Modelling the dynamic response of concrete with the damage plasticity model CDPM2

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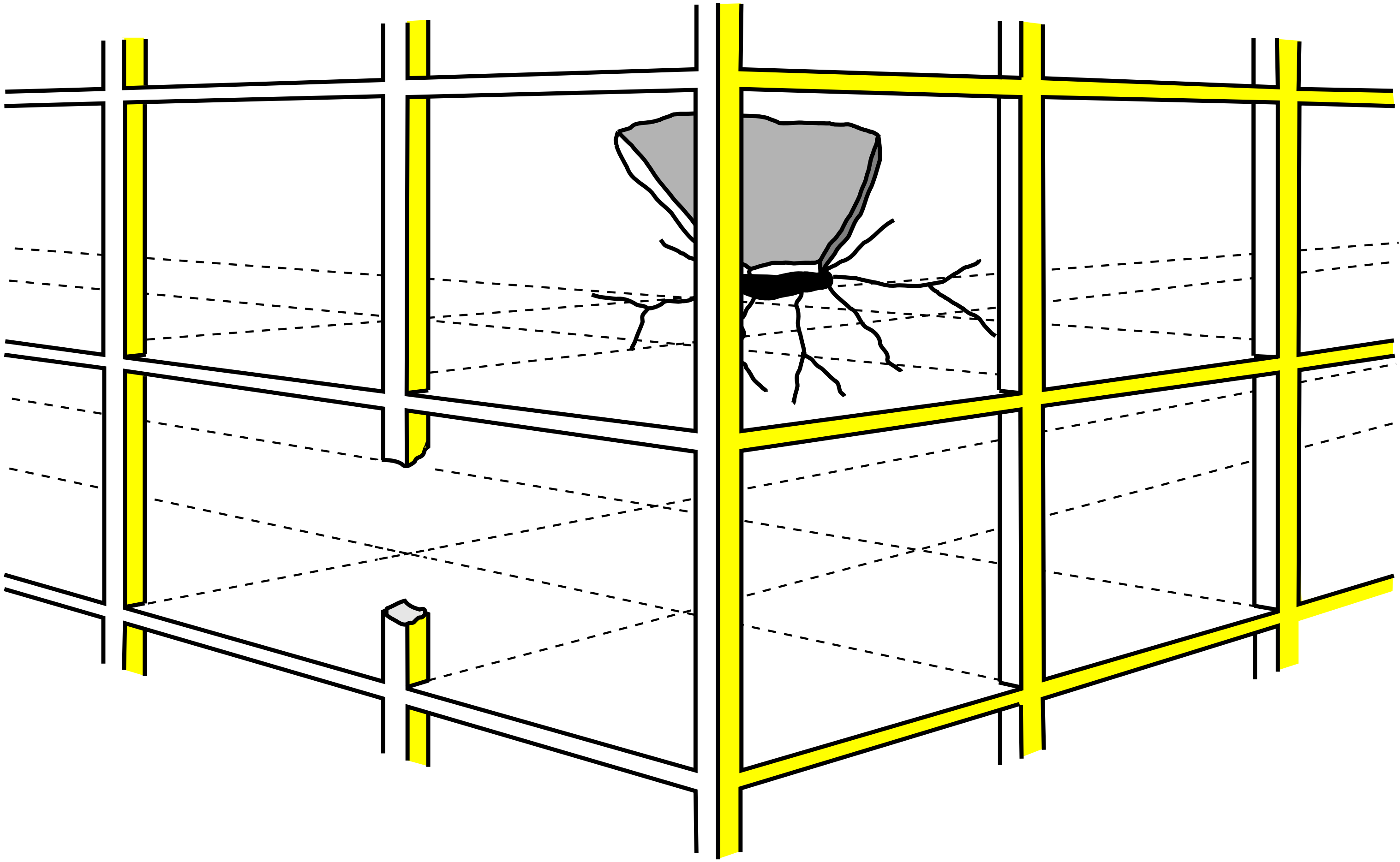
FraMCoS-X, Bayonne, France, 2019

Background: Structural concrete



Aim: Extend CDPM2 to strain rate dependence

Outline

- Overview of CDPM2
- Extension to strain rate dependence
- Comparison with experiments

Plain concrete compact tension test
Ozbolt et al. (2013)

Reinforced concrete slab subjected to blast
Thiagarajan and Johnson (2014)

Ref: Grassl et al. (2013)

Overview of CDPM2

Model for concrete: CDPM2

damage

$$\boldsymbol{\sigma} = (1-\omega)\mathbf{D}_{\mathrm{e}} : \boldsymbol{\varepsilon}$$

plasticity

$$\boldsymbol{\sigma} = \mathbf{D}_{\mathrm{e}} : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_{\mathrm{p}})$$

damage-plasticity

$$\boldsymbol{\sigma} = (1-\omega_{\mathrm{t}})\bar{\boldsymbol{\sigma}}_{\mathrm{t}} + (1-\omega_{\mathrm{c}})\bar{\boldsymbol{\sigma}}_{\mathrm{c}}$$

$$\bar{\boldsymbol{\sigma}} = \mathbf{D}_{\mathrm{e}} : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_{\mathrm{p}}) = \bar{\boldsymbol{\sigma}}_{\mathrm{t}} + \bar{\boldsymbol{\sigma}}_{\mathrm{c}}$$

Ref: Grassl et al. (2013)

Model for concrete: CDPM2

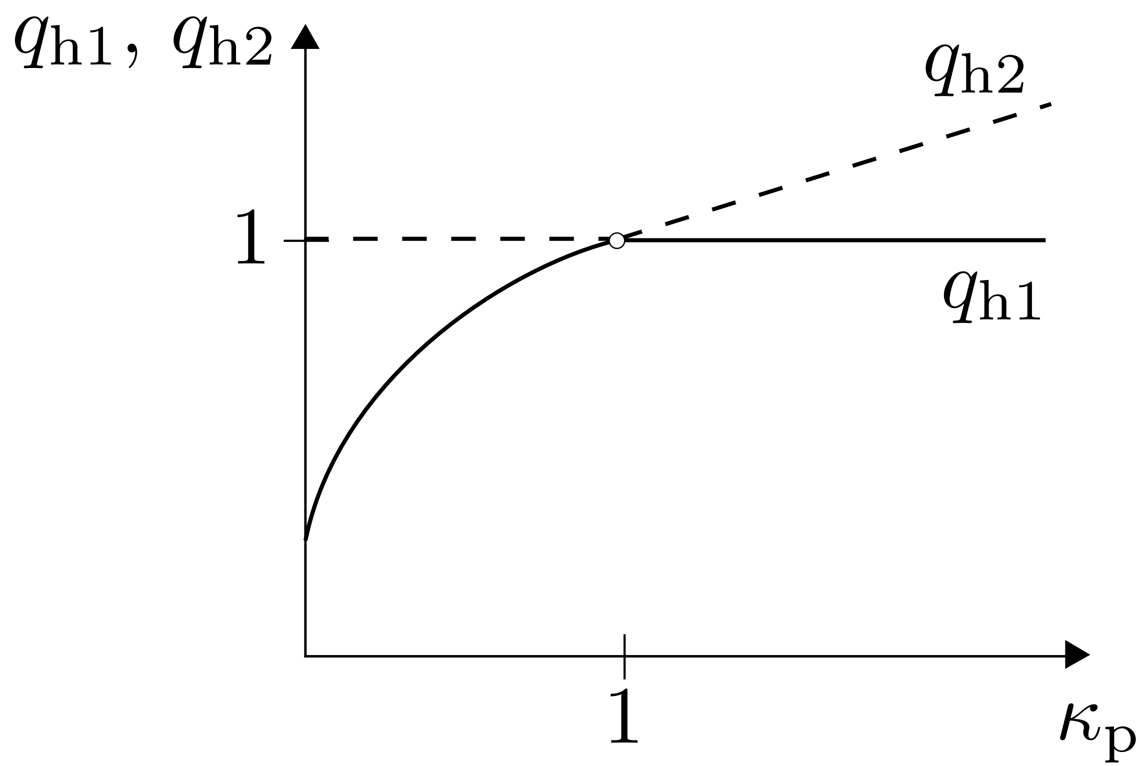
Plasticity

$$f_{\mathrm{p}}(\bar{\boldsymbol{\sigma}}, \mathrm{q}_{\mathrm{h1}}, \mathrm{q}_{\mathrm{h2}})$$

$$\dot{\boldsymbol{\varepsilon}}_{\mathrm{p}} = \dot{\lambda}\,\frac{\partial g_{\mathrm{p}}}{\partial \bar{\boldsymbol{\sigma}}}$$

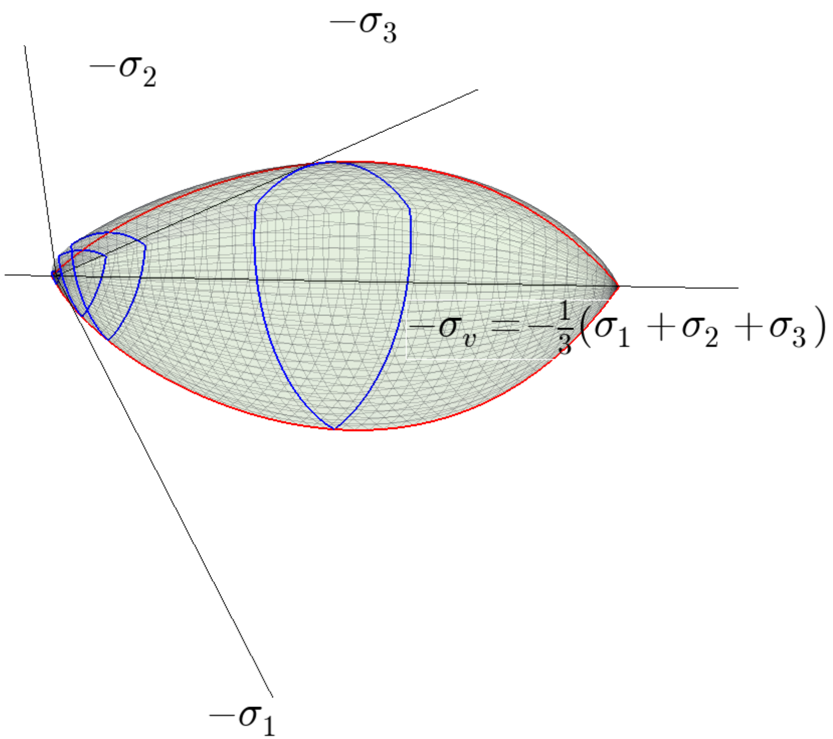
$$\dot{\kappa}_{\mathrm{p}} = \frac{\|\dot{\boldsymbol{\varepsilon}}_{\mathrm{p}}\|}{x_{\mathrm{h}}(\bar{\boldsymbol{\sigma}})}$$

$$f_{\mathrm{p}} \leq 0 \quad \dot{\lambda} \geq 0 \quad \dot{\lambda}\, f_{\mathrm{p}} = 0$$

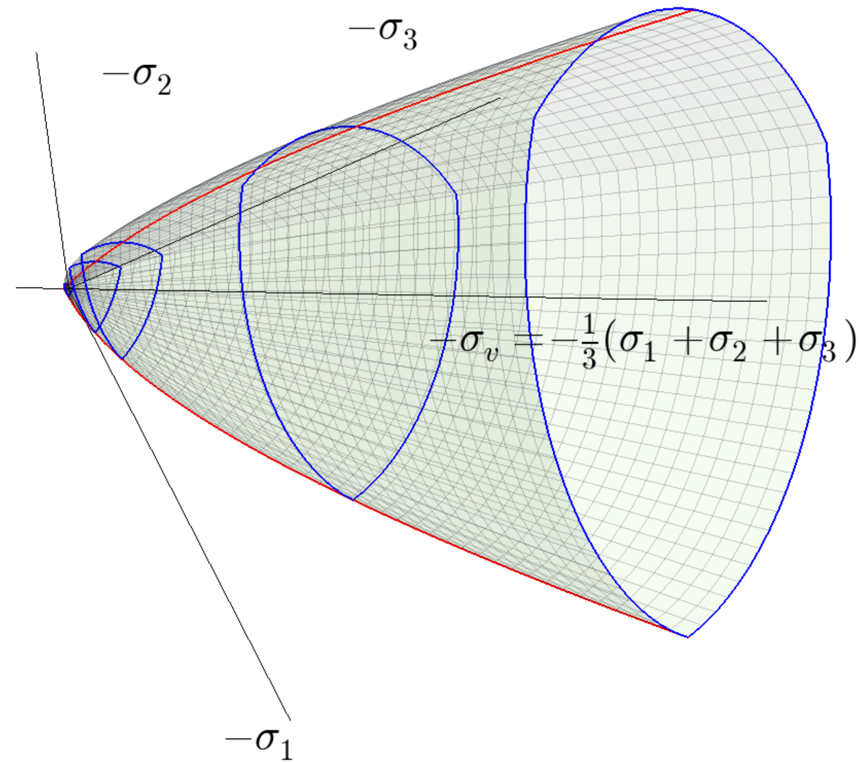


Model for concrete: CDPM2

Yield surface



$\kappa_{\mathrm{p}} < 1$



$\kappa_{\mathrm{p}} \geq 1$

Ref: Menétrey and Willam (1995), Grassl et al. (2013)

Model for concrete: CDPM2

Damage part

$$\tilde{\varepsilon}(\bar{\boldsymbol{\sigma}}) \quad \dot{\tilde{\varepsilon}}_{\mathrm{t}} = \dot{\tilde{\varepsilon}} \quad \dot{\tilde{\varepsilon}}_{\mathrm{c}} = \alpha_{\mathrm{c}} \dot{\tilde{\varepsilon}}$$

Onset of damage: $\tilde{\varepsilon} = \varepsilon_0$

$$\kappa_{\mathrm{dt}} = \max_{\tau \leq t} \tilde{\varepsilon}_{\mathrm{t}} \qquad \dot{\kappa}_{\mathrm{dt1}} = \frac{\|\dot{\varepsilon}_{\mathrm{p}}\|}{x_{\mathrm{s}}} \qquad \dot{\kappa}_{\mathrm{dt2}} = \frac{\dot{\kappa}_{\mathrm{dt}}}{x_{\mathrm{s}}}$$

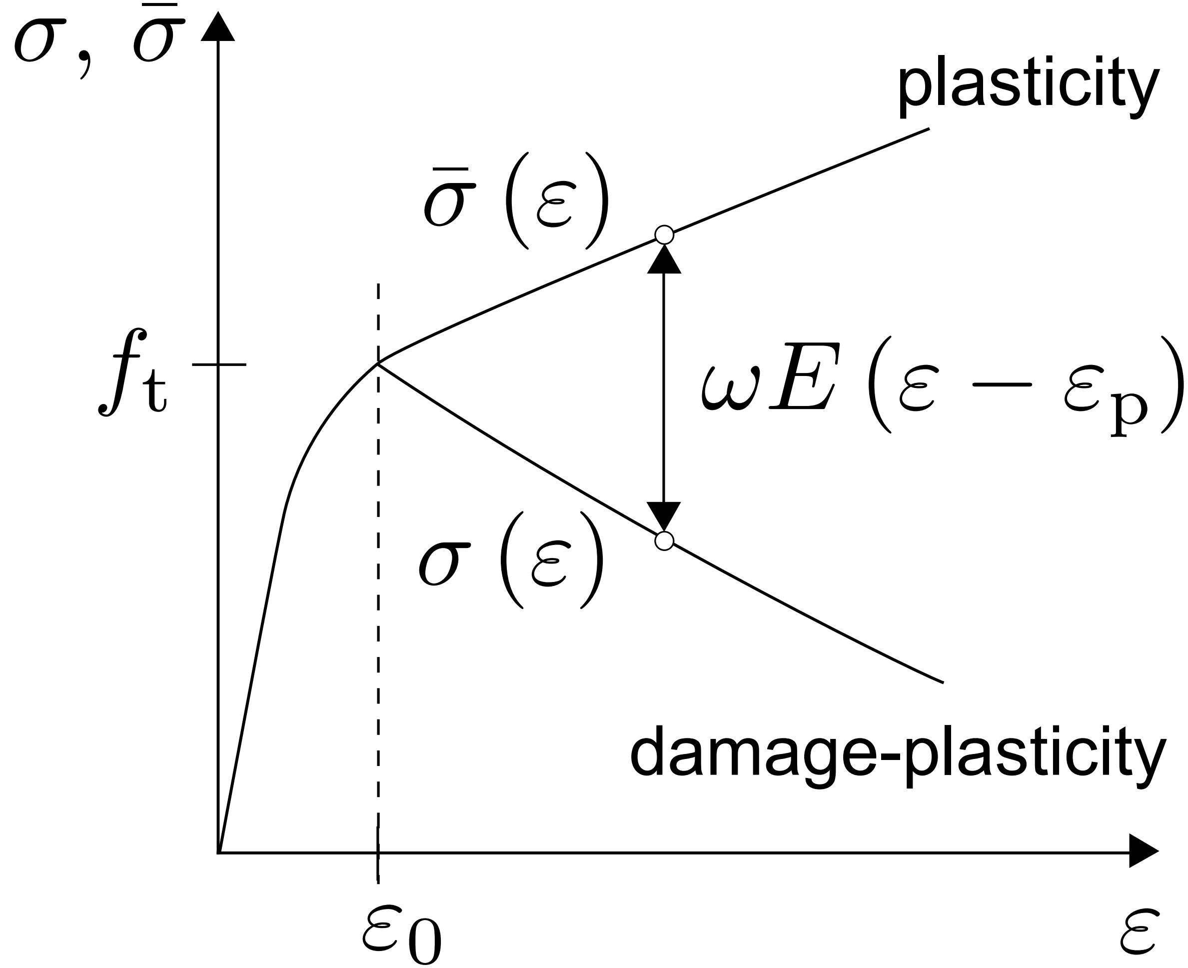
$$\kappa_{\mathrm{dc}} = \max_{\tau \leq t} \tilde{\varepsilon}_{\mathrm{c}} \qquad \dot{\kappa}_{\mathrm{dc1}} = \frac{\alpha_{\mathrm{c}}\, \beta_{\mathrm{c}}\, \|\dot{\varepsilon}_{\mathrm{p}}\|}{x_{\mathrm{s}}} \qquad \dot{\kappa}_{\mathrm{dc2}} = \frac{\dot{\kappa}_{\mathrm{dc}}}{x_{\mathrm{s}}}$$

Damage variables:

$$\omega_{\mathrm{t}}\left(\kappa_{\mathrm{dt}}, \kappa_{\mathrm{dt1}}, \kappa_{\mathrm{dt2}}\right) \qquad \omega_{\mathrm{c}}\left(\kappa_{\mathrm{dc}}, \kappa_{\mathrm{dc1}}, \kappa_{\mathrm{dc2}}\right)$$

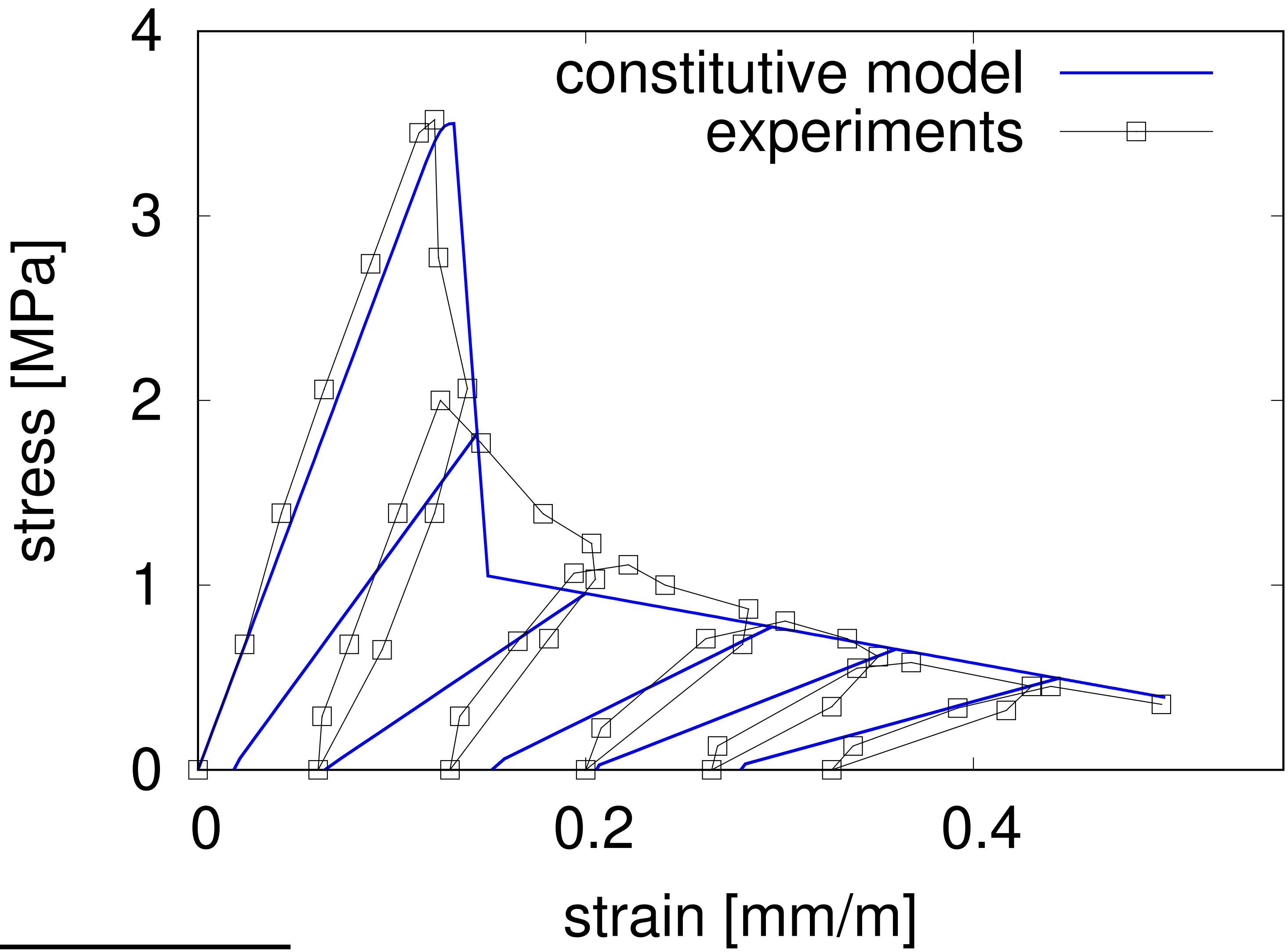
Ref: Grassl et al. (2013)

Schematic tensile response



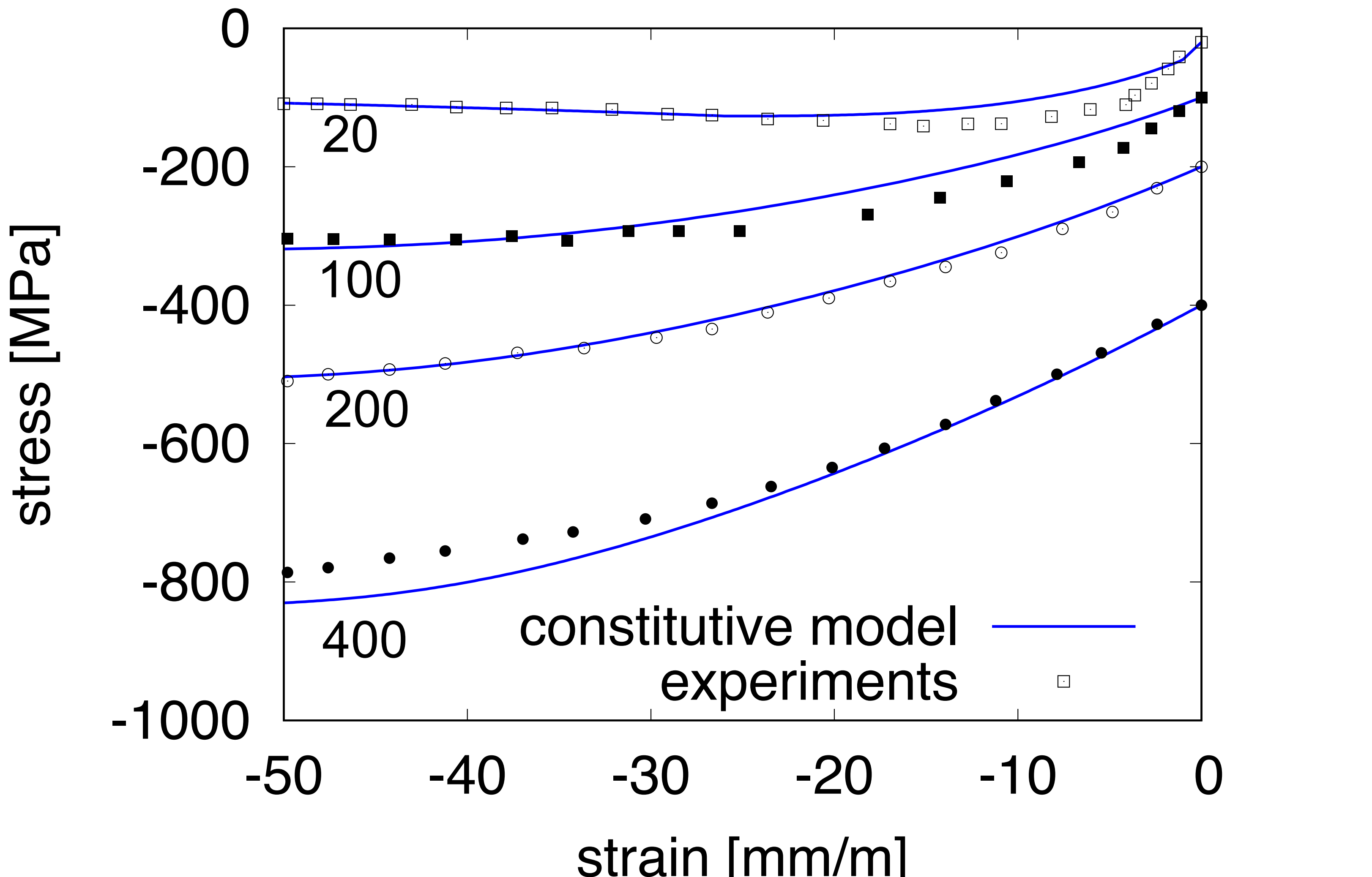
Ref: Grassl et al. (2013)

Constitutive response for tension



Ref: Grassl et al. (2013)

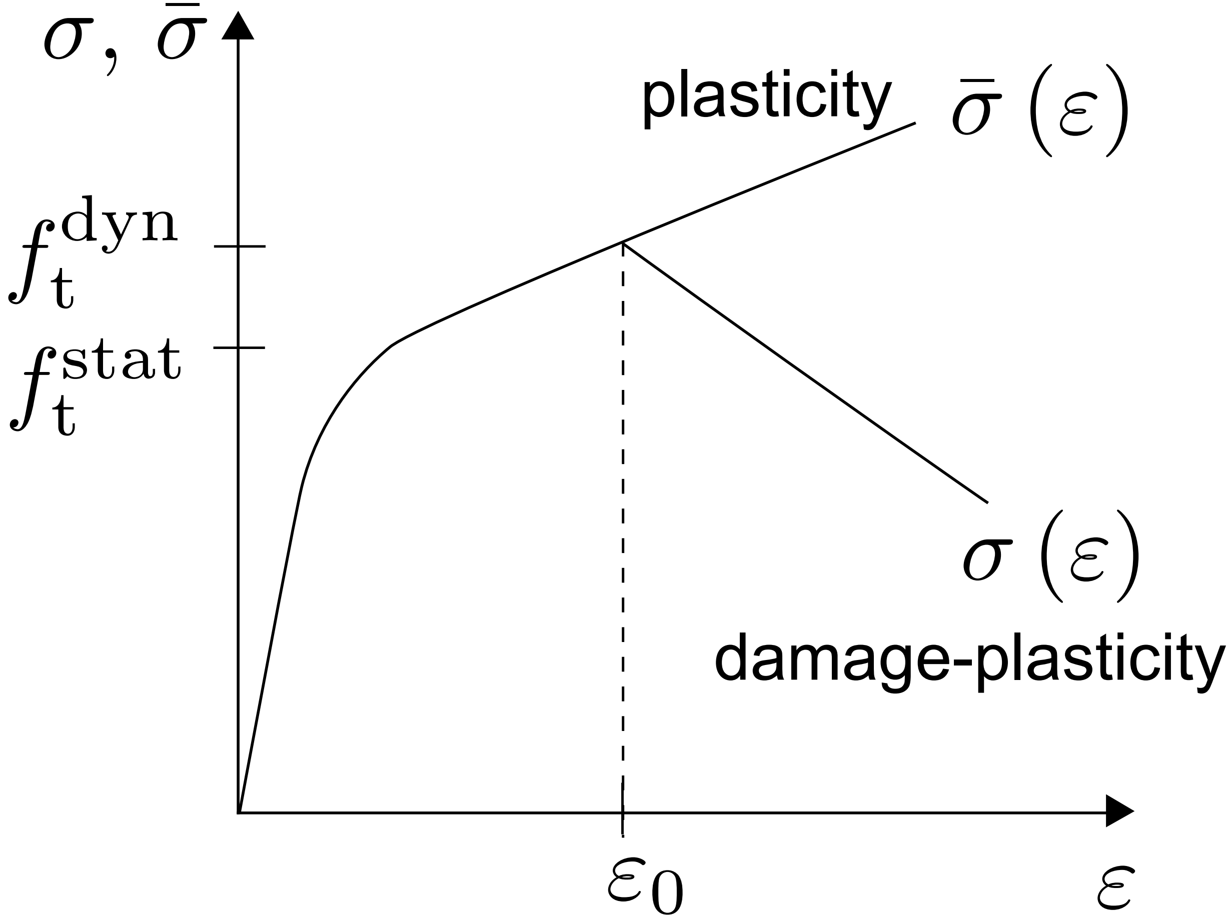
Constitutive response for compression



Ref: Grassl et al. (2013)

Extension to strain rate dependence

Schematic tensile response



Extension to strain rate dependence

Delay onset of damage:

$$\tilde{\varepsilon}(\bar{\boldsymbol{\sigma}}) \qquad \dot{\tilde{\varepsilon}}_{\mathrm{t}} = \frac{\dot{\tilde{\varepsilon}}}{\alpha_{\mathrm{rt}}} \qquad \dot{\tilde{\varepsilon}}_{\mathrm{c}} = \alpha_{\mathrm{c}} \frac{\dot{\tilde{\varepsilon}}}{\alpha_{\mathrm{rc}}}$$

Onset of damage: $\tilde{\varepsilon} = \varepsilon_0$ (Stays the same)

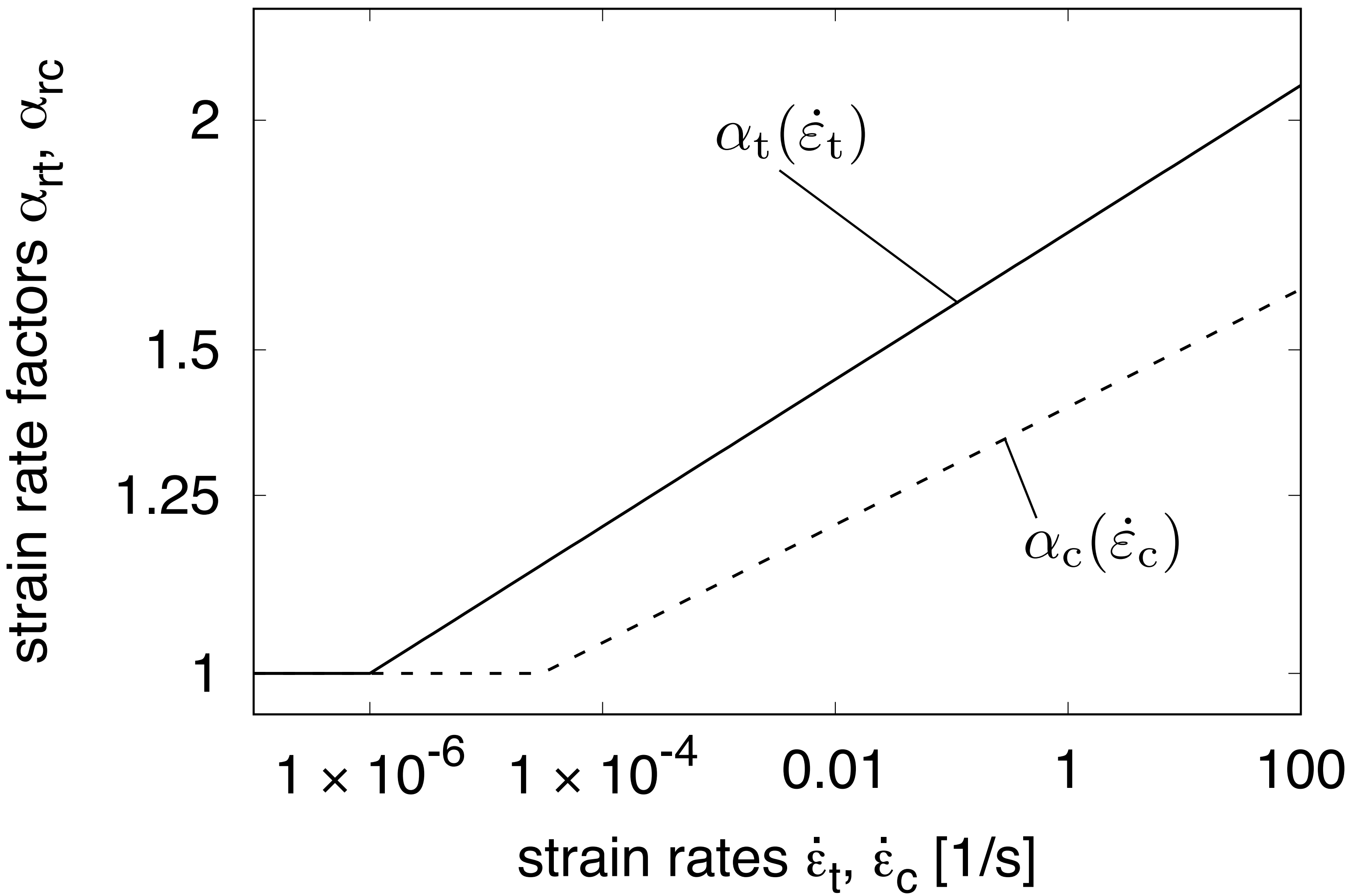
Speed up damage evolution:

$$\kappa_{\mathrm{dt}} = \max_{\tau \leq t} \tilde{\varepsilon}_{\mathrm{t}} \qquad \dot{\kappa}_{\mathrm{dt1}} = \alpha_{\mathrm{rt}}^2 \frac{\|\dot{\varepsilon}_{\mathrm{p}}\|}{x_{\mathrm{s}}} \qquad \dot{\kappa}_{\mathrm{dt2}} = \alpha_{\mathrm{rt}}^2 \frac{\dot{\kappa}_{\mathrm{dt}}}{x_{\mathrm{s}}}$$

$$\kappa_{\mathrm{dc}} = \max_{\tau \leq t} \tilde{\varepsilon}_{\mathrm{c}} \qquad \dot{\kappa}_{\mathrm{dc1}} = \alpha_{\mathrm{rc}}^2 \frac{\alpha_{\mathrm{c}}\, \beta_{\mathrm{c}}\, \|\dot{\varepsilon}_{\mathrm{p}}\|}{x_{\mathrm{s}}} \qquad \dot{\kappa}_{\mathrm{dc2}} = \alpha_{\mathrm{rc}}^2 \frac{\dot{\kappa}_{\mathrm{dc}}}{x_{\mathrm{s}}}$$

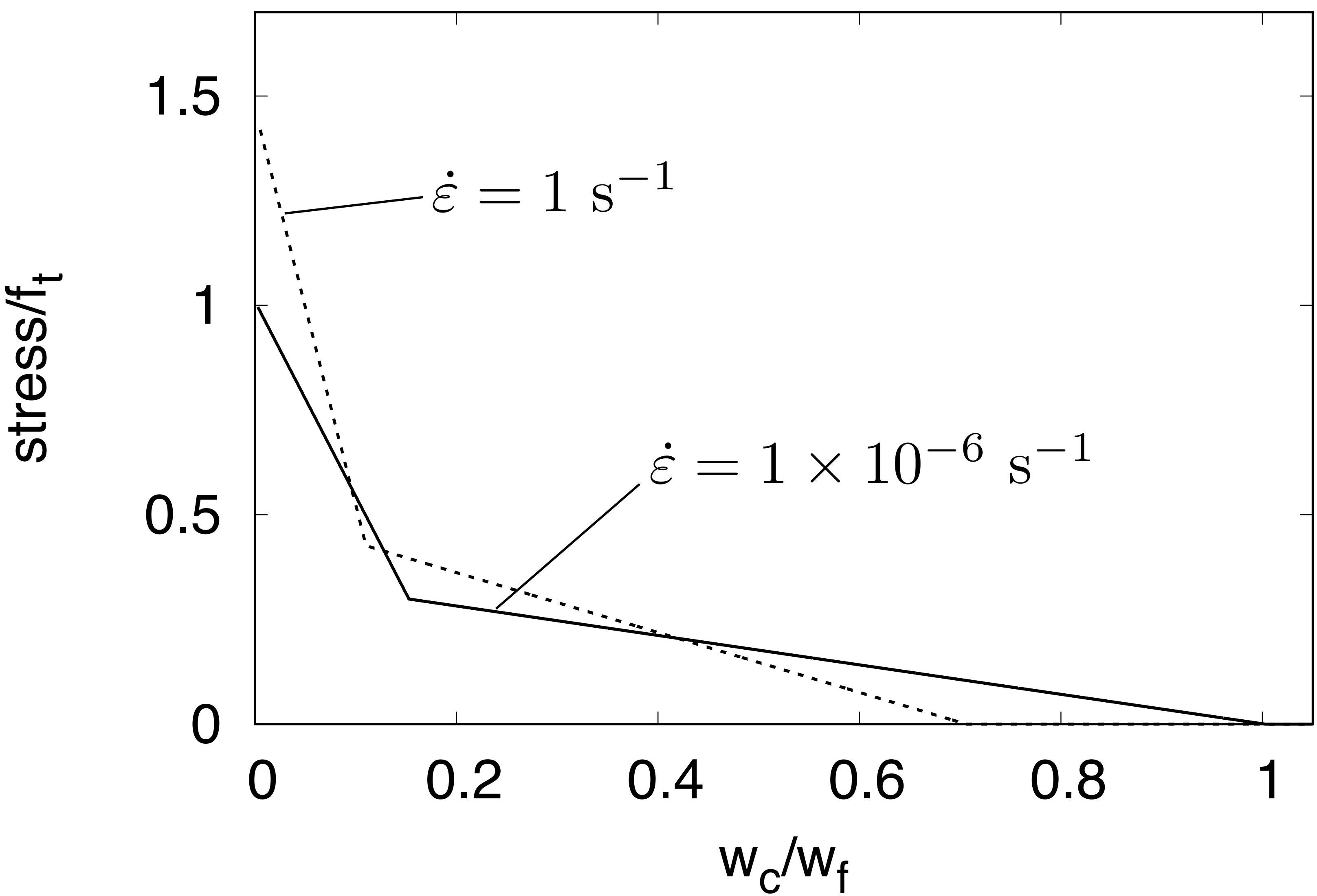
Ref: de Pedraza et al. (2018)

Strain rate factors



Ref: CEB-FIP (2012) (modified), Cusatis (2011), Ozbolt et al. (2014)

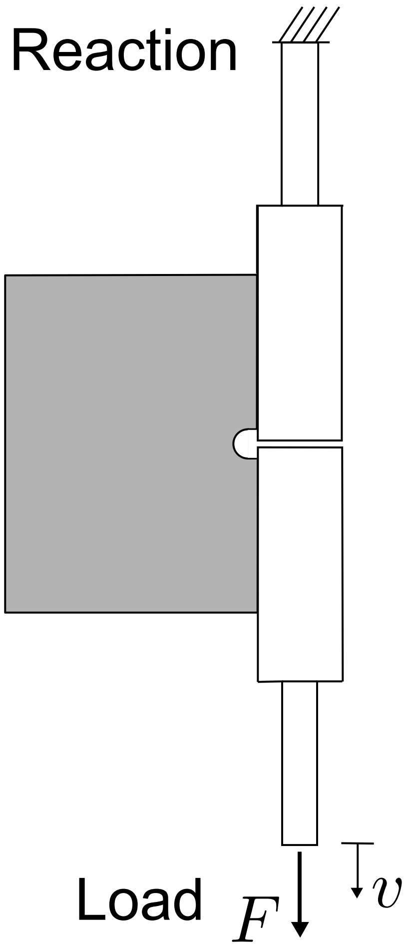
Stress versus crack opening



Comparison with experiments
Plain concrete compact tension test

Compact tension test

Setup



Input

Exp: $f_{\mathrm{c}} = 53\ \mathrm{MPa}$

CEB: $E = 37\ \mathrm{GPa}$

$f_{\mathrm{t}} = 3.8\ \mathrm{MPa}$

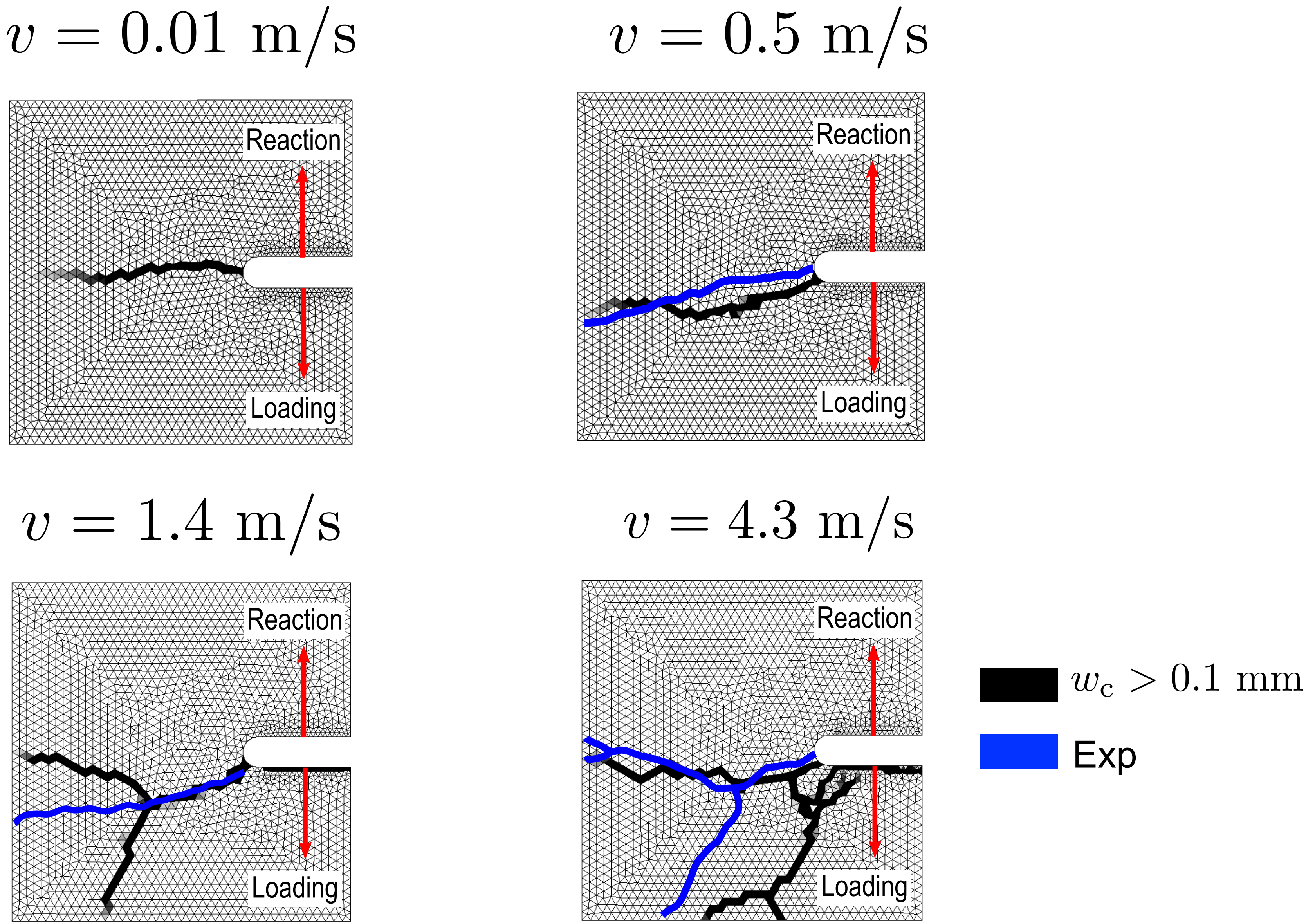
$G_{\mathrm{t}} = 149\ \mathrm{J/m^2}$

Loading rates

$$v = 0.01, 0.5, 1.4 \text{ and } 4.3\ \mathrm{m/s}$$

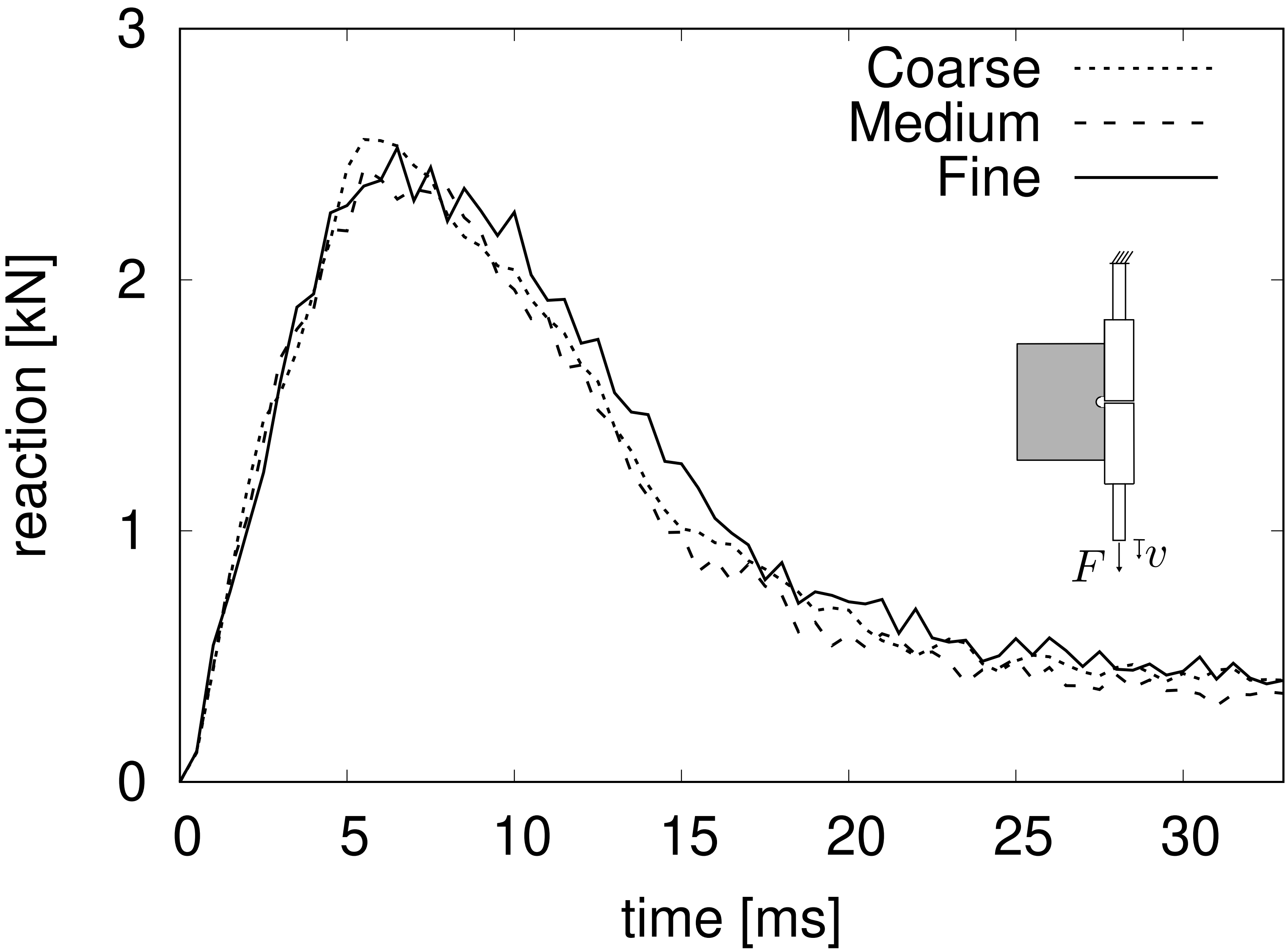
Ref: Ozbolt et al. (2013)

Crack patterns (fine mesh)

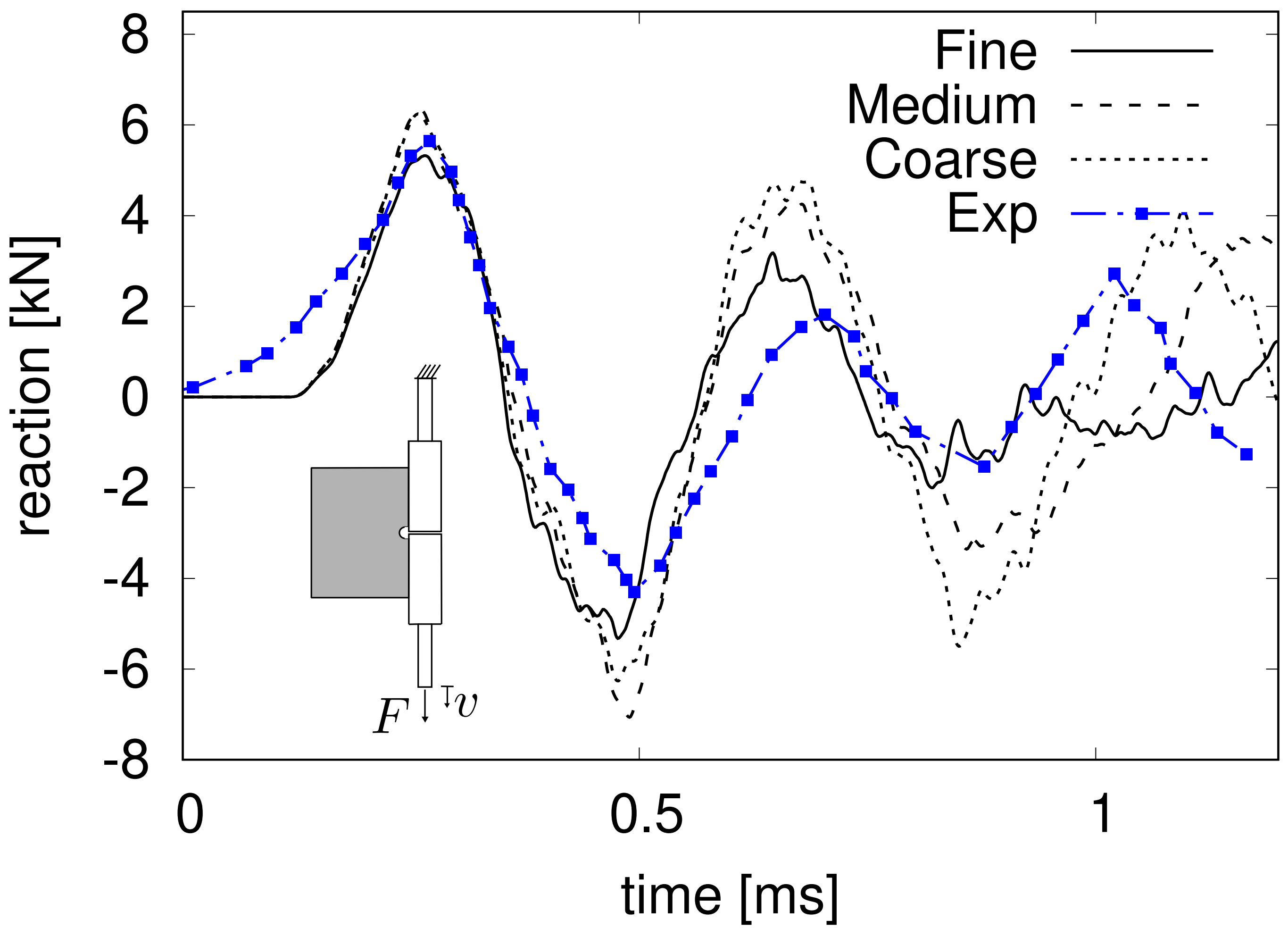


Ref: Ozbolt et al. (2013), Pereira et al. (2017)

reaction versus time $v = 0.01$ m/s



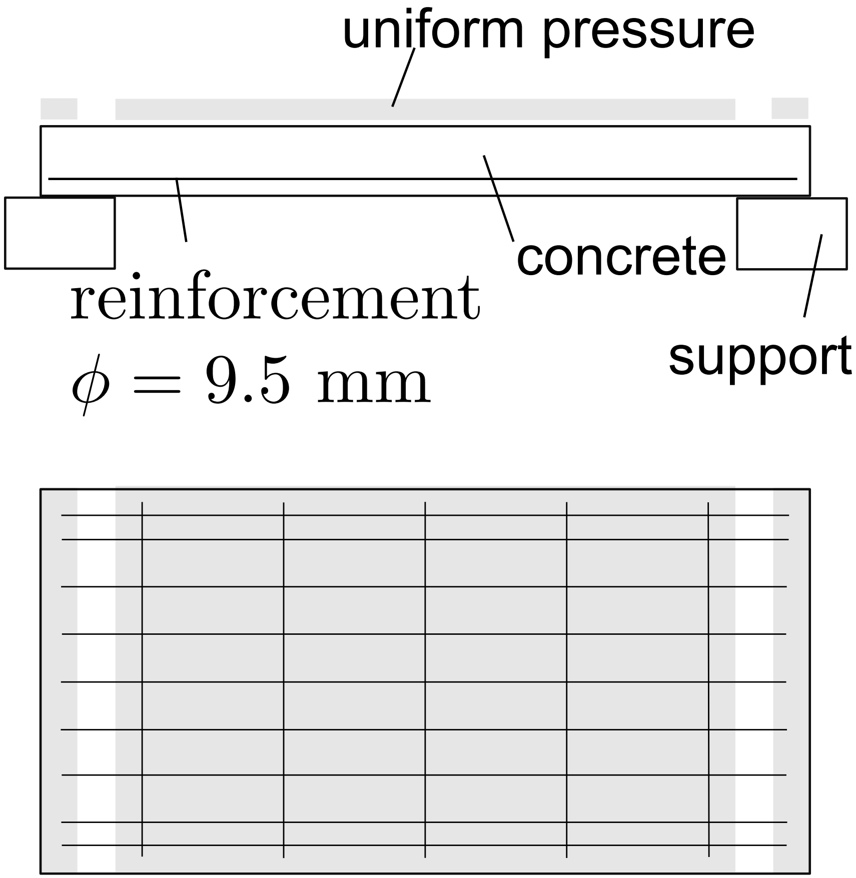
reaction versus time $v = 4.3\ \mathrm{m/s}$



Ref: Ozbolt et al. (2013)

Reinforced slab subjected to blast

Setup:



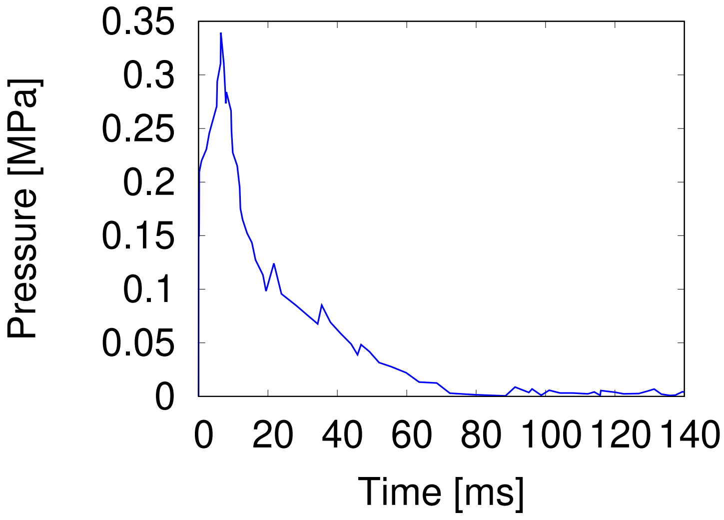
Input:

Exp: $f_c = 34.5$ MPa

$E = 32.5$ MPa

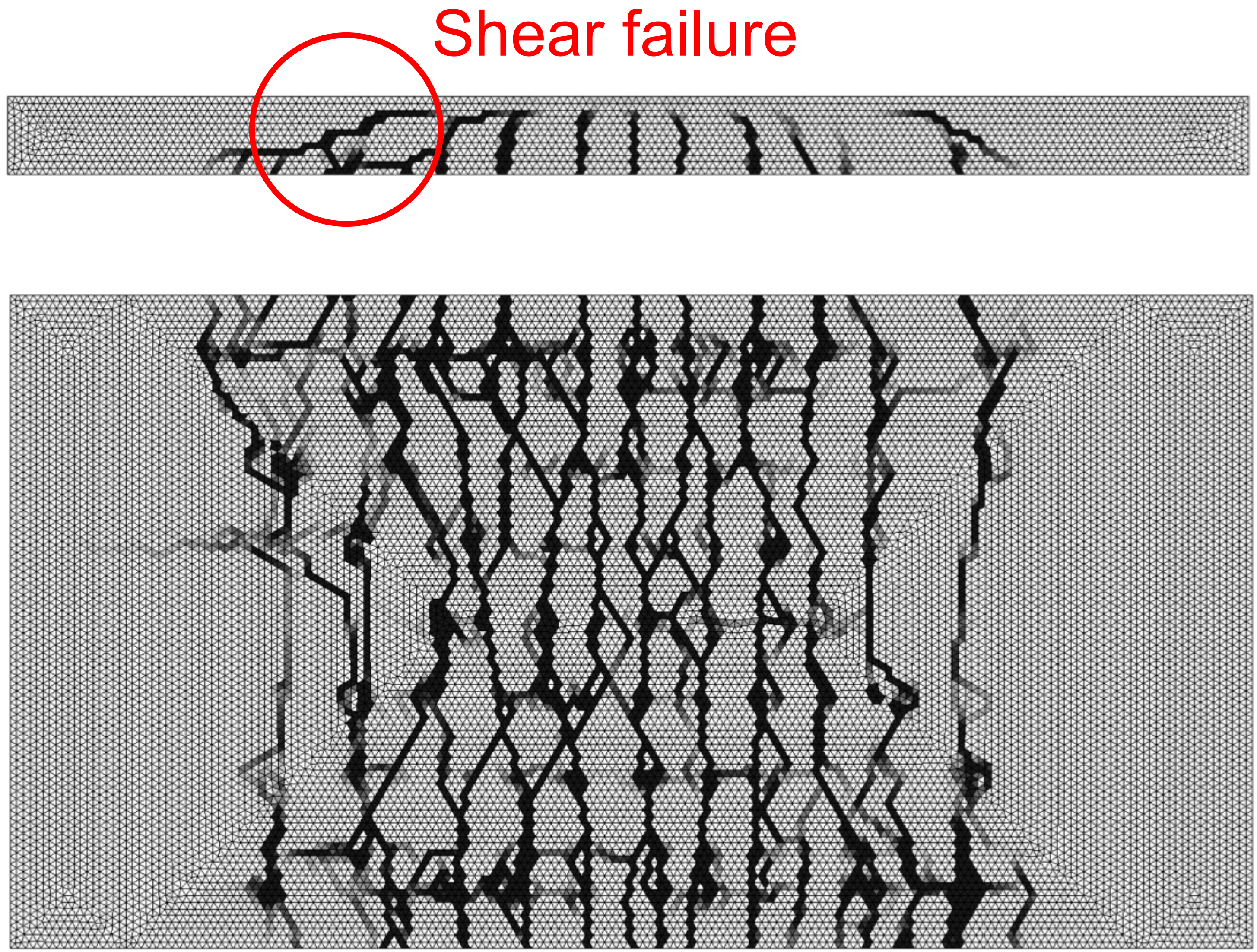
$f_t = 2.7$ MPa

$G_f = 138$ J/m^2



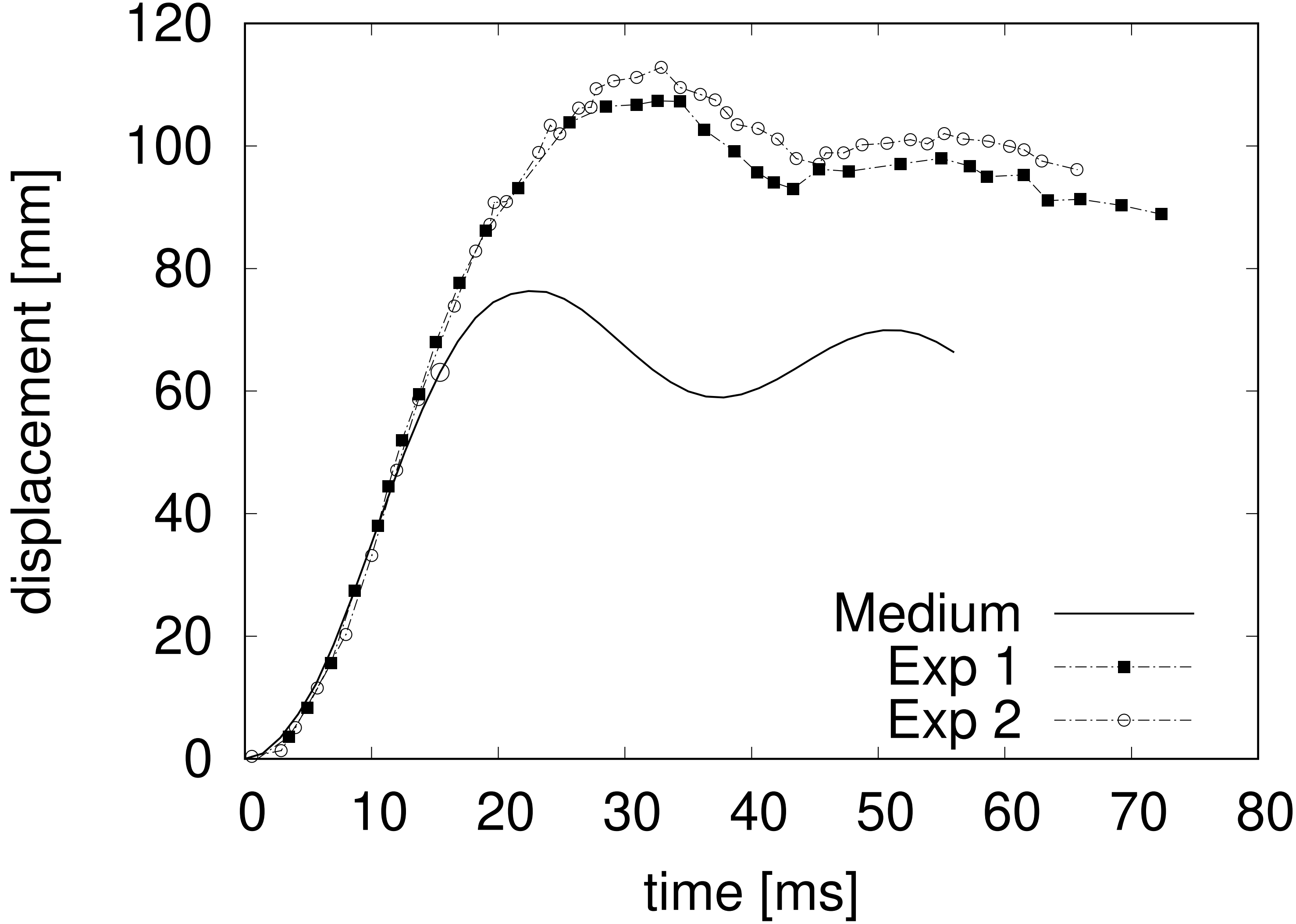
Ref: Thiagarajan and Johnson (2014), Schwer (2014), Ekstrom (2016)

Crack patterns (medium mesh)



■ $w_{\mathrm{c}} > 0.5$ mm

displacement versus time



Ref: Thiagarajan and Johnson (2014)

Conclusions

Extension of CDPM2 to strain rate dependence (rate dependent strength and constant fracture energy):

- Good representation of crack patterns for compact tension test
- Reaction versus time response for compact tension test mesh insensitive
- Initial inelastic response of slab well represented
- Shear capacity of slab underpredicted by model