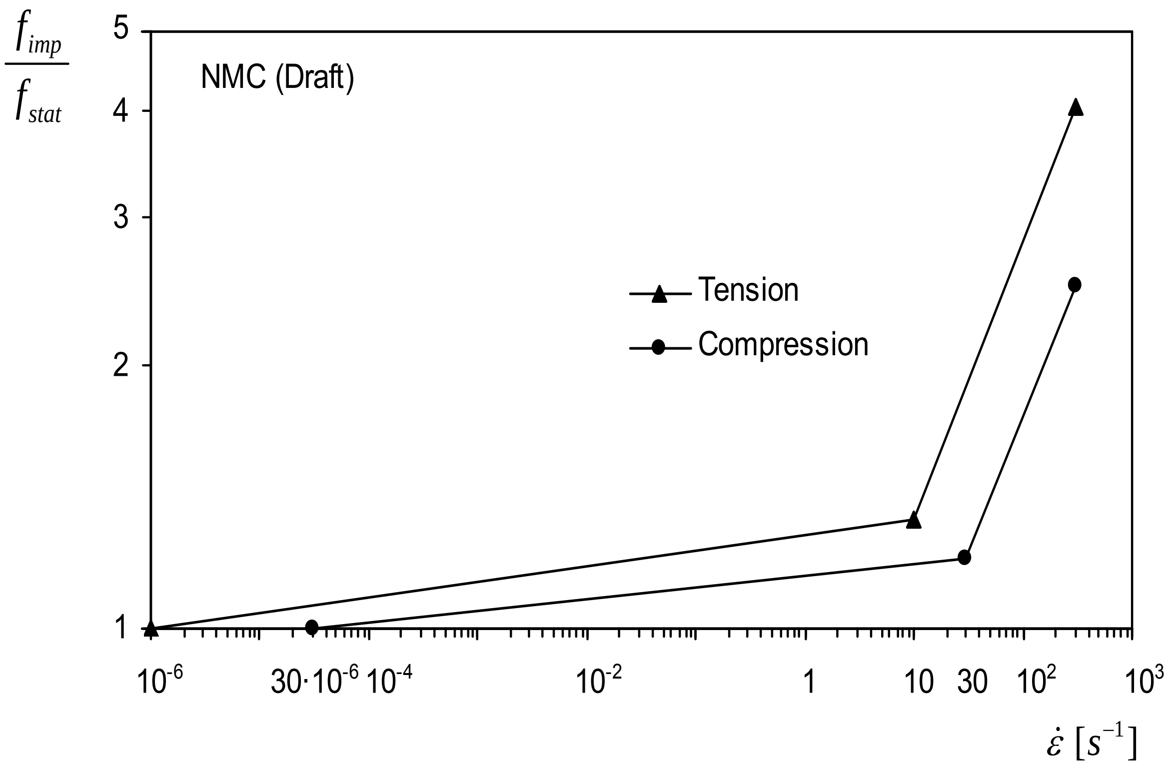
FRACTURE OF CONCRETE AT HIGH LOADING RATES

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: $10^{2} – 10^{6}\ s^{-1}$

Problem: solution of 3D wave propagation equation for nonlinear media !

Introduction

Two different aspects of the problem:

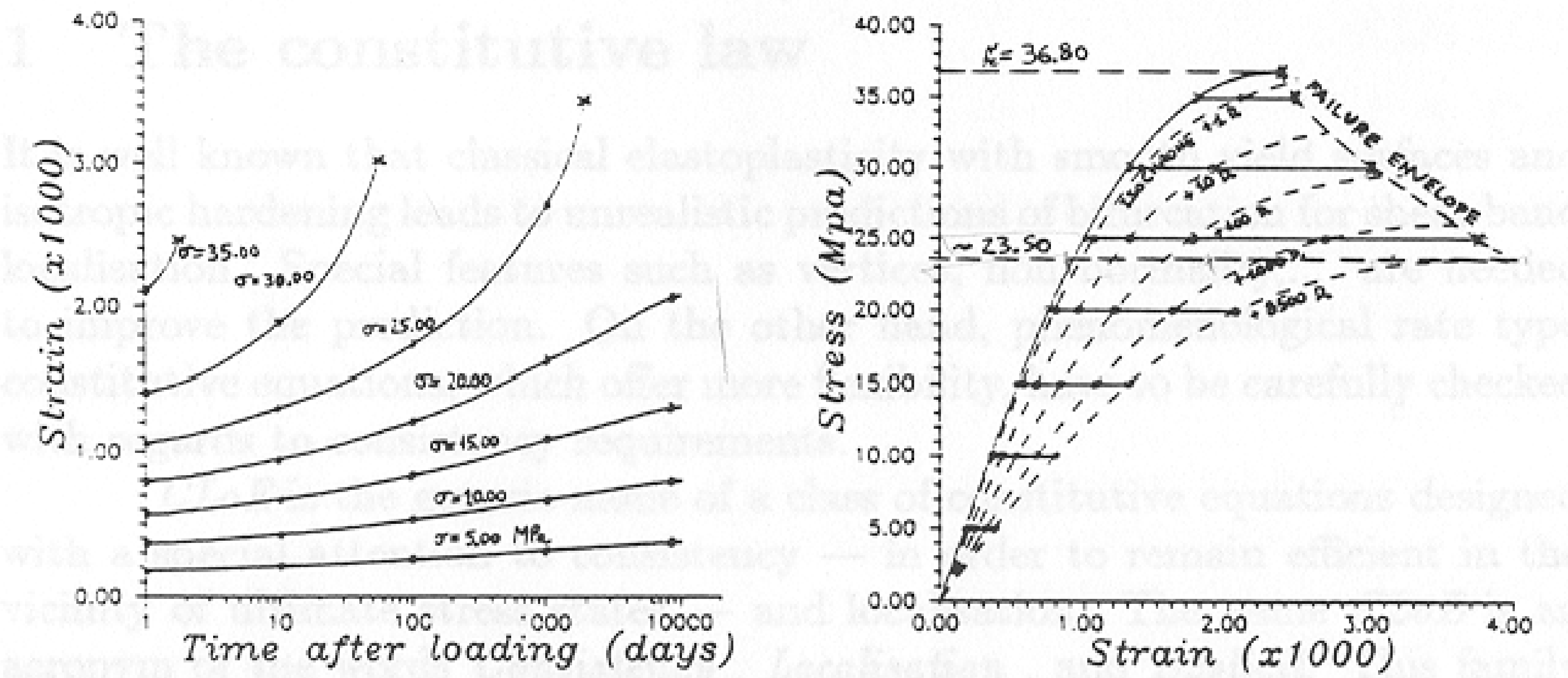
Constitutive law (microstructural phenomena)

- Creep of concrete between cracks - creep-fracture interaction or non (very slow loading: $< 10^{-8}$ s^{-1})
- Rate dependent crack growth & viscosity (moderate loading rates: 10^{-5} – 10^{1} s^{-1})

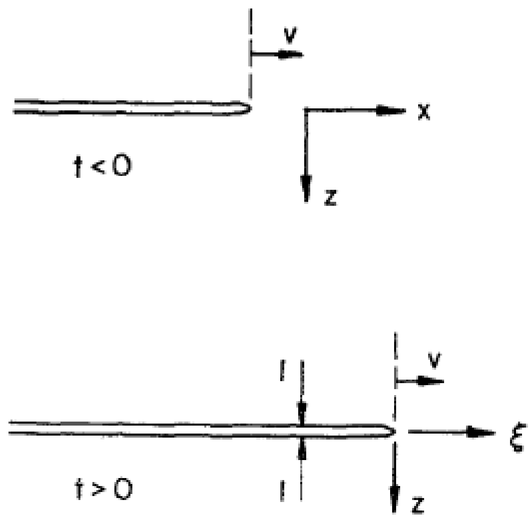
Structural analysis

- Structural inertia (high loading rates – impact: $> 10^{1}$ s^{-1})
  - Single & multi-body dynamics
  - Contact (collision)

Very slow loading: creep of bulk material

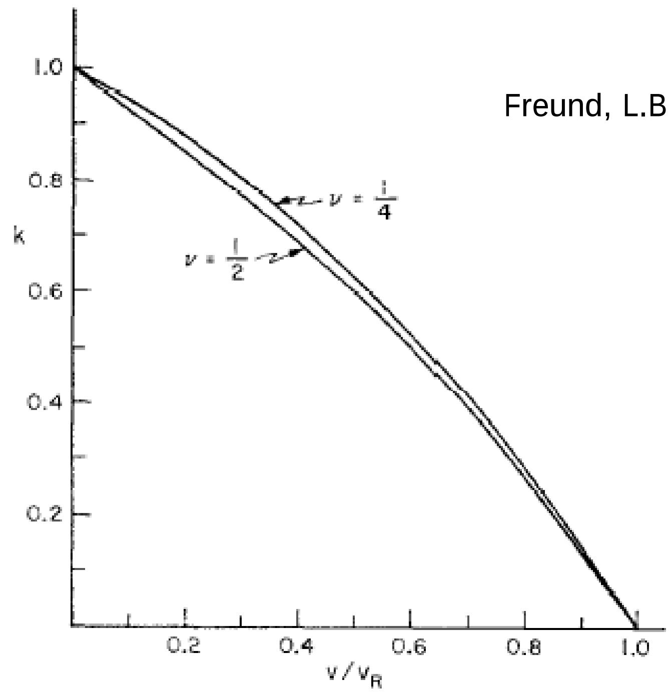


Rate dependent crack growth



$$k = \frac{K_{dynamic}}{K_{static}}$$

Crack propagation in an elastic solid—I.



Freund, L.B. (1971)

The ratio of dynamic to static stress intensity factors vs. dimensionless crack speed for $\nu = 1/4,\ 1/2$.

Rayleigh wave speed :

$$v_R = \xi(\nu)\sqrt{\frac{G}{\rho}} \qquad \textit{for concrete}: \xi(\nu) \approx 0.91$$

General framework for modeling of rate dependent response

- Continuum mechanics
- Irreversible thermodynamics (isothermal conditions)
- Non-linear fracture mechanics
  - smeared crack approach
  - crack band method
- Basic principles of contact mechanics
- Numerical analysis: standard finite elements

3D static & dynamic finite element analysis
(multi-body + contact)

Global equilibrium – Lagrange multipliers for contact problems:

$$\mathbf{M}\ddot{\mathbf{u}}_n + \mathbf{C}\dot{\mathbf{u}}_n + \mathbf{K}\mathbf{u}_n + \mathbf{G}^T_{n+1}\boldsymbol{\lambda}_n = \mathbf{R}_n$$

Impenetrability: $$\mathbf{G}_{n+1}\left\{\mathbf{x}_{n+1}\right\} = \mathbf{0}$$

Strain measure: Green-Lagrange strain tensor

Stress tensor: Co-rotational

FE formulation: Update Lagrange, mesh refinement, re-meshing

Contact: Lagrange multipliers, friction

Solution strategy: Global: explicit FE & Local: implicit contact

Rate dependent crack growth

For continuum with a number of parallel cohesive cracks:

$$\frac{d\varepsilon}{dt} = \frac{\dot{w}}{s_{cr}} + \frac{\dot{\sigma}}{E} \approx \frac{\dot{w}}{s_{cr}}$$

With: ε = average macroscopic strain normal to the crack direction

s_{cr} = spacing of the parallel cracks

E = Young's modulus of bulk material

According to the rate process theory

(Krausz and Krausz, 1988; Bažant et al., 2000)

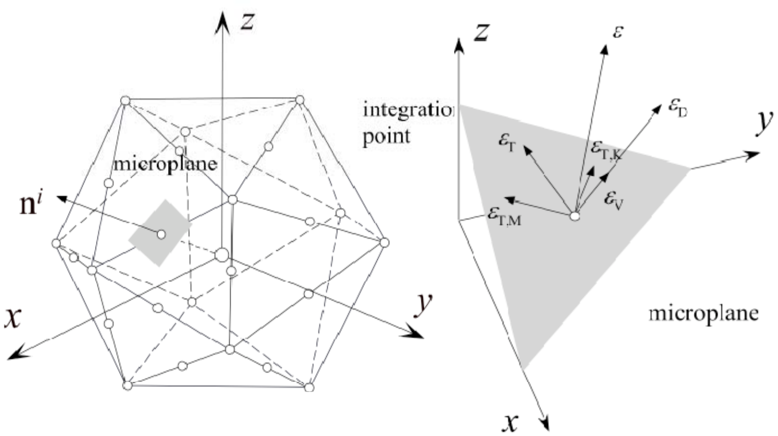
$$\sigma(\varepsilon) = \sigma^0(\varepsilon)\left[1 + C_2 \ln\left(\frac{2\dot{\varepsilon}}{C_1}\right)\right]$$

With: σ^o = rate independent stress; C_1& C_2= constants

Rate sensitive microplane model

Microplane model – relaxed kinematic constraint

(Ožbolt et al., 2001)



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

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

Weak form of equilibrium :

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

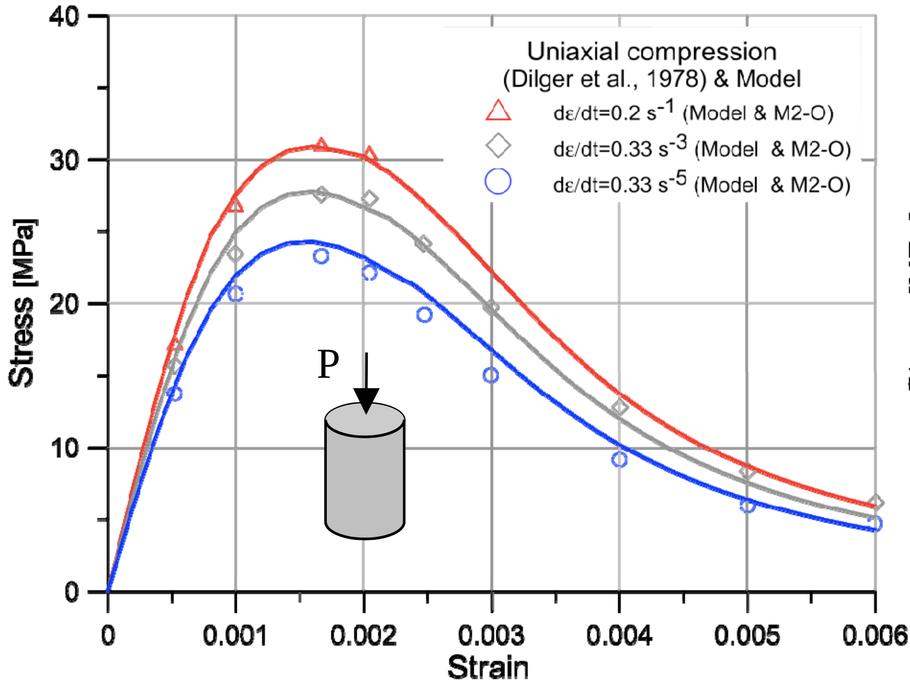
Influence of the strain rate on the microplane stress components

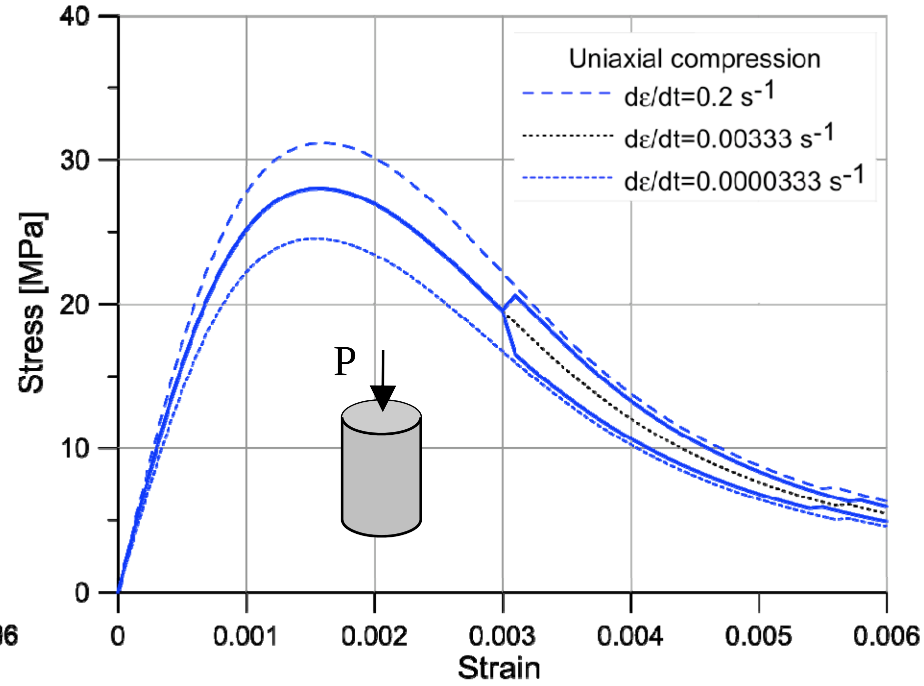
(Bažant et al., 2000; Ožbolt et al., 2005)

$$\sigma_M(\varepsilon_M) = \sigma_M^0(\varepsilon_M)\left[1 + c_2 \ln\left(\frac{2\dot{\gamma}}{c_1}\right)\right] \quad \text{with} \quad \dot{\gamma} = \sqrt{\frac{1}{2}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}} \quad c_1 = \frac{c_0}{s_{cr}}$$

Calibration of the microplane model

constitutive level

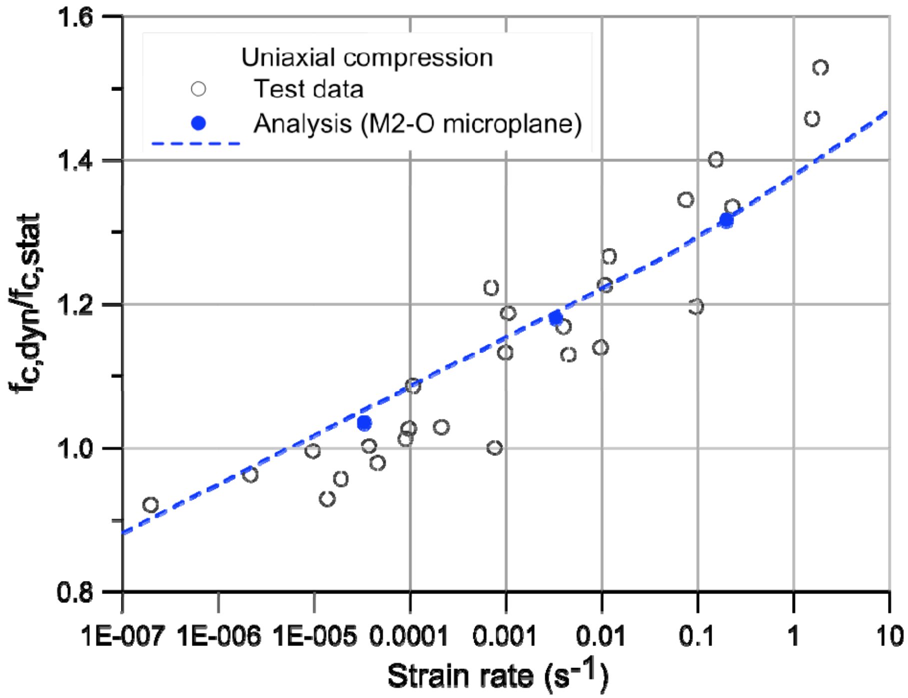


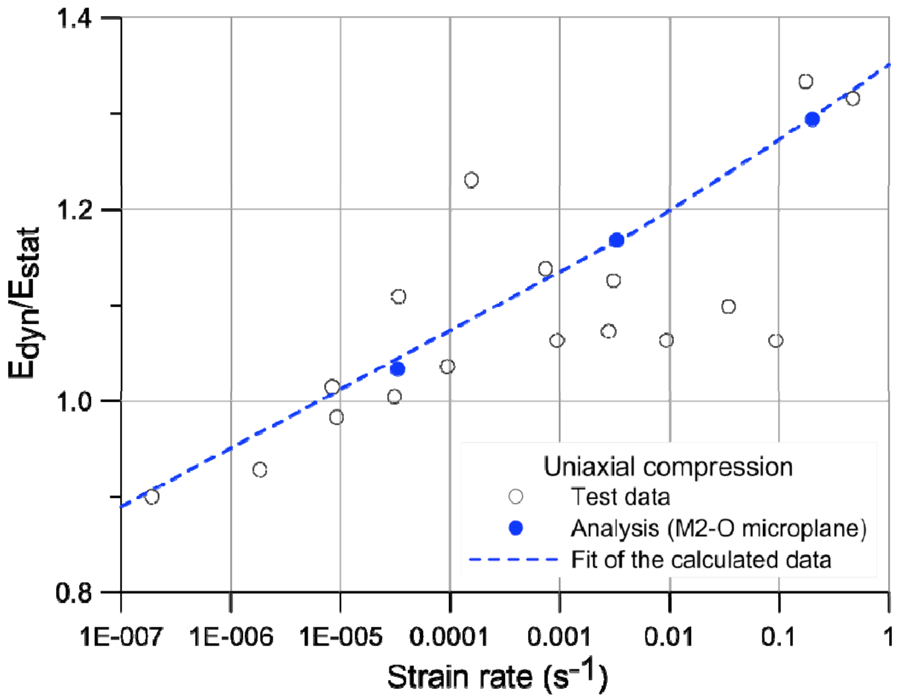


Uniaxial compression (moderate loading rate)

Calibration of the microplane model

constitutive level





Uniaxial compression (moderate loading rate)

3D FE analysis of concrete cylinder

<u>Geometry</u>:

d = 50, 100, 200 mm;   h = 2d

<u>Rate independent material properties :</u>

Young's modulus, E= 30000 MPa

Poisson's ratio, ν= 0.18

f_t= 2.25 MPa

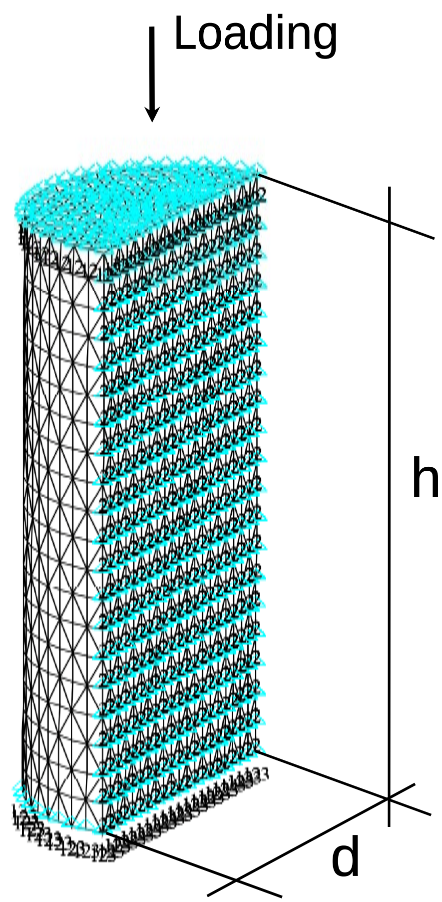
f_c= 23.0 MPa

G_F= 0.08 N/mm

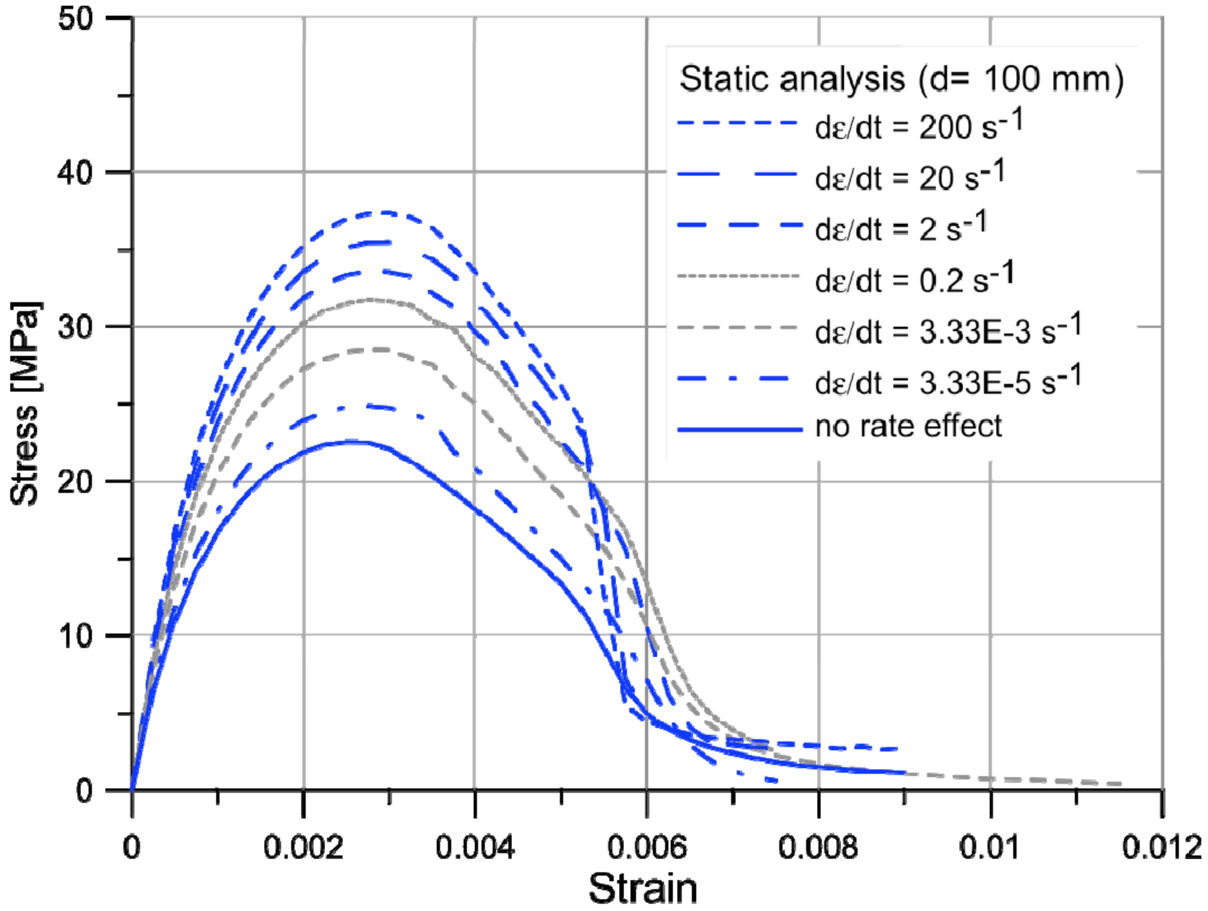
Mass density, ρ= 2.3 T/m^3

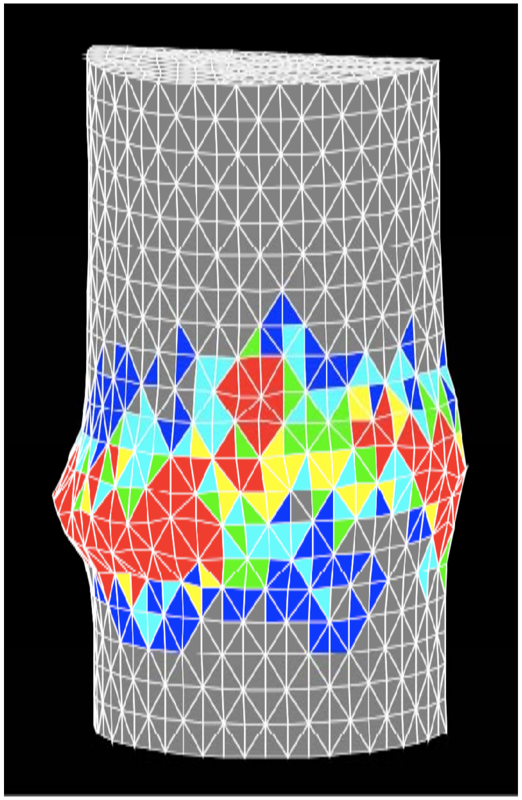
<u>Loading rates dε/dt (displacement control):</u>

0 (no rate effect), 3.33^{-5}, 3.33^{-3}, 0.2, 2, 20, 200 s^{-1}



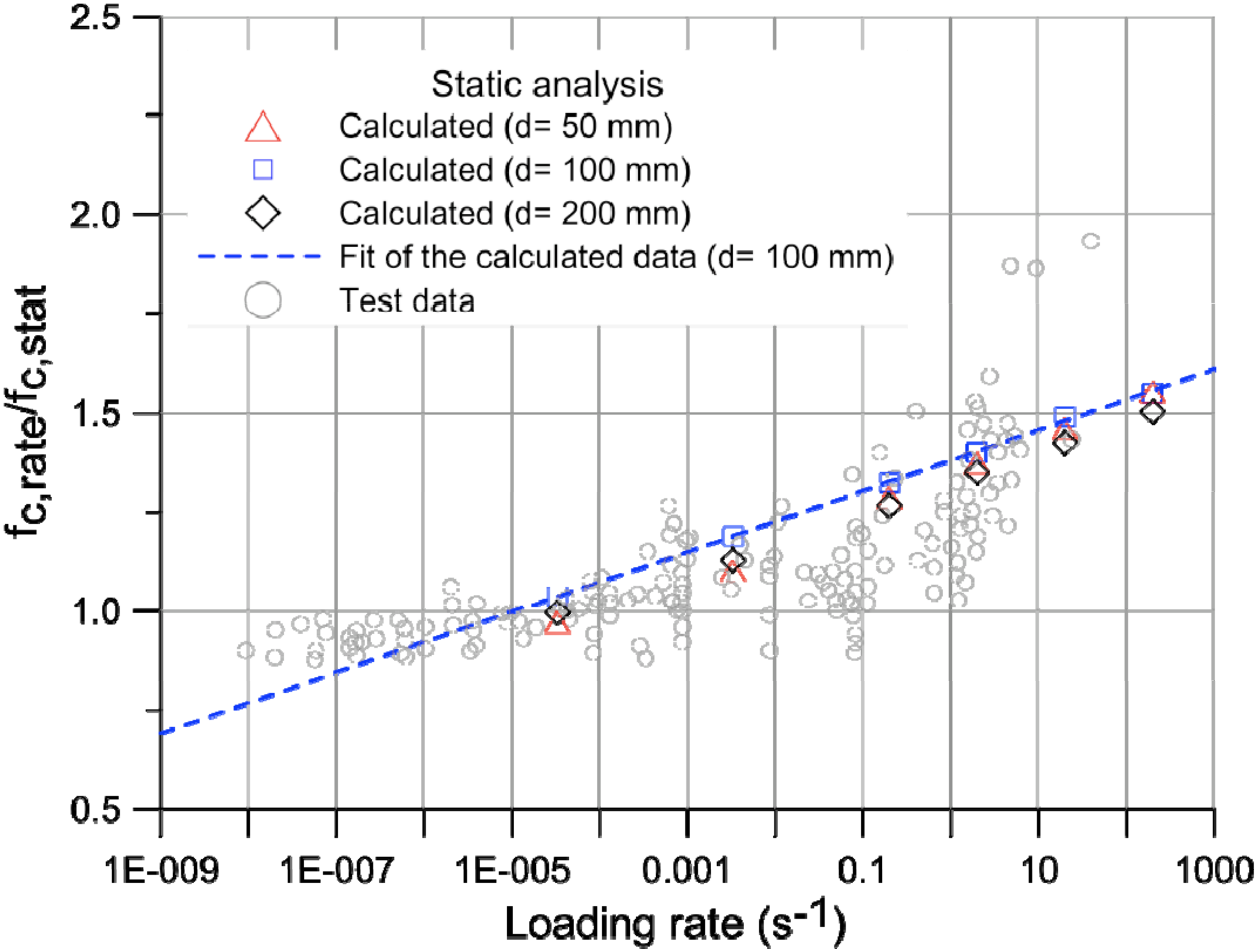
Static analysis





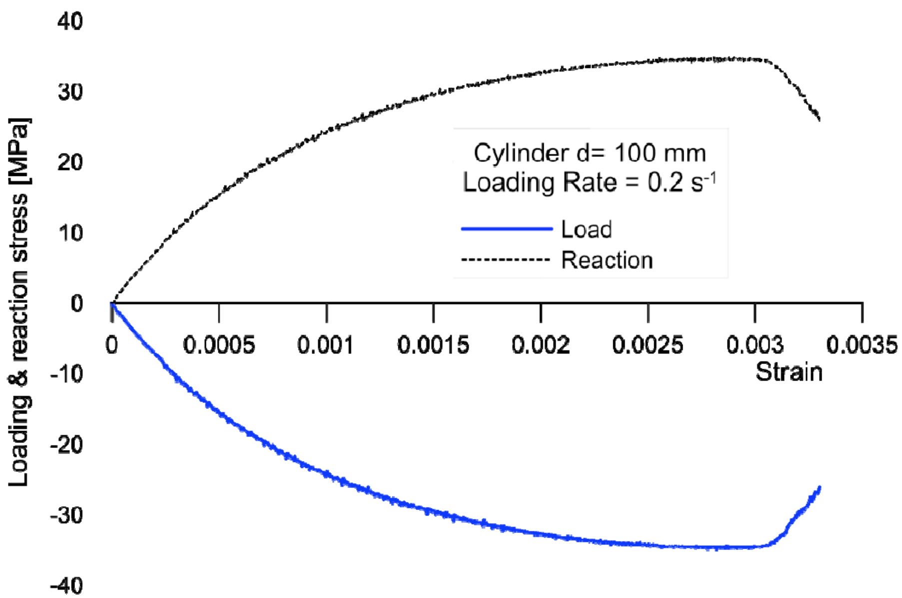
Typical failure mode

Static analysis

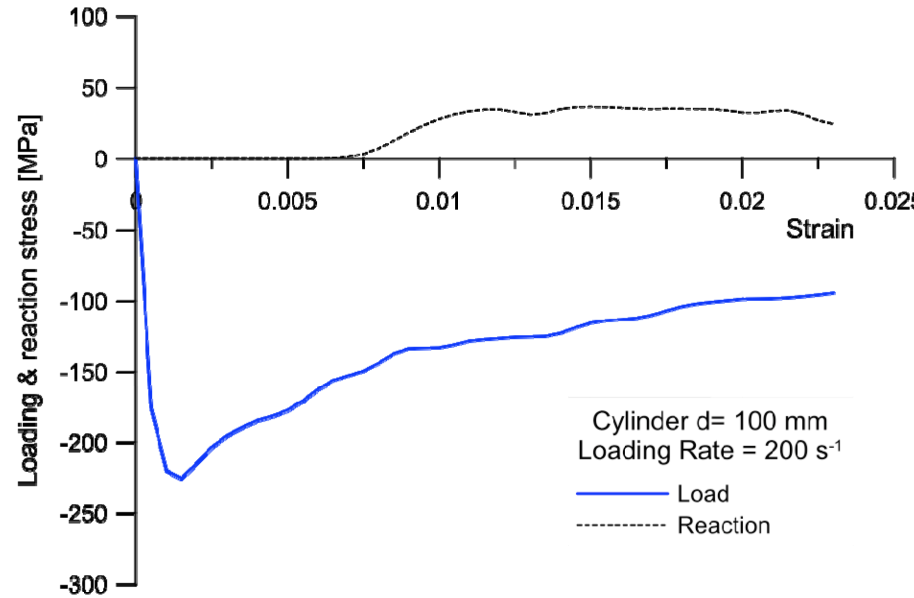


Typical load (reaction) stress-strain curves

static



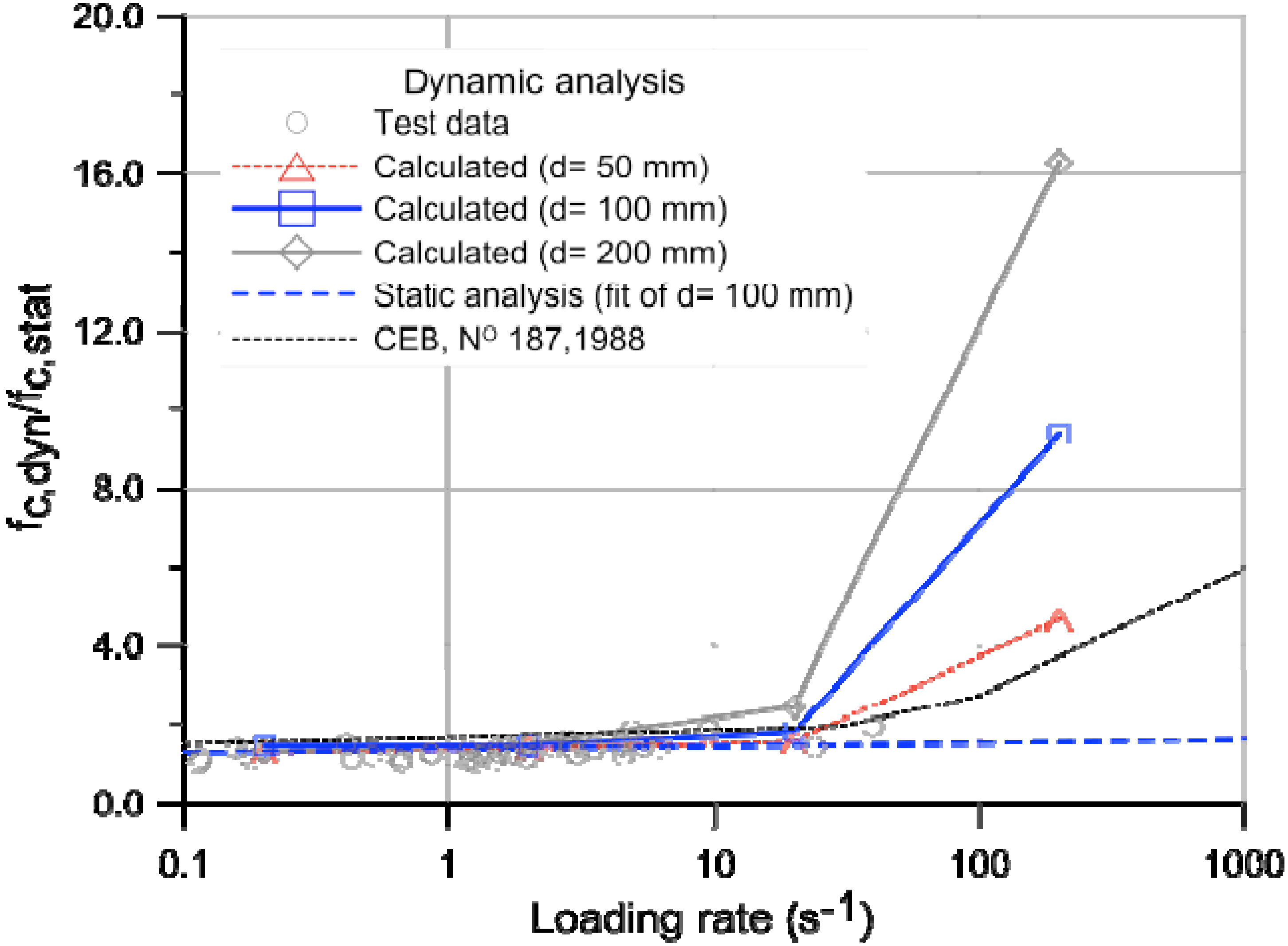
dynamic



d [mm]	0.2 s^{-1}	2 s^{-1}	20 s^{-1}	200 s^{-1}
50	31.6	33.5	37.7	112
100	35.0	35.2	43.3	225
200	32.0	35.8	59.4	392

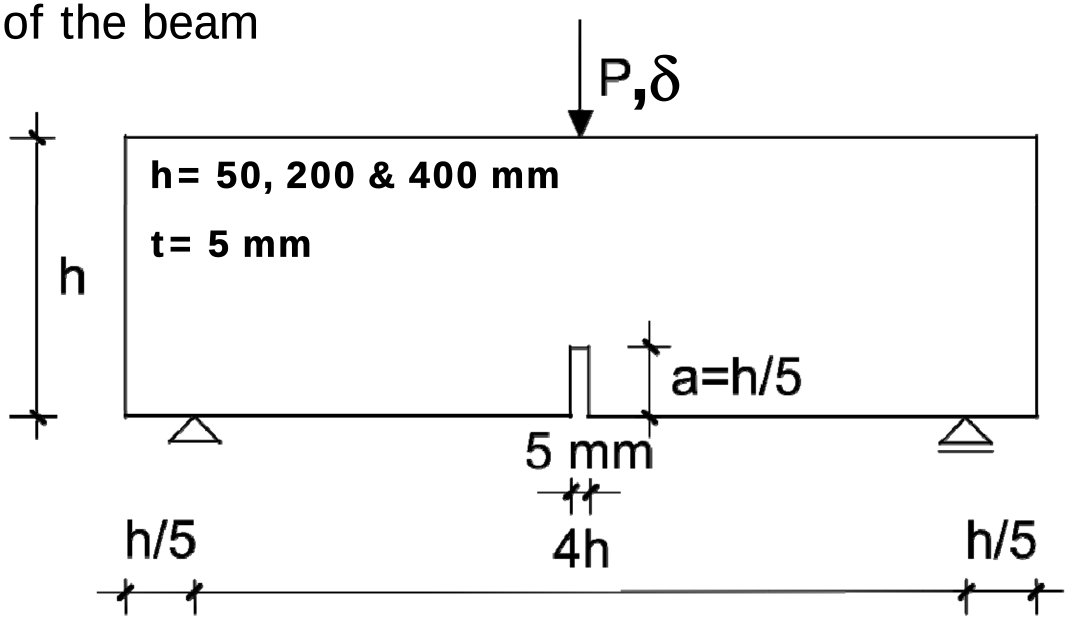
Dynamic analysis - summary of the calculated compressive strengths [MPa]

Strain-rate dependent compressive strength of concrete



Three-point bending – notched beam

Geometry of the beam



Rate independent material properties :

Young's modulus, E_C= 30000 MPa

Poisson's ratio, ν_C= 0.18

f_t= 2.0 MPa; f_c= 30.0 MPa; G_F= 0.10 N/mm

Mass density, ρ_C= 2.3 T/m^3

Loading rates ($\Delta\delta / \Delta t$):

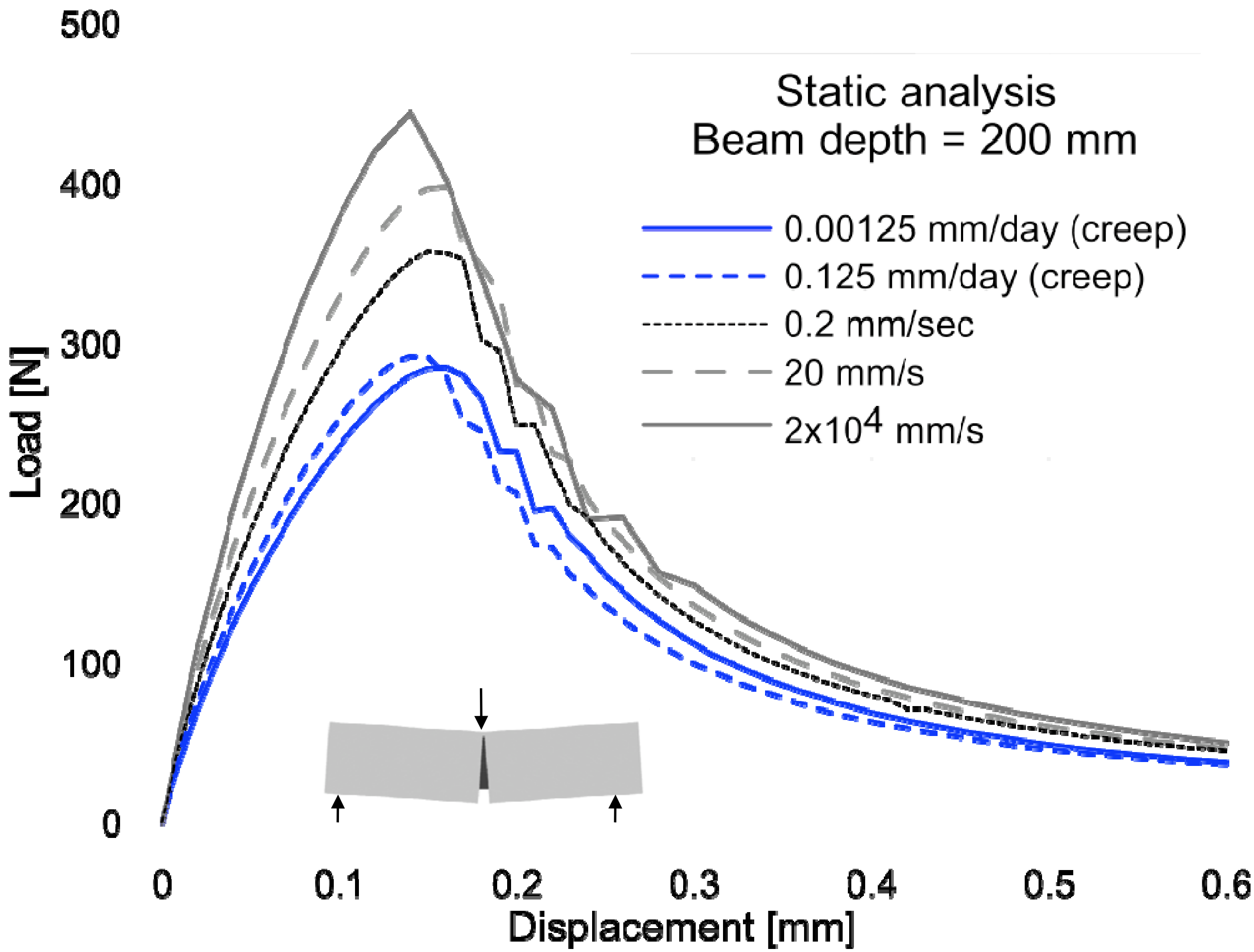
With creep:

1.25×10^{-3}; 1.25×10^{-2}; 1.25×10^{-1} mm/day

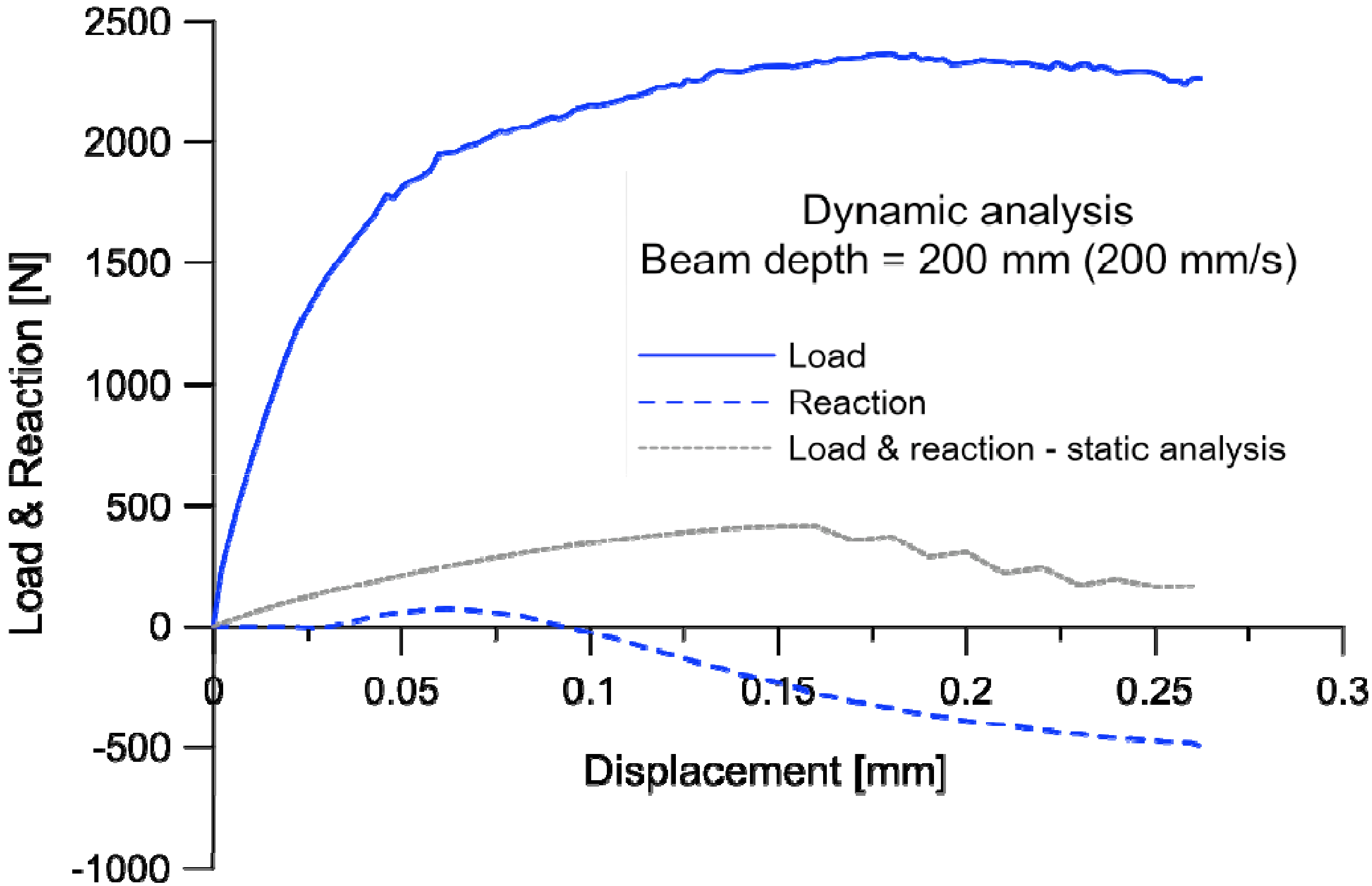
Without creep:

0.20 – 2.0×10^4 mm/sec

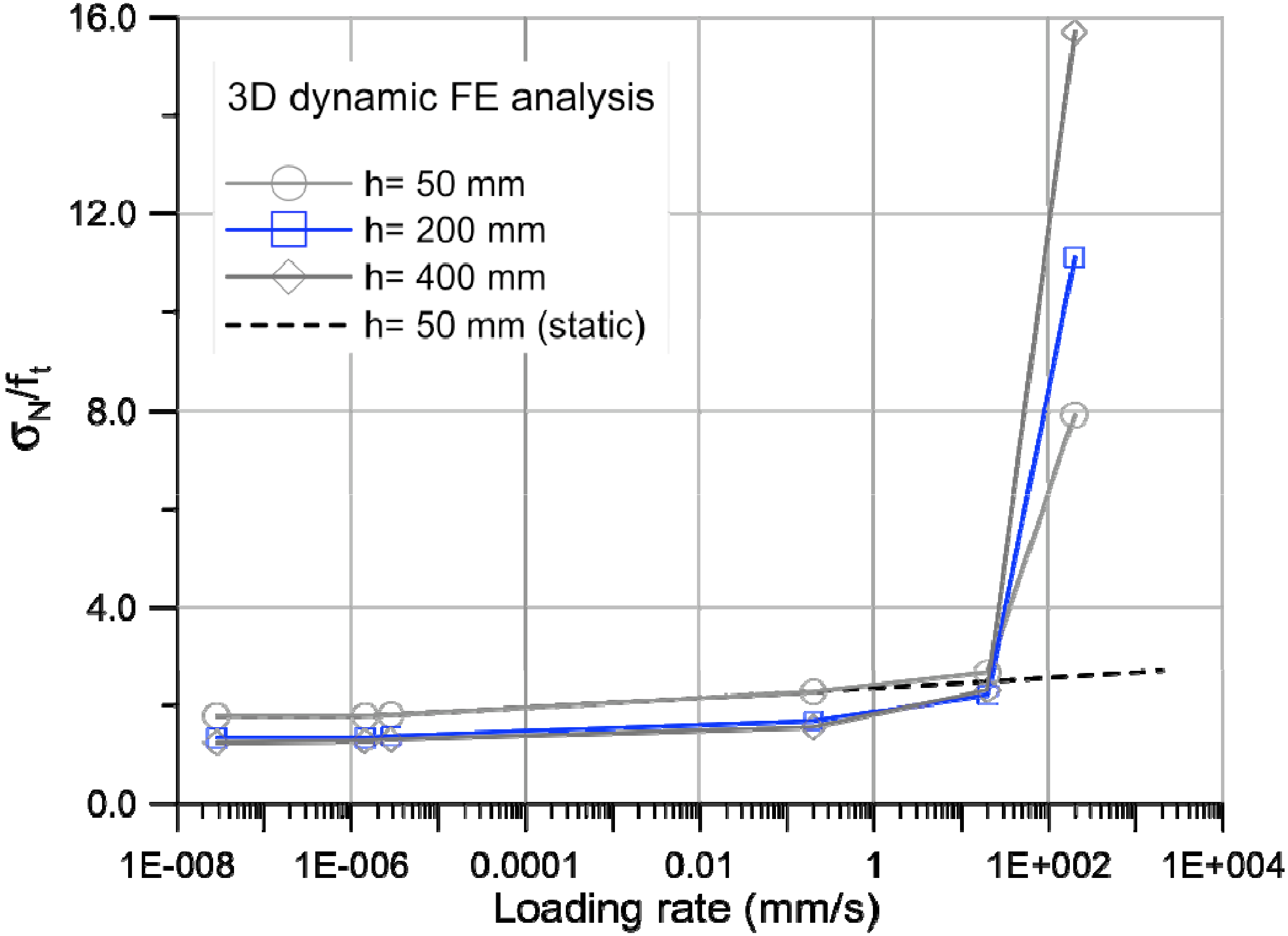
Three-point bending



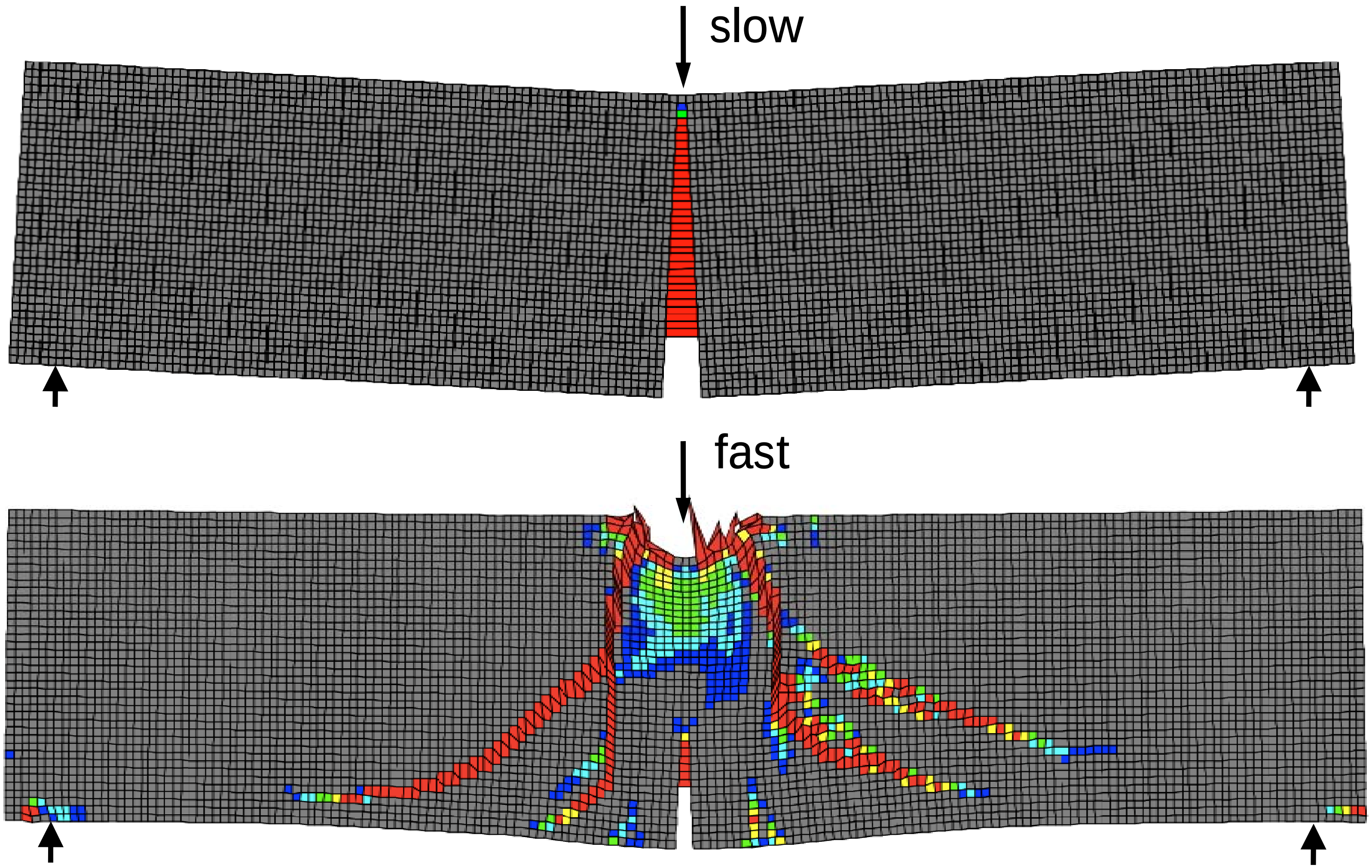
Three-point bending



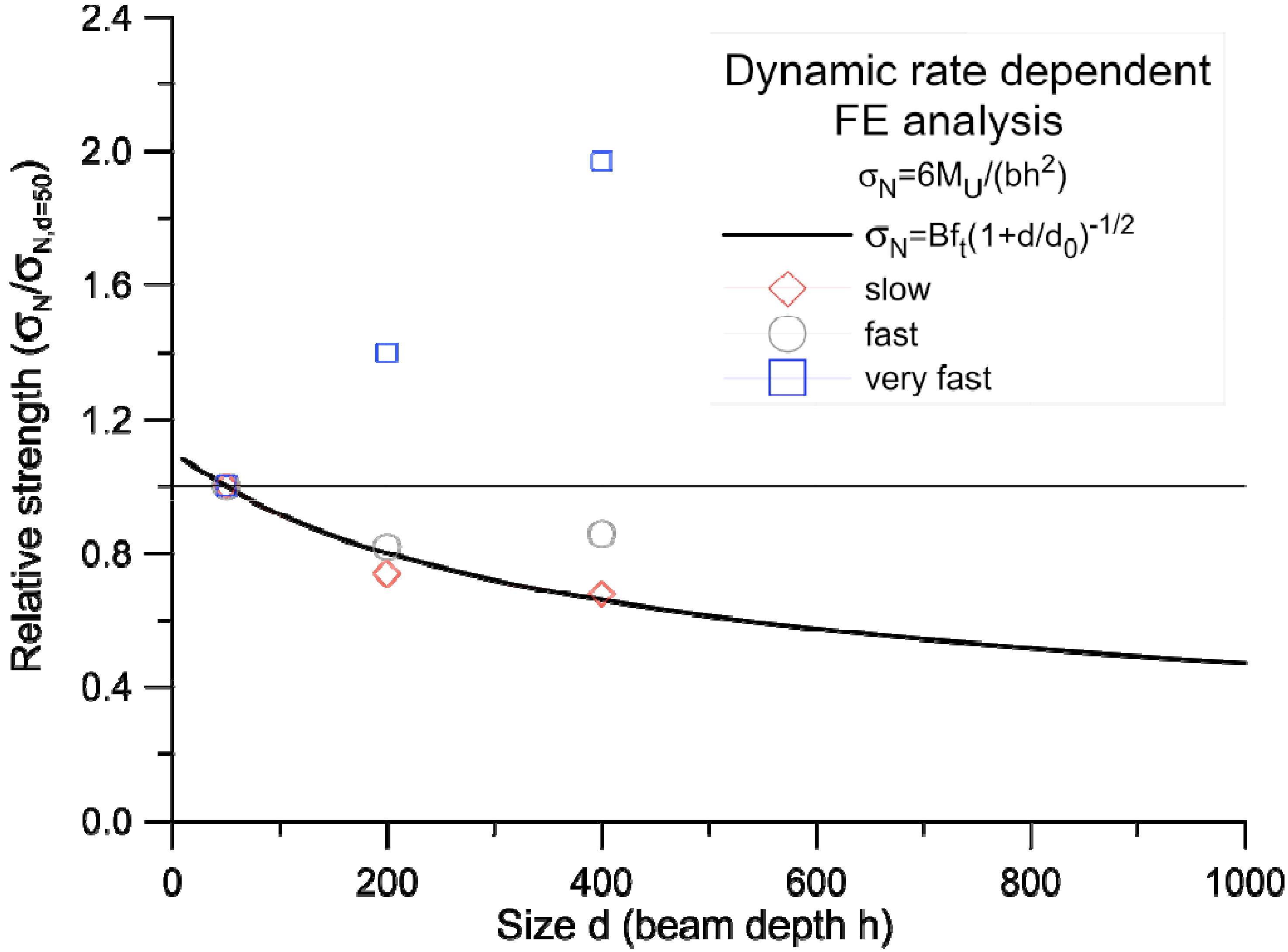
Three-point bending



Three-point bending



Three-point bending



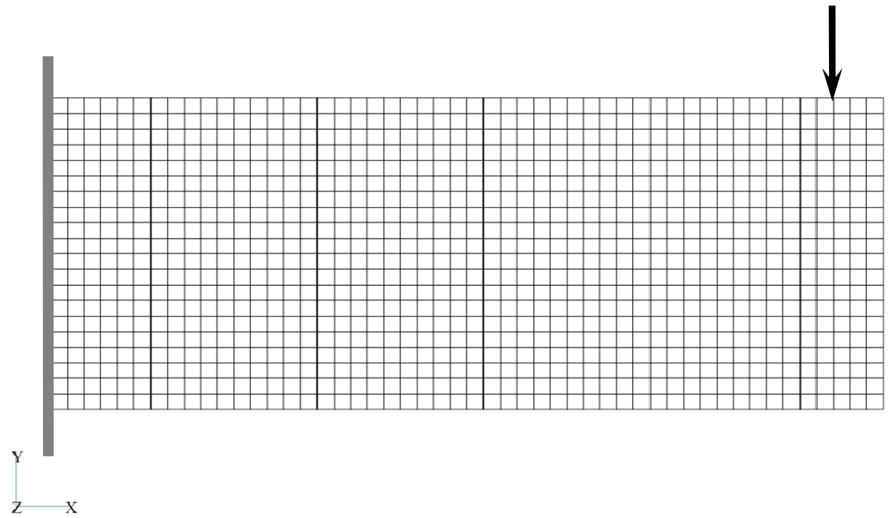
3D FE analysis of cantilever beam

Geometry

L = 500 mm

H = 200 mm

D = 10 mm

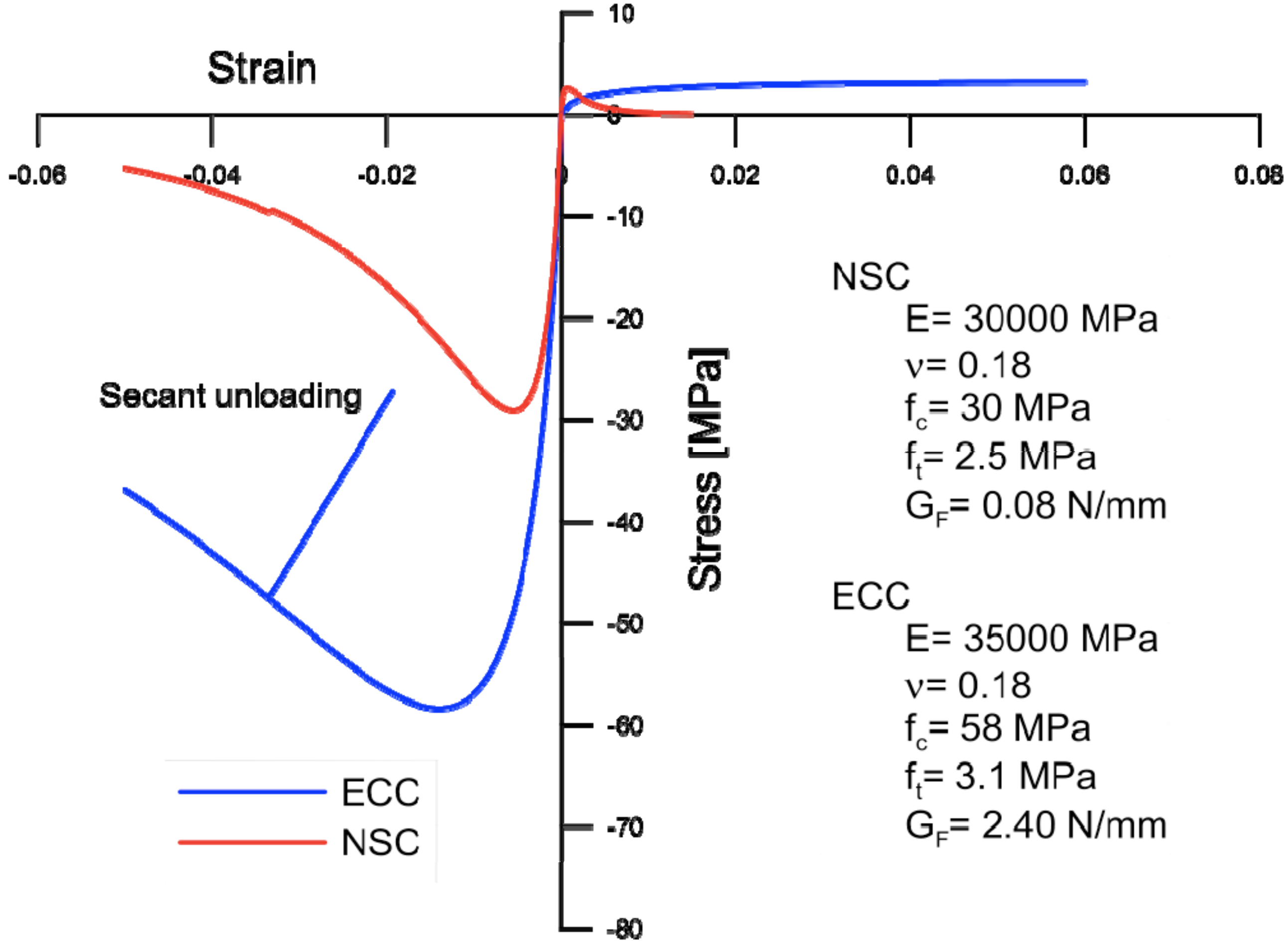


Loading rates (displacement control):

0 (no rate effect), 2, 20, 200, 2 10^3, 2 10^4 mms^{-1}

Material properties

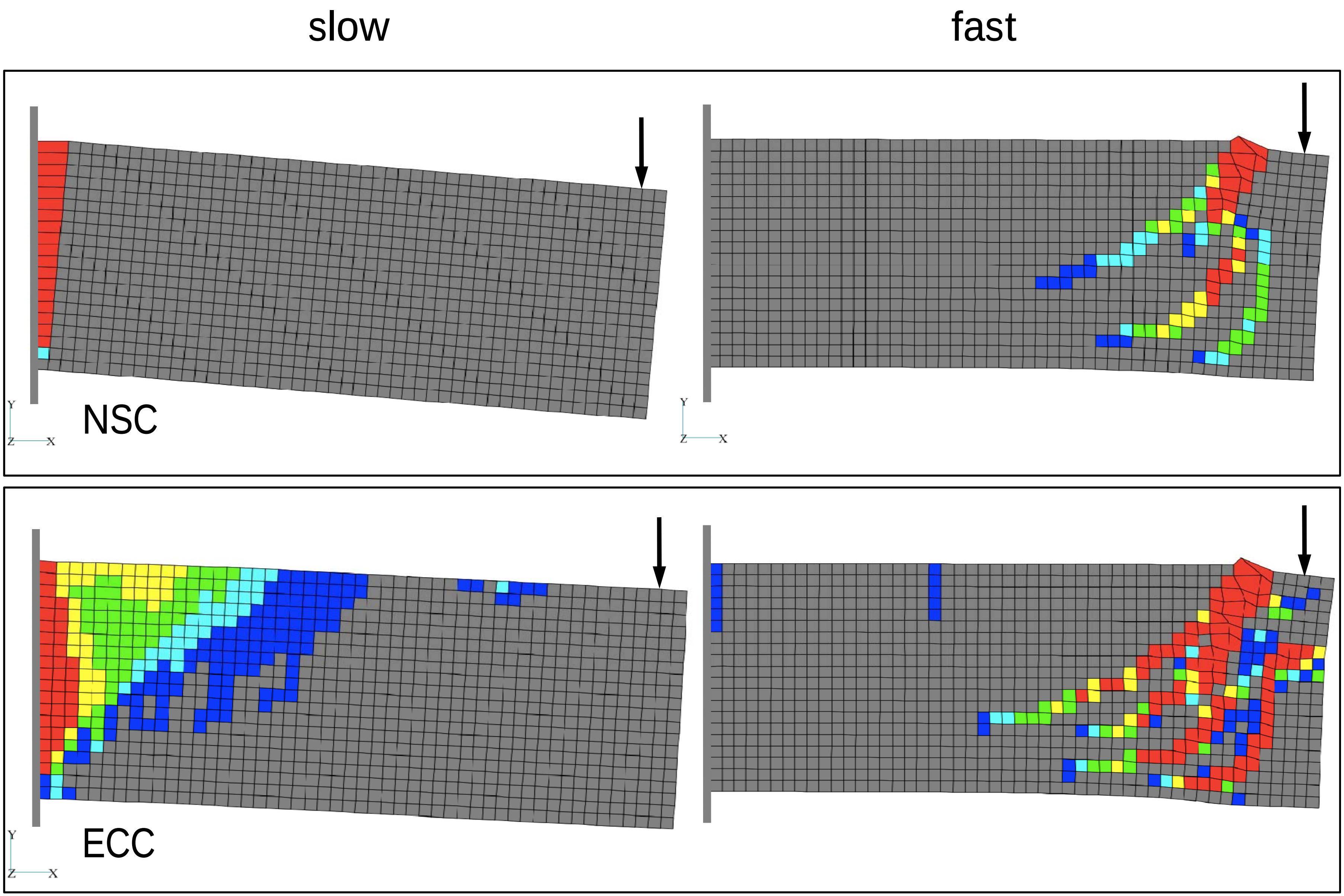
Normal strength concrete (NSC) & high strength fiber reinforced concrete (ECC)



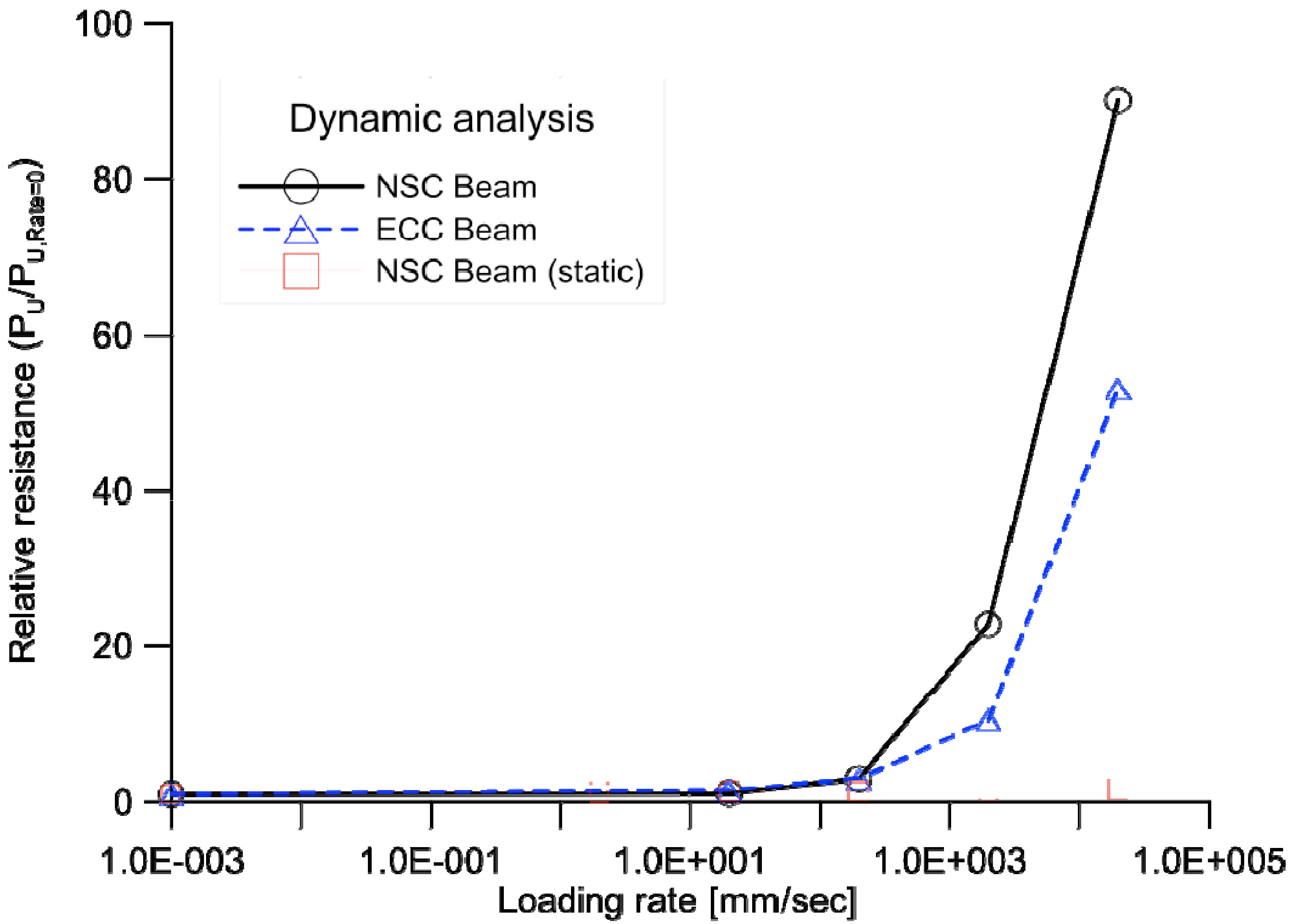
NSC
- E= 30000 MPa
- ν= 0.18
- f_c= 30 MPa
- f_t= 2.5 MPa
- G_F= 0.08 N/mm

ECC
- E= 35000 MPa
- ν= 0.18
- f_c= 58 MPa
- f_t= 3.1 MPa
- G_F= 2.40 N/mm

Rate dependent failure modes

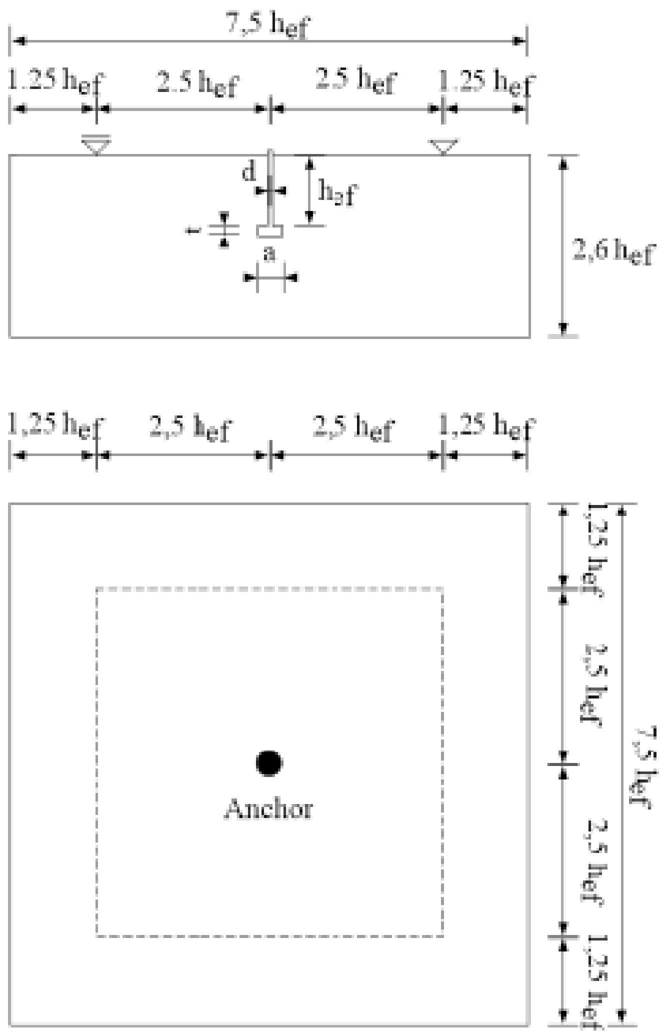


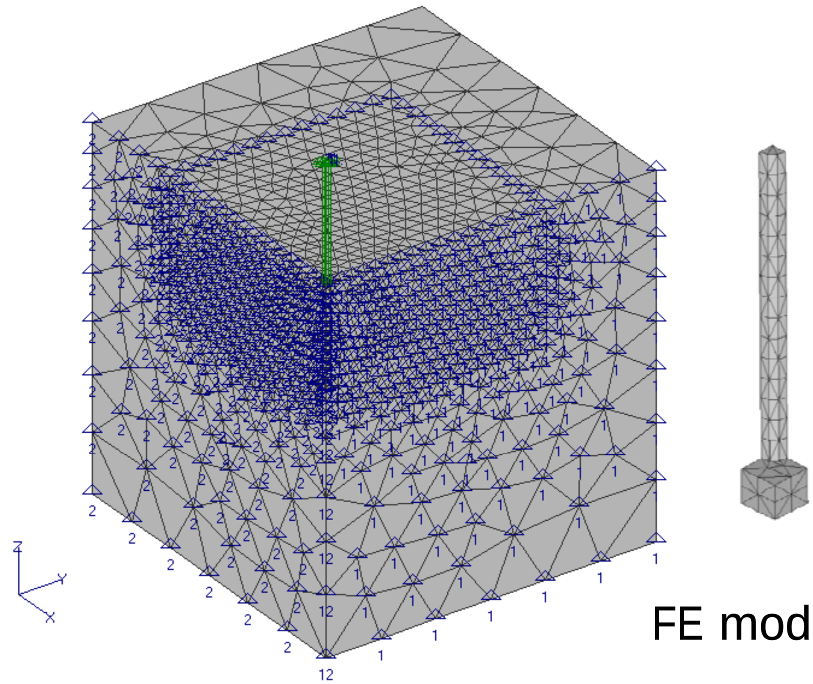
Cantilever beam (NSC & ECC)



Pull-out of the headed stud anchor from a concrete block

Geometry





FE model

h_{ef} [mm]	*d*	*t*	*a*
150	16	17	40
889	95.3	102	216
1500	160.8	169	311

Rate independent material properties :

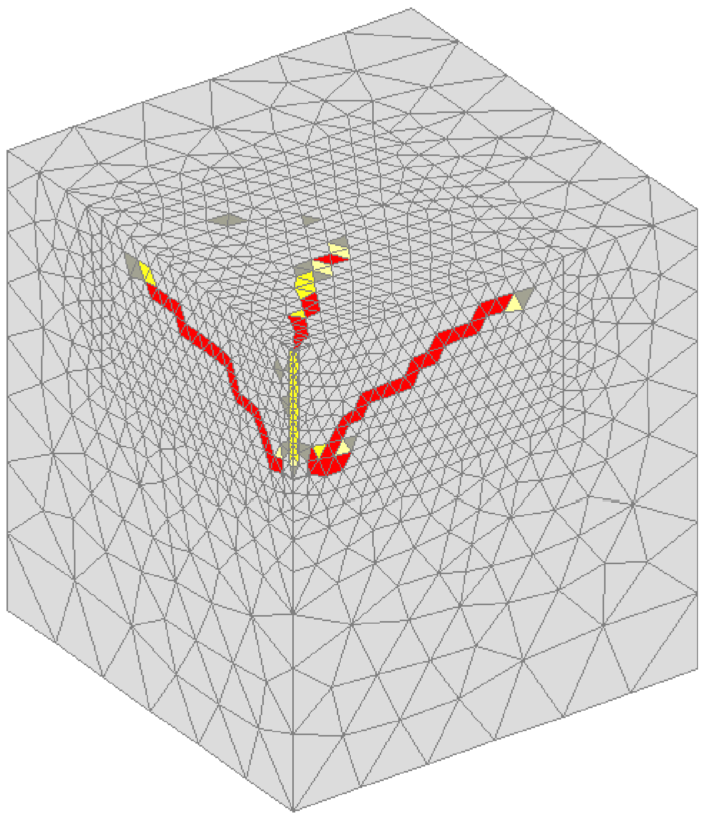
Young‘s modulus, E_C= 30000 MPa; E_S= 200000 MPa

Poisson‘s ratio, ν_C= 0.18; ν_S= 0.33

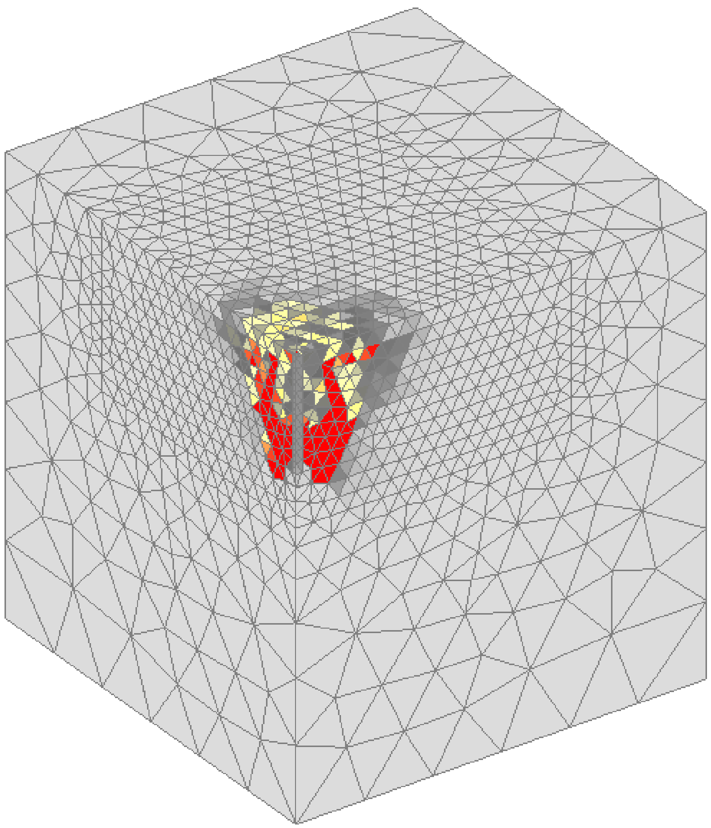
f_t= 2.25 MPa; f_c= 23.0 MPa; G_F= 0.08 N/mm
Mass density, ρ_C= 2.3 T/m^3; ρ_S= 7.4 T/m^3

Steel – linear elastic

Rate dependent failure modes (h_{ef}= 150 mm)

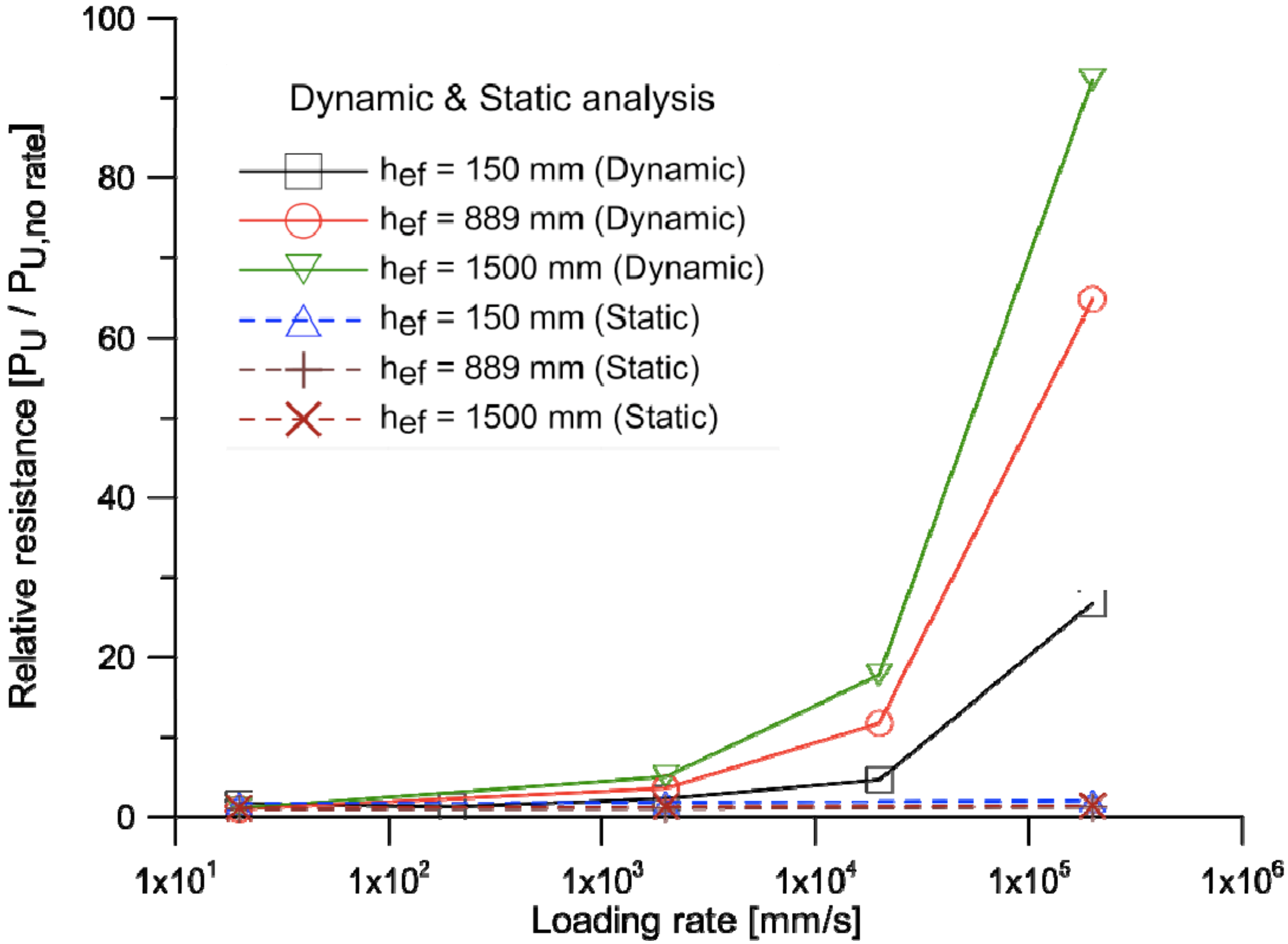


Moderately fast loading (200 mms^{-1})

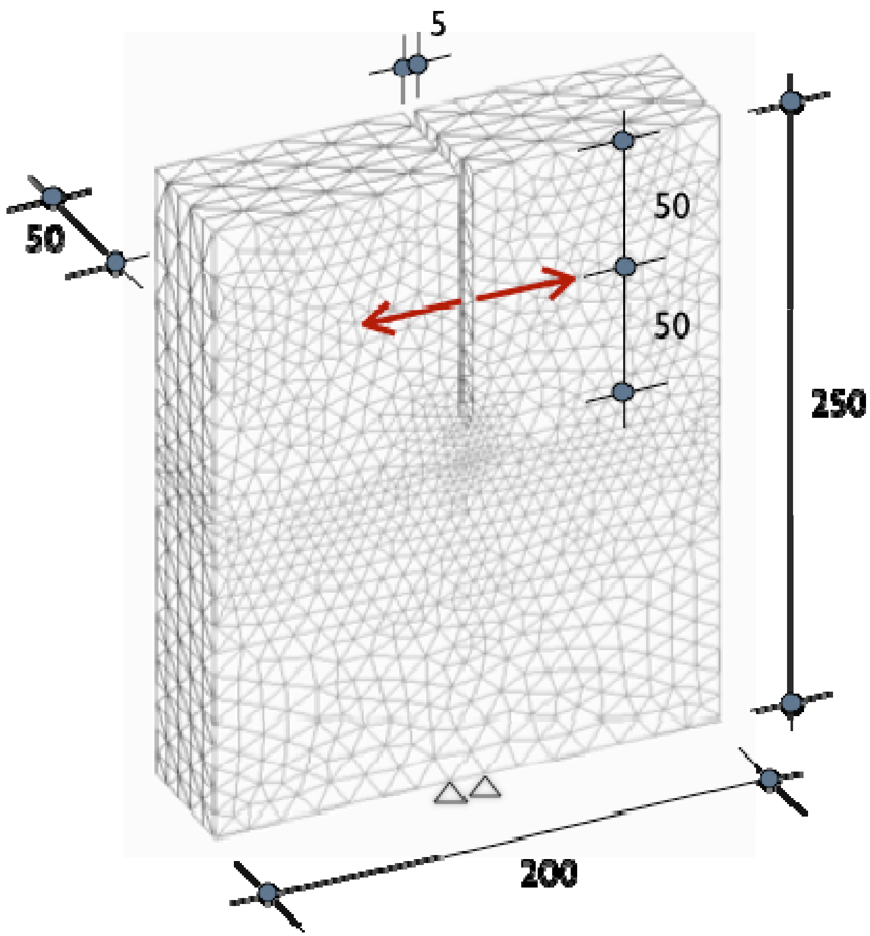


Very fast loading (2 10^5 mms^{-1})

Pull-out of the headed stud anchor from a concrete block



Compact tension specimen



Rate independent material properties :

Young‘s modulus, E_C= 30000 MPa

Poisson‘s ratio, ν_C= 0.18

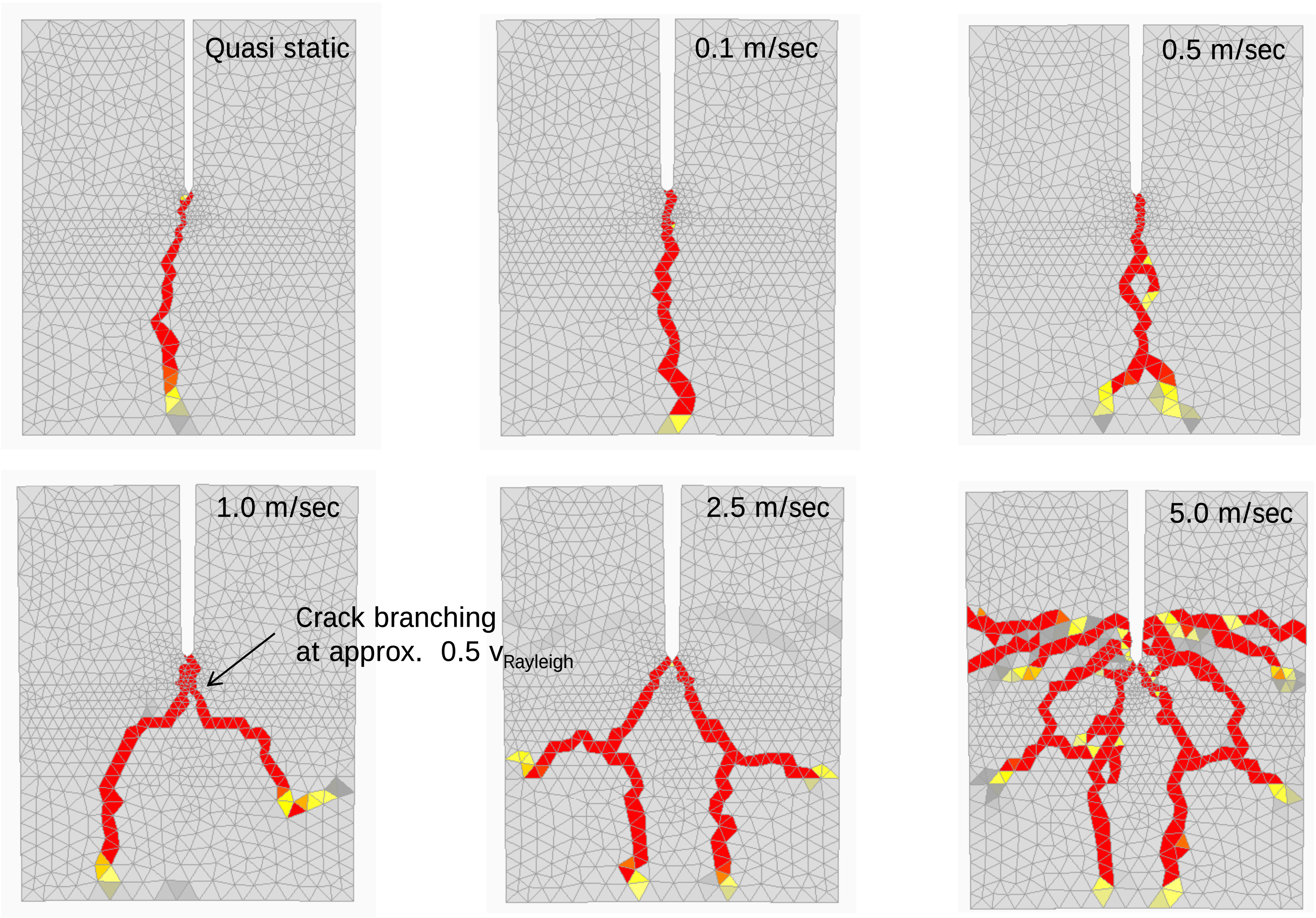
f_t= 3.5 MPa; f_c= 40.0 MPa; G_F= 0.08 N/mm

Mass density, ρ_C= 2.4 T/m^3

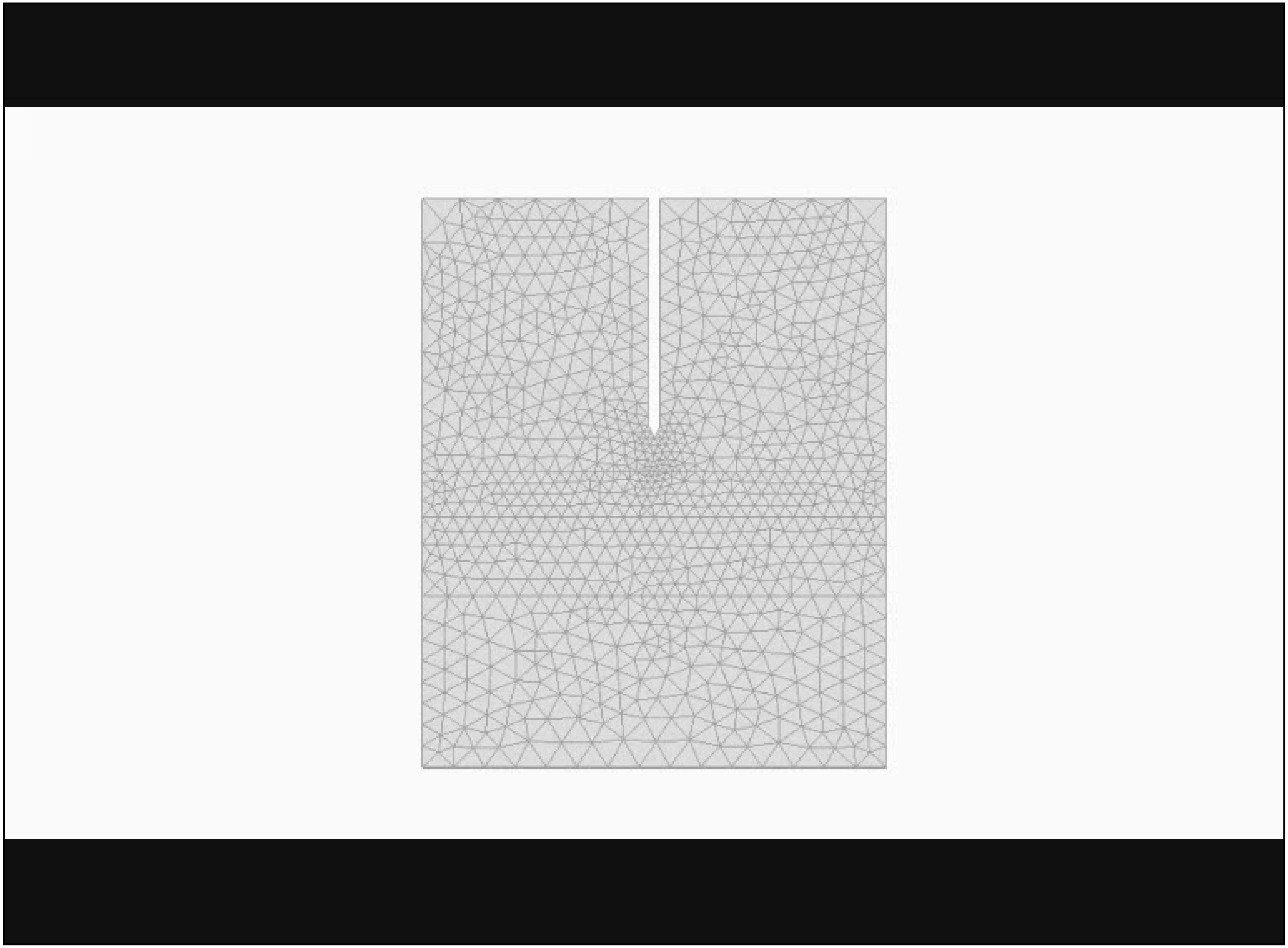
Loading rates (Δ/Δt):

Quasi static, 100, 1000 & 1000 mm/sec

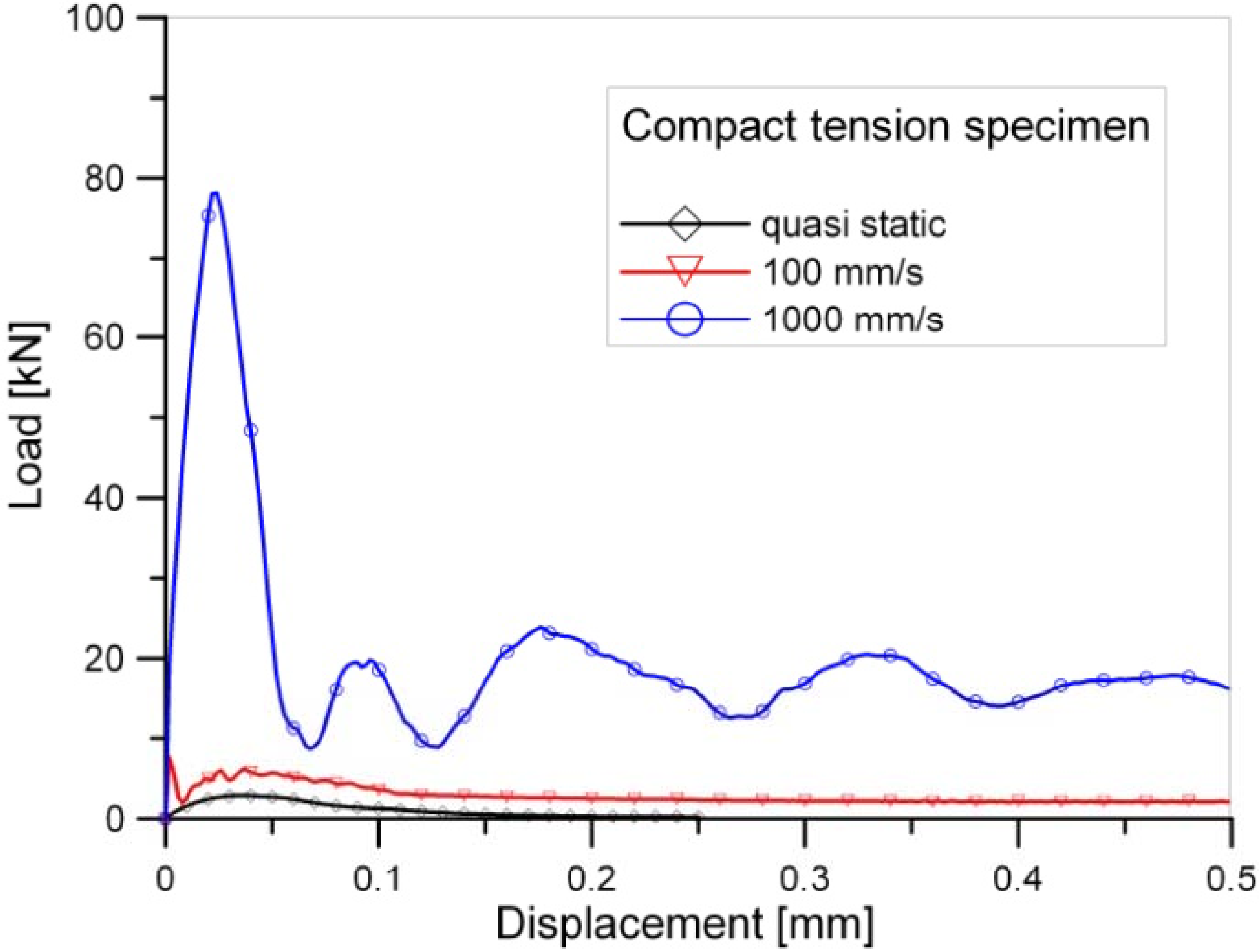
Compact tension specimen



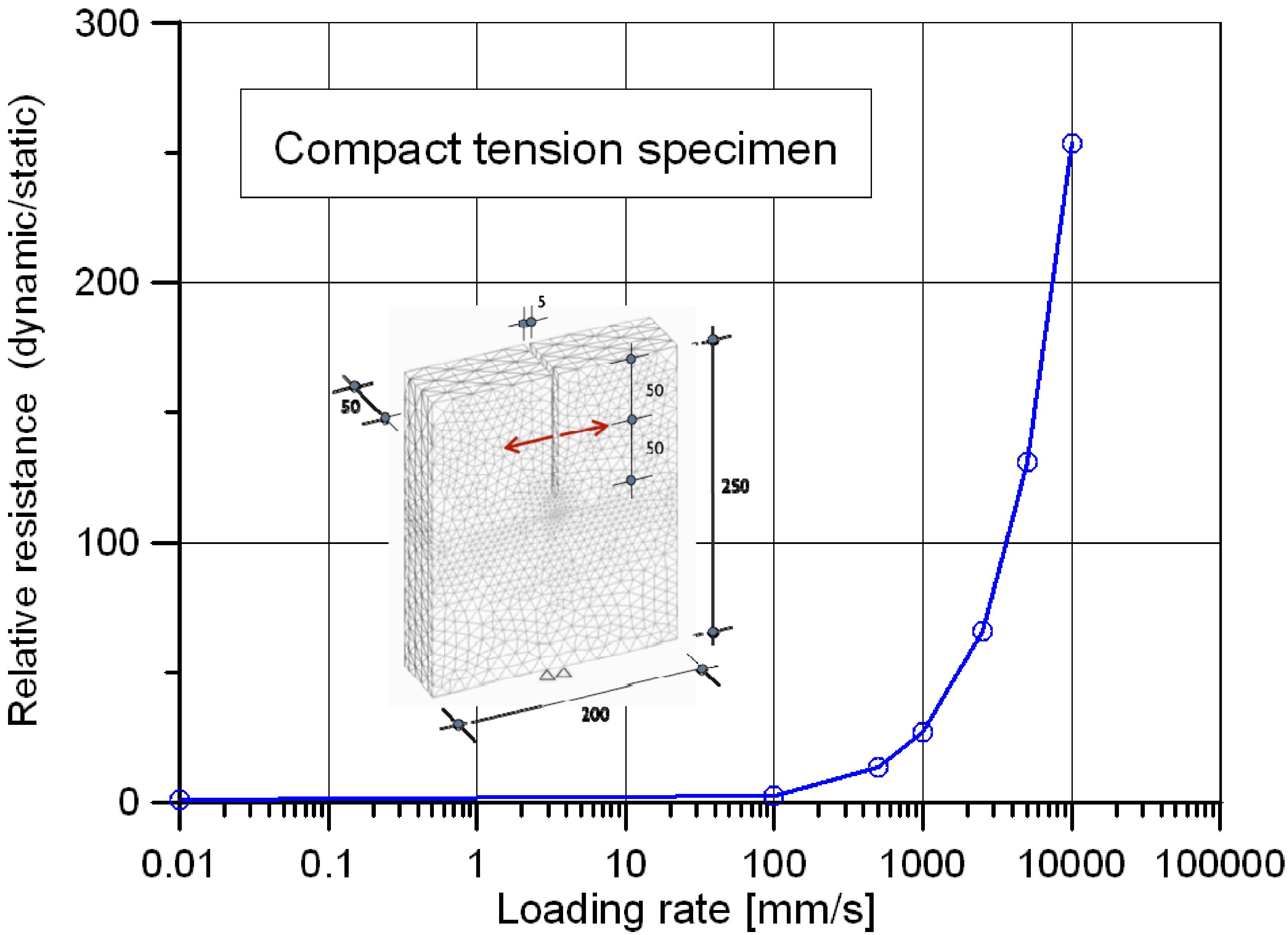
Compact tension specimen



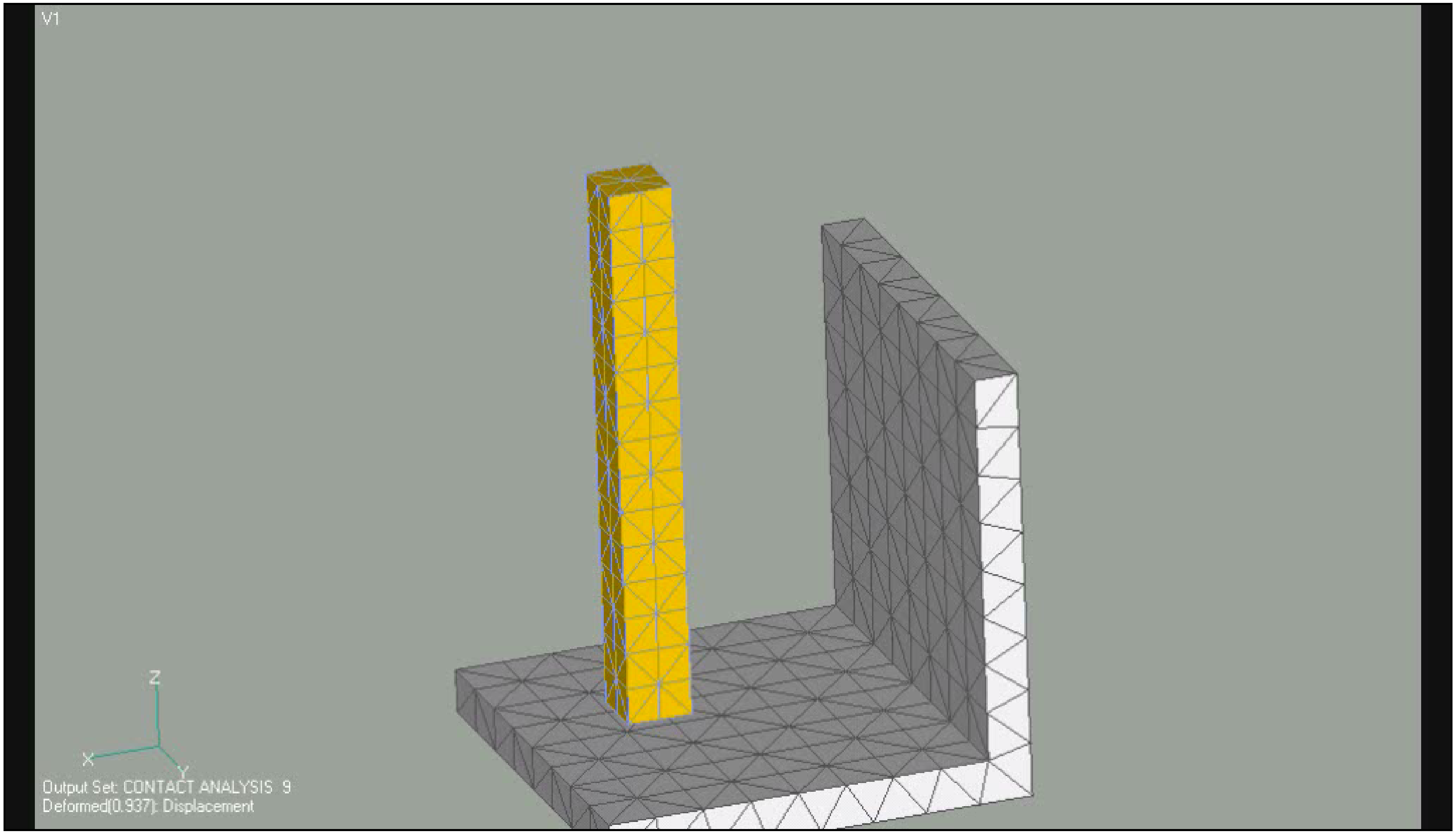
Compact tension specimen



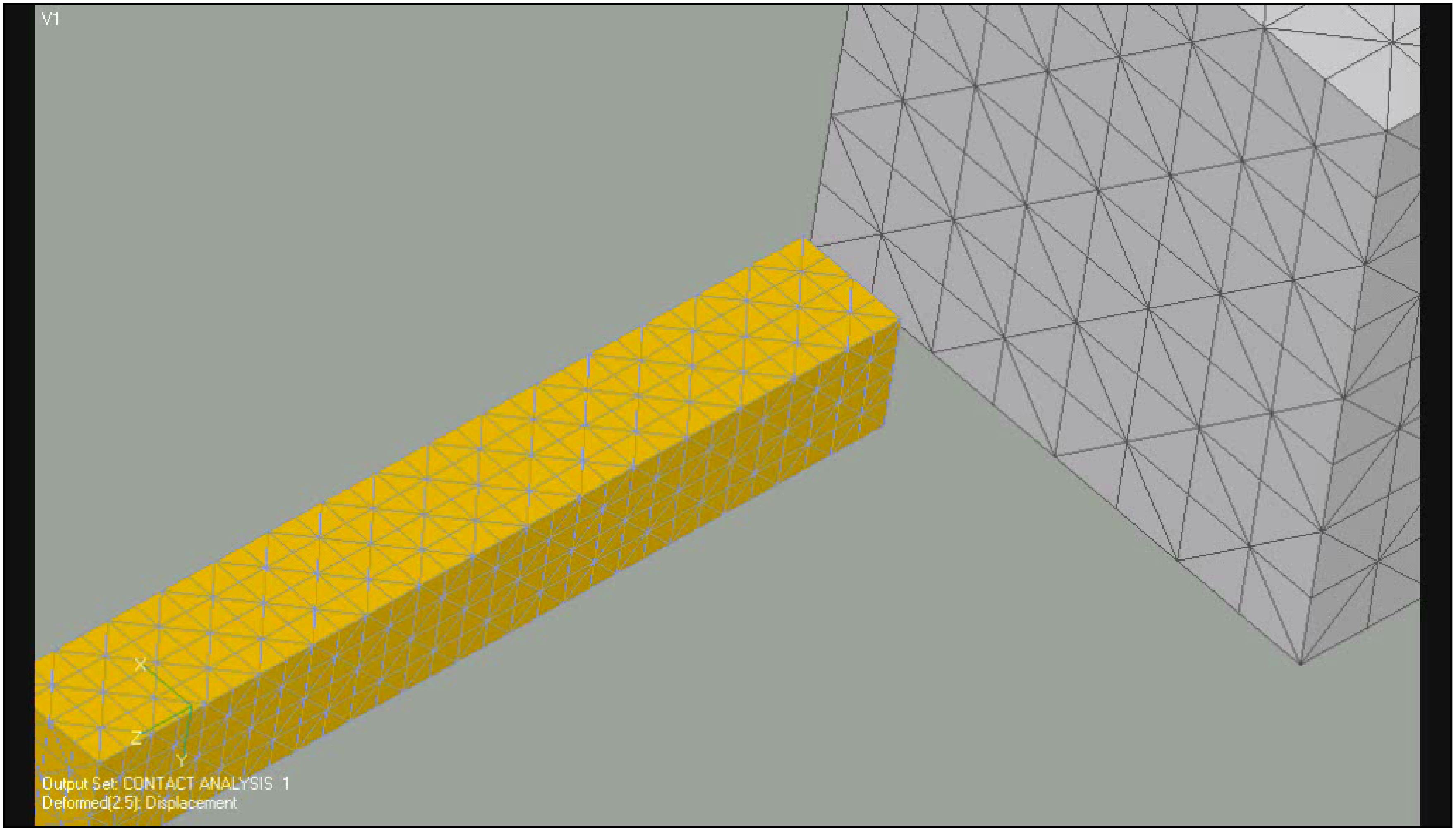
Compact tension specimen



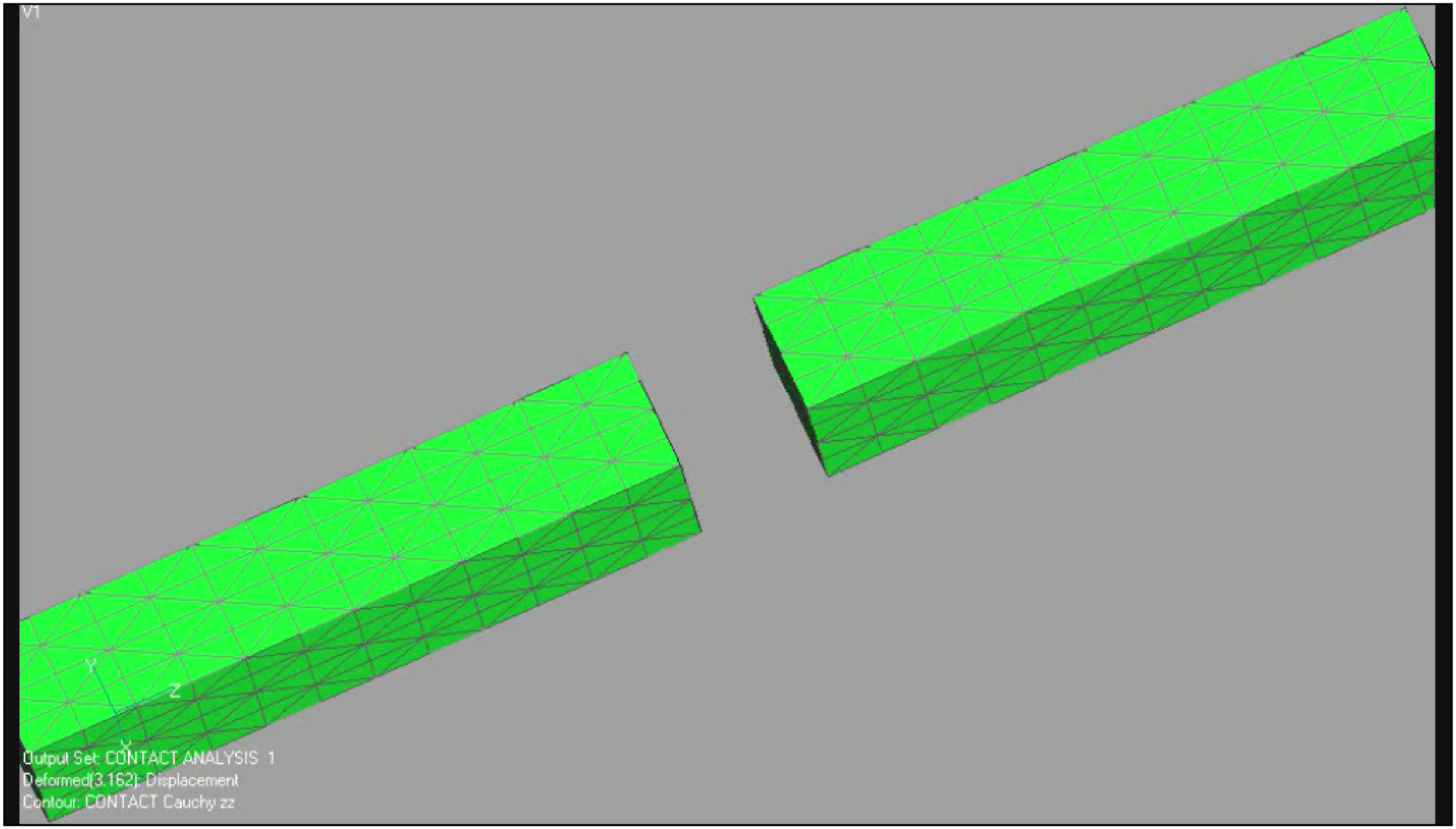
Multi body dynamics & contact



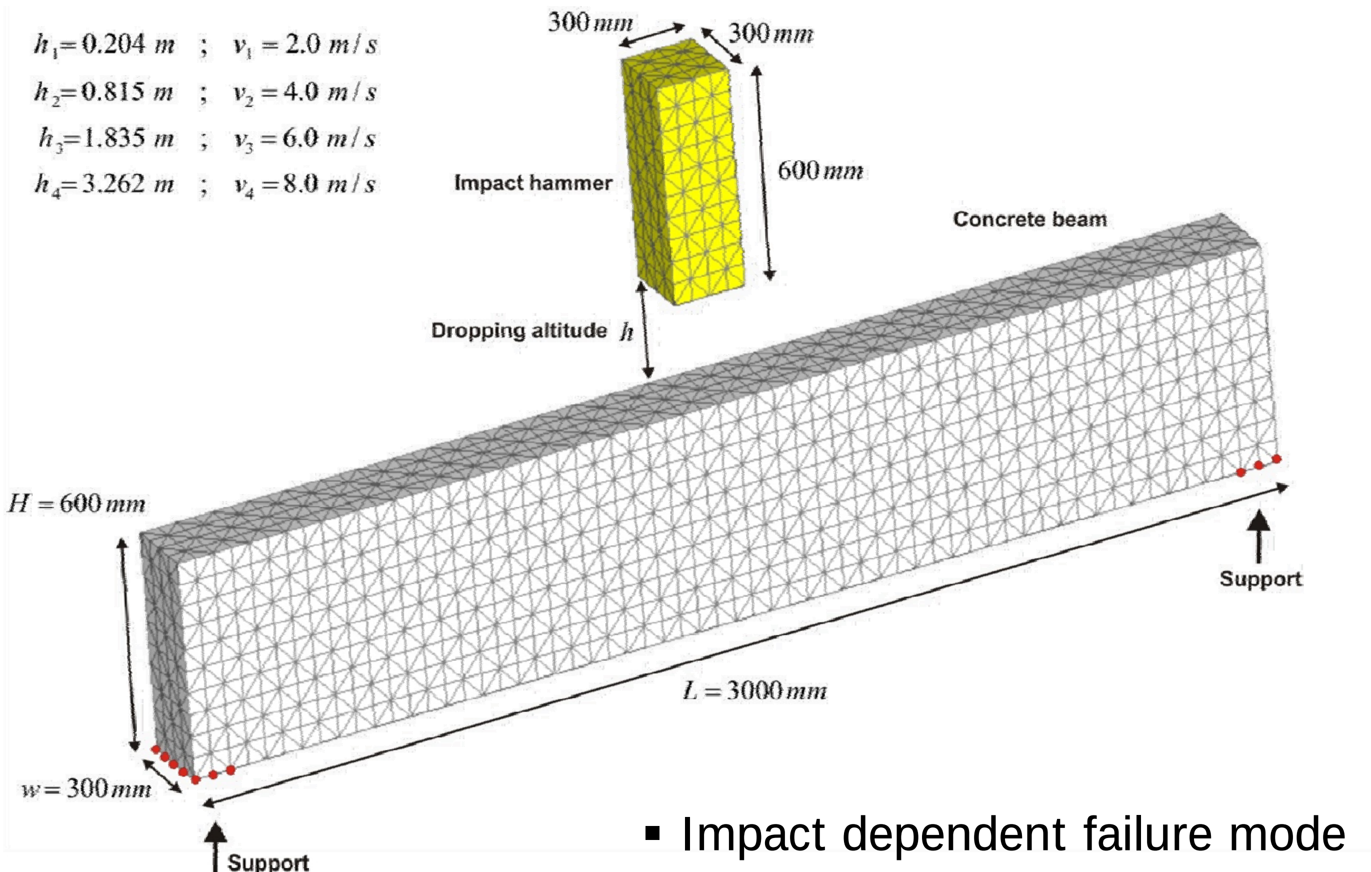
Multi body dynamics & contact



Multi body dynamics & contact

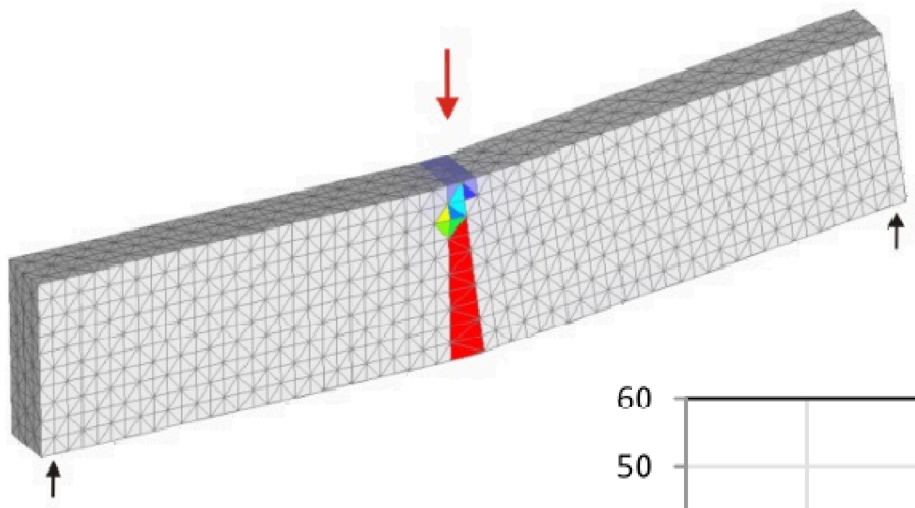


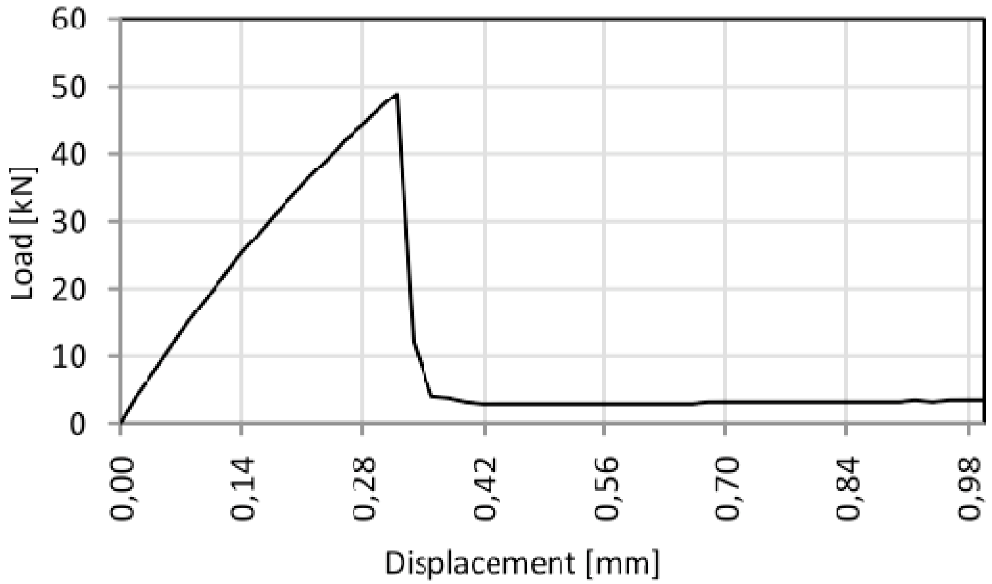
Impact – simply supported plain concrete beam



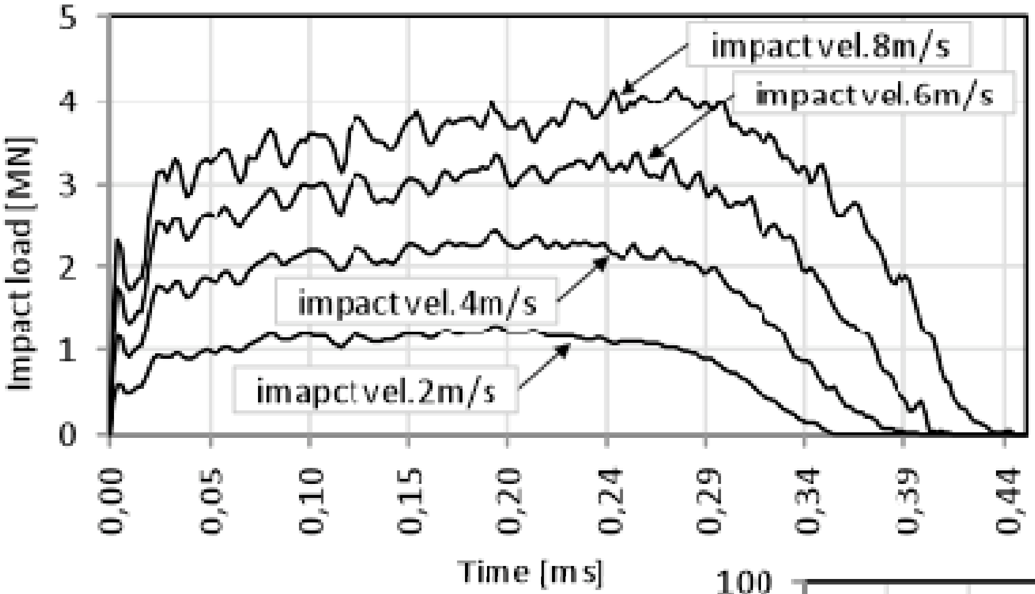
- Impact dependent failure mode
- Crack propagation

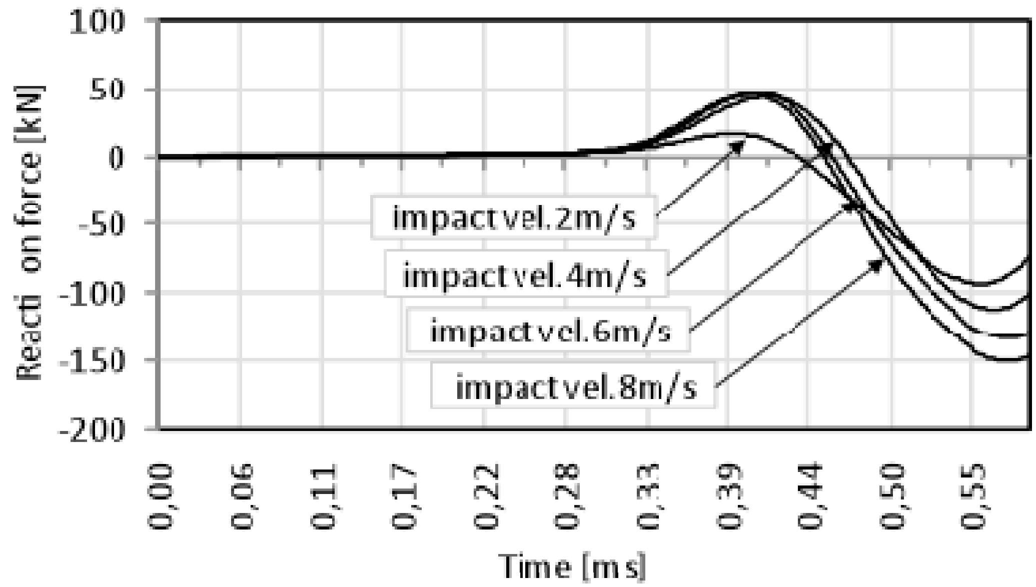
Quasi-static loading



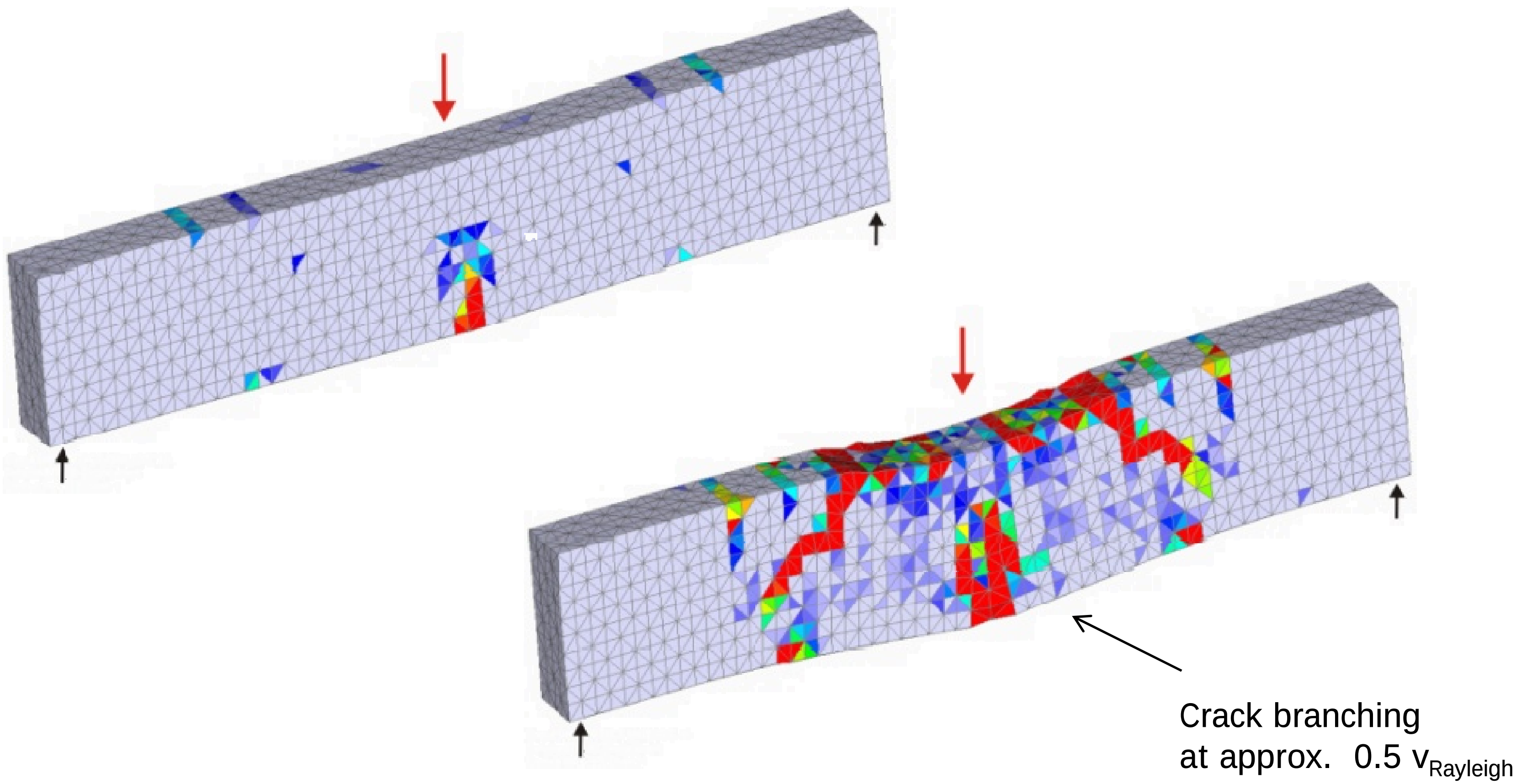


Impact load & reactions



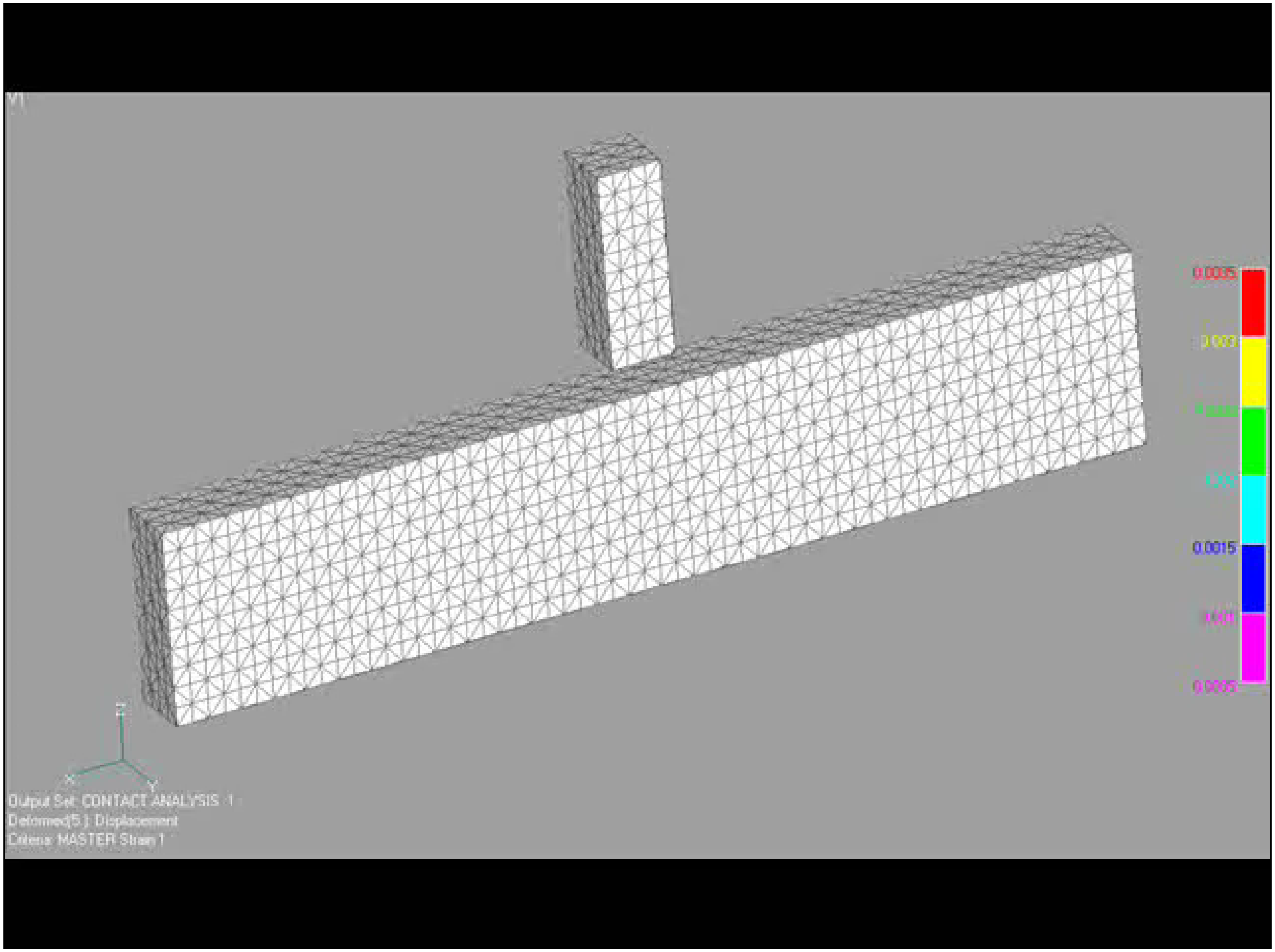


Impact velocity 2 m/s – bending failure

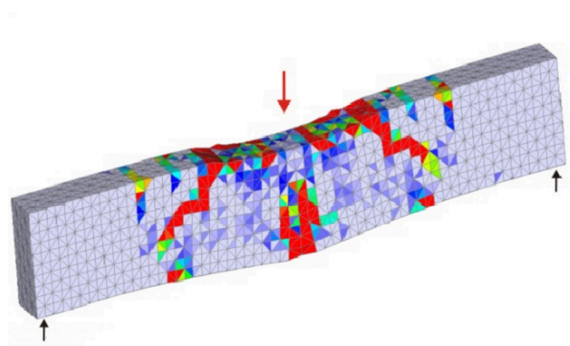


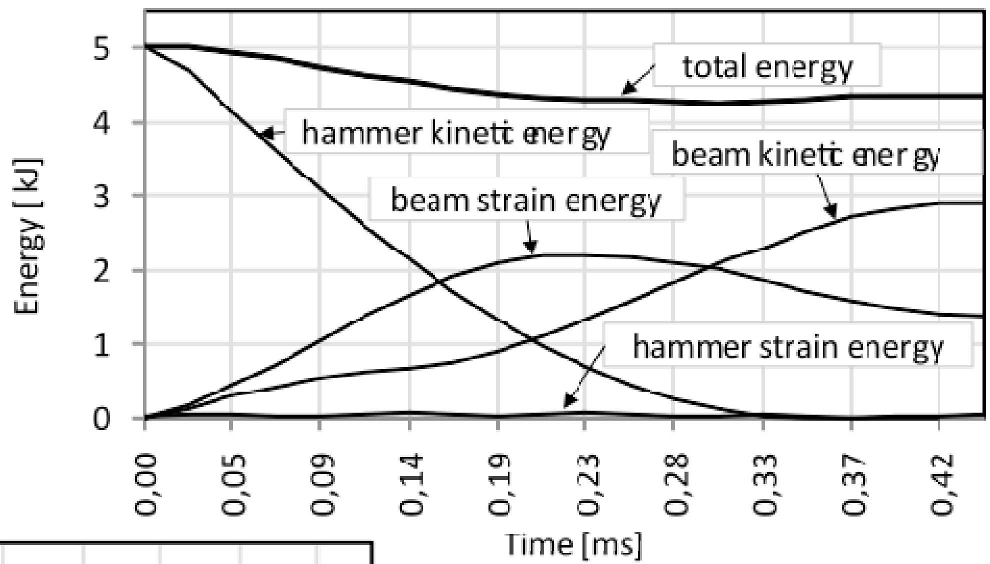
Impact velocity 8 m/s – mixe-mode failure

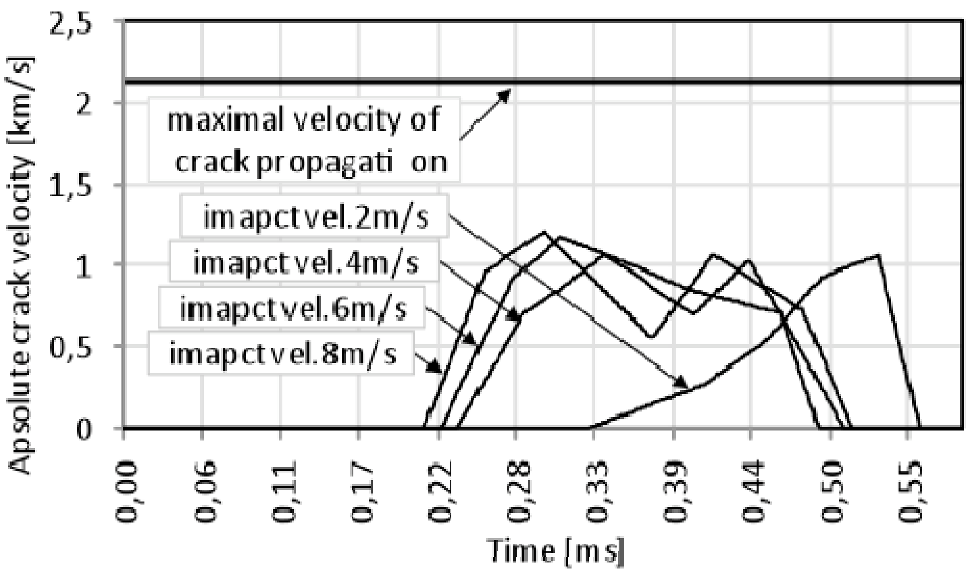
Impact velocity 8 m/s



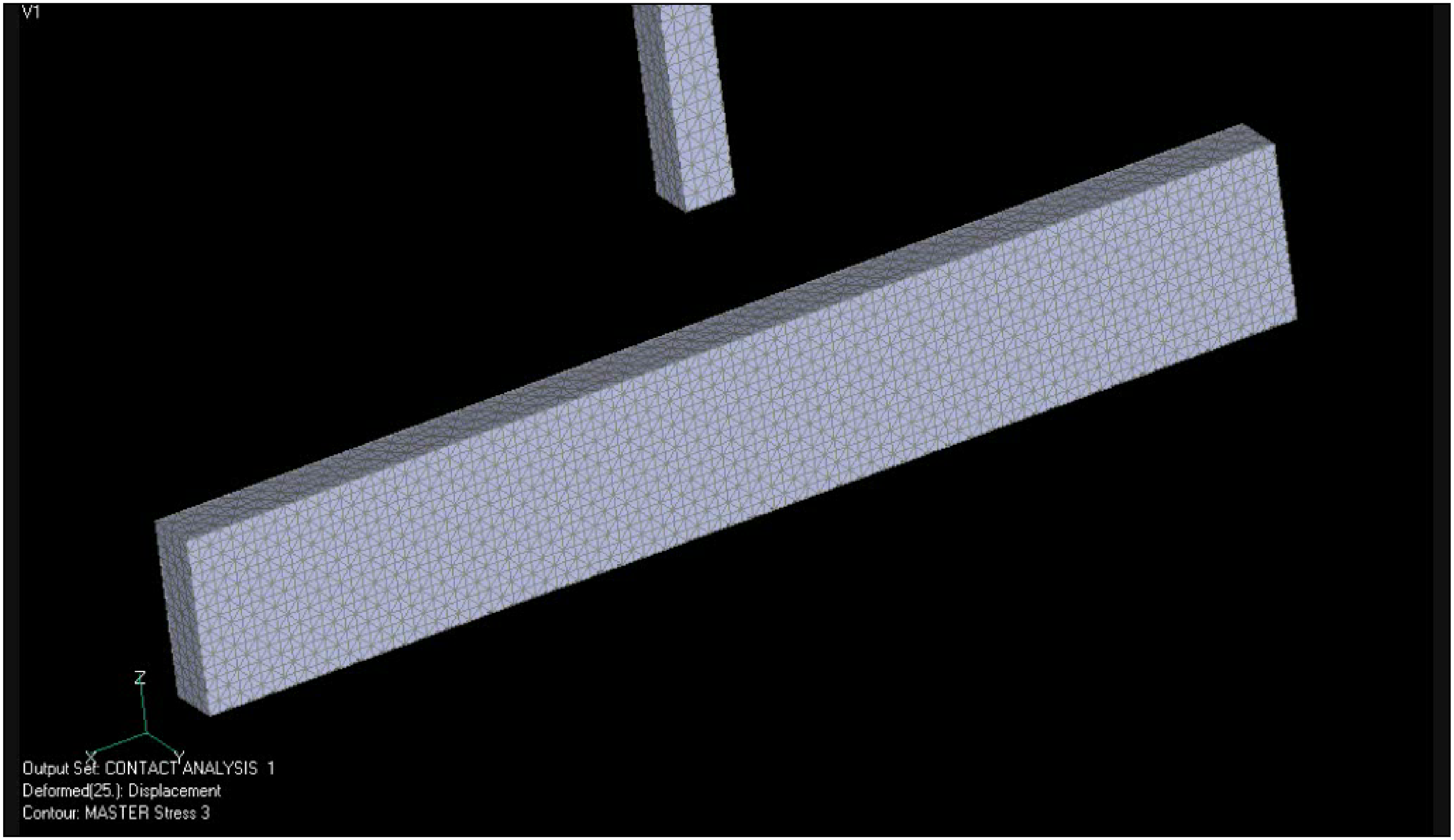
Impact velocity 8 m/s – shear failure



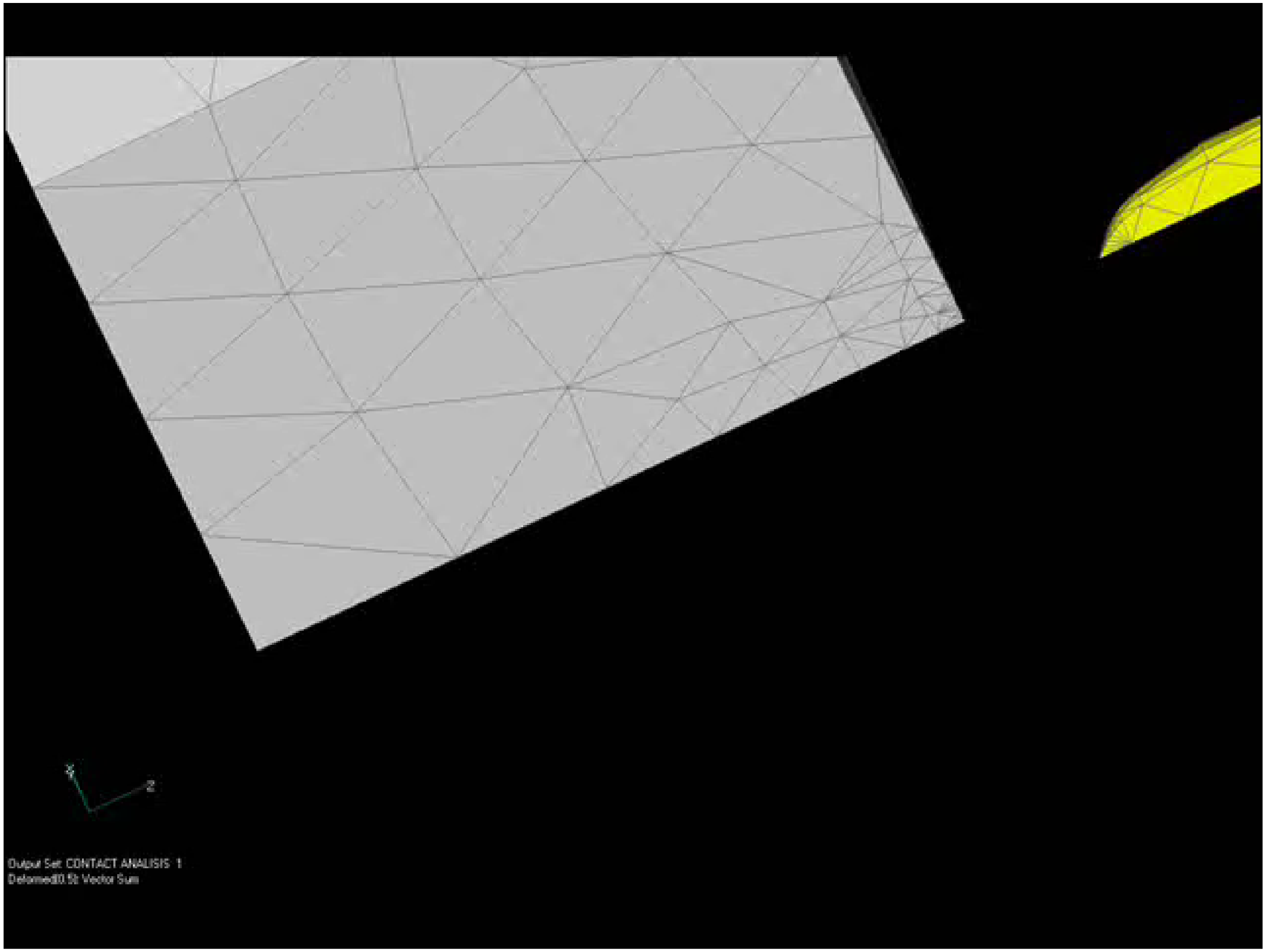




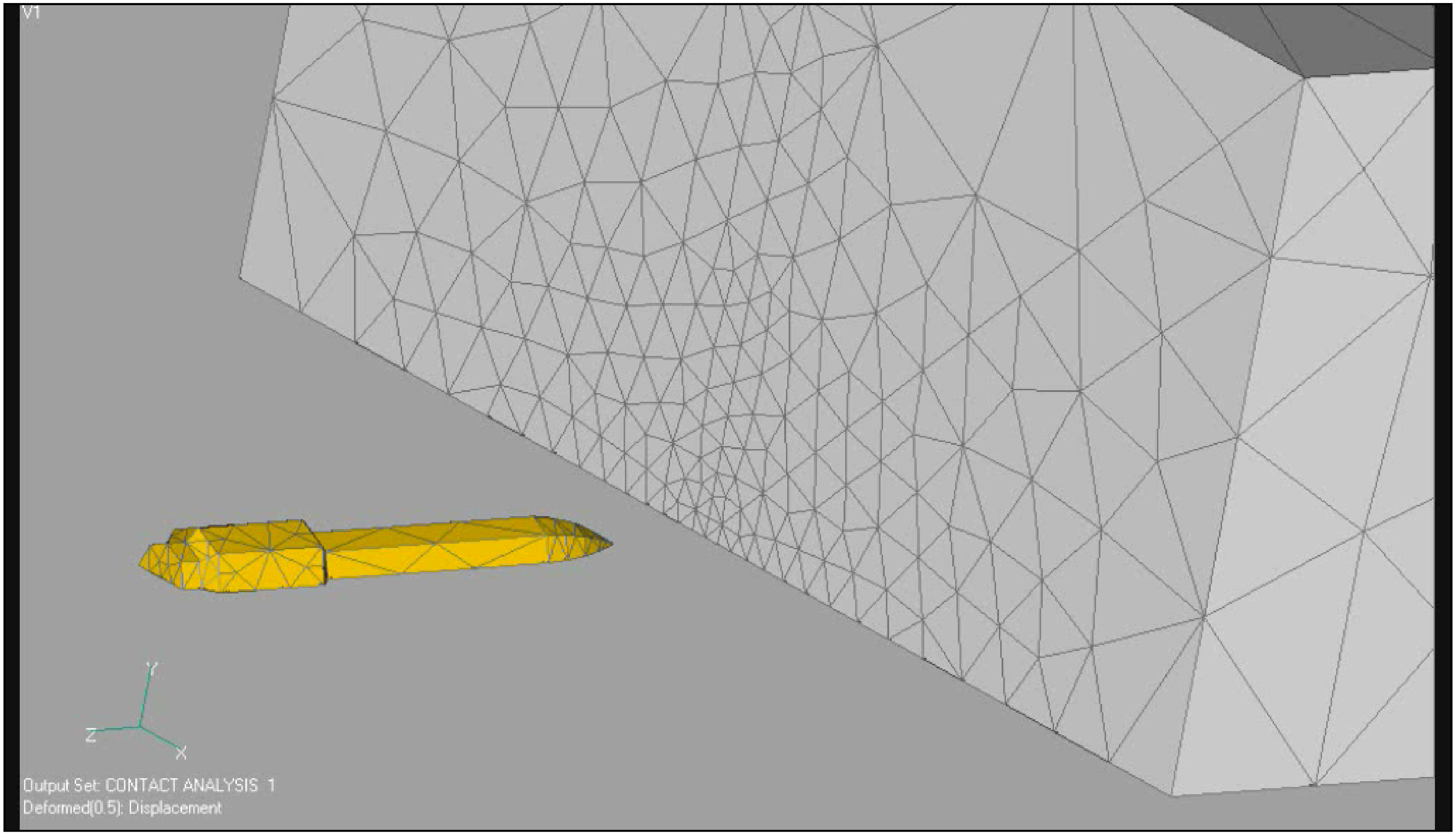
Compressive waves



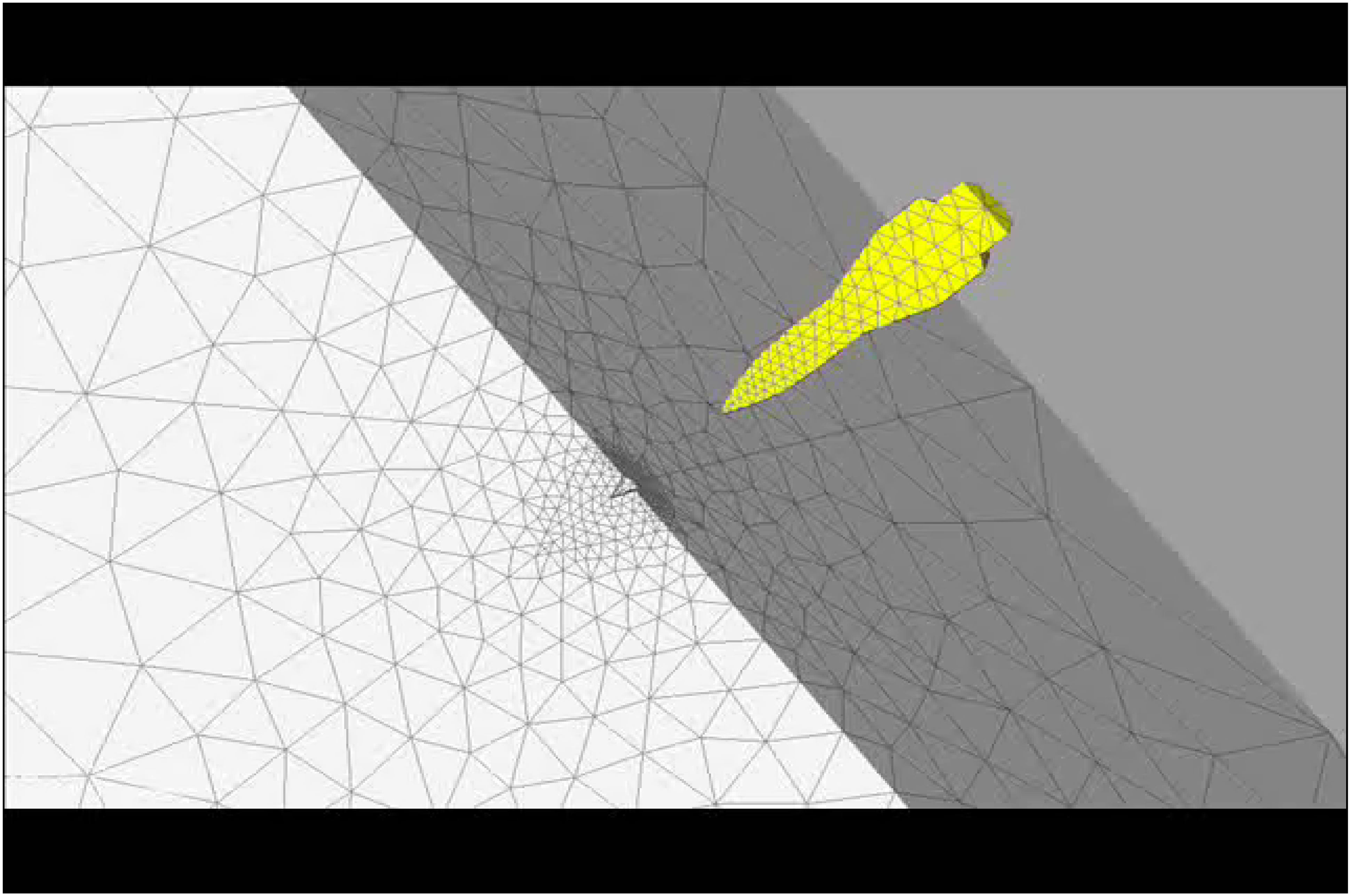
Impact - penetration of nail



Impact - penetration of nail



Impact - penetration of nail



Summary

- With increase of loading rate, resistance and brittleness of the structural response increase and failure mode is rate dependent
- At moderate loading rates the response is controlled by the phenomena at the material micro, however, for higher loading rates inertia forces dominate
- At very high loading rates inertia forces dominate & contact mechanics is important part of the problem to be solved (friction & heat)
- There is a strong influence of the structural size on the loading rate response
- The used rate dependent model is simple and covers a broad range of strain rates