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Dynamic Fracture of Materials: Experimental and Numerical Studies

J. Ožbolt

H.W. Reinhardt, A. Sharma, E. Sola, B. Irhan and D. Ruta

Institute of Construction Materials, University of Stuttgart, Germany

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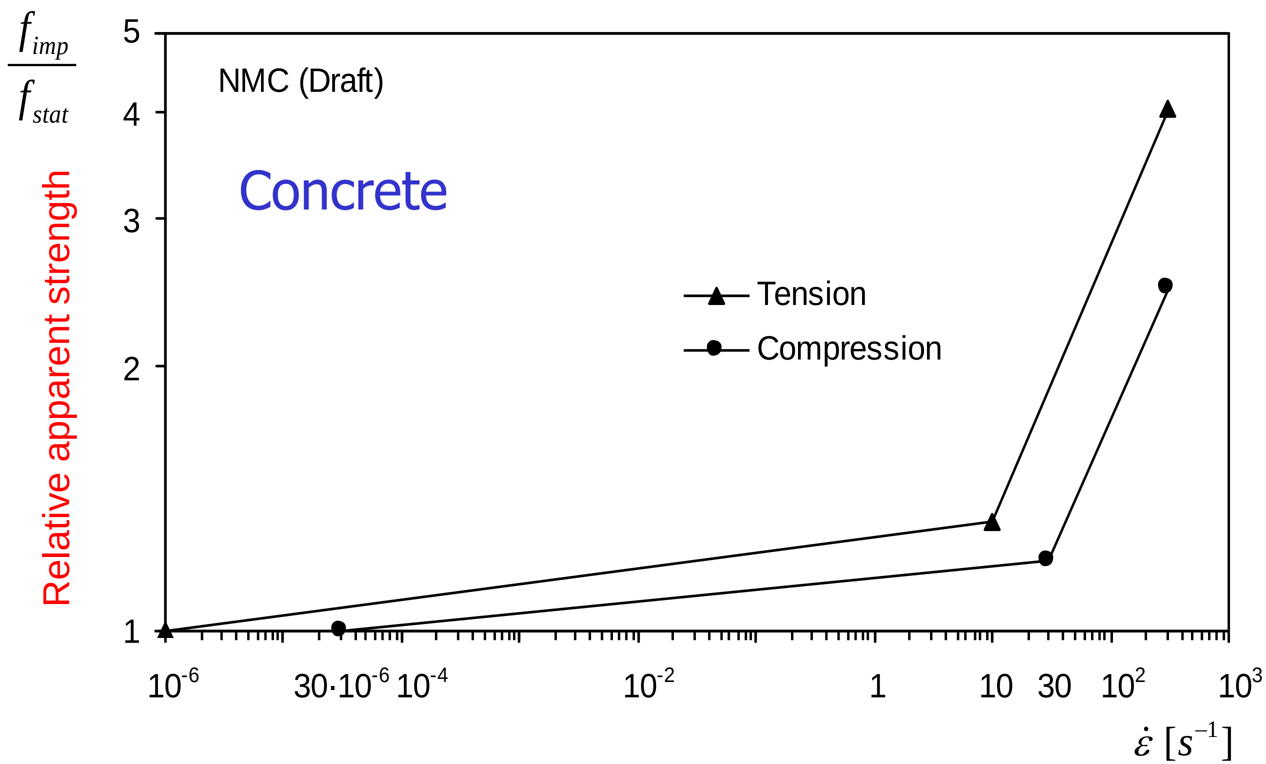
Contens

- Introduction
- Theoretical framework
- Examples (analysis & experiments):
  - Brittle & quasibrittle materials (e.g. glass & concrete)
  - Ductile materials (e.g. steel)
- Split Hopkinson Bar (SHB)
- High velocity projectile impact
- Summary and Conclusions

Introduction



Traffic:	$10^{-6} – 10^{-4}$ s^{-1}
Earthquake:	$5x10^{-3} – 5x10^{-1}$ s^{-1}
Airplane impact:	$5x10^{-2} – 2x10^{0}$ s^{-1}
Hard impact:	$10^{0} – 5x10^{1}$ s^{-1}
Hypervelocity impact:	$10^{2} – 10^{6}$ s^{-1}

Introduction

Macro & meso scale modeling level

(1) Effects covered by constitutive law

- Rate dependent growth of microcracks
- Viscosity due to the water content, e.g. concrete
- Thermo-mechanical coupling (impact)

(2) Inertia effects – covered by dynamic analysis

- Structural inertia
- Hardening & softening of materials
- Crack propagation: velocity & branching
- ……..

Experimental investigations (e.g. tension)

- Direct tensile tests:

  $d\varepsilon/dt < 0.1/s$

- Indirect tensile tests

  - Split Hopkinson Bar (SHB):

    $0.1/s < d\varepsilon/dt < 10/s$

  - Modified Split Hopkinson Bar (MSHB), spalling tests:

    $10/s < d\varepsilon/dt < 200/s$

  - Compact tension specimen (CTS)

    $d\varepsilon/dt < 50/s$

Numerical analysis

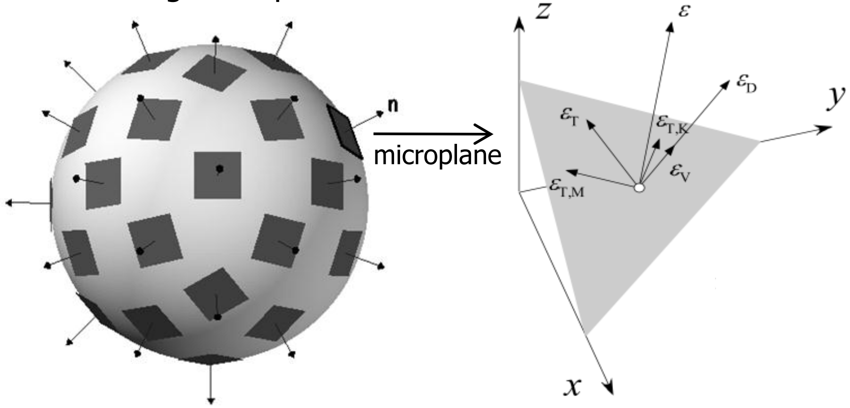
General framework for modeling of rate dependent response

- Continuum mechanics
- Irreversible thermodynamics
- Constitutive law – temperature dependent microplane model
- Non-linear fracture mechanics
  - smeared crack approach
  - crack band method
- Basic principles of contact mechanics & Thermo-mechanical coupling
- Standard finite elements & fragmentation

Microplane model

- Relaxed kinematic constraint (Ožbolt at al. 2001, 2014)
- Rate dependency: Rate process theory
  (Bažant et al. 2000, Ožbolt et al. 2006)
- Large strain generalization: Green-Lagrange strain & Co-rotated
  Cauchy stress tensor (Bažant et al. 2000)
- Thermo-mechanical coupling (Ožbolt at al. 2005, Irhan 2014)

FE integration point



Kinematic constraint : from $\varepsilon_{ij} \rightarrow \varepsilon_V, \varepsilon_D, \varepsilon_{Tr}$

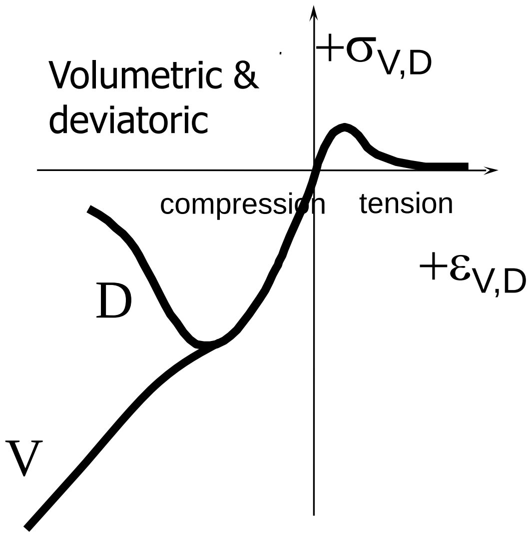
$$\sigma_V^0 = F_V(\varepsilon_V) \quad ; \quad \sigma_D^0 = F_D(\varepsilon_D) \quad ; \quad \sigma_{Tr}^0 = F_{Tr}(\varepsilon_{Tr}, \varepsilon_V)$$

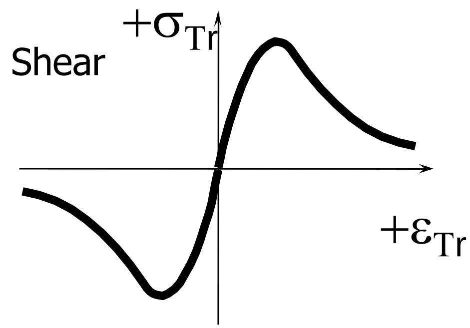
Weak form of equlibrium :

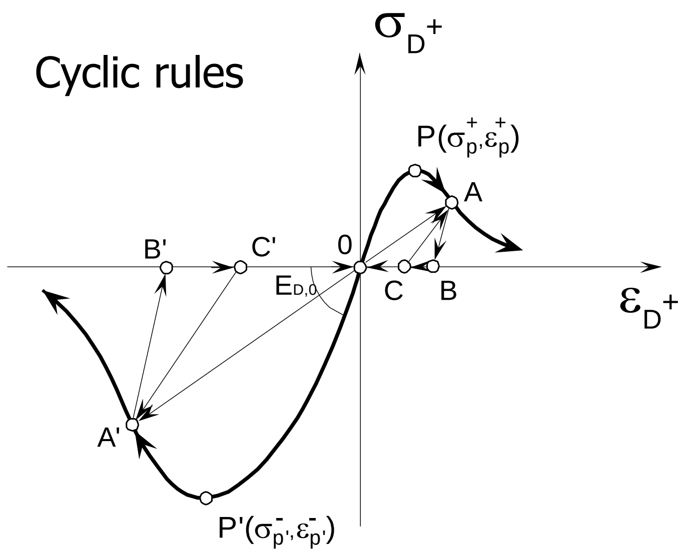
$$\sigma_{ij}^0 = \sigma_V^0 \delta_{ij} + \frac{3}{2\pi}\int_S \sigma_D^0 \left(n_i n_j - \frac{\delta_{ij}}{3}\right) dS + \frac{3}{2\pi}\int_S \frac{\sigma_{Tr}^0}{2}\left(n_i \delta_{rj} + n_j \delta_{ri}\right) dS$$

Materials: brittle, quasi-brittle & ductile

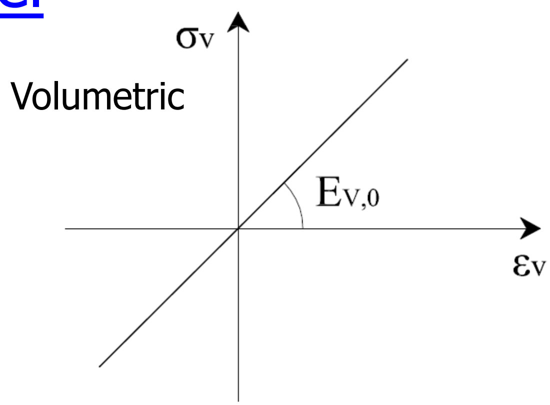
Concrete

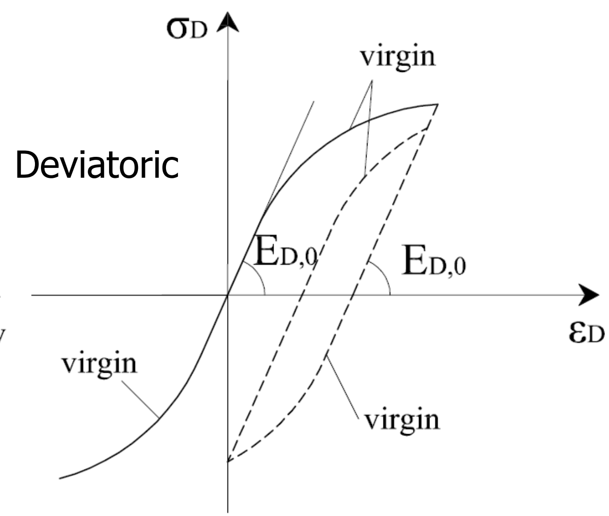


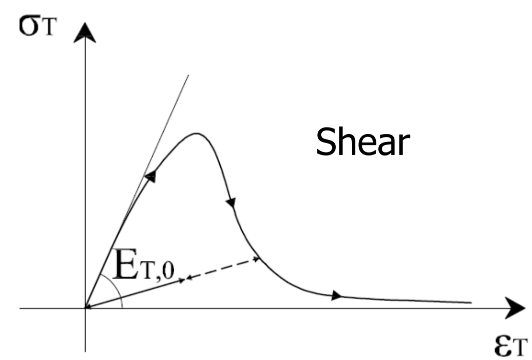




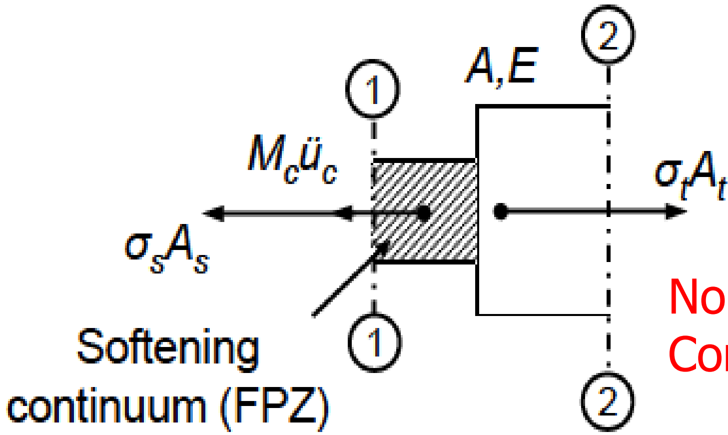
Steel







Effect of inertia due to softening (or hardening)
(direct tension)



Non-uniform displacement field
Consequence: acceleration field

$$\sigma_s A_s + M_c \ddot{u}_c = \sigma_t A_t \quad \text{or} \quad \sigma_t = \frac{\sigma_s A_s + M_c \ddot{u}_c}{A_t}$$

$$\sigma_t = \frac{\sigma_s A_s}{A_t} + \frac{M_c \ddot{u}_c}{A_t} \quad \text{with} \quad \sigma_{t,s} = \frac{\sigma_s A_s}{A_t}; \quad \sigma_{t,I} = \frac{M_c \ddot{u}_c}{A_t}$$

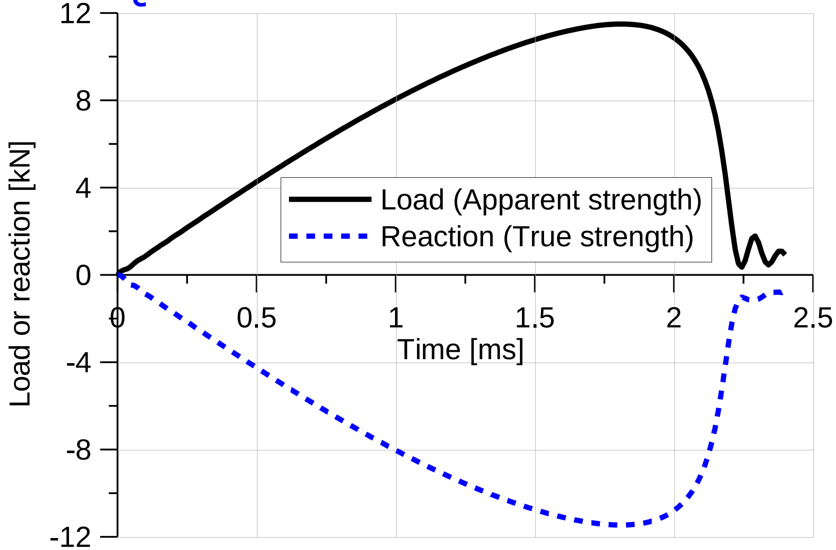
Experimentally measured

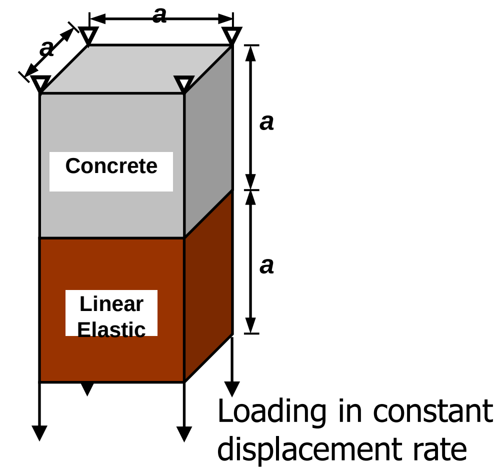
Contribution of inertia due to softening

Contribution of material strength

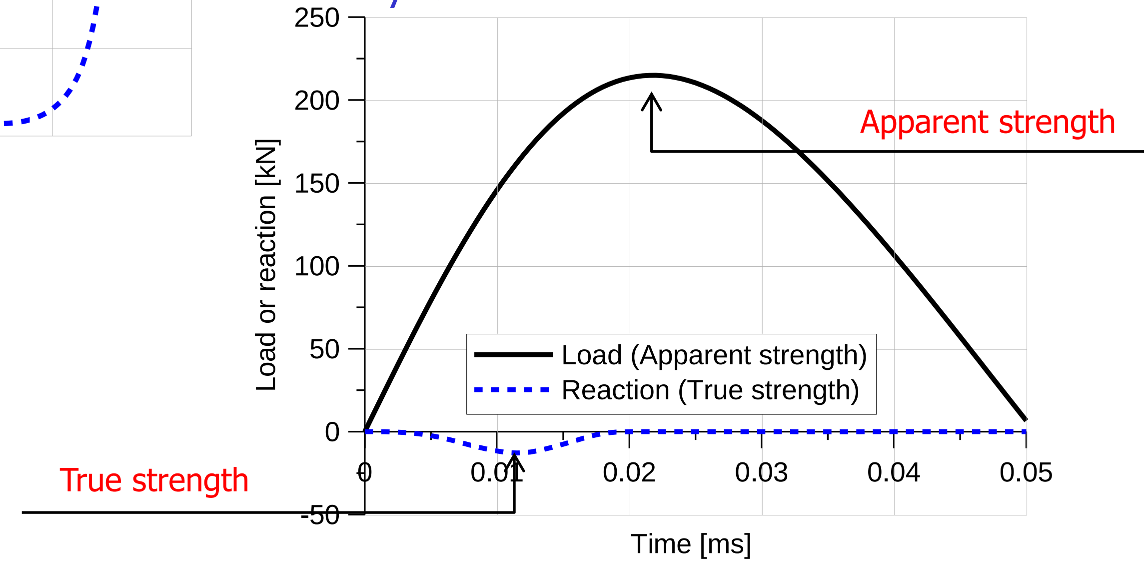
True vs. apparent tensile strength

Quasi-static



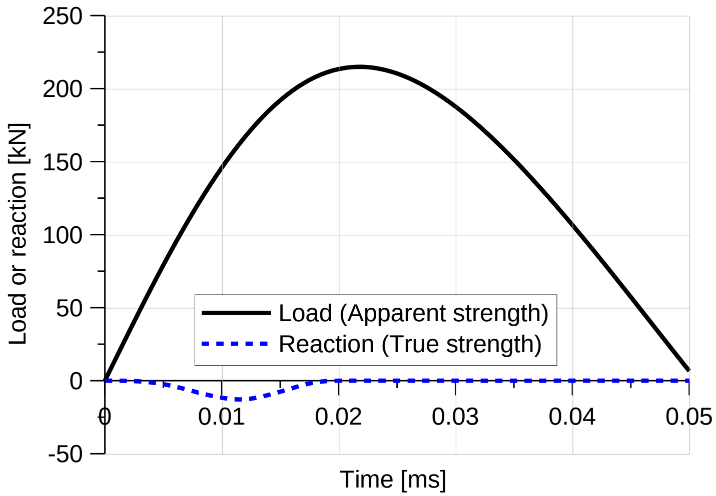


Dynamic

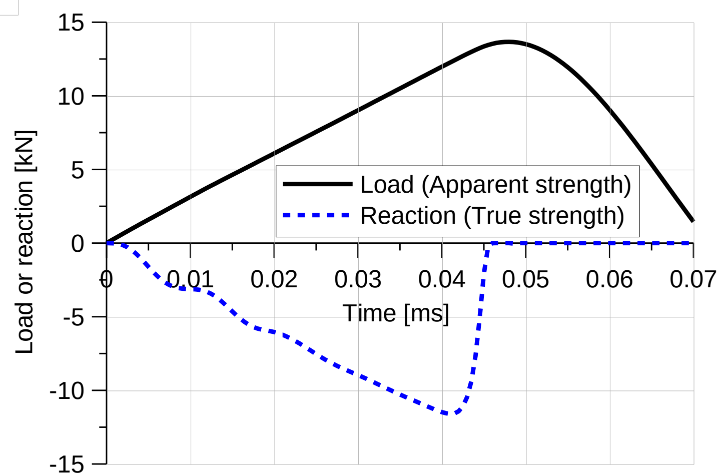


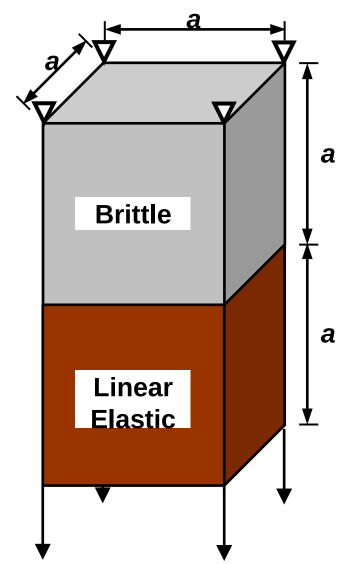
True vs. apparent tensile strength

Concrete



Brittle material (glass)

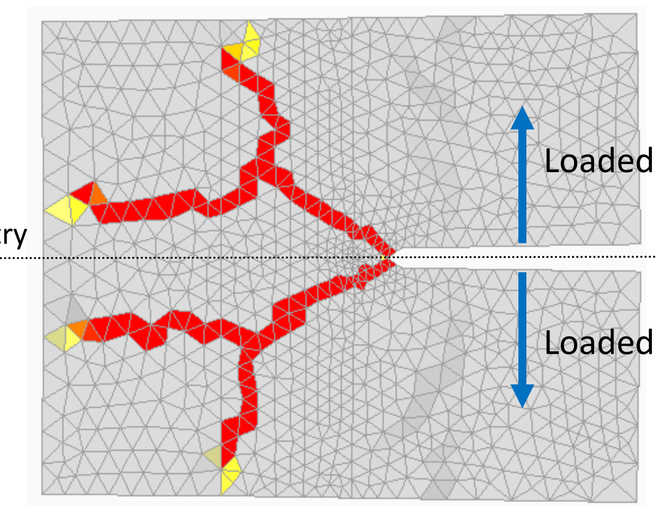


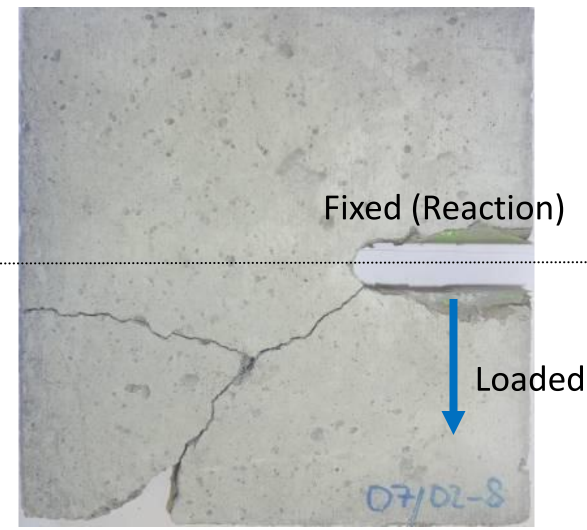


CT concrete specimen

Pre-test analysis

symmetry

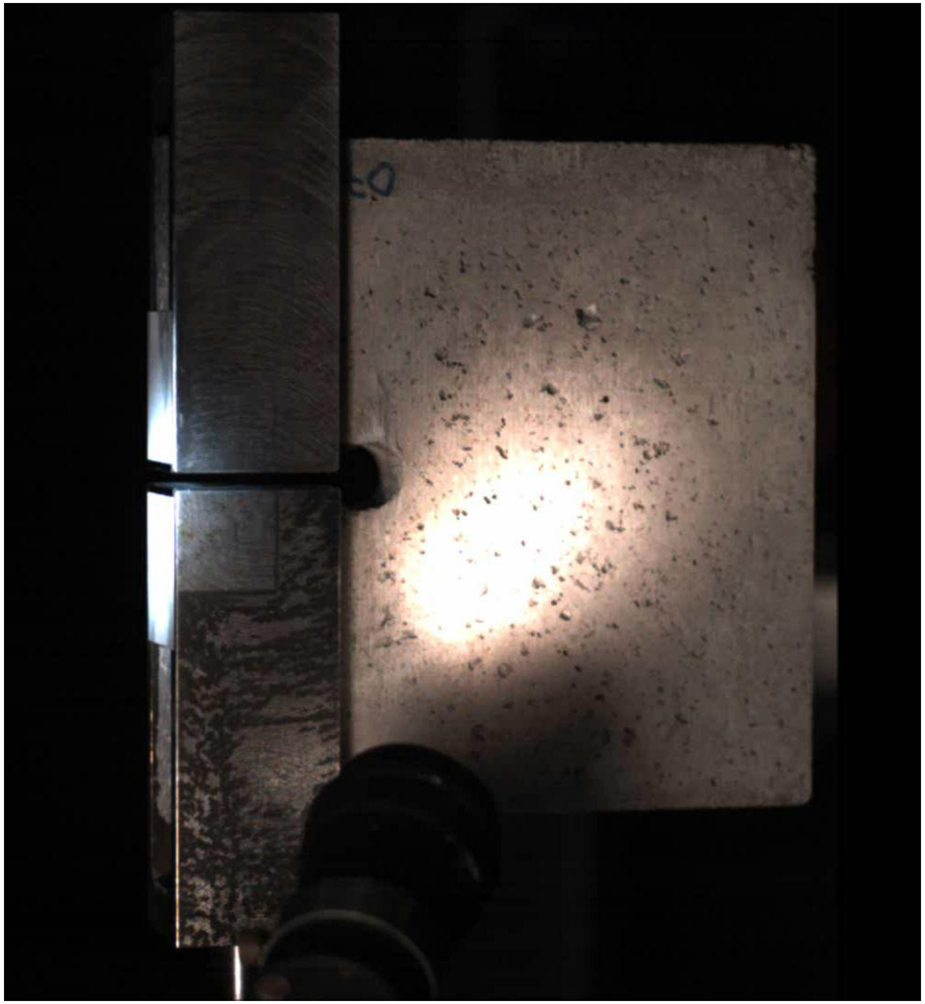




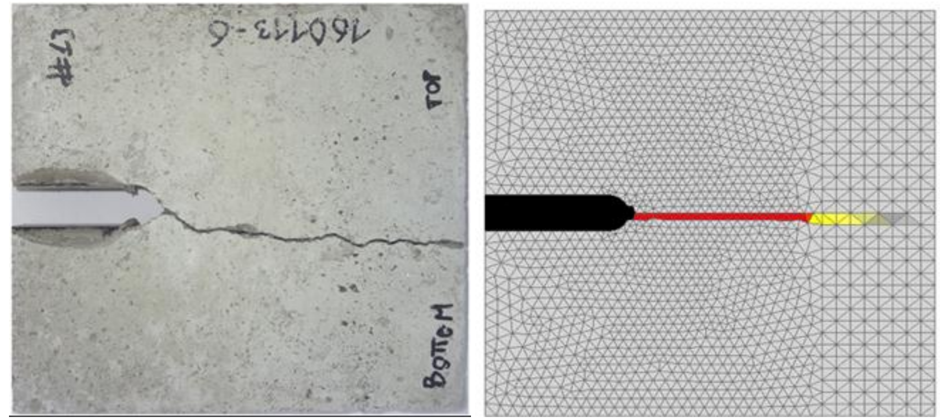
Numerically predicted, loading rate 2.5 m/sec
(Ožbolt et al. , 2011)

Experimental result, loading rate 3.3 m/sec
(Ožbolt et al. , 2013)

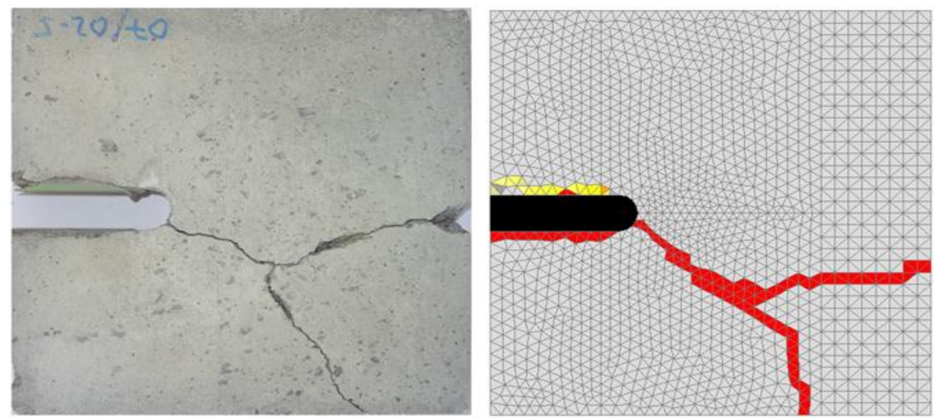
Experiment (4.30 m/s)



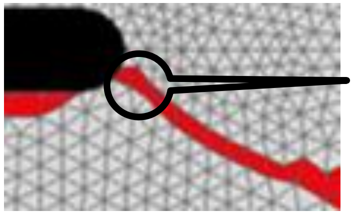
Loading rate: 0.035 m/s

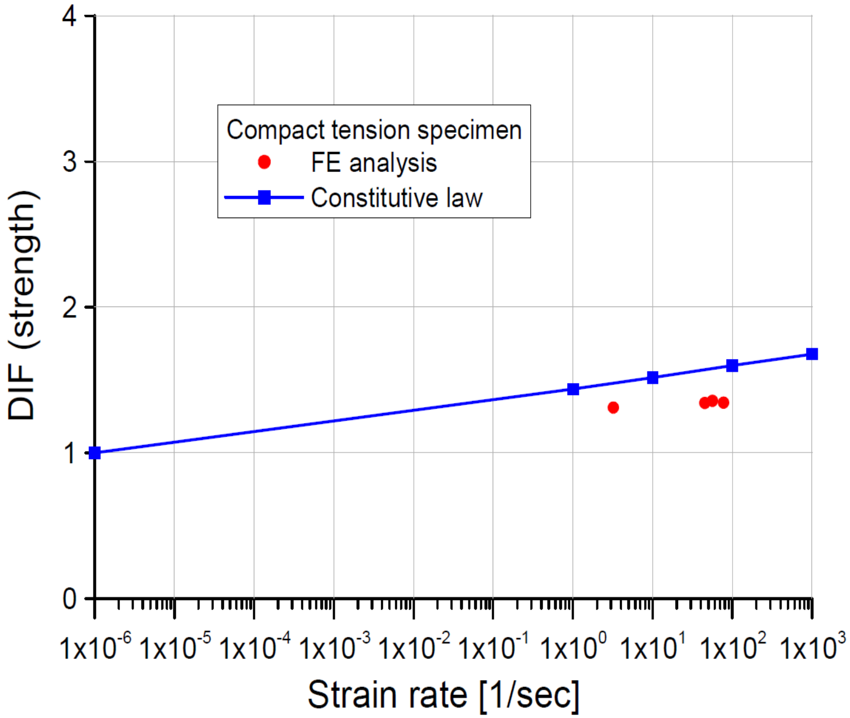


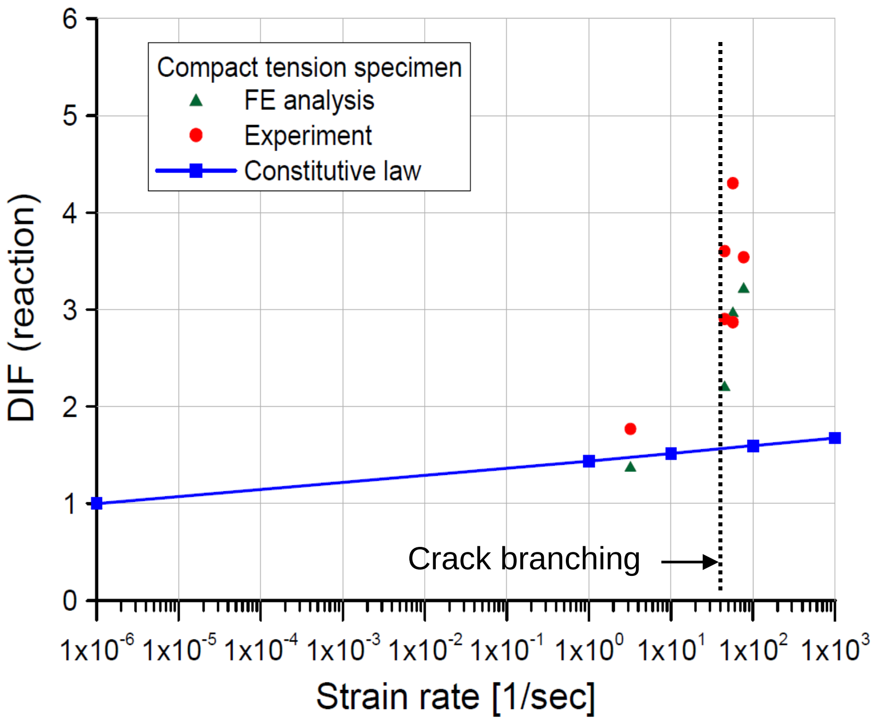
Loading rate: 4.30 m/s



CT specimen – concrete

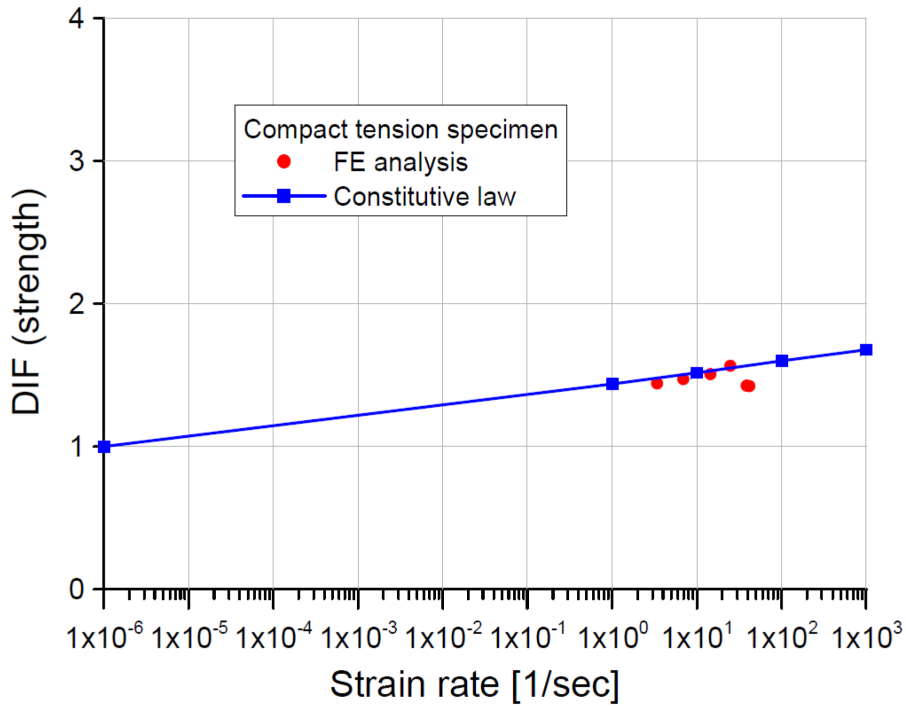


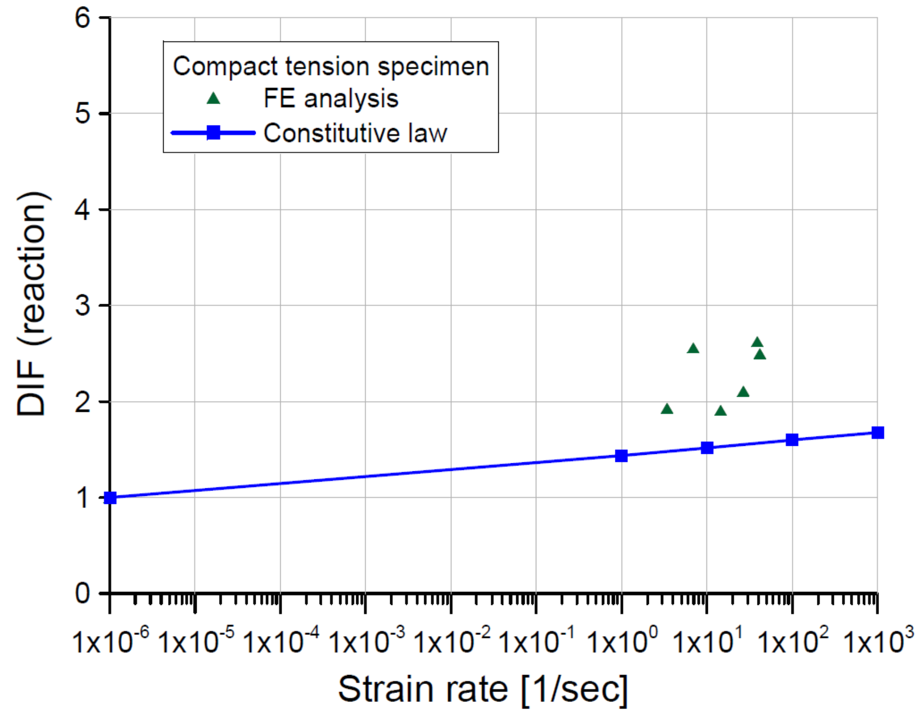




- DIF for strength follows rate dependent constitutive law
- DIF for reaction:
  - Up to strain rate ≈ 50/s, linear rise in DIF (controlled by constitutive law)
  - For strain rate > 50/s, sudden and progressive increase in DIF (controlled by inertia)

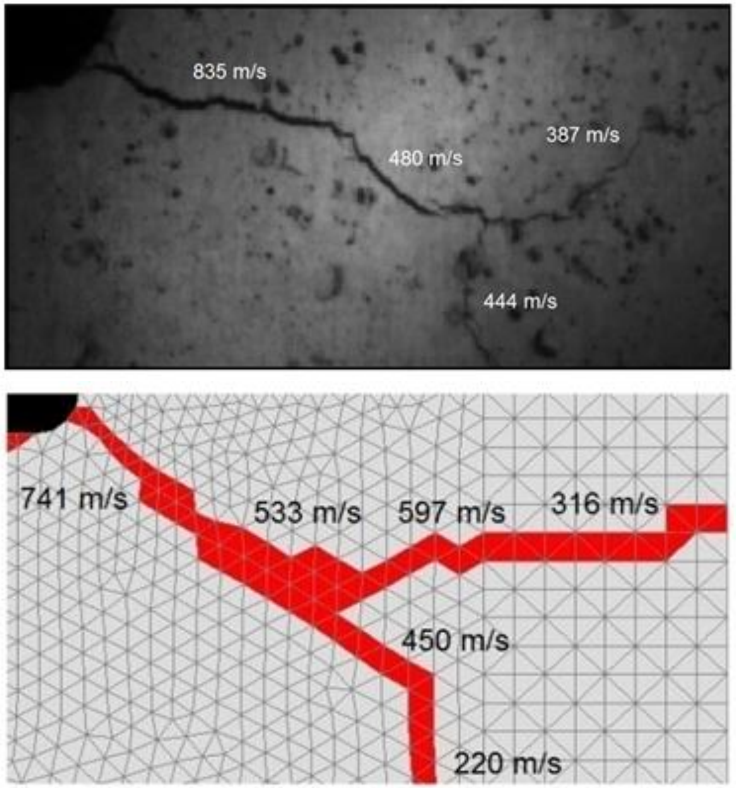
CT specimen - brittle material





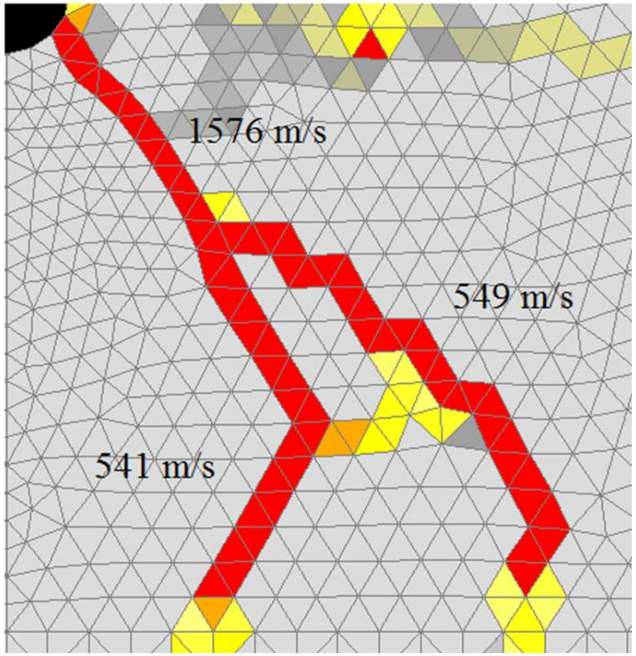
Crack velocity

Quasi-brittle (concrete)



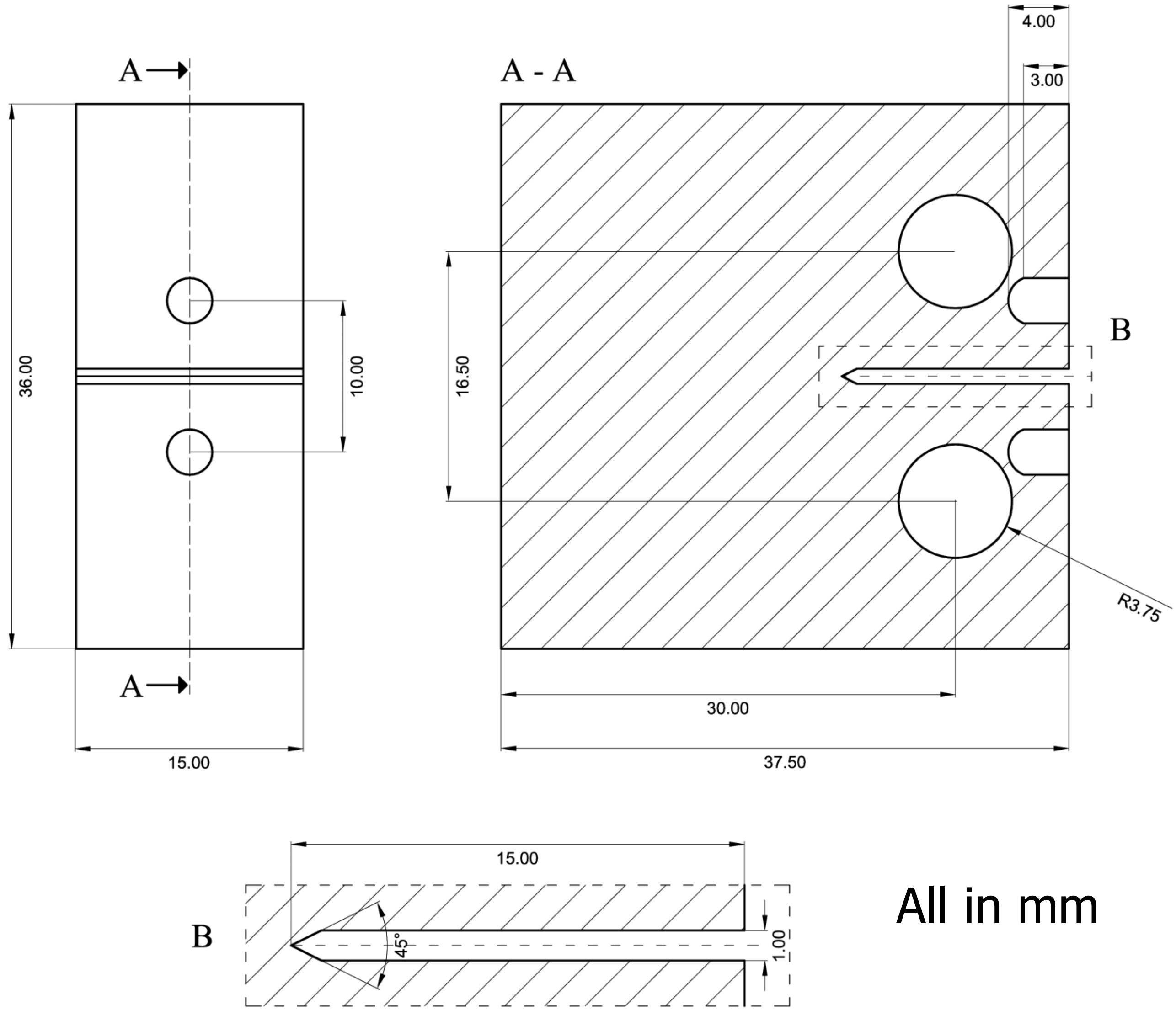
Loading rate: 4.30 m/s

Brittle (glass)



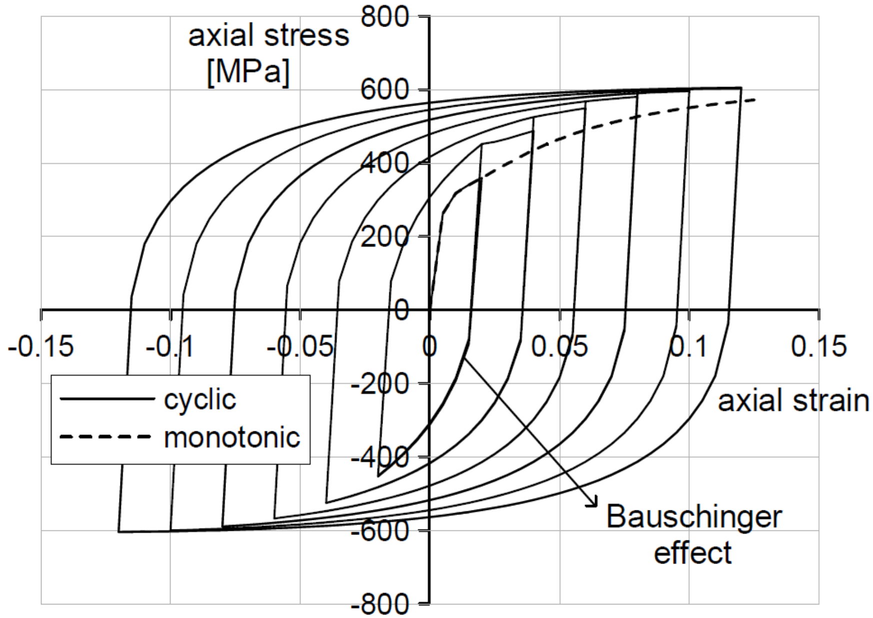
Loading rate: 3.30 m/s

CT specimen - steel



All in mm

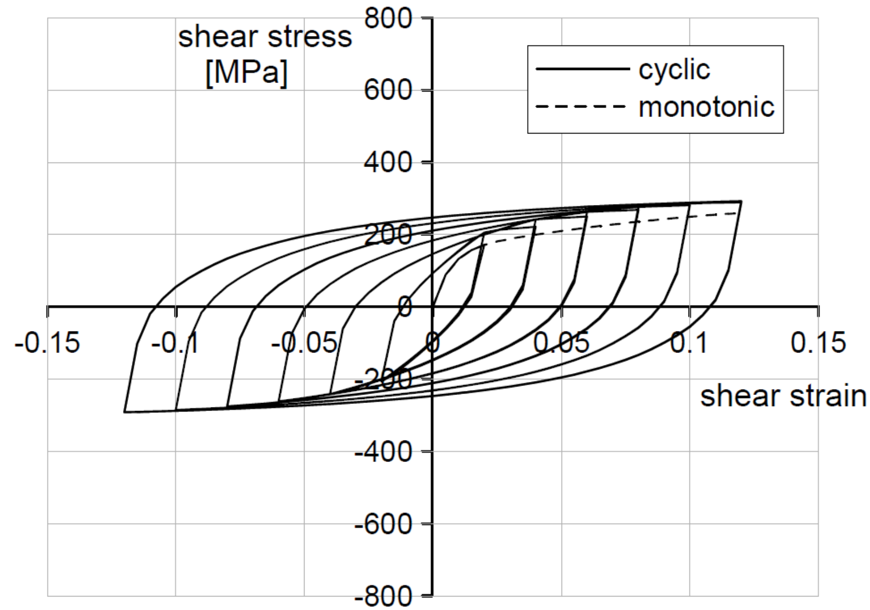
Properties of steel



Uniaxial tension

Young`s modulus	210 GPa
Poisson`s ratio	0.33
Yield stress	350 MPa
Strength	600 MPa
Ultimate strain	0.25

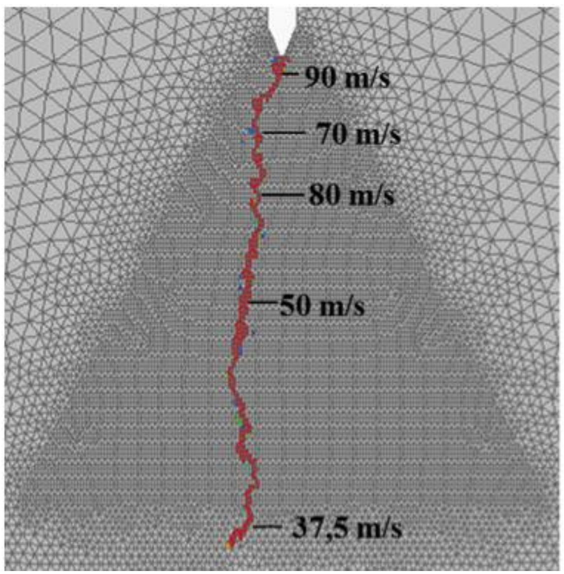
Shear



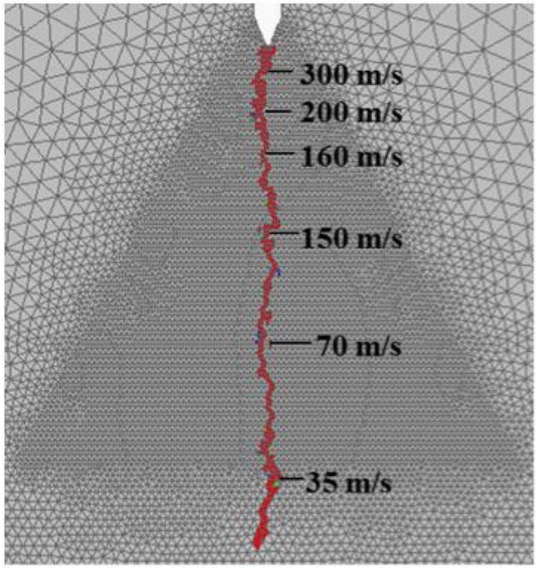
Constitutive law:
microplane model for steel

Crack velocity & crack branching

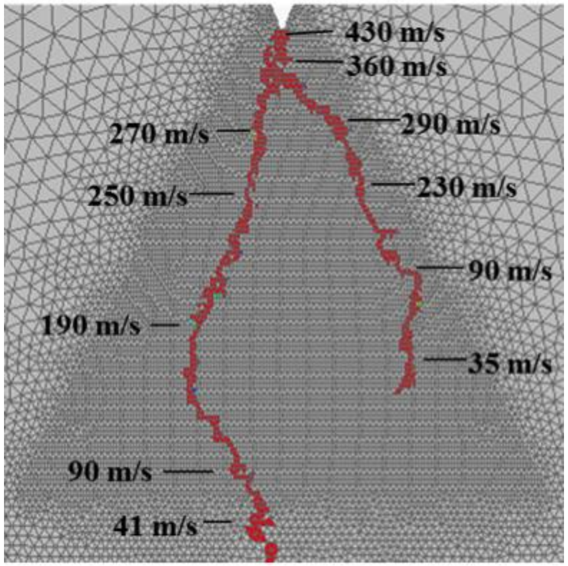
Loading rate: 1 m/s

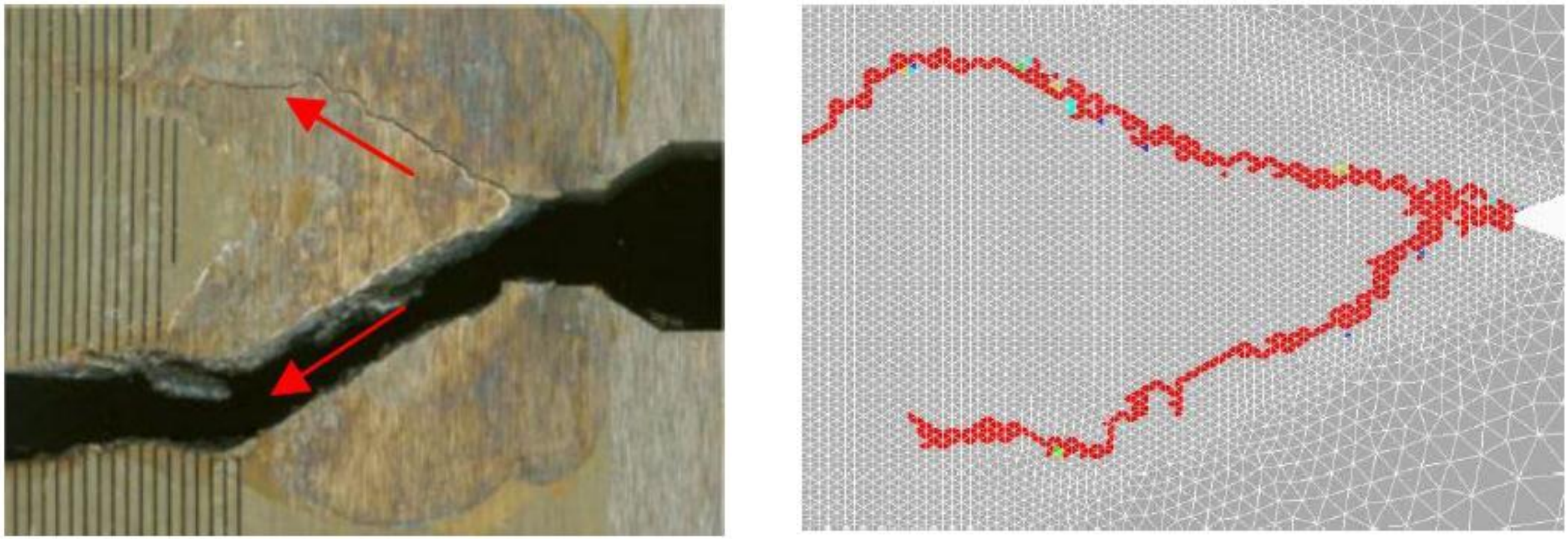


Loading rate: 50 m/s



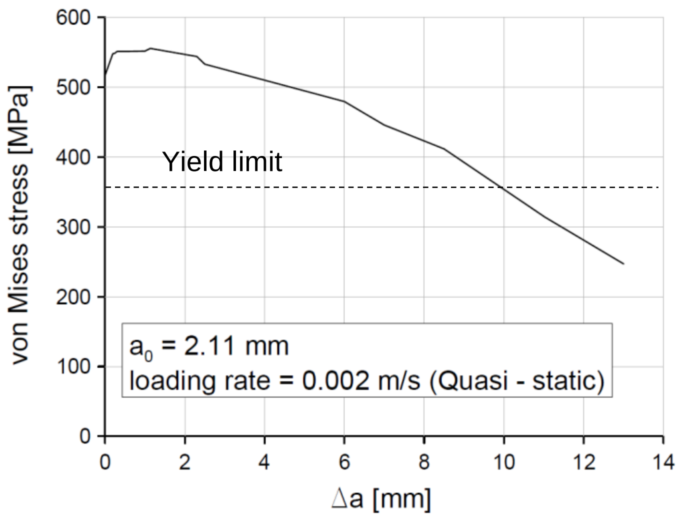
Loading rate: 100 m/s

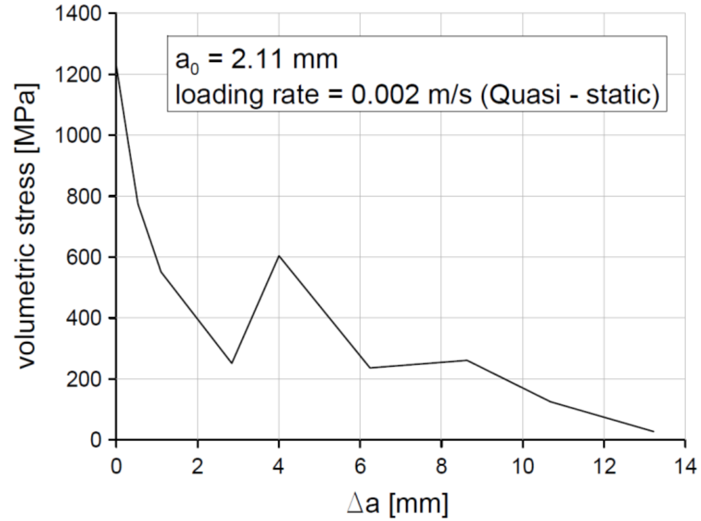




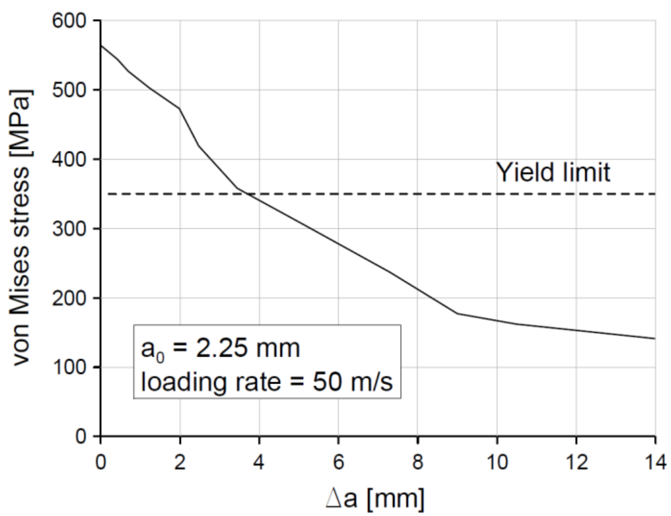
Crack branching: experiment (left, Bousquent et al., 2011) and numerical prediction (right, loading rate 100 m/s)

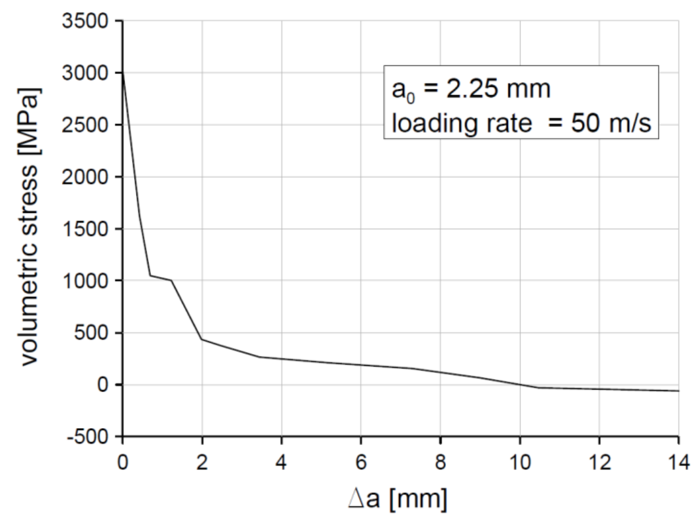
Strength (von Mises stress) along the plastification zone





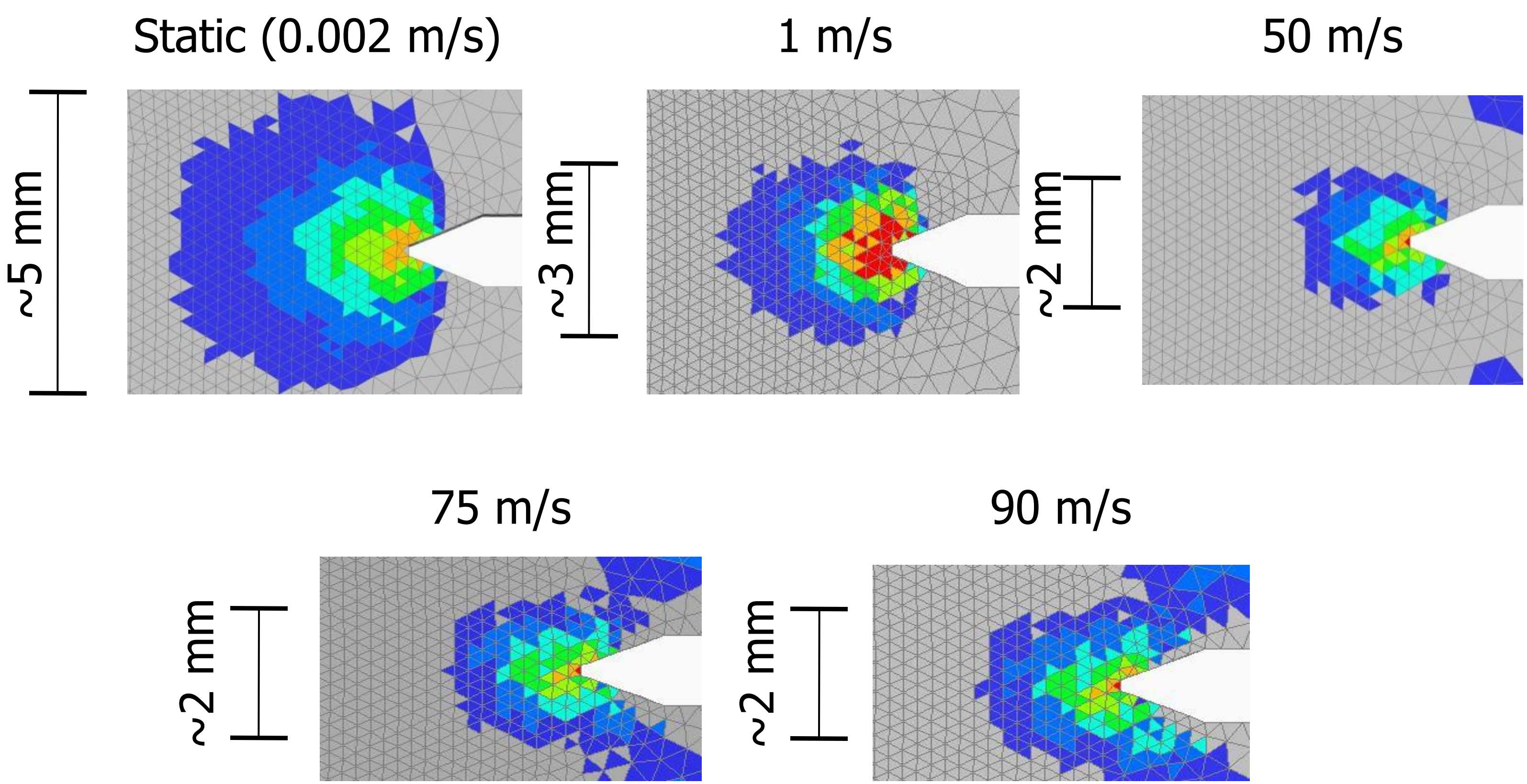
Quasi-static





50 m/s

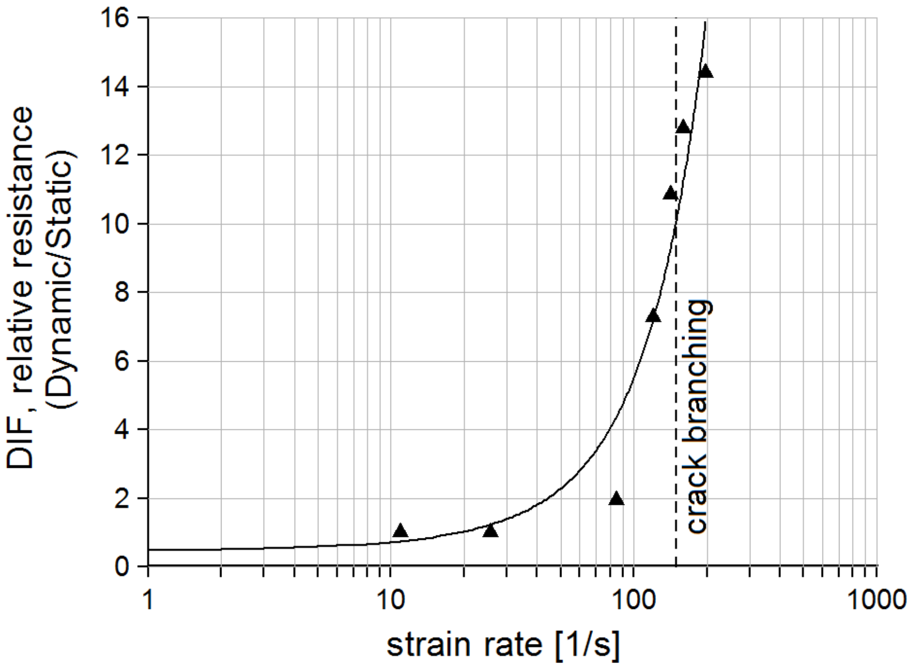
Size of the plastification zone



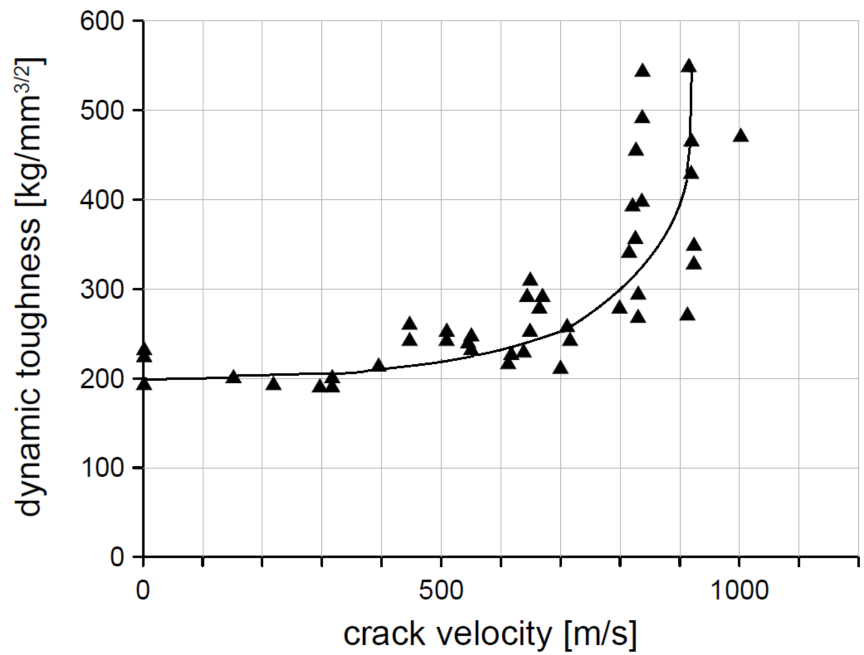
grey: stress < 350 MPa = yield stress

DIF on load & toughness

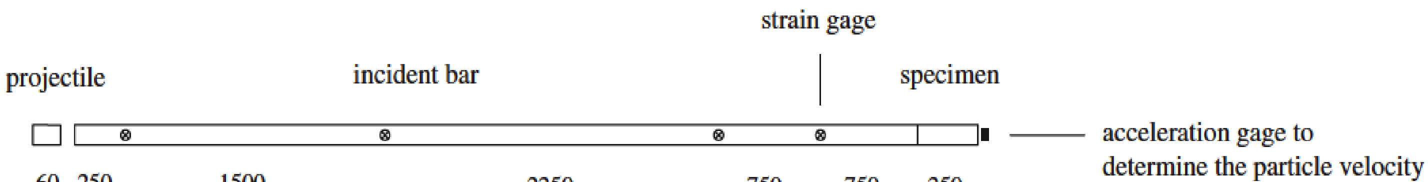
Numerically predicted resistance



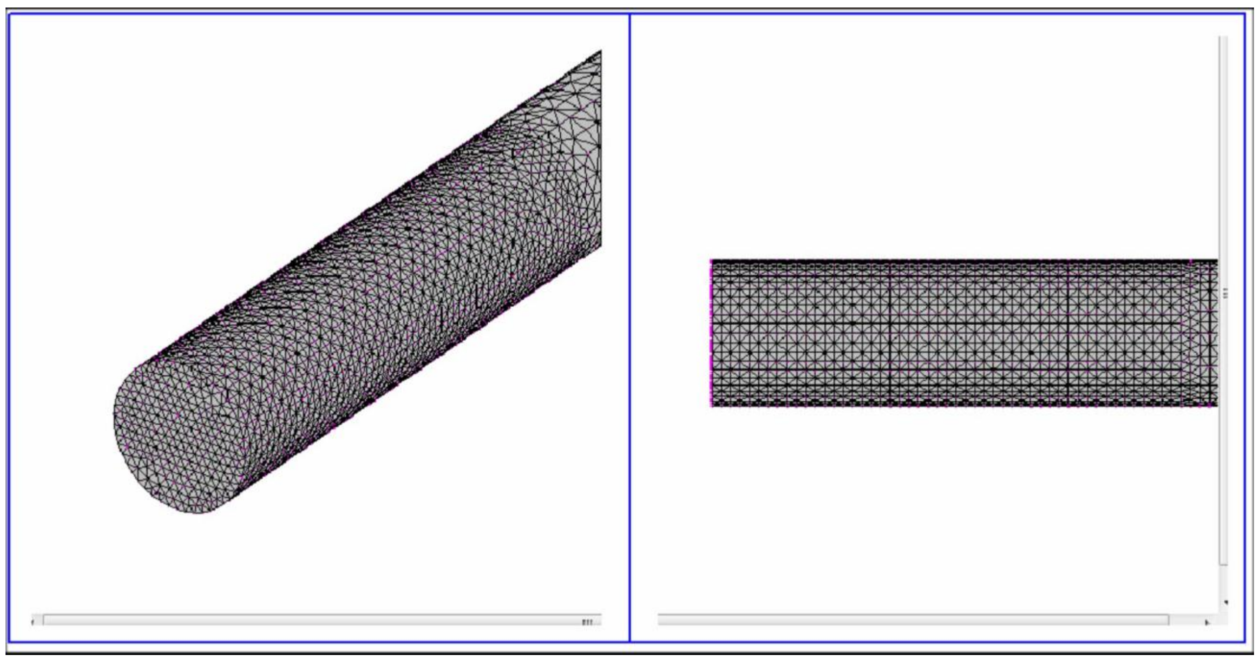
Apparent fracture toughness as a function of crack velocity at -40°C (Kanazawa et al., 1981)



SHB: experiment vs. numerical analysis

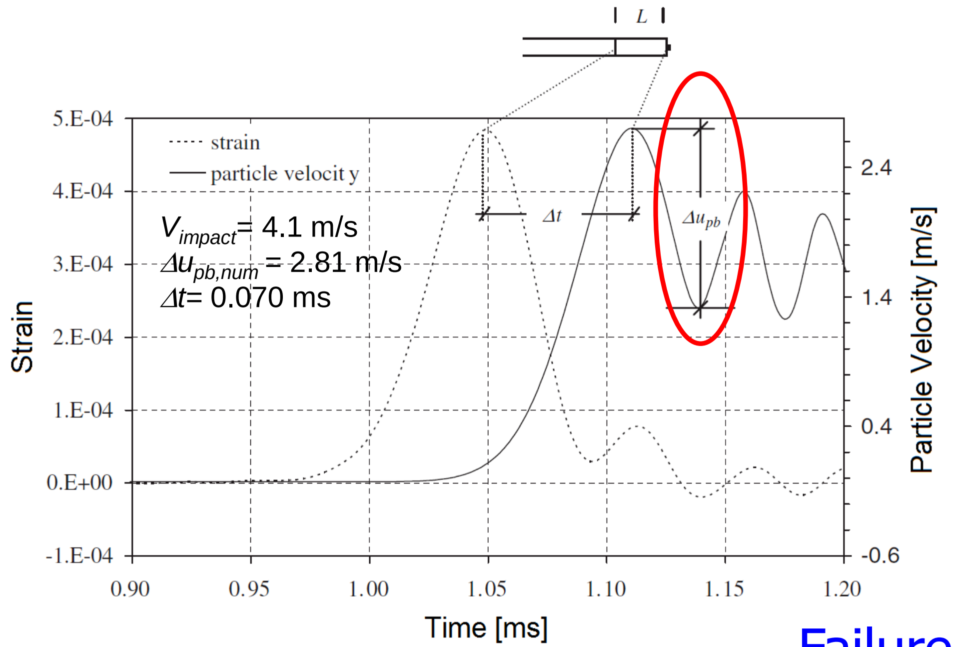


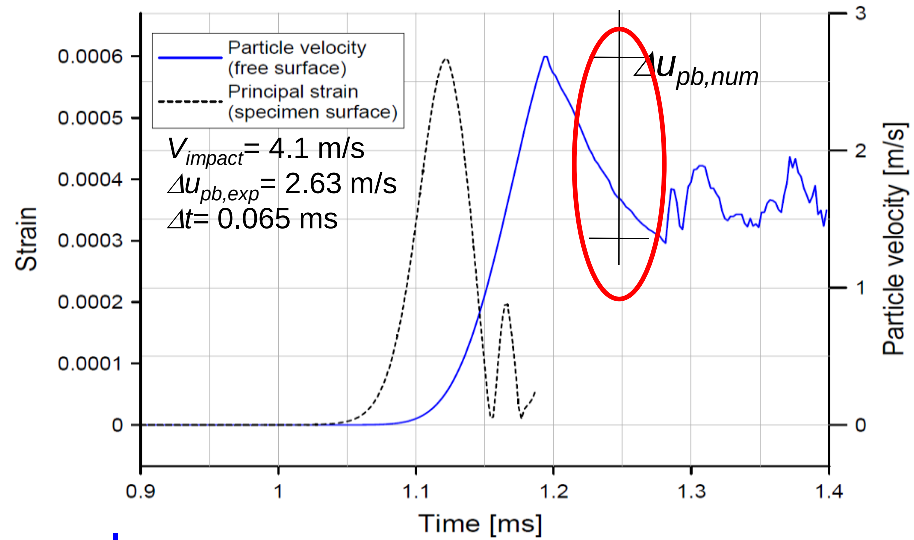
(Schuler et al., 2005)



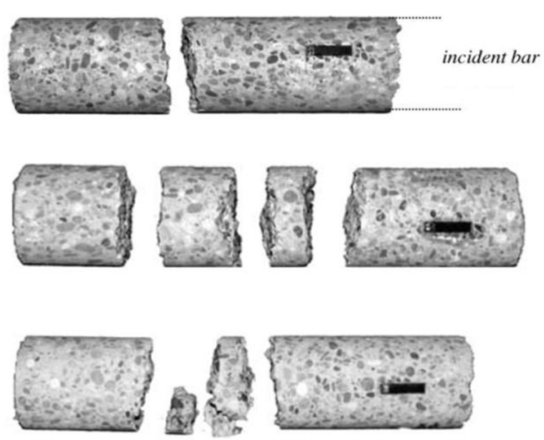
(Irhan et al., 2015)

SHB: experiment vs. numerical analysis





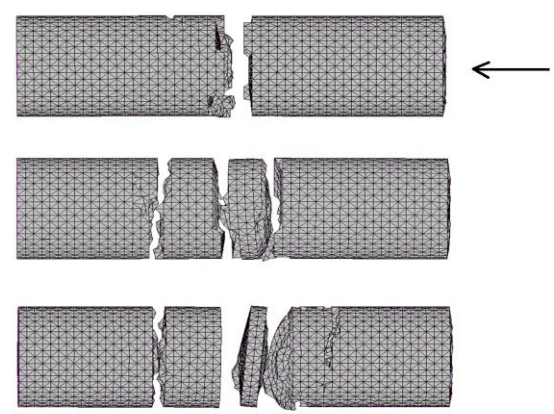
Failure modes



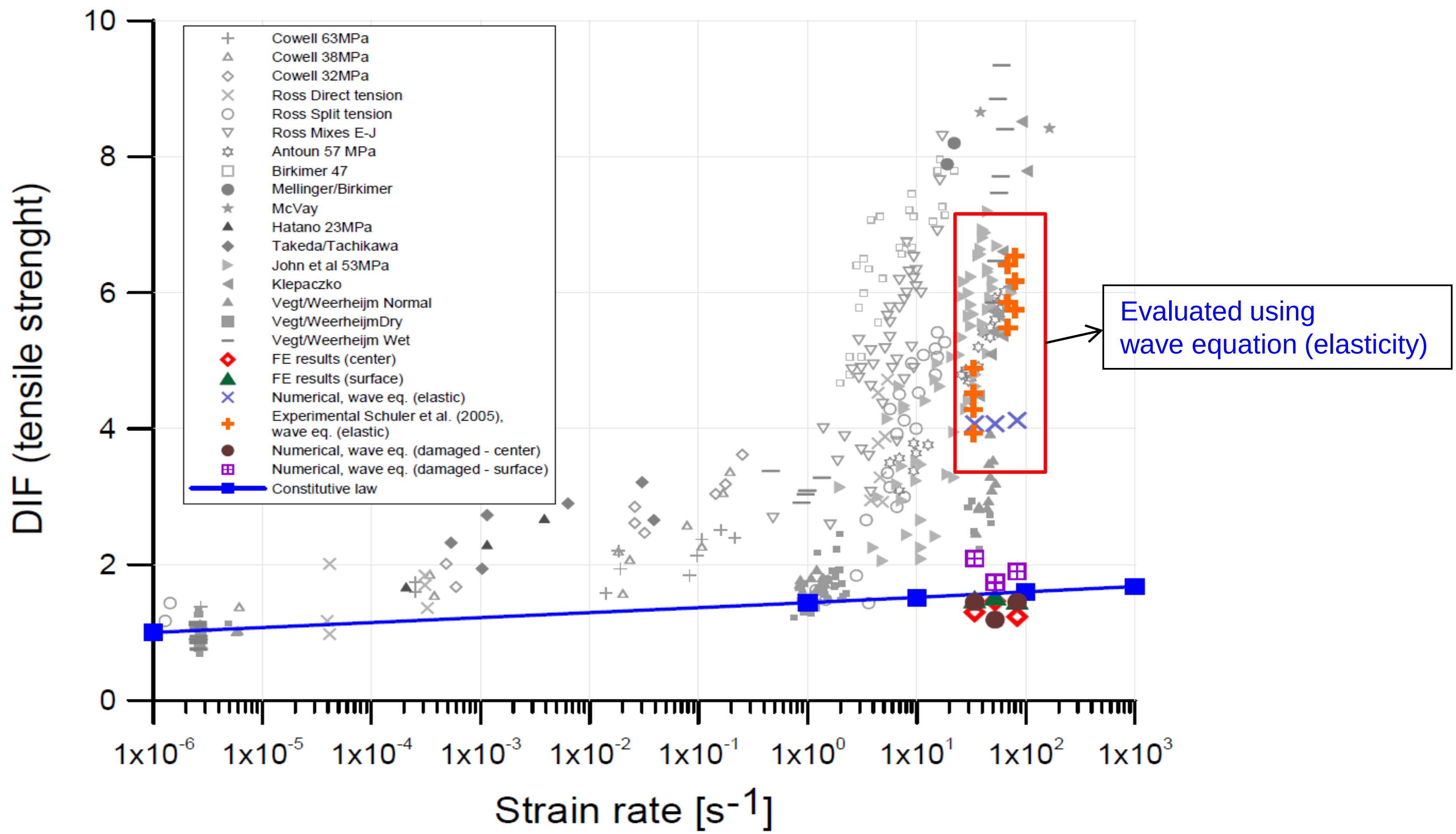
V_{impact}= 4.1 m/sec

V_{impact}= 7.6 m/sec

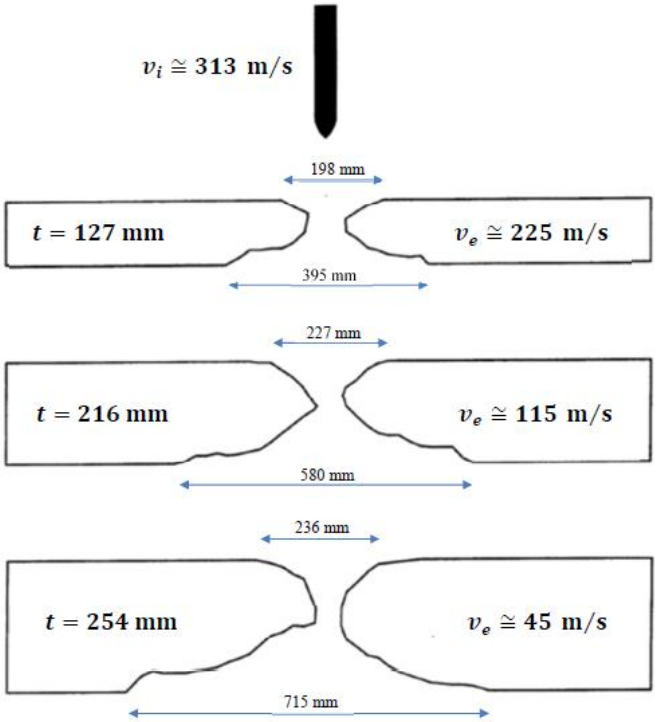
V_{impact}= 11.1 m/sec

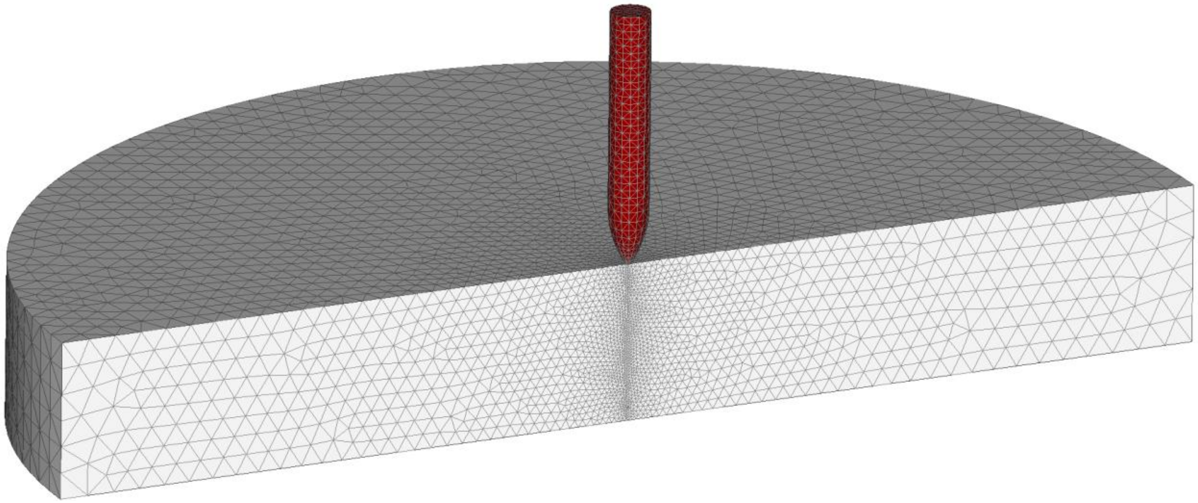


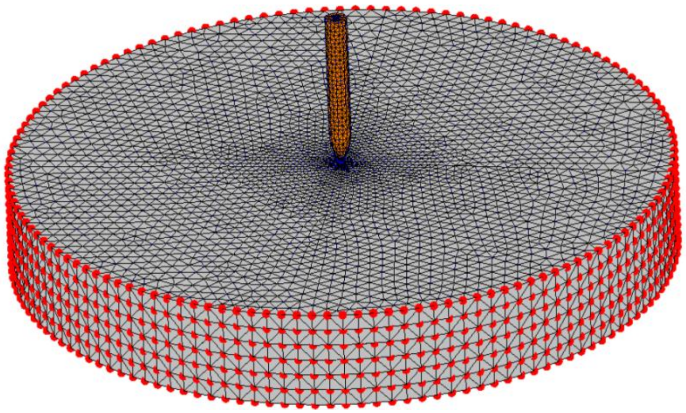
SHB: experiment vs. numerical analysis



Projectile impact with plain concrete slab
(Cargile, 1999)

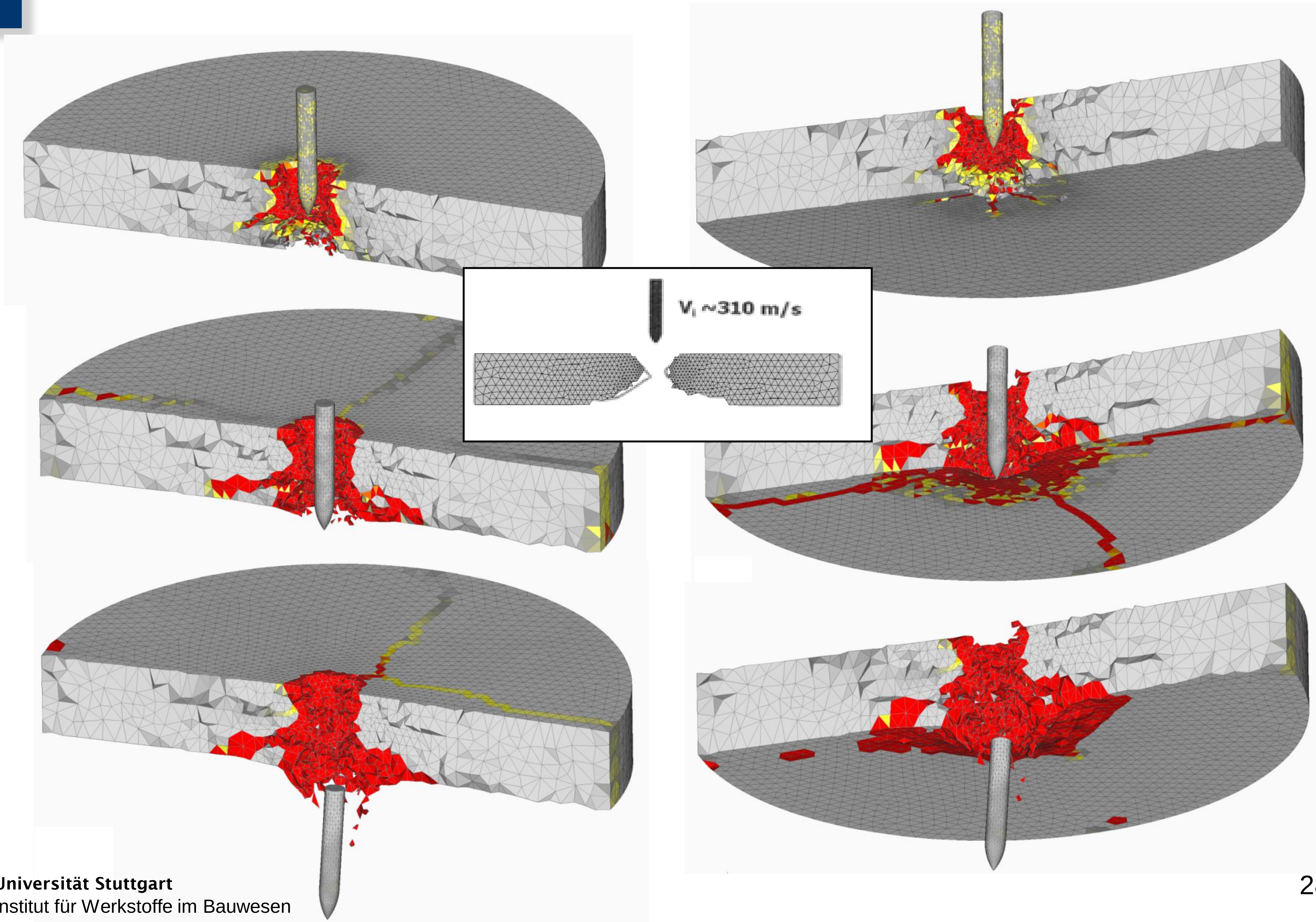




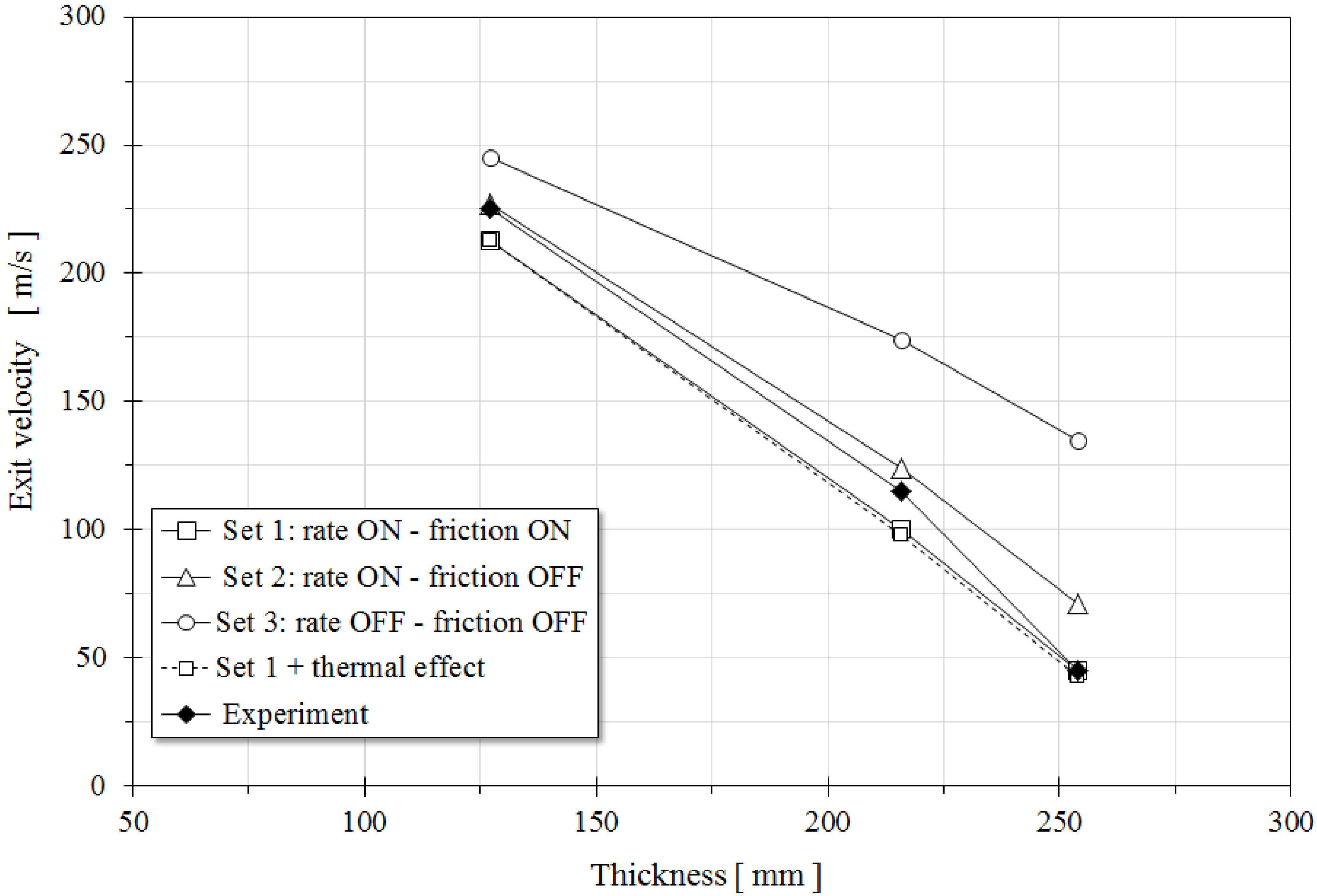


Slab diameter = 1.52 m
Concrete:

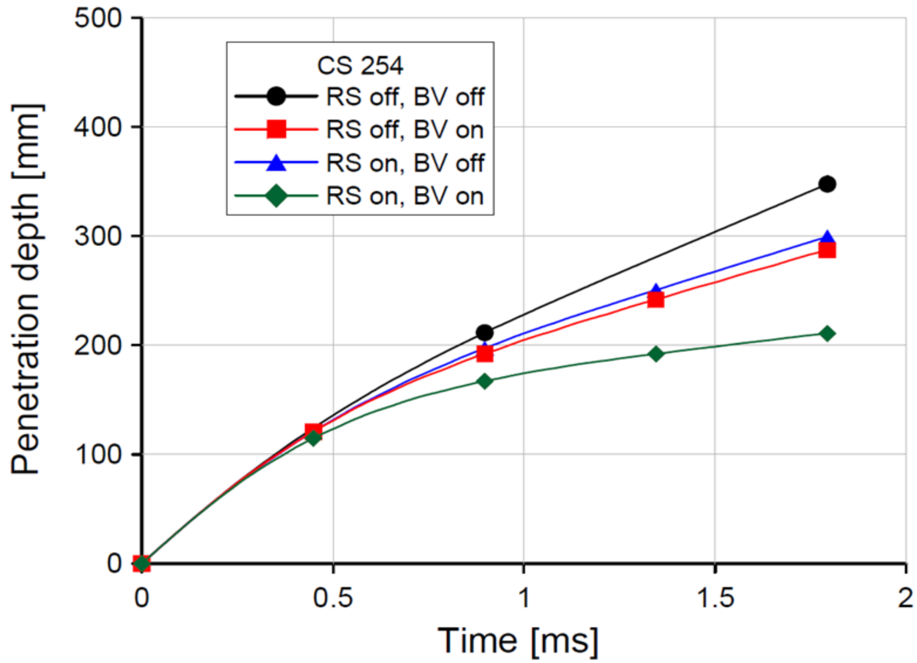
E_c= 28 GPa; ν= 0.18
f_c= 45.5 MPa; f_t= 3.1 MPa; G_F= 90 J/m^2

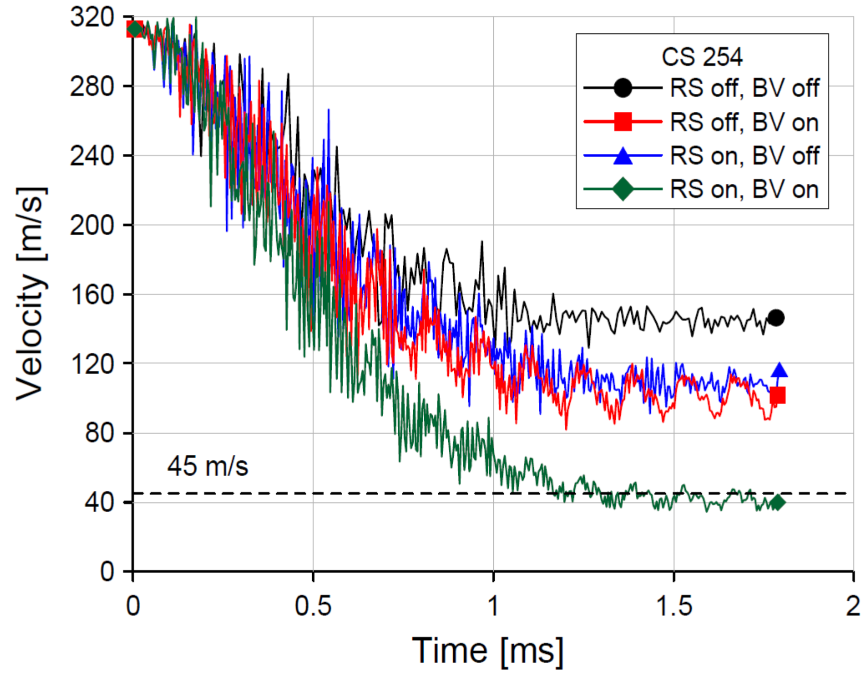

V_i ~310 m/s

Parametric study

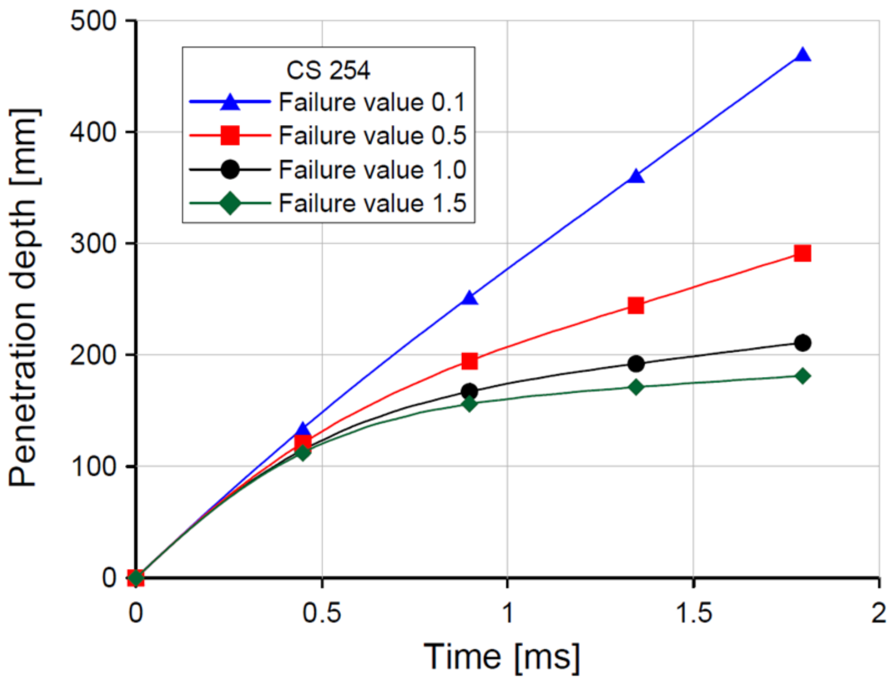


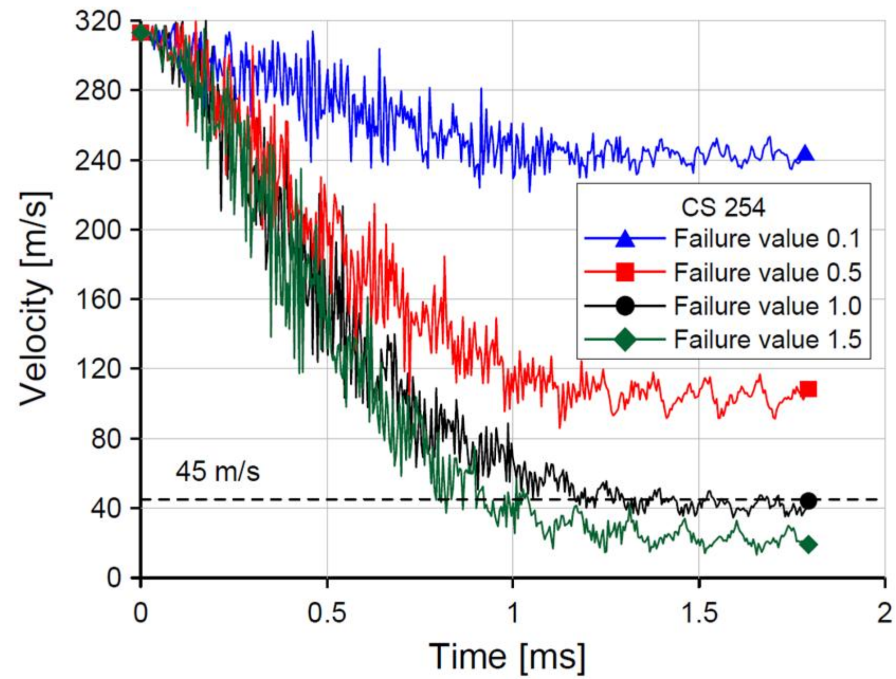
Parametric Study: contribution of bulk viscosity





Parametric Study: influence of deletion criteria





Optimum deletion value (max. principal strain)= 1.0

Summary & Conclusions

- The employed 3D FE code based on the microplane model together with simple finite elements is able to realistically reproduce fracture behavior of different materials at high loading rates.
- Inertia effects are responsible for: (i) rate dependent resistance and toughness, (ii) failure mode and (iii) crack branching.
- There are different kind of inertia effects on different scales: inertia due to micro-cracking, hardening & softening, speed of crack propagation & branching, structural inertia, …
- Consequently, inertia effects should not be a part of the rate sensitive constitutive law, they should come out from dynamic analysis automatically.
- Although steel does not exhibit strain rate sensitivity, due to high non-linear behavior (hardening) its dynamic fracture is strongly influenced by loading rate.