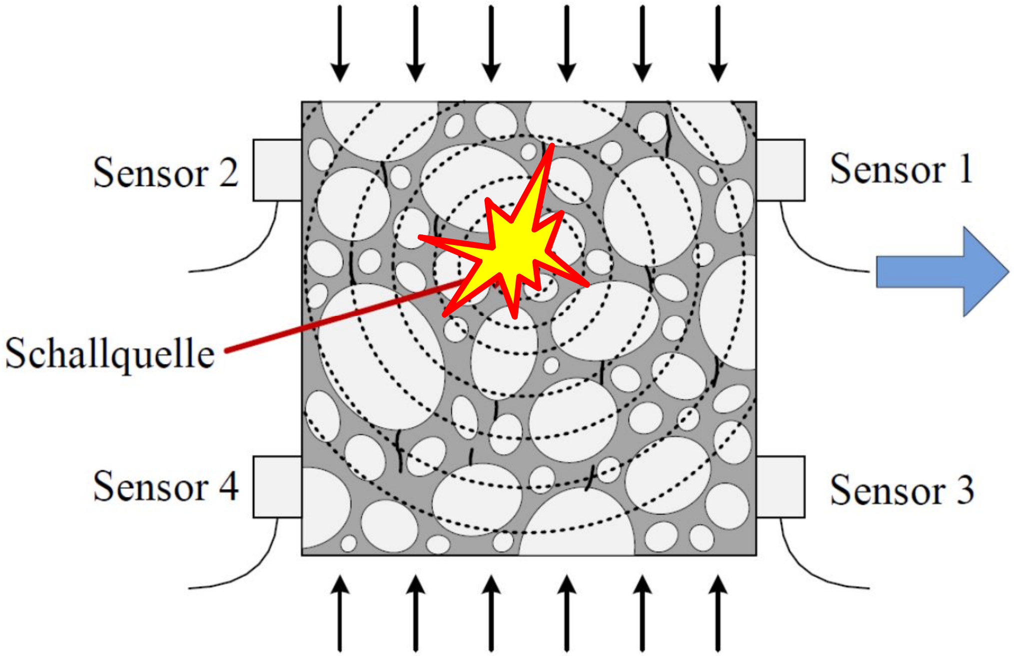


Thiele, 2013

Optical systems

- Surface based
- Showing distribution of strains
- Many micro-cracks are needed for good results
- Good for getting an idea of failure process
- Difficult to use for quantification

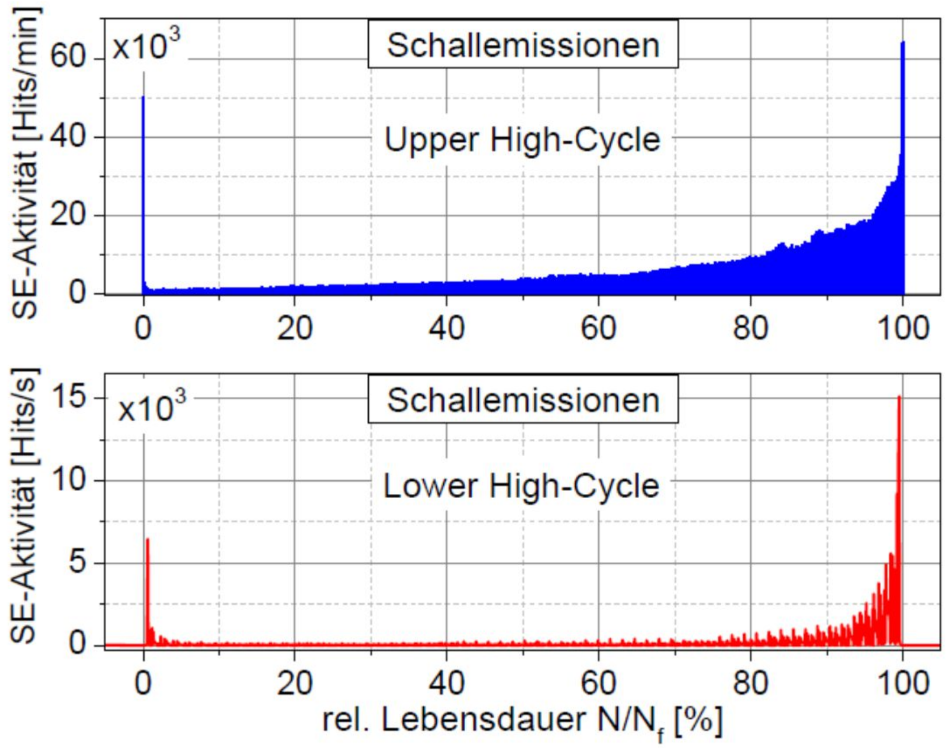
Acoustic-emission



- Enlarging of cracks causes an acoustic pulse
- Several attached sensors measure e.g. time, amplitude, duration, …
- The number of pulses can be counted
- Localization is generally possible

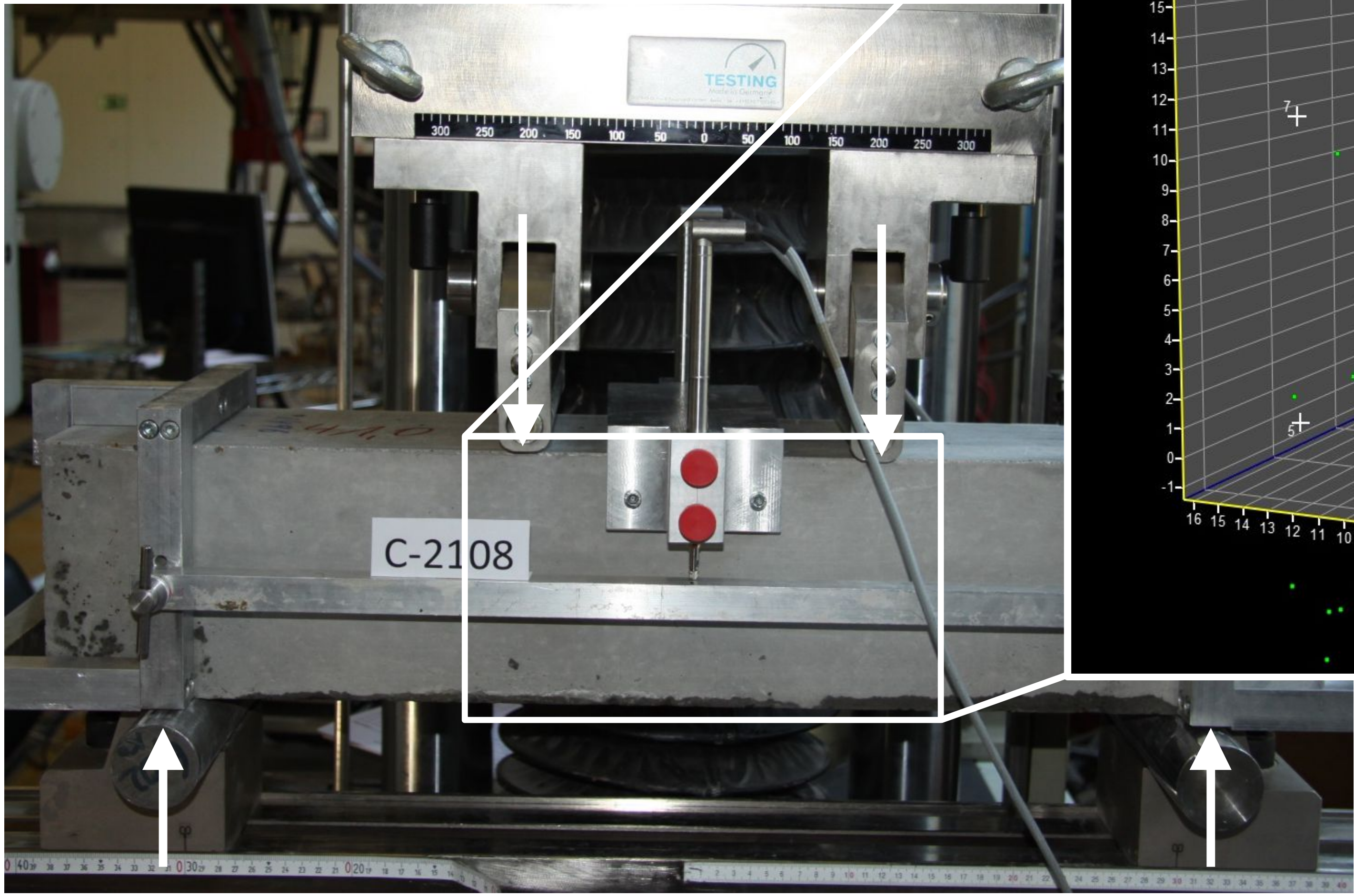
Acc.to. Thiele, 2013

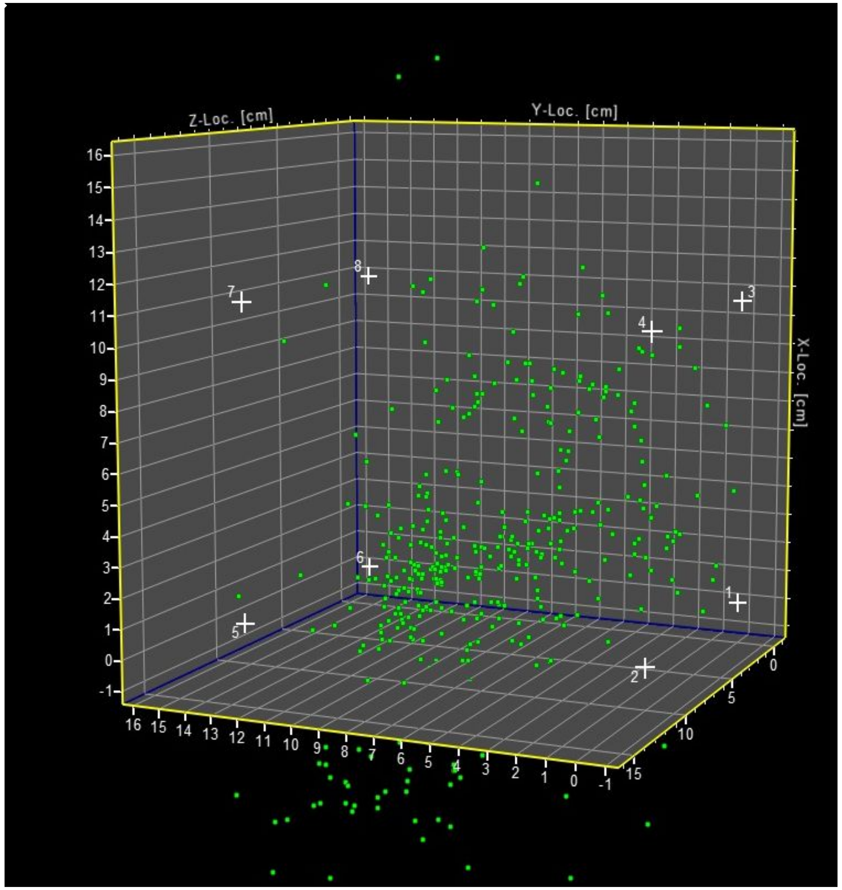
Acoustic-emission



- Getting an idea of the *intensity of micro-cracking/* deterioration
- For localized cracking phenomena fracture process zone can be displayed
- Getting an idea of *degree of localization* of failure process
- *Difficult* to use *for quantification*

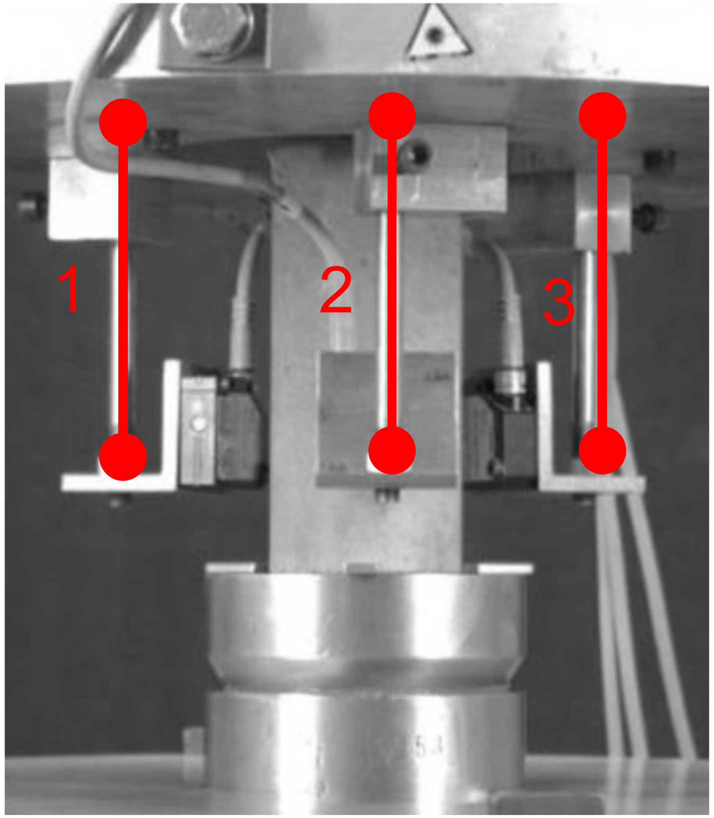
Acoustic-emission

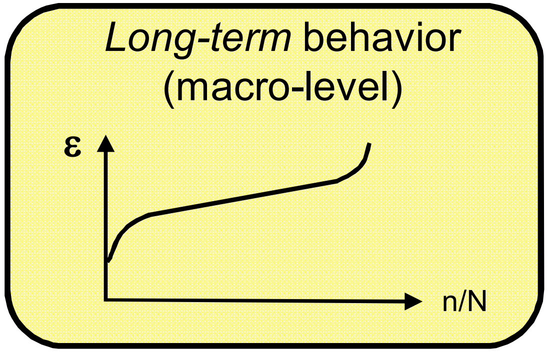


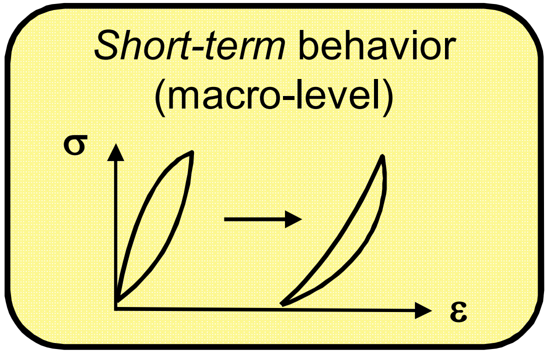


- Introduction
- Definition and Requirements
- Deterioration Process Analyses
- ***Quantification of deterioration***
- Calibration of Material Models
- Summary

Deterioration Indicators for Quantification



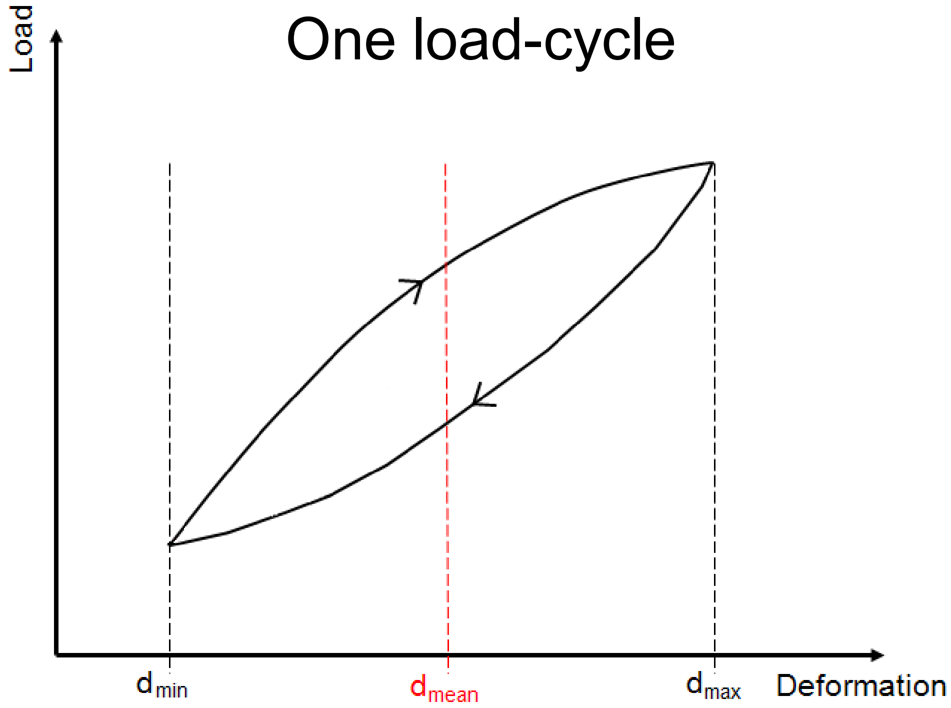


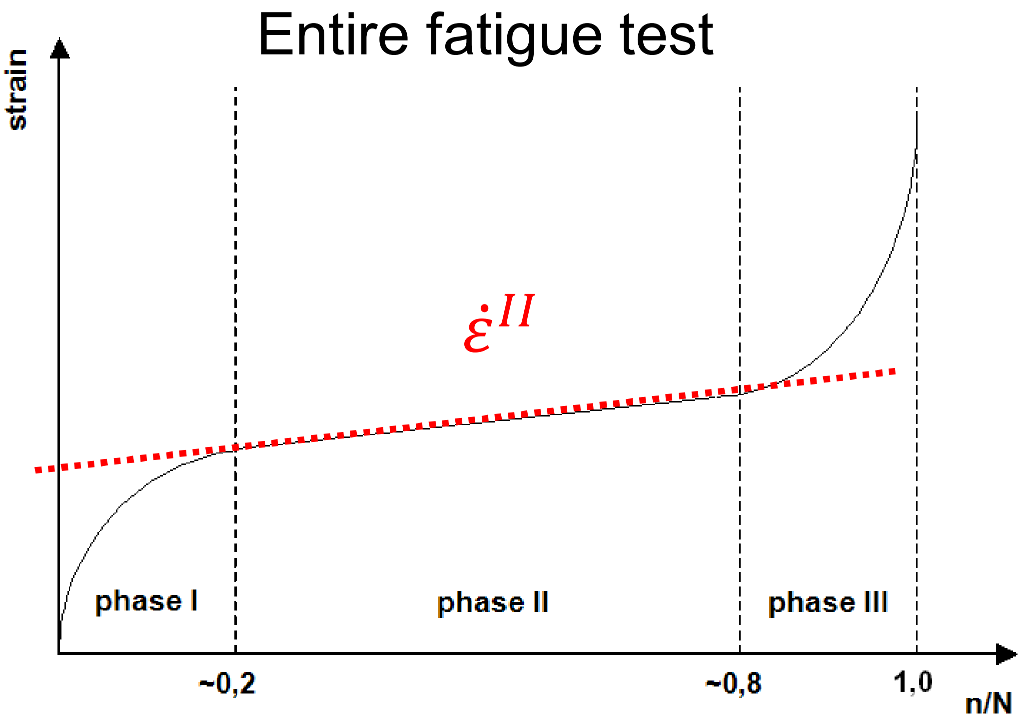


Typically 3 LVDT's are used to measure the deformation development as a *mean value*.

BERGISCHE UNIVERSITÄT WUPPERTAL

Strain Development



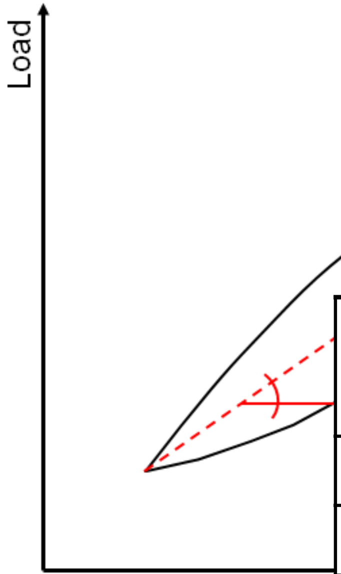


- Typical 3-phase curve of the strain/deterioration development
- The percentages of phase transitions depend on compressive strength
- The damage evolution in phase II is more or less linear and depends on the load-level.

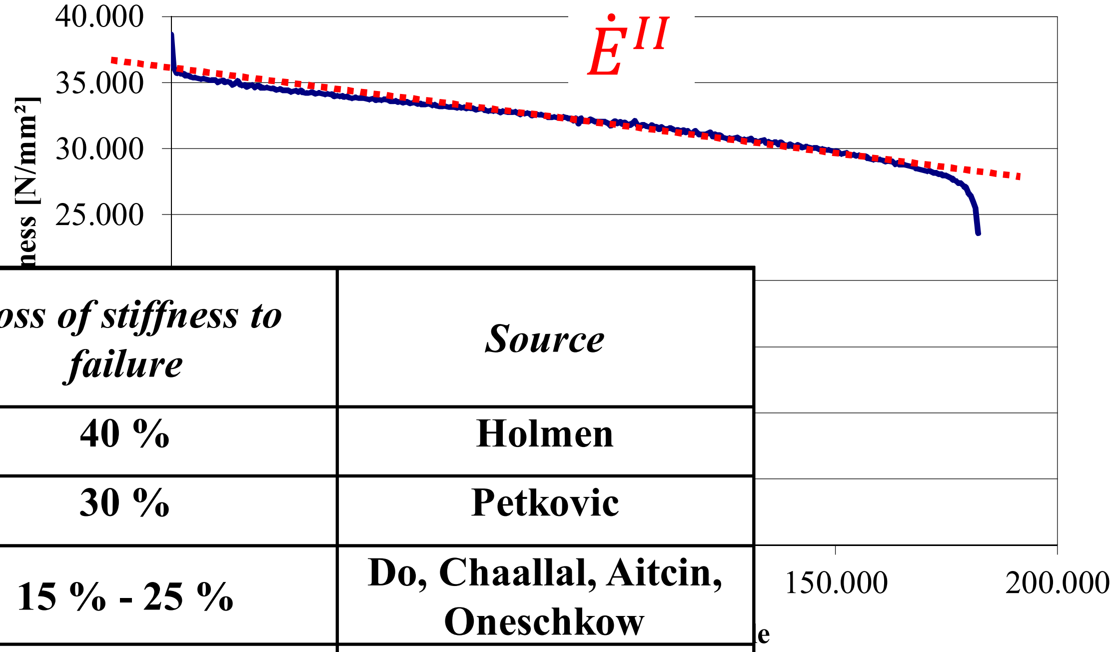
Nunez, 2013

Stiffness Development

One load-cycle



Entire fatigue test



Compressive strength	*Loss of stiffness to failure*	*Source*
~ 40 N/mm²	40 %	Holmen
~ 70 N/mm²	30 %	Petkovic
~90 N/mm²	15 % - 25 %	Do, Chaallal, Aitcin, Oneschkow
~110 N/mm²	5 % - 15 %	Do, Chaallal, Aitcin, Oneschkow, Anders

- In principle 3-phase development comparable to deformation
- Loss of stiffness depends on the compressive strength
- Stiffness itself is stress dependant

Nunez, 2013

Calculation without deterioration

Experiment → Deformation

↓ Calibration/ validation

$$\boldsymbol{\sigma} : \mathbf{D}^0 = \boldsymbol{\varepsilon}$$

σ :

D^0 :

→ A lot of experiments with very different boundary conditions exist for calibration

$\boldsymbol{\varepsilon}$: strain field / strain at a grid point

Calculation taking deterioration into account

Experiment 1 → Deformation

Experiment 2 → Indicator for Deterioration

Deformation → Indicator for Calibration

$$\boldsymbol{\sigma} : \left(\mathbf{D}^{0} + \mathbf{D}^{da}\right) = \boldsymbol{\varepsilon}$$

→ The number of tests offering information on deterioration development reduces significantly

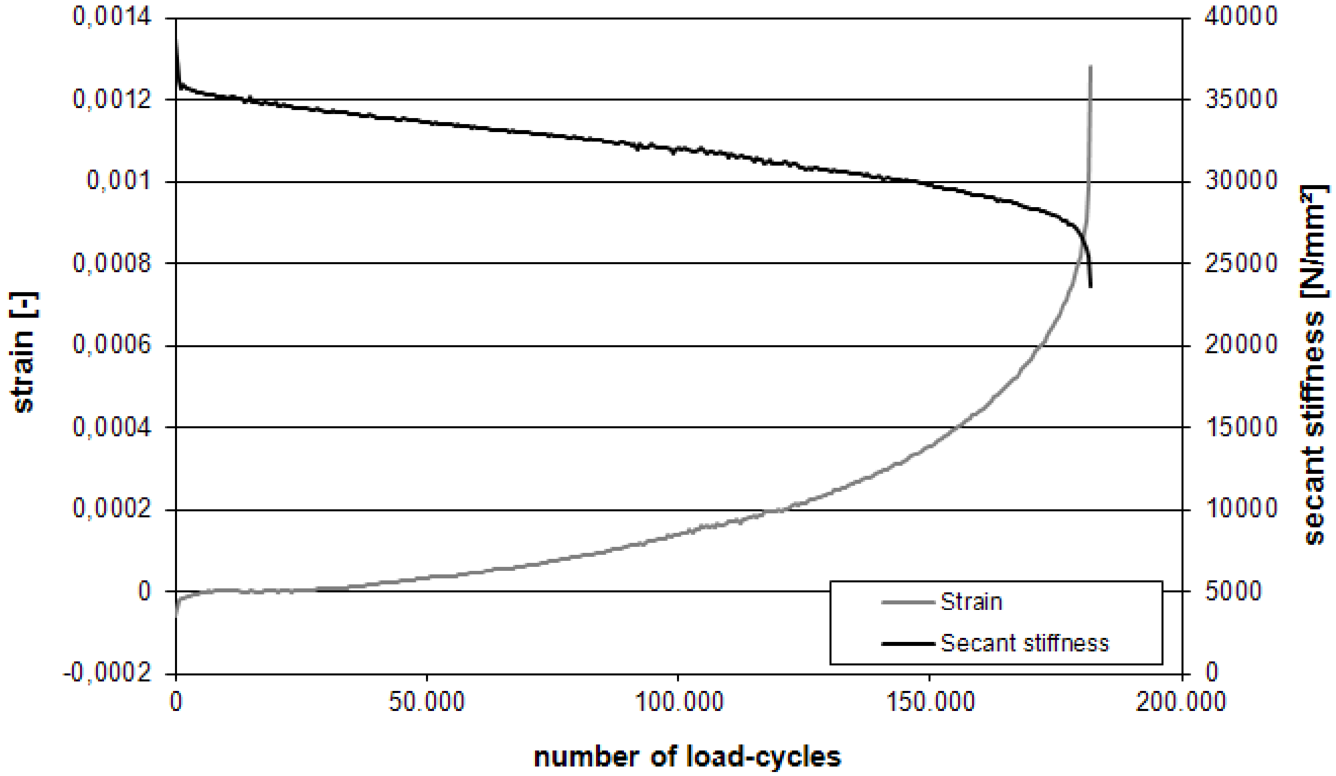
σ :

D^0 :

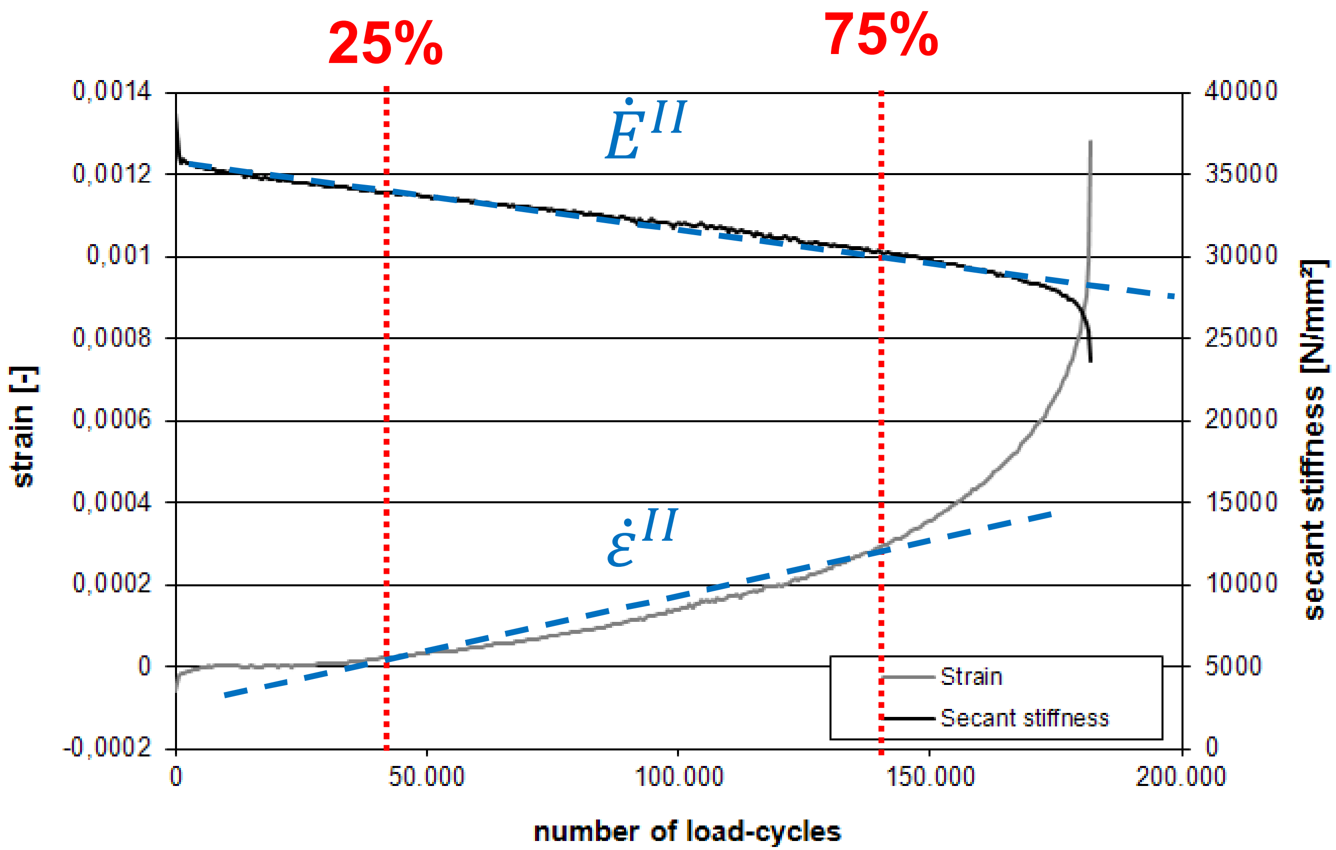
D^{da} :

ε : strain field / strain at a grid point

Comparison of Deterioration Indicators



Comparison of Deterioration Indicators

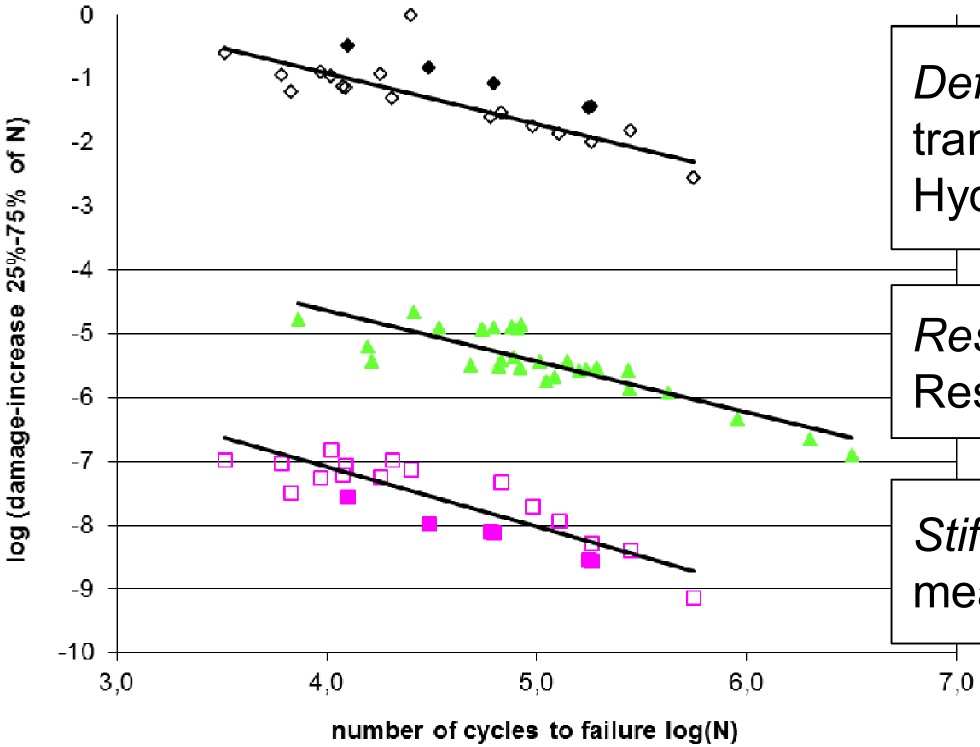


Strain and secant stiffness seem to have different curve-characteristics.

But strain and stiffness are just different manifestations of the micro-crack development.

Lohaus, Anders, 2007

Deterioration evolution in secondary cyclic creep



Deformation measures by LVDT & Piston transducer measurements
Hydraulic device (~10 Hz)

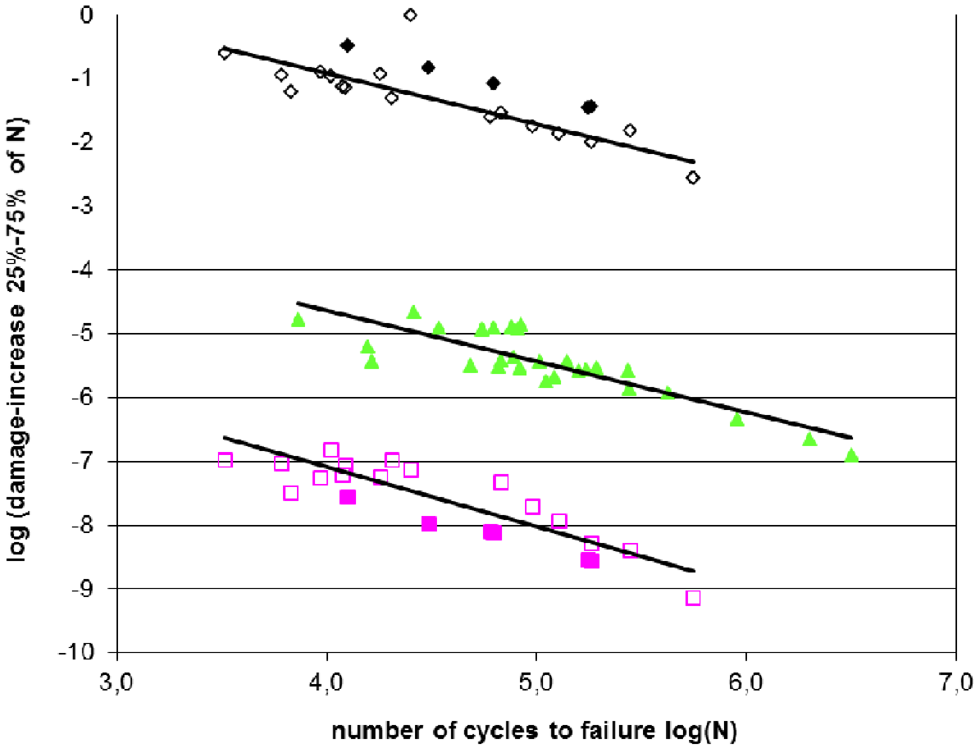
Resonance frequency
Resonance testing device (~ 60Hz)

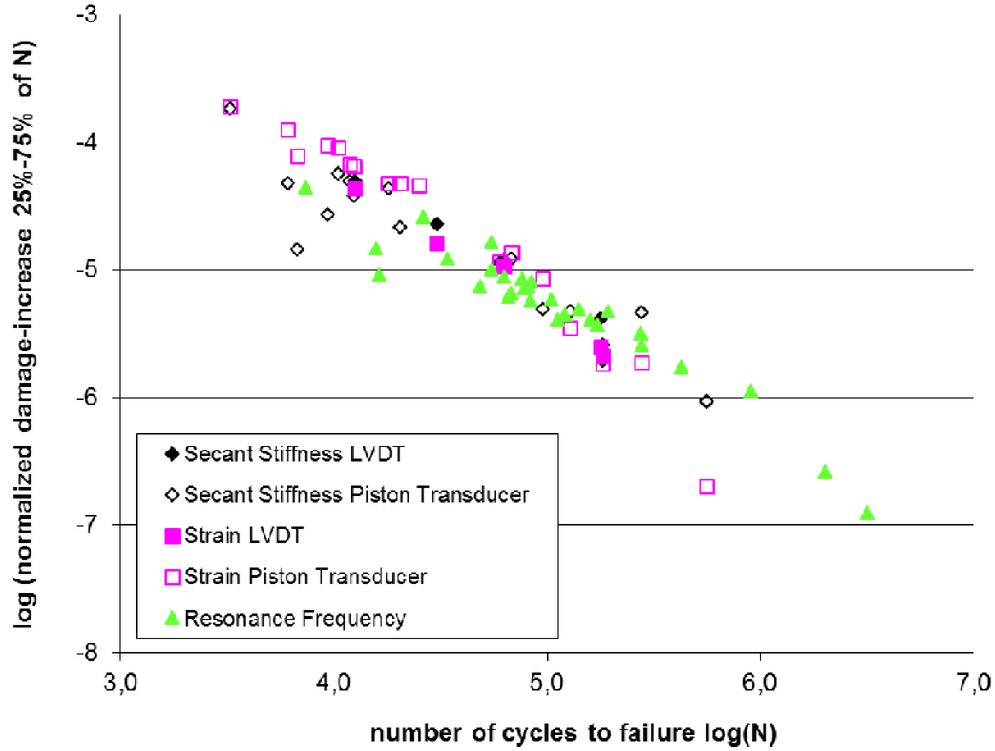
Stiffness from LVDT & Piston transducer measurements

$$\log(\overline{\dot{S}_{II}}) = \log\left(\frac{S_{0,75\cdot N} - S_{0,25\cdot N}}{\left(n_{0,75\cdot N} - n_{0,25\cdot N}\right)\cdot}\right)$$

Lohaus, Anders, 2007

Deterioration evolution in secondary cyclic creep

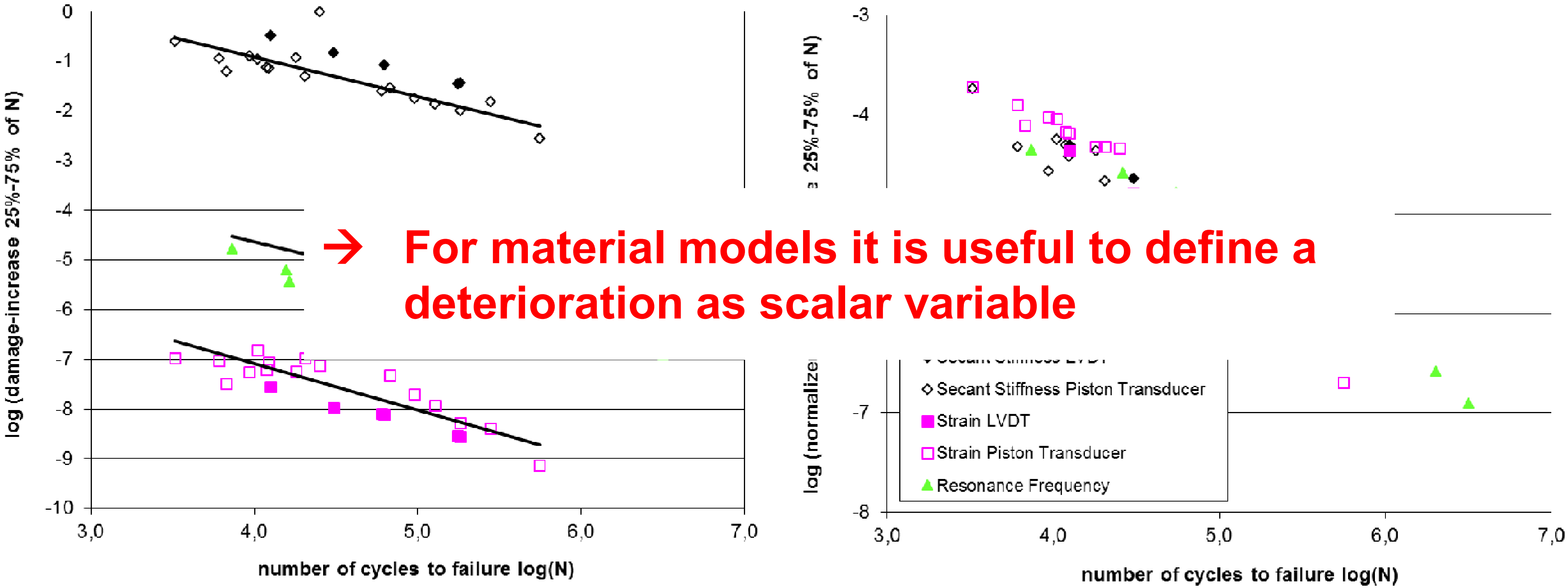




$$\log(\bar{\dot{S}}_{II}) = \log\left(\frac{S_{0,75\cdot N} - S_{0,25\cdot N}}{\left(n_{0,75\cdot N} - n_{0,25\cdot N}\right)\cdot\left(S_{1,0\cdot N} - S_{0,0\cdot N}\right)}\right)$$

Lohaus, Anders, 2007

Deterioration evolution in secondary cyclic creep

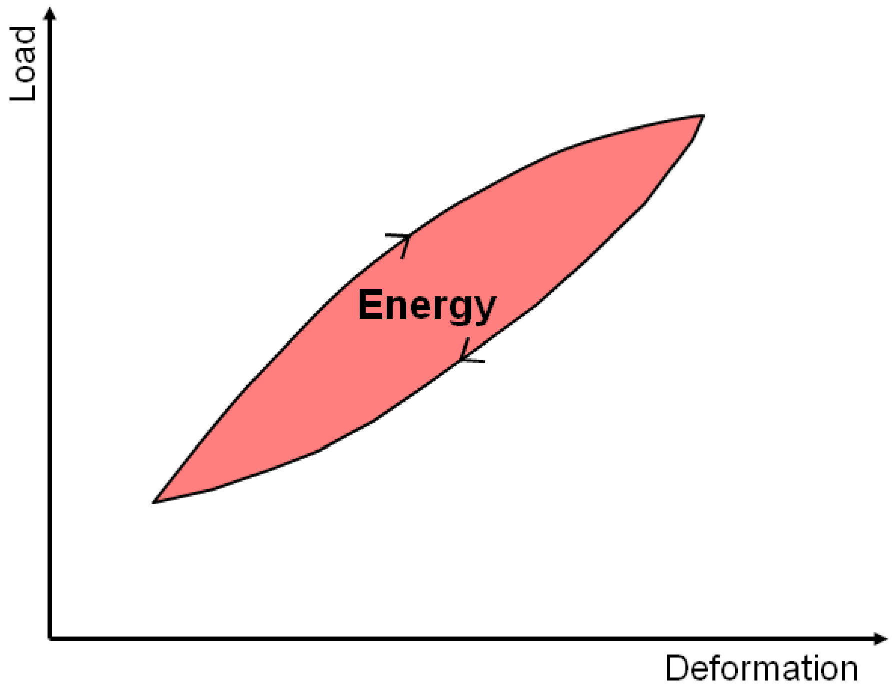


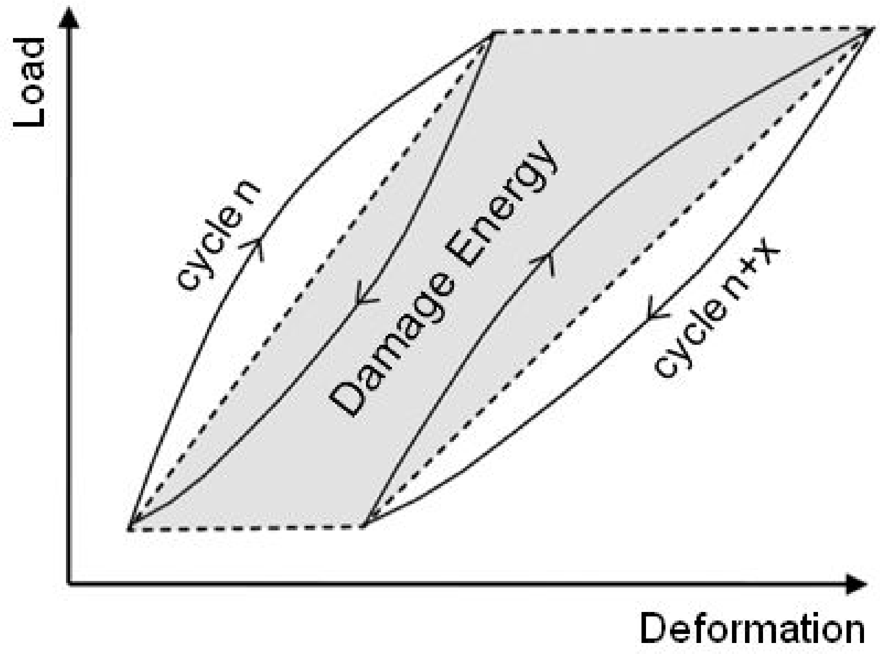
→ For material models it is useful to define a deterioration as scalar variable

$$\log(\dot{\bar{S}}_{II}) = \log\left(\frac{S_{0,75 \cdot N} - S_{0,25 \cdot N}}{\left(n_{0,75 \cdot N} - n_{0,25 \cdot N}\right) \cdot \left(S_{1,0 \cdot N} - S_{0,0 \cdot N}\right)}\right)$$

Lohaus, Anders, 2007

Energy-based indicators



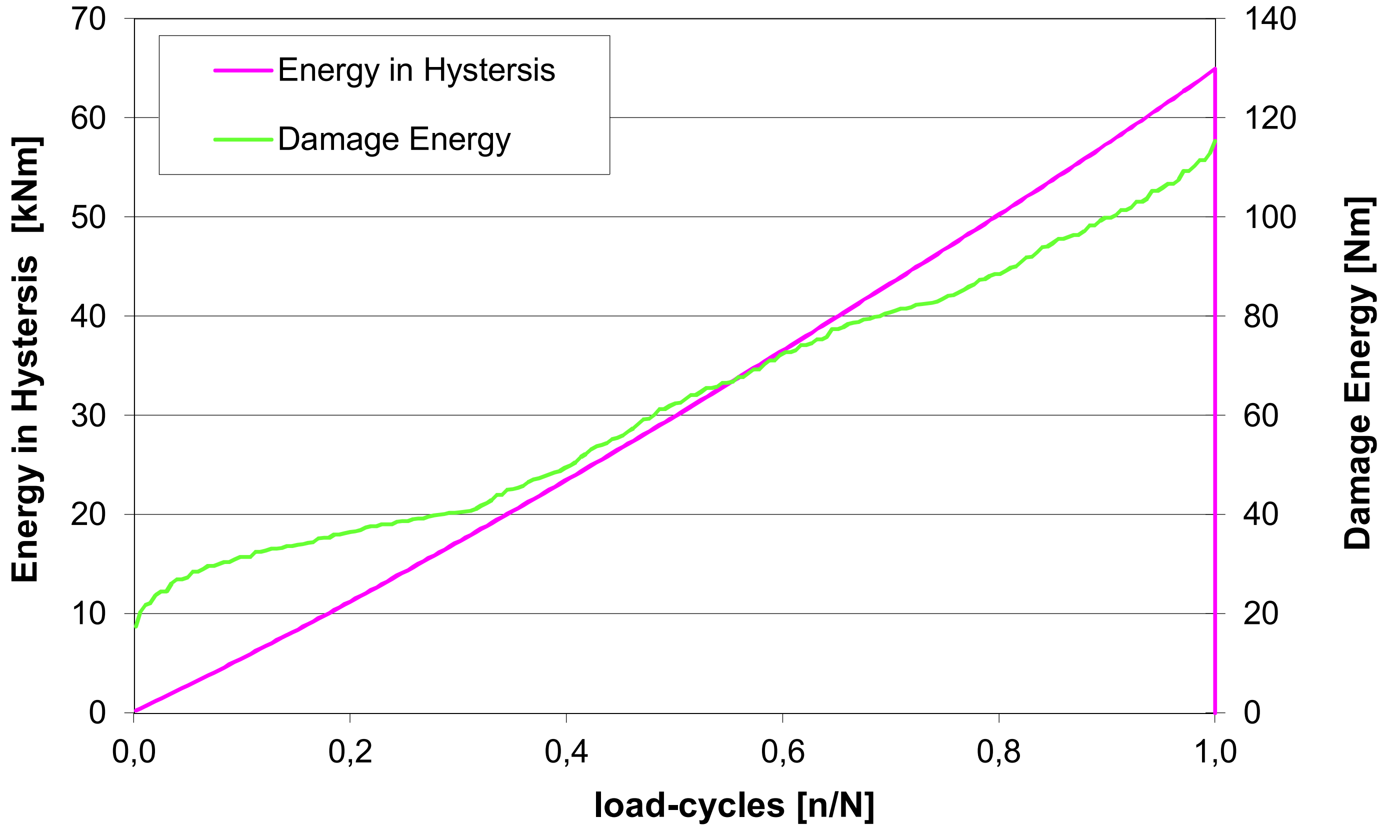


Useful for low-cycle tests (earthquake)
In high-cycle tests reversible parts of energy included

"*Damage or Expended Energy*" only including irreversible parts of energy (damage and creep)

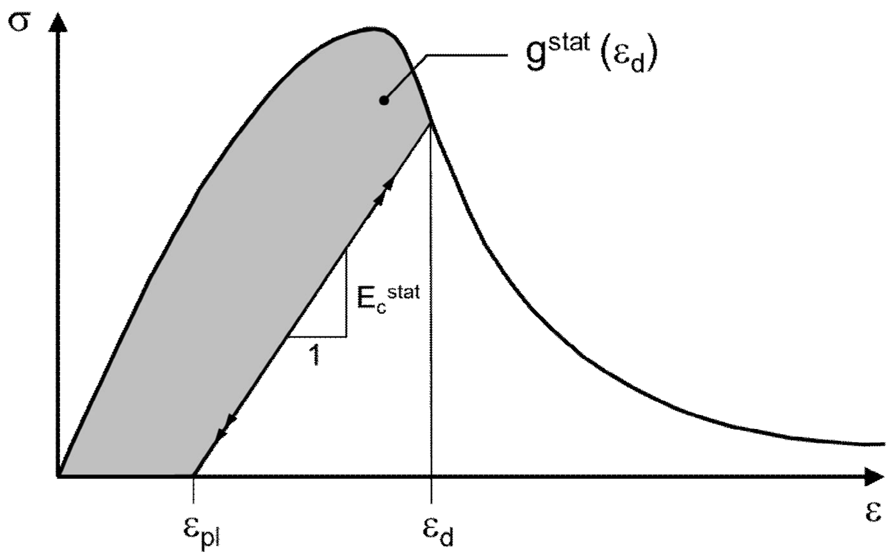
BERGISCHE UNIVERSITÄT WUPPERTAL

Development of Energy Indicators

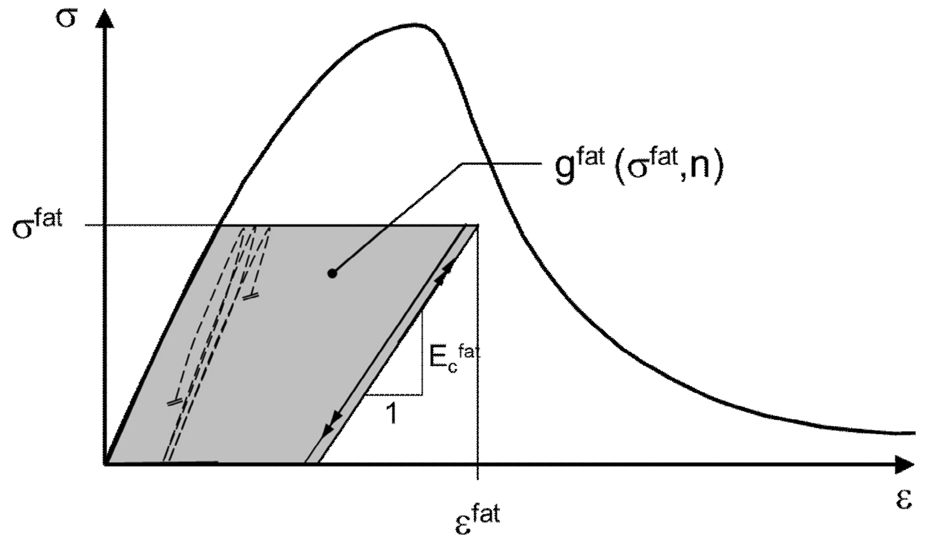


Energy-based Model by Pfanner

Static Test



Fatigue Test



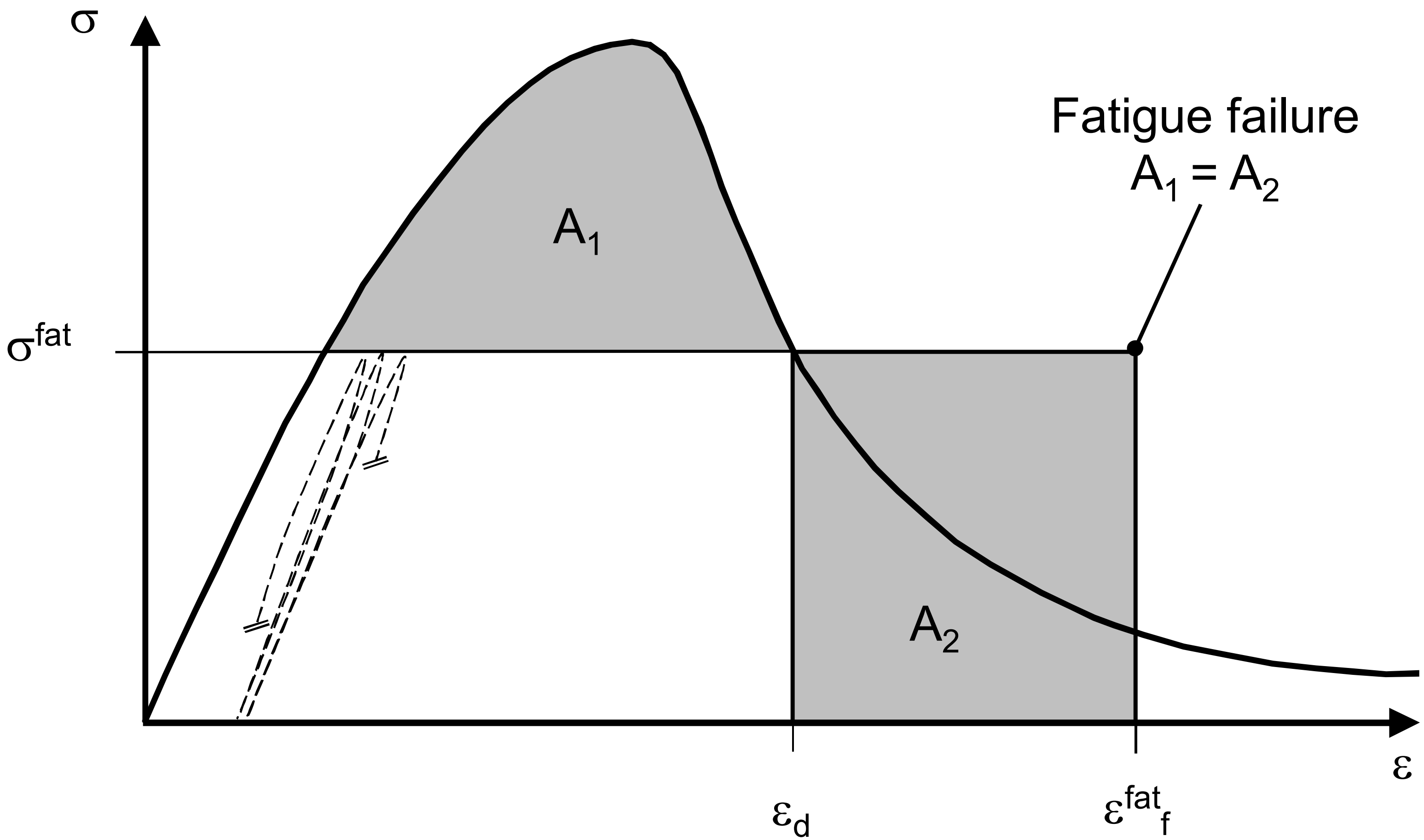
Pfanner, 2007

$$g^{stat}(\varepsilon_d) \overset{!}{=} g^{fat}(\sigma^{fat}, n)$$

$$E_c^{stat} = E_c^{fat} = (1-D)\cdot E_c^0 \qquad 0 \le D \le 1$$

Necessary material parameters: E_c, ε_c, f_c, G_{cl}

Energy-based Model by Pfanner

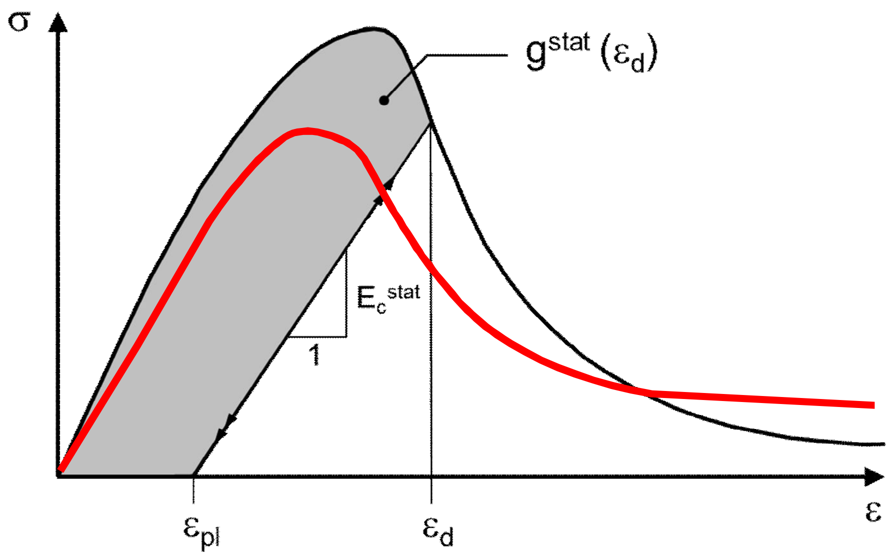


Pfanner, 2007

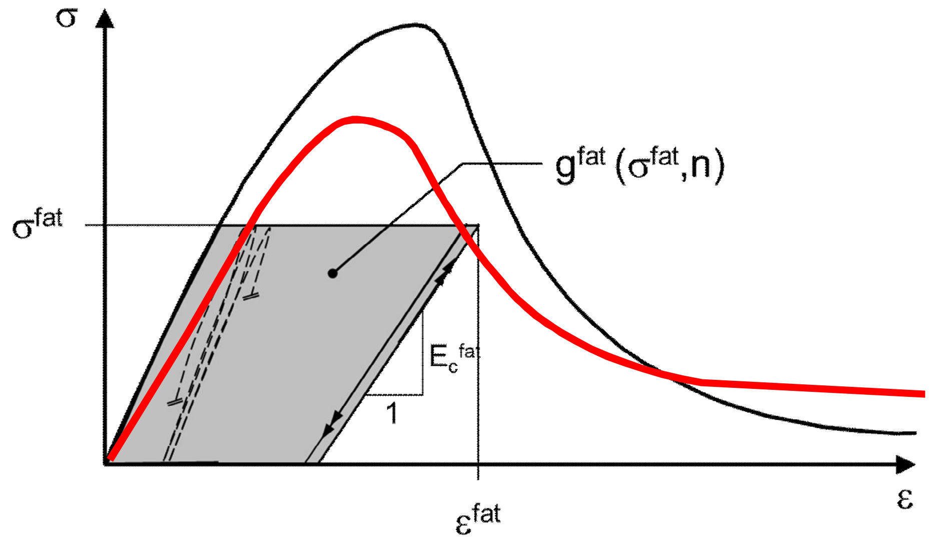
→ Strains at failure can exceed the static stress-strain curve

Extension of the Pfanner-Model to freezing-thawing

Static Test



Fatigue Test



$$g^{stat}(\varepsilon_d) \overset{!}{=} g^{fat}(\sigma^{fat}, n)$$

$$E_c^{stat} = E_c^{fat} = (1-D) \cdot E_c^0 \qquad 0 \leq D \leq 1$$

Necessary material parameters: E_c, ε_c, f_c, G_{cl}

Comments on the Pfanner Model

Advantages

It is an energy-based deterioration criterion *allowing to calculate the evolution* of damage/stiffness for calculation purposes
→ predicting deterioration not validating

To transfer from deterioration as scalar value to the *development of deterioration* curve-fitting is used

Possibility to *include durability-related deterioration*

Comments on the Pfanner Model

Disadvantages

It is validated for numerical problems driven by *1D failure*

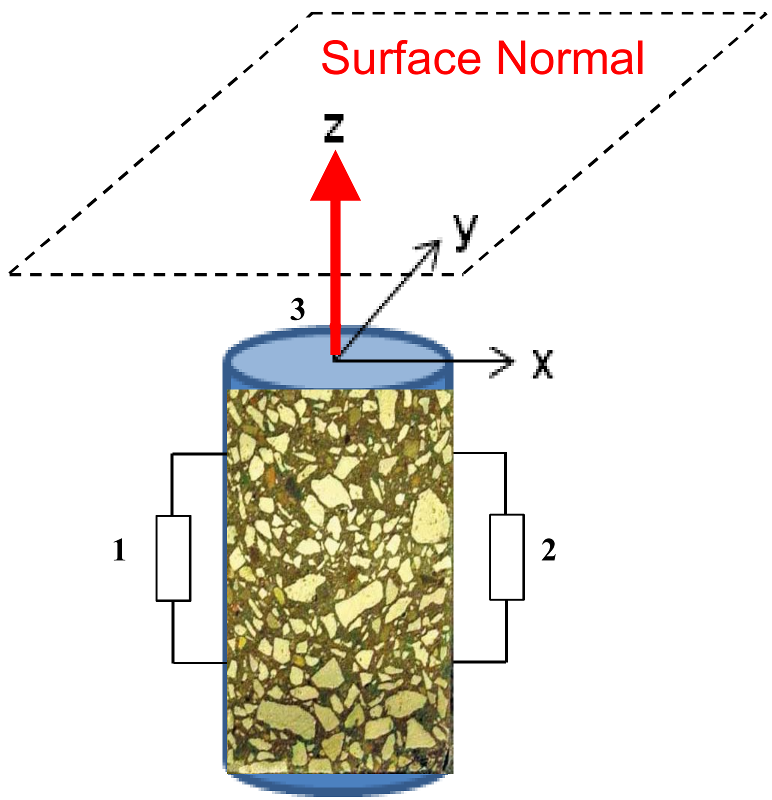
Concrete is treated as *isotropic.*

It is valid for a *constant upper load-level*
Extensions to blockwise loading was implemented
by Göhlmann (2010)

Does not take creep effects into account

Why is this approach still not sufficient???

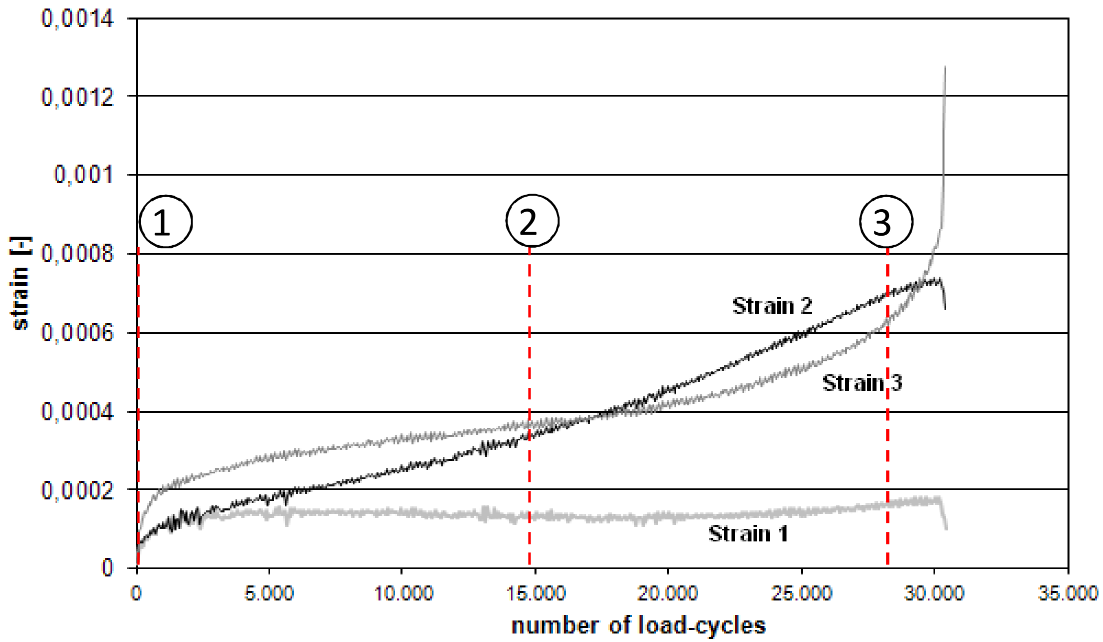
Having a glimps at meso-scale using the same tests

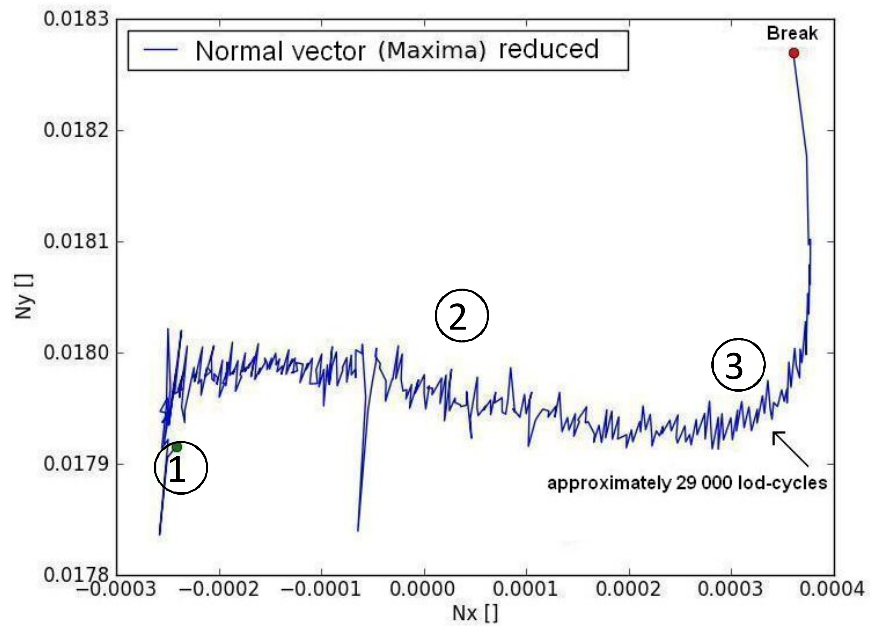


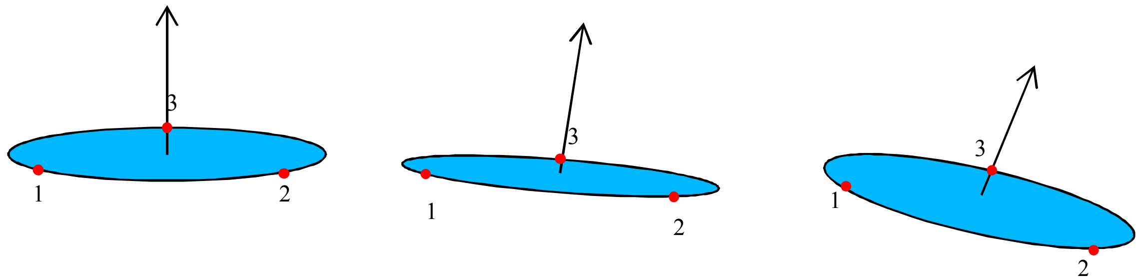
Possibility to calibrate meso-scale models

- CT-Measurements needed for distribution of aggregates / fibers / etc.
- Interpreting the specimen as a structural member and not as isotropic material
- The surface normal and its development can be calculated
- This requires very precise placing and testing

Surface Normal







$\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0$ (1)

$\varepsilon_1 < \varepsilon_2 < \varepsilon_3$ (2)

$\varepsilon_1 < \varepsilon_3 < \varepsilon_2$ (3)

Contents

- Introduction
- Definition and Requirements
- Deterioration Process Analyses
- Quantification of deterioration
- ***Calibration of Material Models***
- Summary

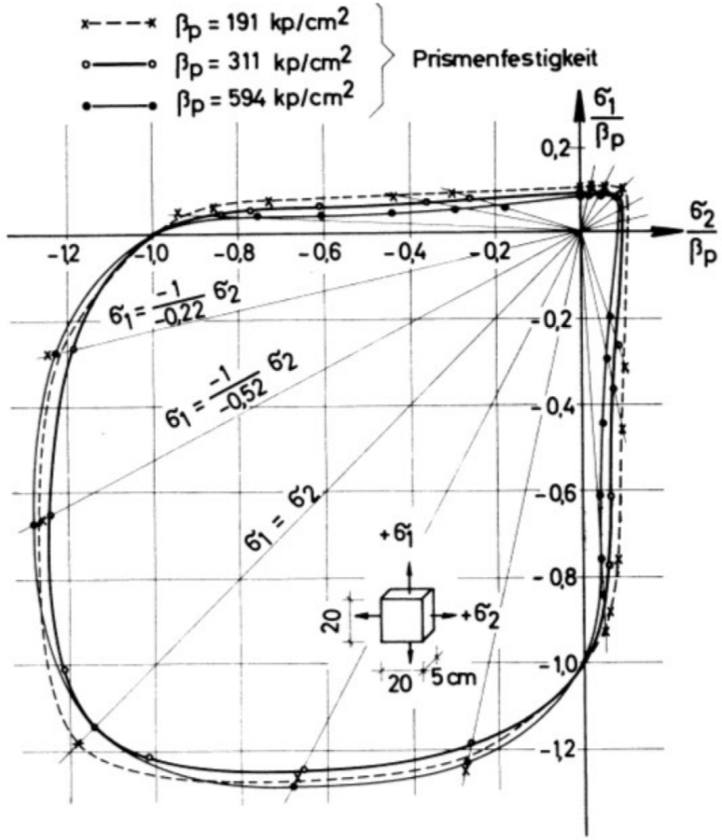
Plasticity & Deterioration approaches

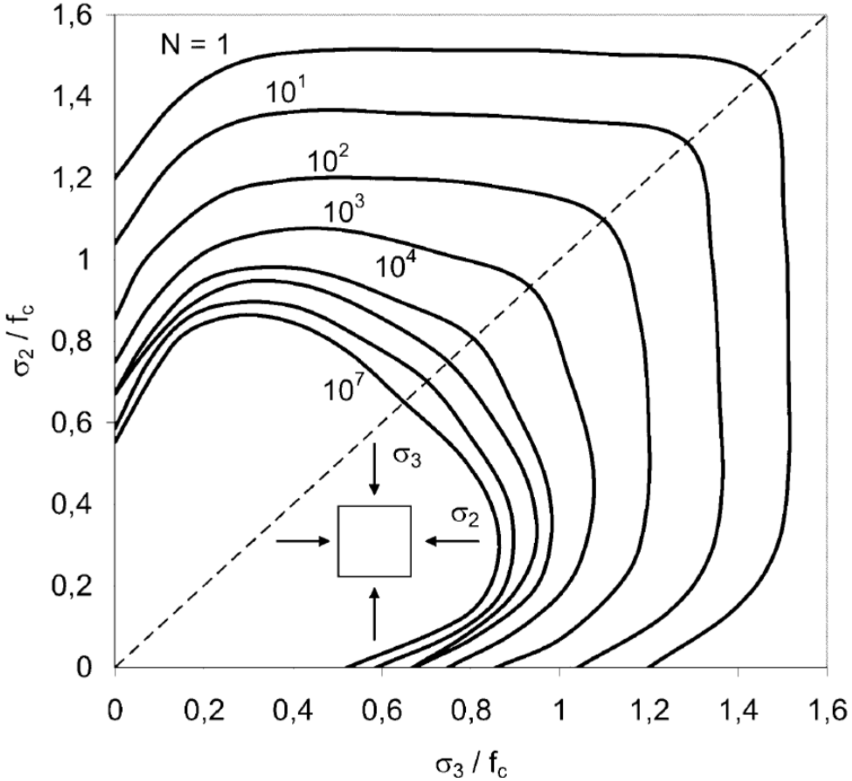
Experimental data regarding:

- Yielding surfaces
- Approaches for softening
- Approaches for deterioration
- Fracture surfaces

$$\boldsymbol{\sigma} : \left(\mathbf{D}^{0} + \mathbf{D}^{da}\right) = \boldsymbol{\varepsilon}$$

2D Tests with respect to fracture-surface

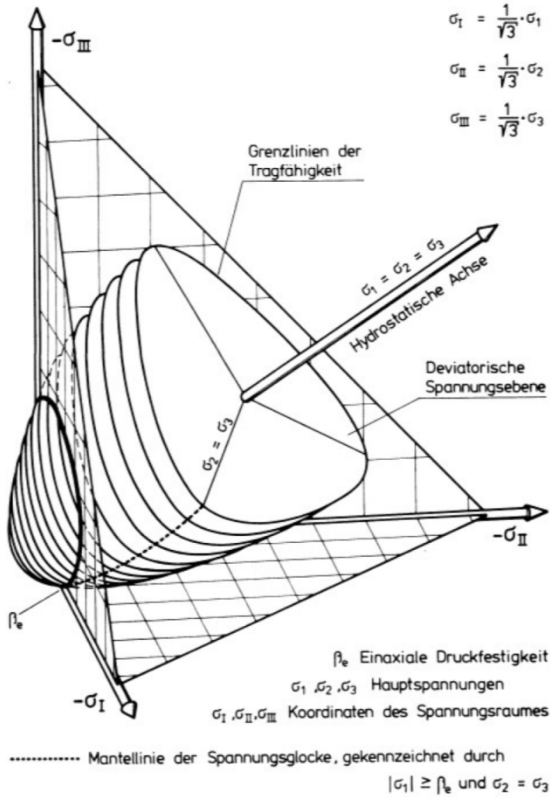




Su, 1988

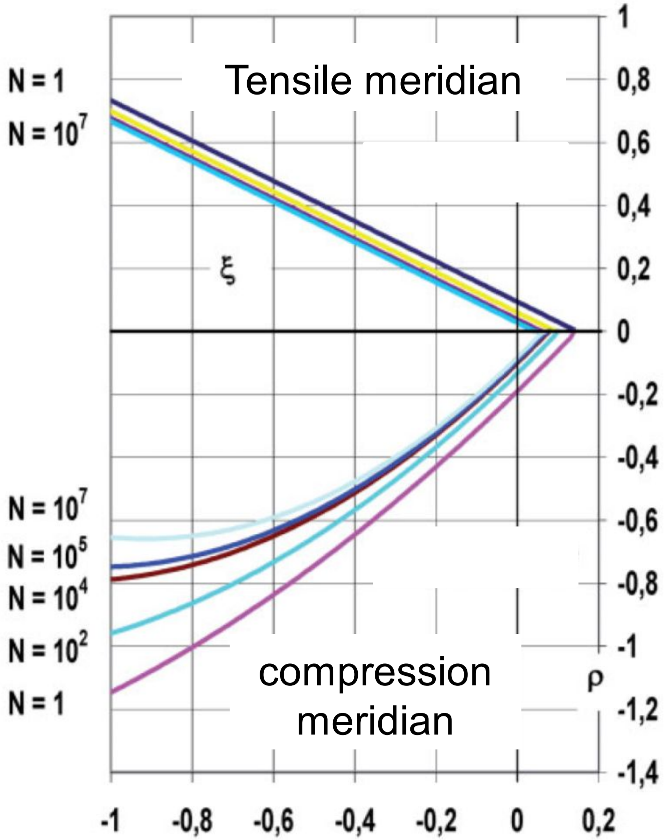
→ Information on the fracture surface and its evolution is available but *not for deterioration to failure*

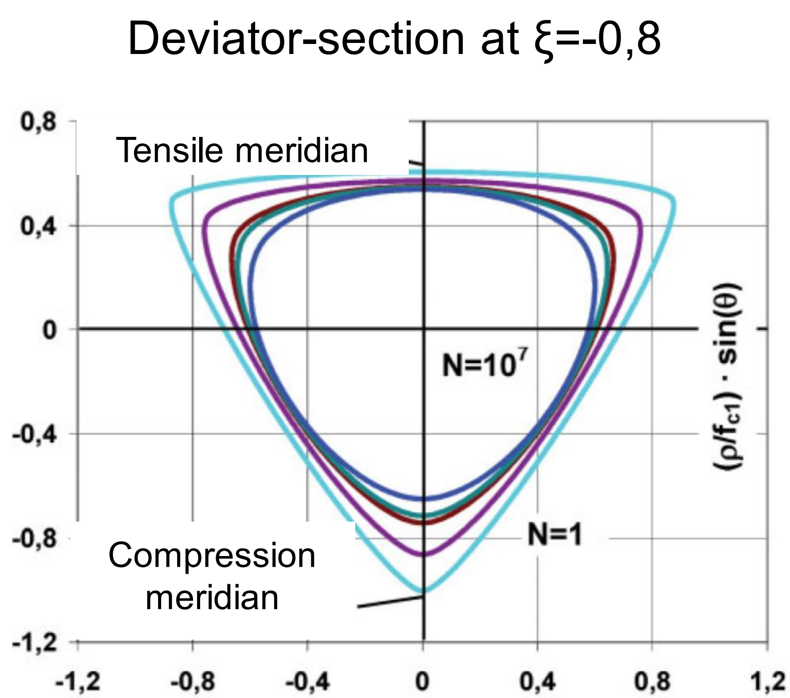
Development of stress-strain curves in 3D



→ Experimental results for calibration get extremely rare

3-Phase Model for UHPC by Grünberg et al.

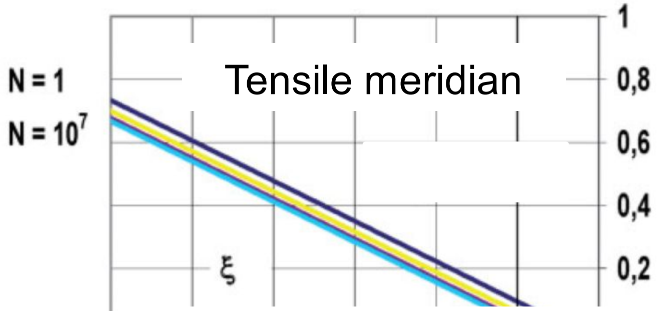




Grünberg, 2007

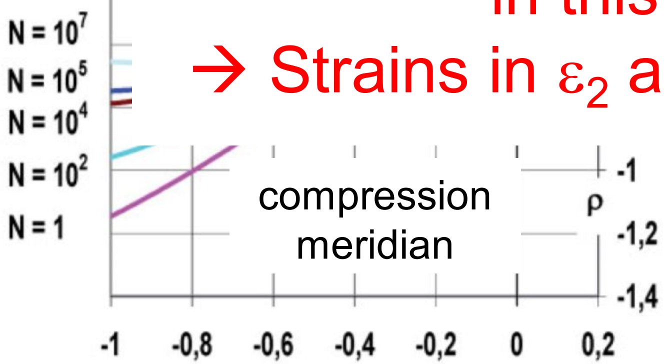
→ Information on the fracture surface and its evolution is available but *not for evolution of deterioration in 2D*

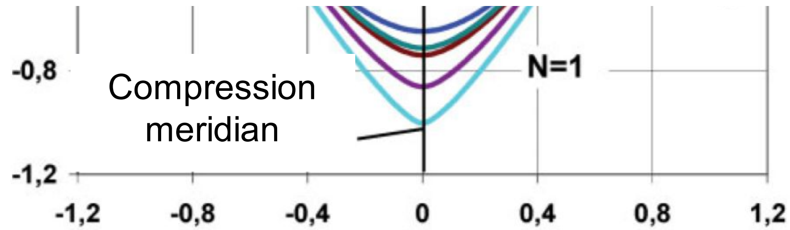
3-Phase Model for UHPC by Grünberg et al.



→ Experiments for the deterioration development in this case *are not available*.

→ Strains in ε_2 and ε_3 directions are not measured



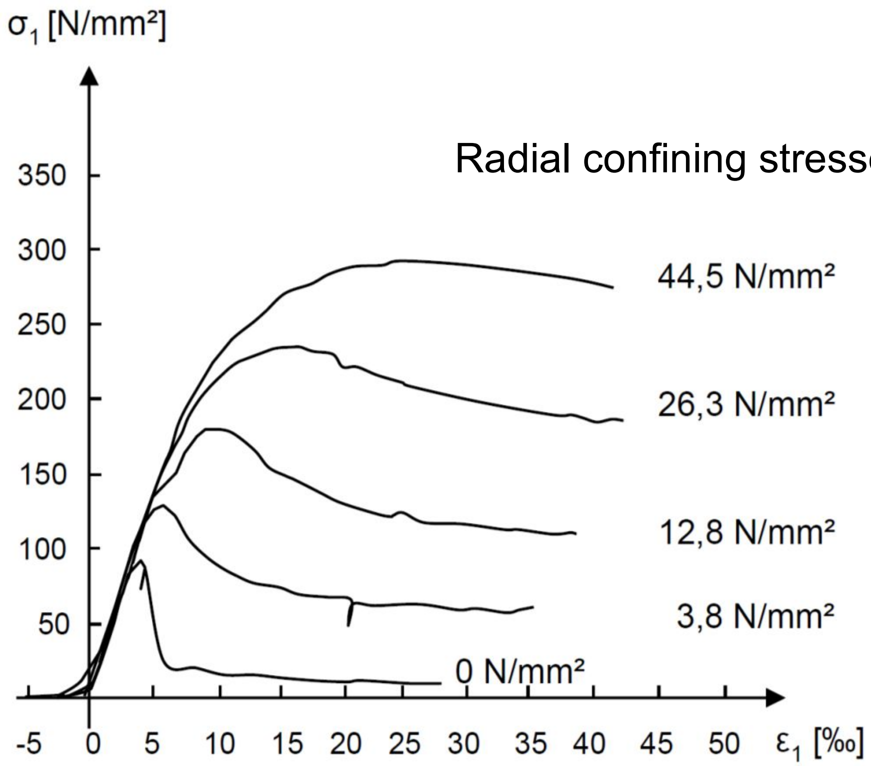


Grünberg, 2007

→ Information on the fracture surface and its evolution is available but *not for evolution of deterioration in 2D*

BERGISCHE UNIVERSITÄT WUPPERTAL

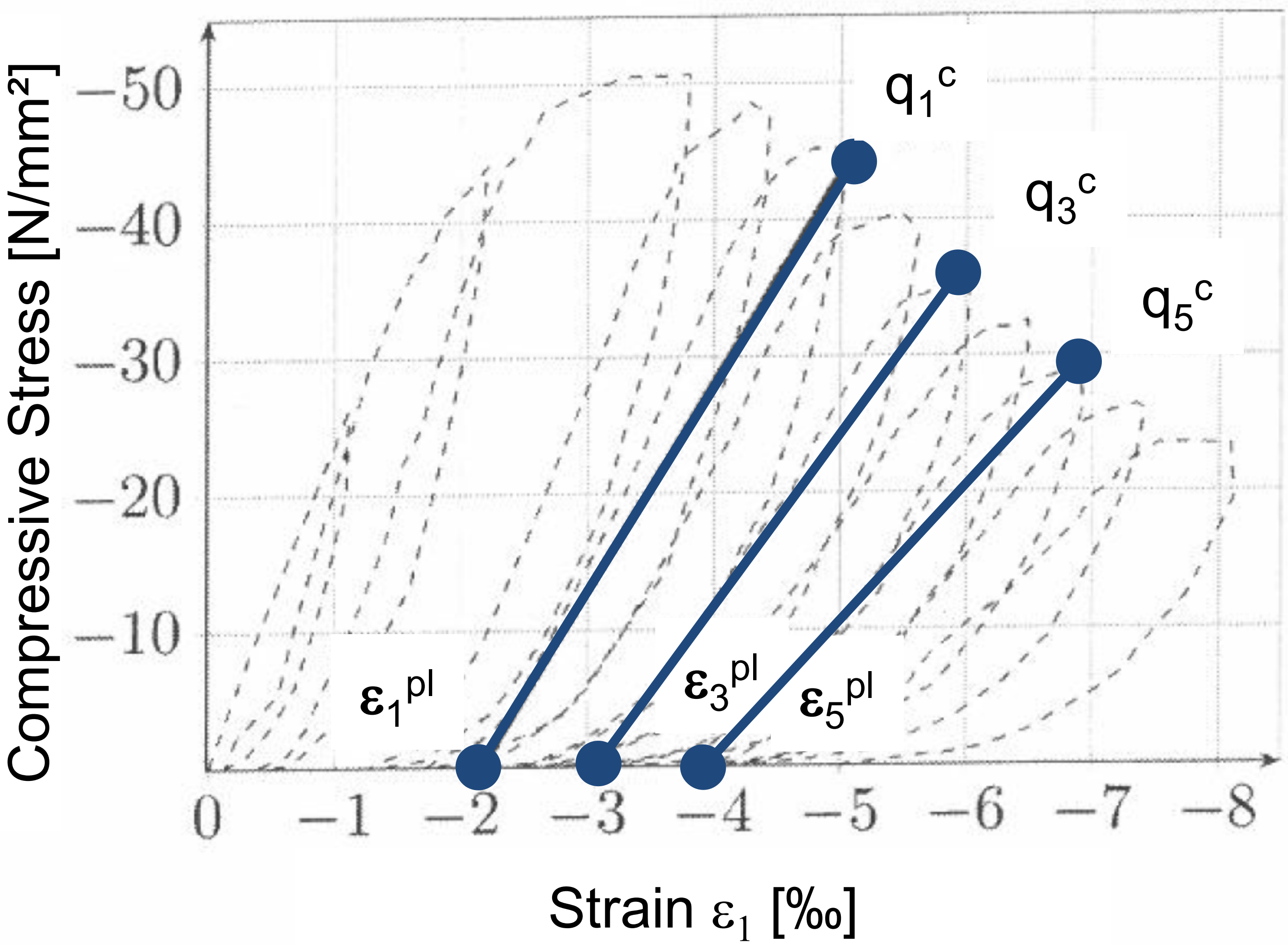
Development of stress-strain curves in 3D



Curbach, 2002

→ Experimental results for calibration get extremely rare

Approach of the MaBet "Multiaxiales Betonmodell"



Vogdt, 2017 uses tests by van Mier from the 60s

Contents

Summary I

- Deterioration indicators can have *different functions*.
- For older, less complex models a *lot of tests* for calibration *exist*.
- *Complex plasticity & damage models* need a lot of information, only *single experiments exist* for these models, especially in 2D and 3D.
- It is important to *clearly fix boundary conditions* for the *models* (e.g. Poissons-ratio) as well as the *specific tests*.
- To fix plastic strains, *quasi-dynamic/ cyclic tests* are required, with measurements of strains in all 3-dimensions

Summary II

- *Confining 3D-stresses* significantly affect σ-ε-curves
- In future, *visco-elastic* and *visco-plastic* strains should be additionally considered, because they *increase plastic strains, but not damage*.

→ In future more specific tests are needed-

→ It is very important to jointly work on material and experiment

Vielen Dank für Ihre Aufmerksamkeit

Literature I

Thiele, 2013: Thiele, Marc: Experimentelle Untersuchung und Analyse der Schädigungsevolution in Beton unter hochzyklischen Ermüdungsbeanspruchungen. BAM-Dissertationsreihe, Berlin 2013

Oneschkow, 2014: Oneschkow, Nadja: Analyse des Ermüdungsverhaltens von Beton anhand der Dehnungsentwicklung. – Hannover : Leibniz Universität Hannover. Institut für Baustoffe, 2014 (Berichte aus dem Institut für Baustoffe, Leibniz Universität Hannover ; 13), XV, 337 S. ISBN 978-3-936634-14-3

Nunez, 2014: Núñez Aldave, J. K.; Anders, S.: Fatigue Behaviour of High-Performance Concrete – Comparison of Damage Indicators for Numerical Modelling. Proceedings of the XIVth Bilateral Czech/German Symposium, 4th to 7th June 2014, Wuppertal

Nunez, 2013 : Núñez Aldave, J. K.; Anders, S.: Ermüdungsverhalten von Hochleistungsbeton – Vergleich von Schädigungsindikatoren. Beiträge zur 1. Jahrestagung des Deutschen Ausschuss für Stahlbeton mit 54. Forschungskolloquium. 07./08. November 2013, Ruhr-Universität Bochum

Lohaus, Anders, 2007 : **Lohaus, L.; Anders, S.; Wefer, M.:** High-Cycle Fatigue of Ultra-High Performance Concrete (UHPC) - Fatigue Strength and Damage Development. In: Proceeding of the 3rd Int. Conference on Lifetime Oriented Design Concepts, 12.-14.11.2007, Bochum

Pfanner, 2003 : Pfanner, D.: Zur Degradation von Stahlbetonbauteilen unter Ermüdungsbeanspruchung.

Dissertation Ruhr-Universität Bochum, VDI Verlag, VDI Reihe 4 Nr. 189, Düsseldorf, 2003.

Göhlmann, 2010 : Göhlmann, J.: Zur Schädigungsberechnung an Betonkonstruktionen für Windenergieanlagen unter mehrstufiger und mehraxialer Ermüdungsbeanspruchung, Dissertation, 2010, ISBN 978-3-8167-8210-0

Literature II

Su, 1988 : Su, E.C.M.; Hsu, T.T.C.: Biaxial Compression Fatigue and Discontinuity of Concrete. *ACI Materials Journal*, Mai-Juni, 1988

Curbach 2002: Curbach, M.; Speck, K.: Mehraxiale Festigkeit von duktilem Hochleistungsbeton. *Deutscher Ausschuss für Stahlbeton*, Heft 524, Beuth Verlag, Berlin, 2002

Grünberg et al. 2007: Grünberg, J.; Lohaus, L.; Ertel, C.; Wefer, M.: Mehraxiales mechanisches Ermüdungsmodell von Ultra-hochfestem Beton. Beton- und Stahlbetonbau 102 (2007), Heft 6, Ernst&Sohn Verlag, Berlin

Vogdt, 2017: Vogdt, F. D.: Multiaxiales Betonmodell „MaBet". Beiträge zur 3. Jahrestagung des Deutschen Ausschuss für Stahlbeton mit 56. Forschungskolloquium. 19./20. Oktober 2017, Universität Kaiserslautern