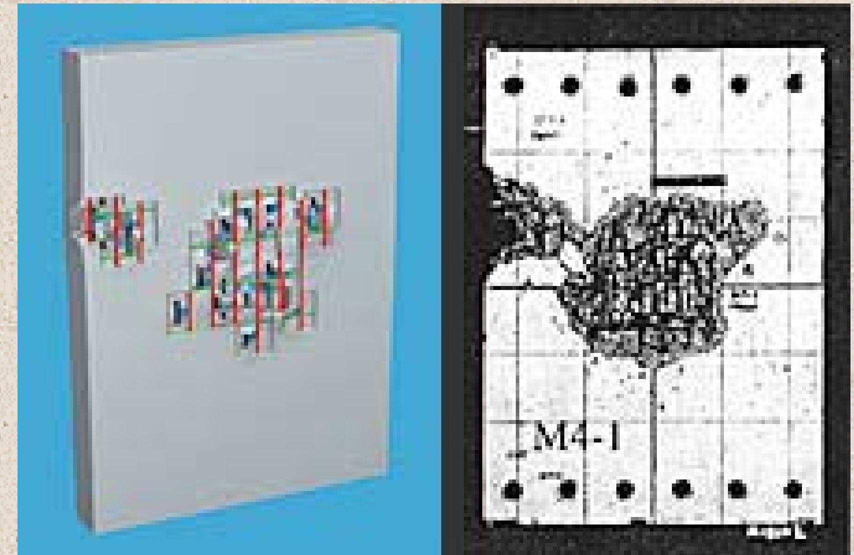
Robustness of Structures
COST Action TU0601
1st Workshop, February 4-5, 2008, ETH Zurich, Zurich, Switzerland

Robustness oriented analysis of concrete structures subjected to blast exposure



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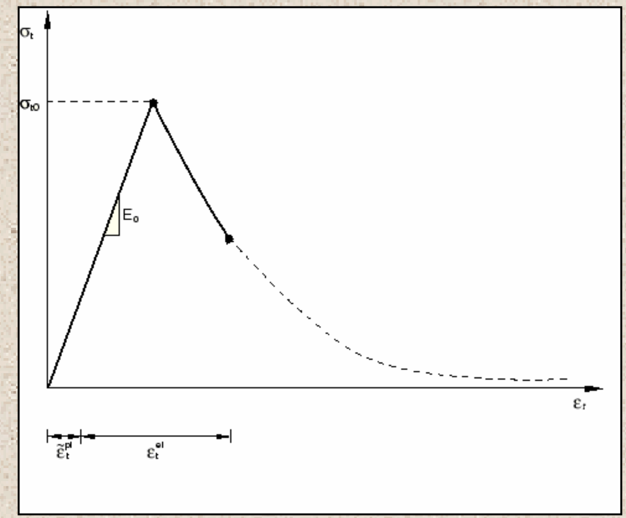
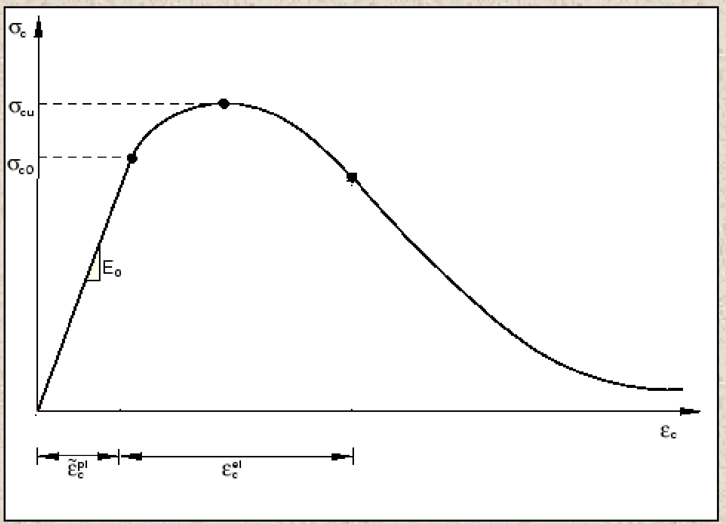
MATERIAL MODEL FOR CONCRETE – BASIC FEATURES

- Different compressive and tensile characteristics;
- Initial linear-elastic behaviour;
- Hardening/softening in compression;
- Softening in tension;
- Damage;
- Rate-dependent behaviour;



Tension



Compression

M.Basista, W.K.Nowacki (Eds), *Modeling of Damage and Fracture Processes in Engineering Materials,* IPPT, 1998

RATE-DEPENDENT PLASTIC-DAMAGE MATERIAL MODEL FOR CONCRETE

- **Continuum Damage Mechanics**
  Kachanov (1958)

- **Helmholtz free energy potential**
  Lubliner (1972), Mazars and Pijaudier-Cabot (1989)

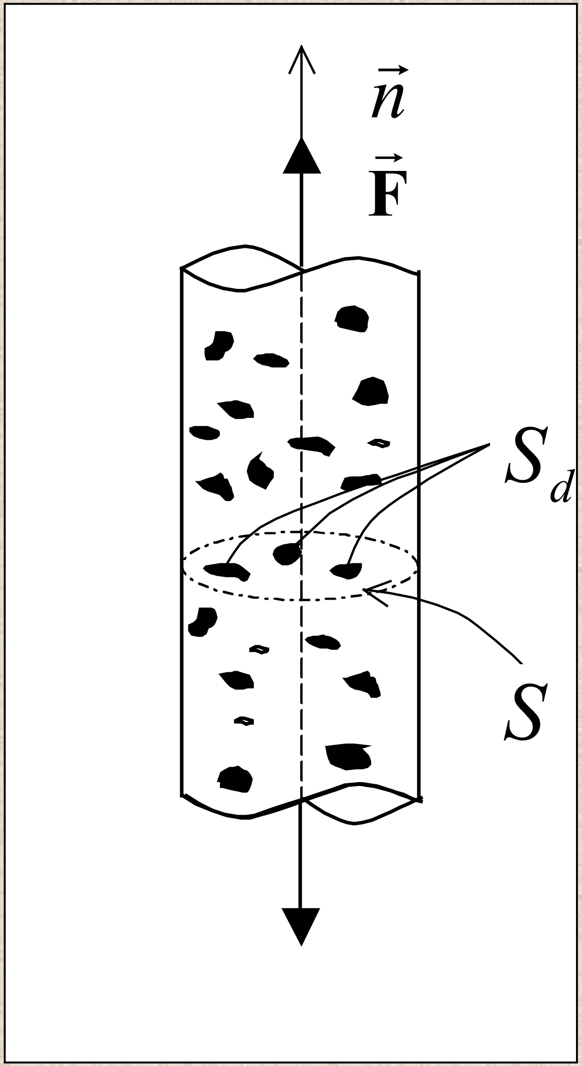
- **Two independent internal scalar damage variables:** d^+, d^-
  (tension, compression)
  Lemaitre (1984)

- ***Effective stress*** **concept**
  Lemaitre and Chaboche (1978)

- **Rate dependent behavior**
  Simo and Ju (1987)

Kachanov, L.M. (1986), Introduction to Continuum Damage Mechanics, *Martinus Nijhoff Publishers*
Lubliner, J. (1972), On the Thermodynamical Foundations of Non-Linear Solid Mechanics, *Int. J. Non-Linear Mech.*, Vol. 7
Mazars, J.; Pijaudier-Cabot, G. (1989), Continuum Damage Theory. Application to Concrete, *J. of Eng. Mech., ASCE,* Vol. 115
Lemaitre, J. (1984), How to Use Damage Mechanics, *Nuclear Engineering and Design*, Vol. 80
Lemaitre, J. (1996), A Course on Damage Mechanics, *Springer*
Simo, J.C.; Ju, J.W. (1987), Strain and Stress Based Continuum Damage Models, *Int. J. Solids Structures, Vol. 23*

Effective stress $\overline{\sigma}$, damage parameter d



$$\sigma = \frac{\vec{\mathrm{F}}}{S}$$

$$\overline{\sigma} = \frac{\vec{\mathbf{F}}}{S - S_d}$$

$$\overline{\sigma} = \frac{\sigma}{1-d}; \qquad d = \frac{S_d}{S}$$

$$0 \leq d \leq 1$$

General 3D representation:

$$\overline{\sigma} = \mathbf{D}_o : (\varepsilon - \varepsilon^p)$$

Helmholtz free energy

$$\Psi(\varepsilon,\varepsilon^p,d^+,d^-) = (1-d^+)\Psi_0^+(\varepsilon,\varepsilon^p) + (1-d^-)\Psi_0^-(\varepsilon,\varepsilon^p)$$

$$\Psi_0^+ = \Psi_0^+(\overline{\sigma}(\varepsilon,\varepsilon^p)) = \frac{1}{2}\overline{\sigma}^+ : \mathbf{D_0^{-1}} : \overline{\sigma}$$

$$\Psi_0^- = \Psi_0^-(\overline{\sigma}(\varepsilon,\varepsilon^p)) = \frac{1}{2}\overline{\sigma}^- : \mathbf{D_0^{-1}} : \overline{\sigma}$$

$$\overline{\sigma}^+ = \langle \overline{\sigma} \rangle = \sum_{i=1}^{3} \langle \overline{\sigma}_i \rangle \, \mathbf{p_i} \otimes \mathbf{p_i}$$

$$\overline{\sigma}^- = \rangle \overline{\sigma} \langle = \sum_{i=1}^{3} \rangle \overline{\sigma}_i \langle \, \mathbf{p_i} \otimes \mathbf{p_i}$$

Characterization of damage

Equivalent tensile stress $$\bar{r}^+ = \sqrt{\bar{\sigma}^+ : \mathbf{D}_0^{-1} : \bar{\sigma}^+}$$

Equivalent compressive stress $$\bar{r}^- = \sqrt{\sqrt{3}(K\bar{\sigma}_{oct}^- + \bar{\tau}_{oct}^-)}$$

$$\bar{\sigma}_{oct}^- = \frac{1}{3} tr(\bar{\sigma}^-); \quad \bar{\tau}_{oct}^- = \sqrt{\frac{2}{3} J_2}; \quad K = \sqrt{2}\,\frac{1 - R_0}{1 - 2R_0}; \quad R_0 = \frac{f_{0_{2D}}^-}{f_{0_{1D}}^-}$$

Damage criteria:

$$g^+(\bar{r}^+, r^+) = \bar{r}^+ - r^+ \leq 0$$

$$g^-(\bar{r}^-, r^+) = \bar{r}^- - r^- \leq 0$$

Evolution of damage variables (Oliver, 1990)

Tension:

$$\dot{d}^{+} = \dot{\bar{r}}^{+} \frac{\partial G^{+}(\bar{r}^{+})}{\partial \bar{r}^{+}} = \dot{G}^{+} \geq 0$$

$$d^{+} = 1 - \frac{r_0^{+}}{\bar{r}^{+}} e^{A^{+}(1 - \frac{\bar{r}^{+}}{r_0^{+}})}$$

Compression:

$$\dot{d}^{-} = \dot{\bar{r}}^{-} \frac{\partial G^{-}(\bar{r}^{-})}{\partial \bar{r}^{-}} = \dot{G}^{-} \geq 0$$

$$d^{-} = 1 - \frac{r_0^{-}}{\bar{r}^{-}}(1 - A^{-}) - A^{-} e^{B^{-}(1 - \frac{\bar{r}^{-}}{r_0^{-}})}$$

Olivier, J.; Cervera, M.; Oller, S.; Lubliner, J. (1990), Isotropic Damage Models and Smeared Crack Analysis of Concrete, ***Proc. 2nd Int. Conf. on Comp. Aided Analysis and Design of Conc. Struct.,*** **Zell am See, Austria**

Evolution of plastic strain tensor

$$\dot{\varepsilon}^p = \beta E H(\dot{d}^-) \frac{\langle \overline{\sigma} : \dot{\varepsilon} \rangle}{\overline{\sigma} : \overline{\sigma}} \mathbf{D_0^{-1}} : \overline{\sigma}$$

$$\beta - material\ parameter: \qquad \varepsilon^p = \beta(\varepsilon - \varepsilon_0)$$

$$H(\dot{d}^-) - Heaviside\ function$$

Cauchy stress

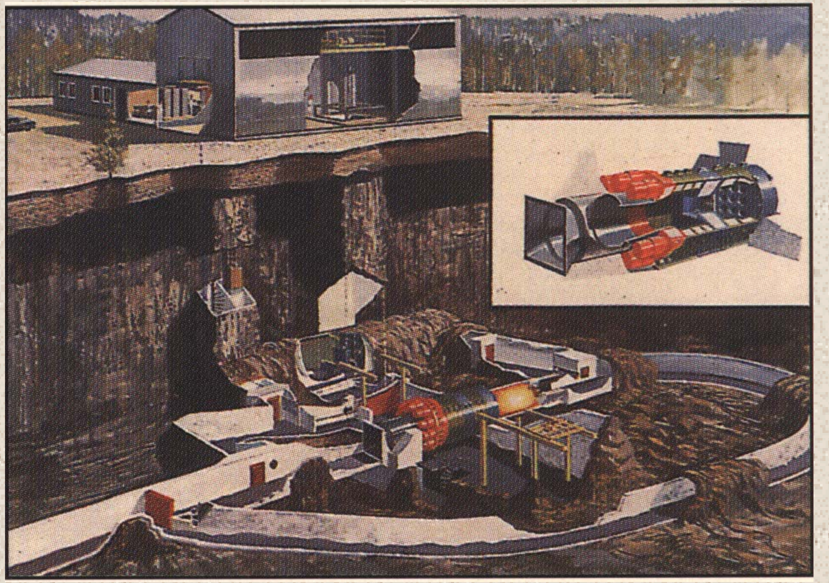
$$\sigma = \frac{\partial \Psi}{\partial \varepsilon}; \qquad \varepsilon = \varepsilon^e + \varepsilon^p$$

$$\frac{\partial \Psi}{\partial \varepsilon^e} = \sigma = (1 - d^+)\overline{\sigma}^+ + (1 - d^-)\overline{\sigma}^-$$

Yankelevsky, D.Z,; Reinhardt, H.W (1987), Model for Cyclic Compressive Behavior of Concrete, *J. of Struct. Eng., ASCE,* Vol. 113

CONCRETE SLAB SUBJECTED TO BLAST LOAD

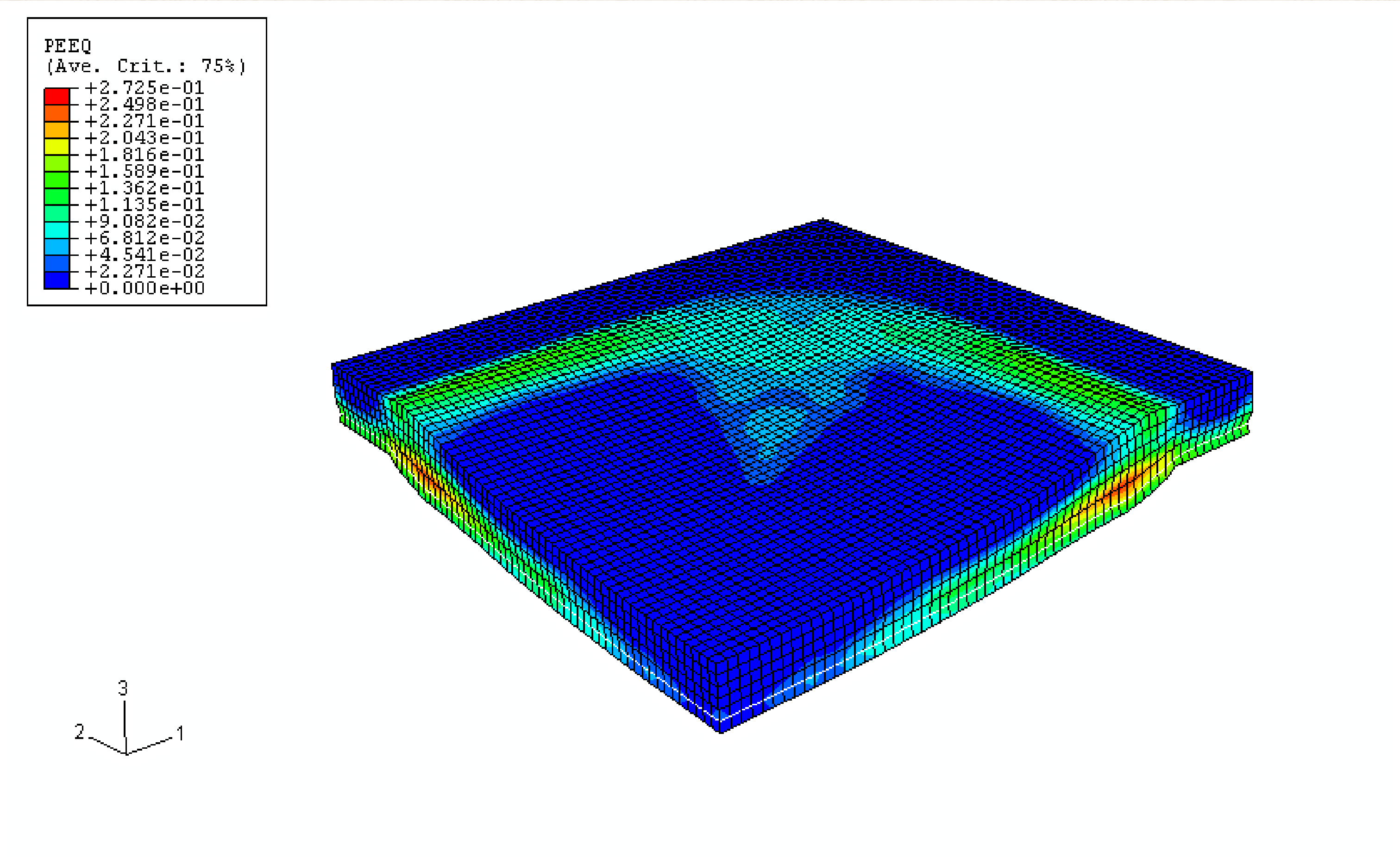
Lennart Agardh, FOA, National Defence Research Establishment,
Märsta, Sweden, 1996



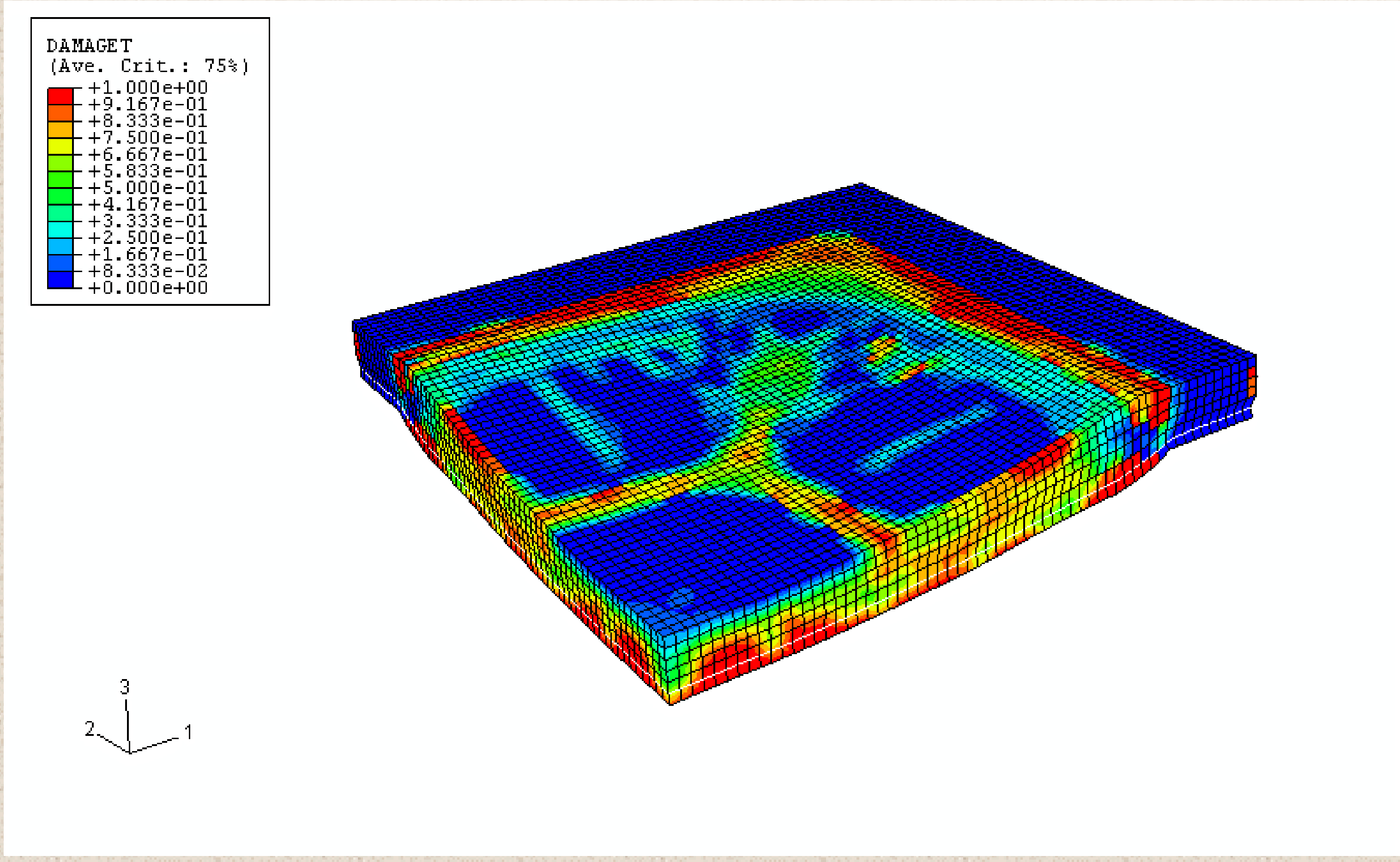
- Square (1.2 x 1.2 x 0.06 m), reinforced, clamped slabs subjected to blast loading in a shock tube.
- Material: OPTIROC, steel fibre concrete, fibres Dramix ZC30/50
- Reinforcement in both directions: Φ8/0.08 m.
  Steel KS40 (σ_y = 400 MPa).
- Charges (plastic): 0.25 / 0.5/ 0.75 / 2.0 / 3.0 / 4.0 / 5.0 kg
  Distance: 20 m.

Slab D1, upper surface. Blast load 5 kg

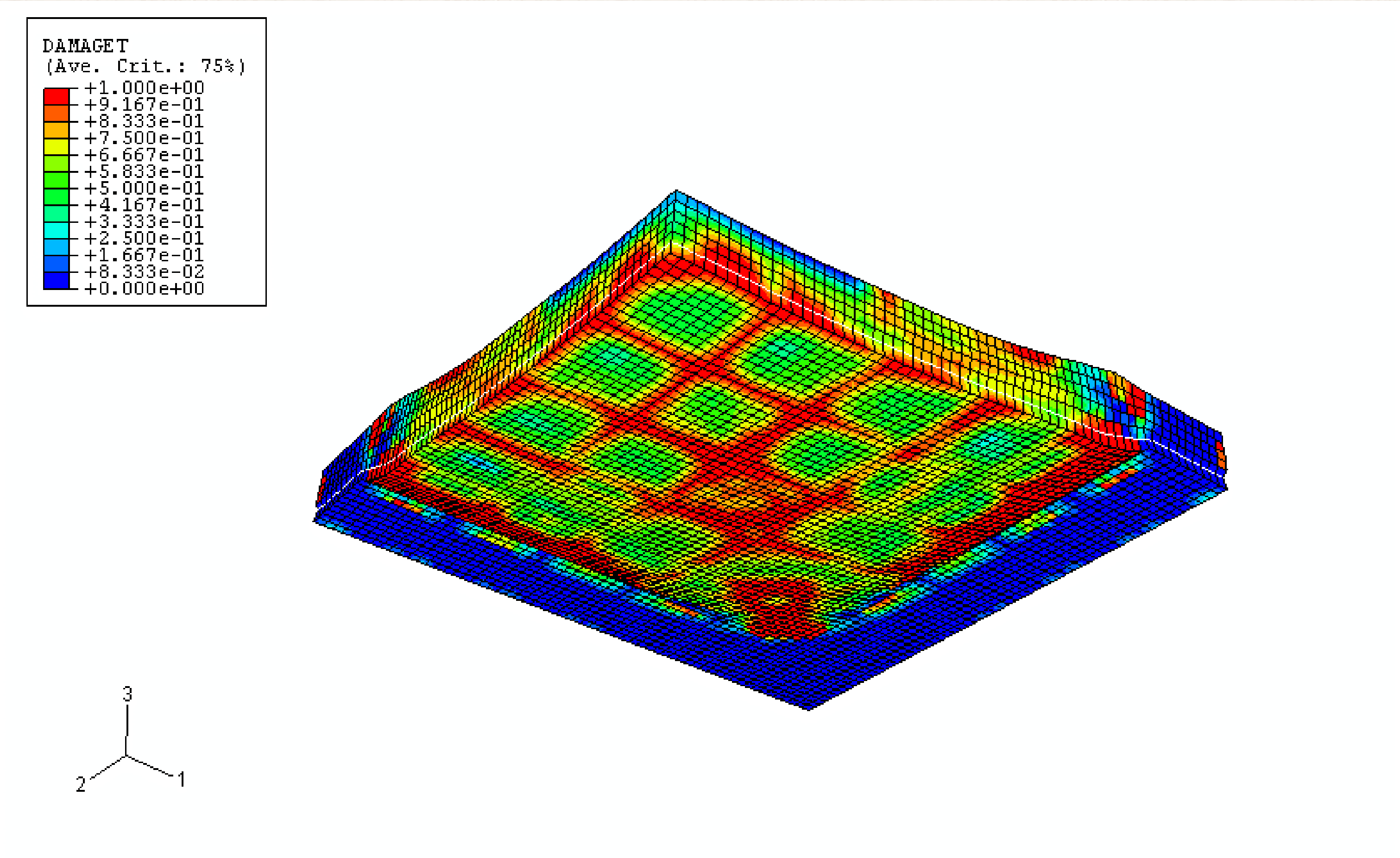
Test D1: charge 5 kg, PEEQ



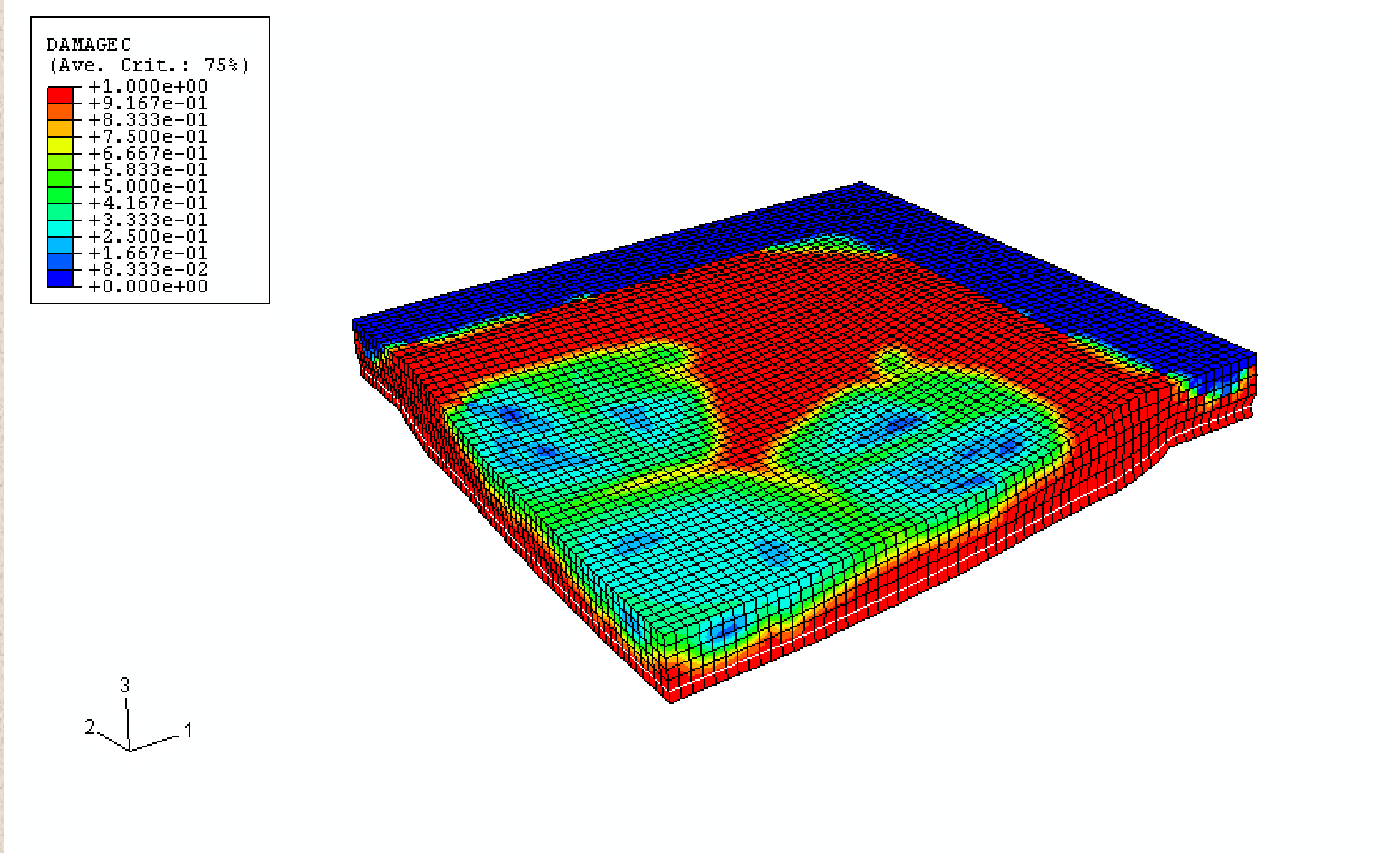
Test D1: charge 5 kg, DT



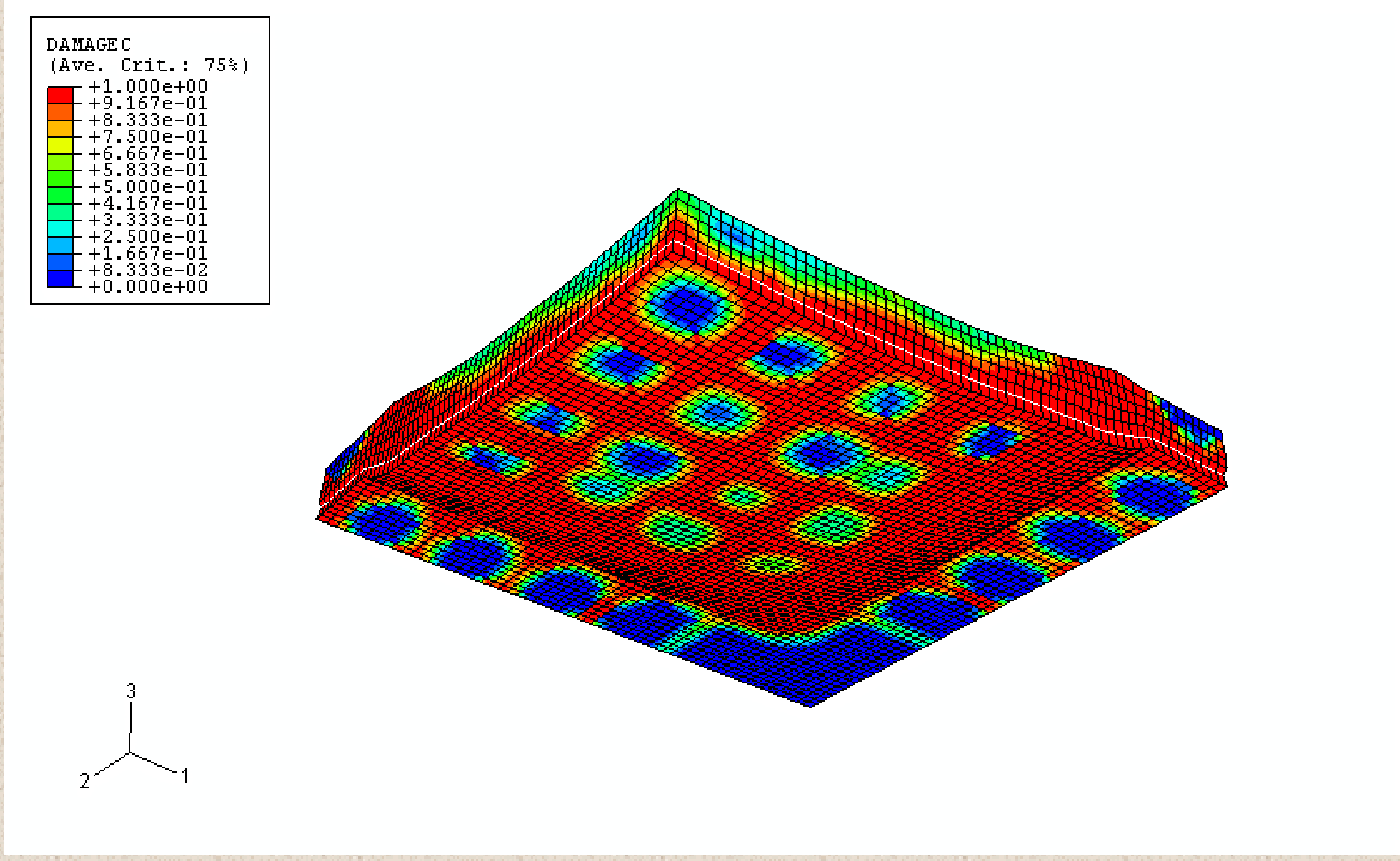
Test D1: charge 5 kg, DT

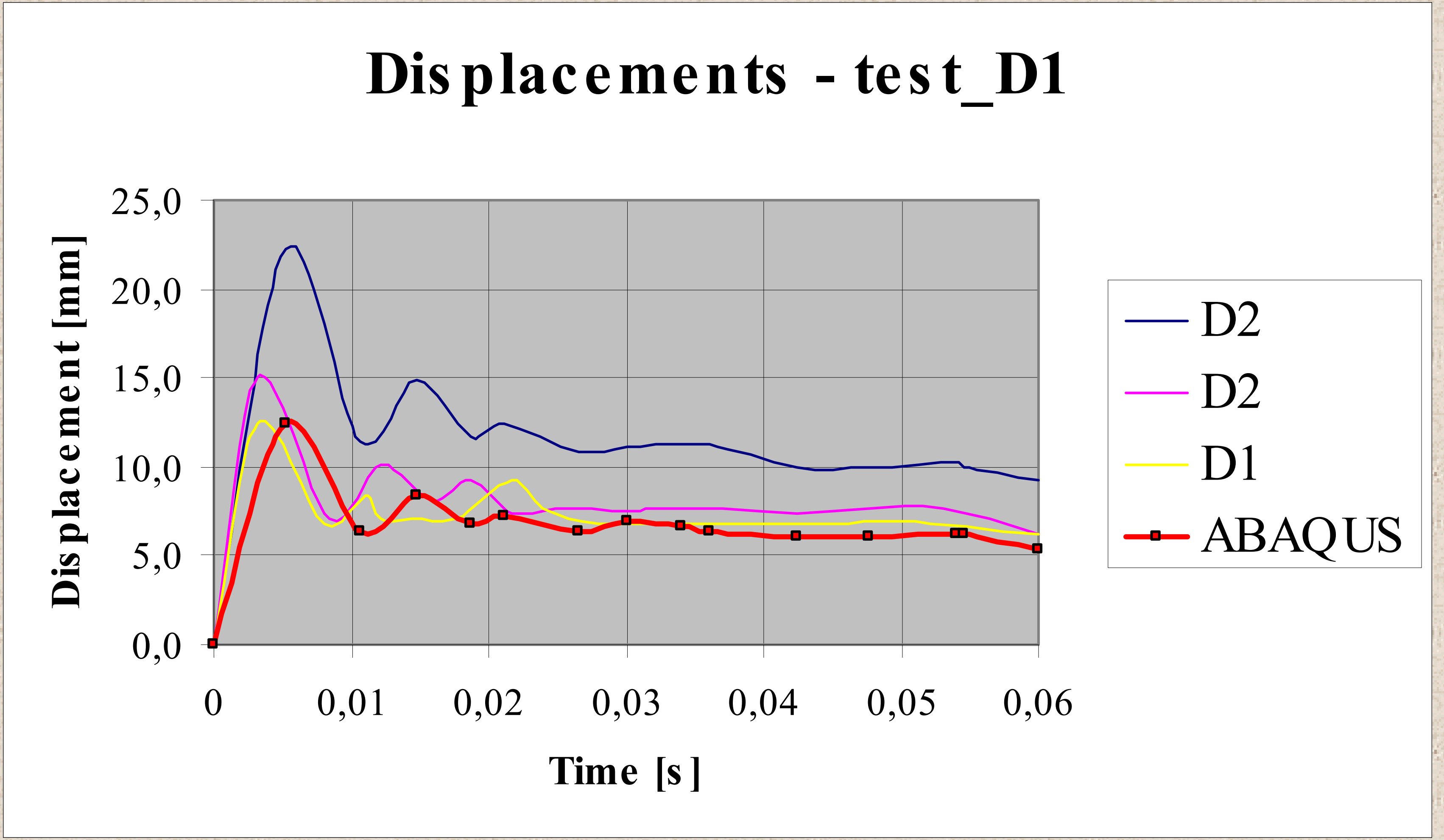


Test D1: charge 5 kg, DC



Test D1: charge 5 kg, DC




Displacements - test_D1
Displacement [mm]
25,0
20,0
15,0
10,0
5,0
0,0
0
0,01
0,02
0,03
0,04
0,05
0,06
Time [s]
D2
D2
D1
ABAQUS

CONCLUSIONS

- Relatively simple material models for concrete, based on scalar representation of damage, are useful for many practical applications
- Further verification of the described model is needed for structures with high level of damages
- Optimisation of subroutine VUMAT is necessary in order to reduce the time of analysis
- Presence of rebar should be modeled in a more effective way
- For many problems it is necessary to model the whole system: structure-environment-explosive. Further study on this problem is indispensable

* D.Kraus, J.F.Wunderlich, K.Thoma, The interaction of high explosive detonation with concrete structures, Proc. of EURO-C International Conference, Innsbruck, 1994