Cellular Automata Finite Element (CAFE) modelling of transitional ductile-brittle fracture in steel

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Local approach to fracture

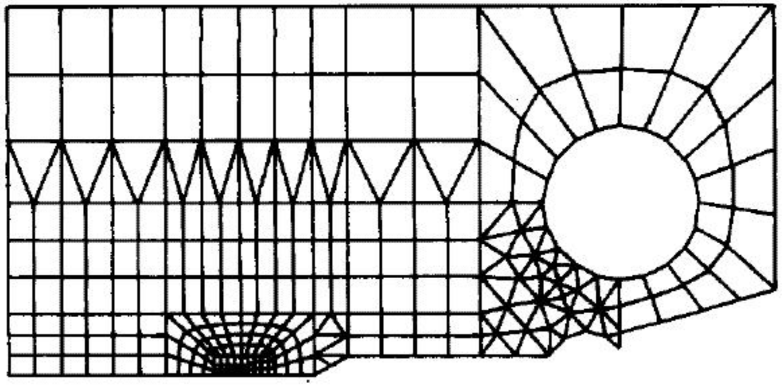


Fig. 8. Mesh of CT specimen.

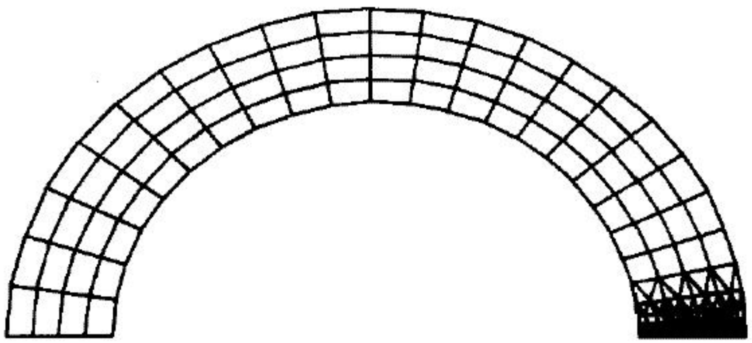


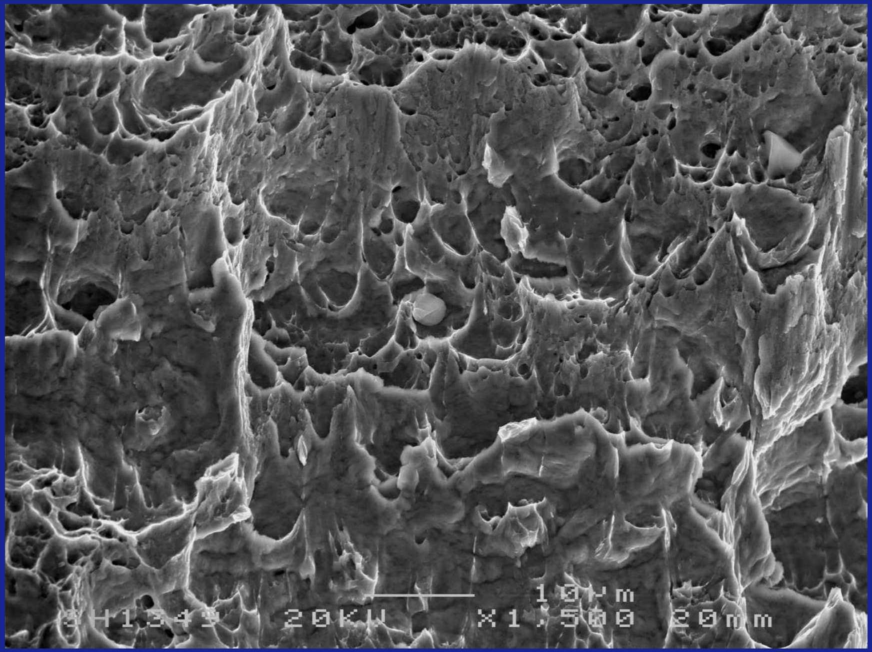
Fig. 9. Mesh of the cylinder.

E. Eripret, G. Rousselier / Nuclear Engineering and Design 152 (1994) 11-18

Successful prediction of 4 NESC spinning cylinder tests, i.e. the amount of ductile crack growth before final fracture, time to fracture, etc.

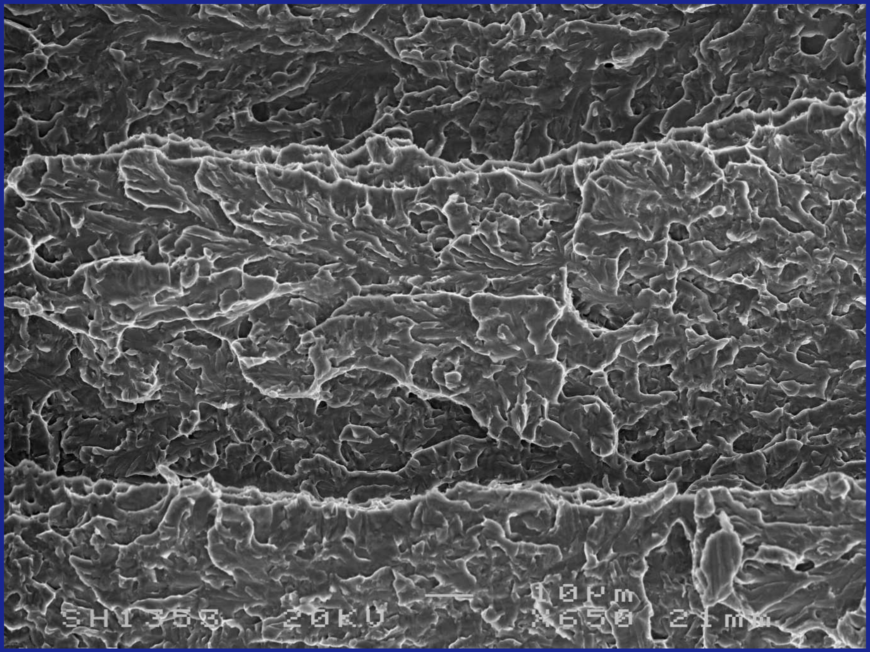
Local approach: FE size meaning

Ductile fracture



FE size $= L_D$

Brittle fracture



FE size $= L_B$

FE fracture modelling: three problems

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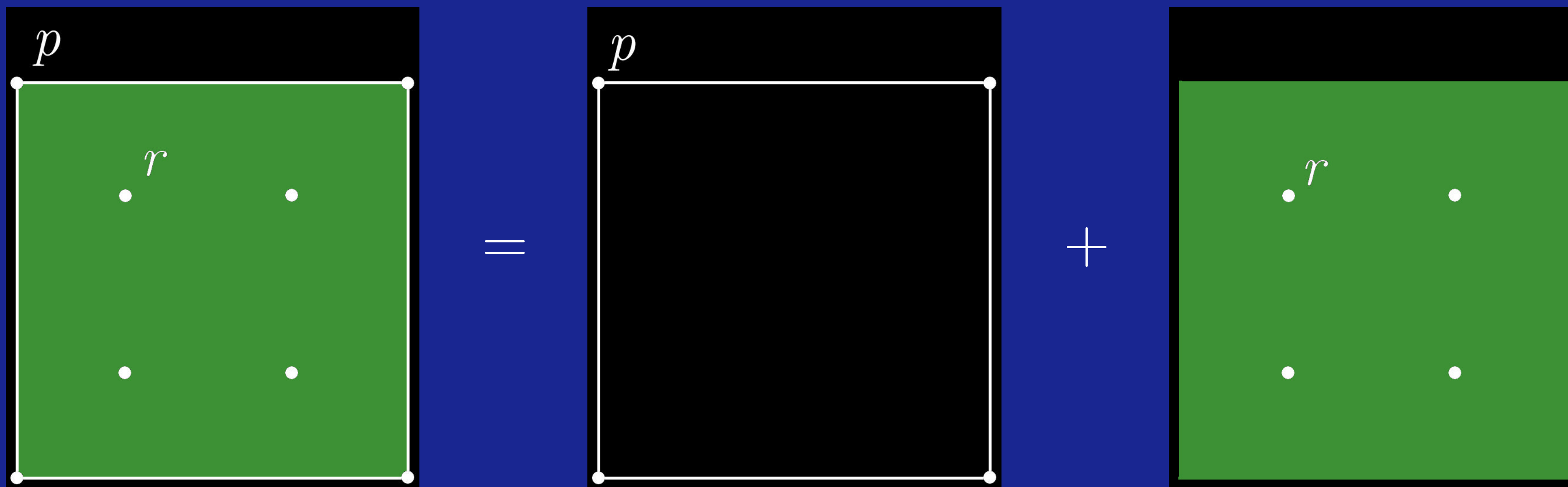
The source: FE is a *material* and a *structural* unit simultaneously

Solution: remove material from FE

Material FE | Structural FE | Material



D_{ijkl}, $N^p(\xi_k)$, $\dot{\sigma}^r_{ij} = f(\dot{\epsilon}^r_{ij})$ | D_{ijkl}, $N^p(\xi_k)$ | $\dot{\sigma}^r_{ij} = f(\dot{\epsilon}^r_{ij})$

All material information is moved from FE into an appropriate number of Cellular Automata arrays.

Hence a CAFE model.

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- A limited number of cell states e.g. $alive$, $\Upsilon = 1$ or $dead$, $\Upsilon = 0$
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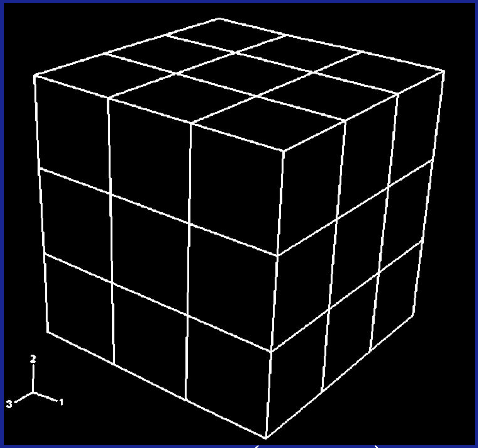
- Cells do not deform, they only change state

The CAFE model: 3 steps

1. Material as CA

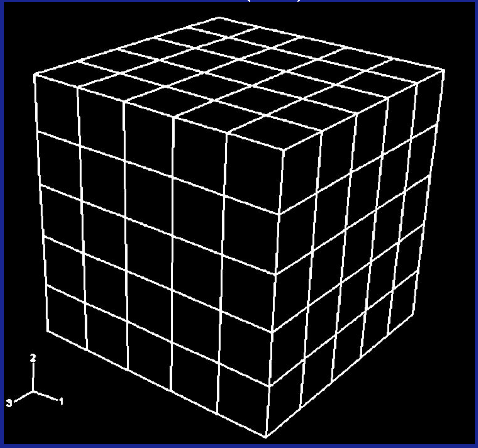
Ductile CA



$$\downarrow \Upsilon_{m(D)}(t_{i+1})$$

$$\Upsilon_{m(B)}(t_{i+1}) \uparrow$$

Brittle CA



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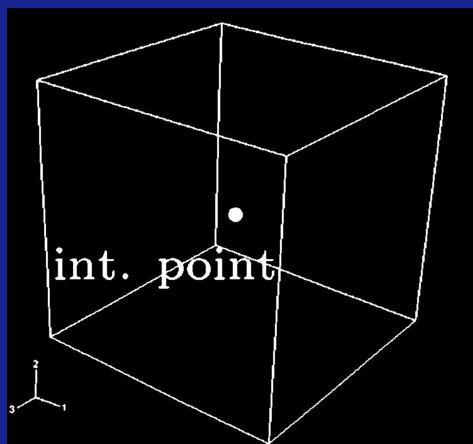
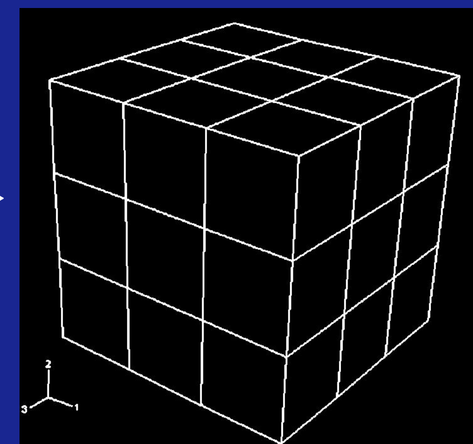


FE

$\beta(t_{i+1}), \sigma_{ij}(t_i) \rightarrow$



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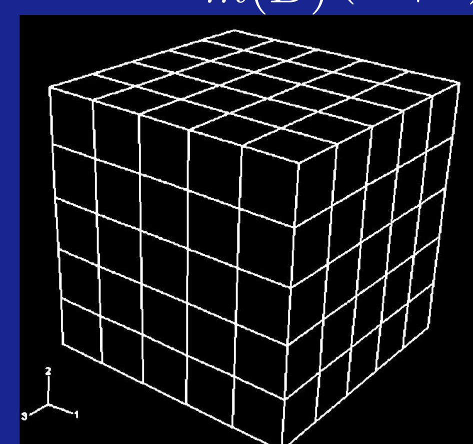

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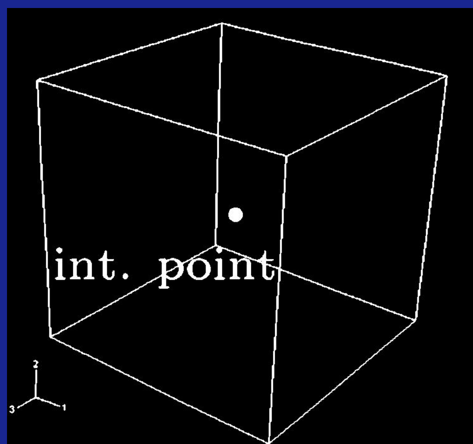

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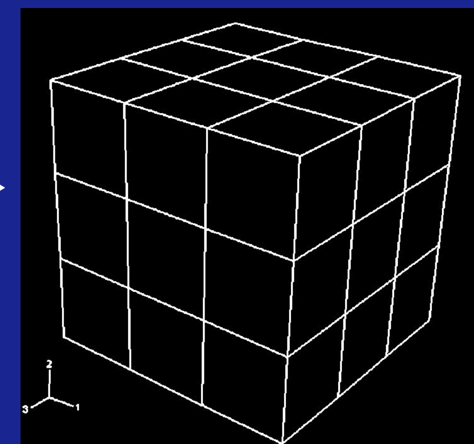
$\beta(t_{i+1}), \sigma_{ij}(t_i) \longrightarrow$

$\longleftarrow Y_a(t_{i+1})$



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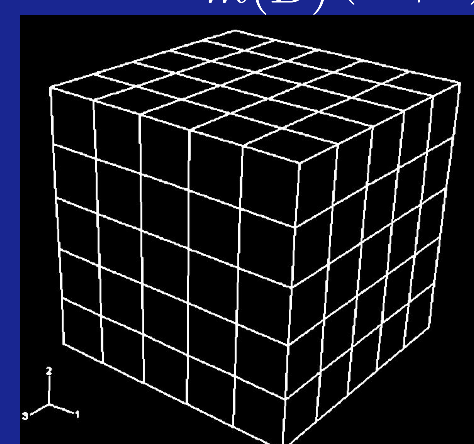

The FE part

- Rousselier (1981) ductile damage model

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- Each step the volumetric and the deviatoric plastic strain increments, $\Delta\epsilon_m^p$ and $\Delta\epsilon_{eq}^p$, and the damage variable, β, are updated:

$$\Delta\epsilon_m^p - \Delta\epsilon_{eq}^p \frac{B(\beta)}{3\sigma_1} Dexp\left(\frac{\sigma_m}{\rho\sigma_1}\right) = 0$$

$$\frac{\sigma_{eq}}{\rho} - H\left(\epsilon_{eq}^p\right) + B(\beta)\, Dexp\left(\frac{\sigma_m}{\rho\sigma_1}\right) = 0$$

$$\sigma_m = \sigma_m^e - 3K\Delta\epsilon_m^p$$

$$\sigma_{eq} = \sigma_{eq}^e - 3G\Delta\epsilon_{eq}^p$$

$$\Delta\beta = \Delta\epsilon_{eq}^p Dexp\left(\frac{\sigma_m}{\rho\sigma_1}\right);\quad \rho(\beta) = \frac{1}{1 - f_0 + f_0 exp\beta};\quad B(\beta) = \frac{\sigma_1 f_0 exp\beta}{1 - f_0 + f_0 exp\beta}$$

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- $\beta(t_{i+1})$ calculated at the FE level is distributed across all ductile cells
- The ductile failure criterion: a cell m is considered dead if $\beta^{m}(t_{i+1}) \geq \beta_{\mathrm{F}}^{m}$

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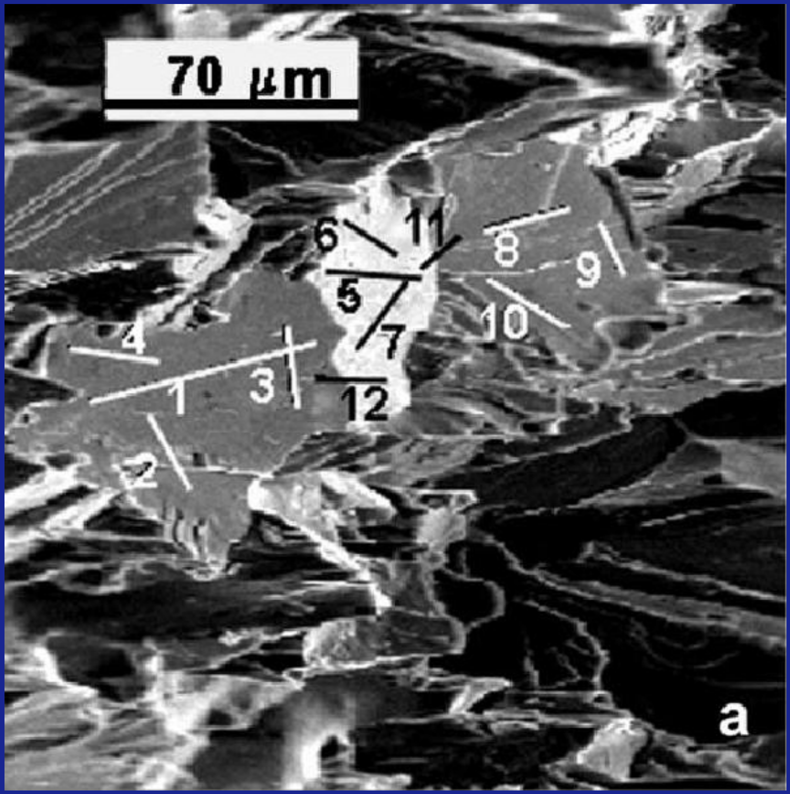
- A crack arrest will occur if $|\alpha^m - \alpha^l| \geq \theta_F$

Grain misorientation, θ



Bhattacharjee and Davis (2002) Scripta materialia 47, 825-831

Brittle fracture can propagate through grains with small θ

But if θ is large, crack deviation or even arrest might occur

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- CAFE does true coupled ductile–brittle modelling.
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- CAFE simulates a progressive brittle fracture propagation.
  CAFE is NOT a weakest link model
- CAFE can simulate crack arrest, predict the cleavage initiation sites, estimate the shape of the brittle area.
  The weakest link model cannot

CAFE implementation

- The user material subroutine VUMAT for the Abaqus/Explicit version 6.2 FE code

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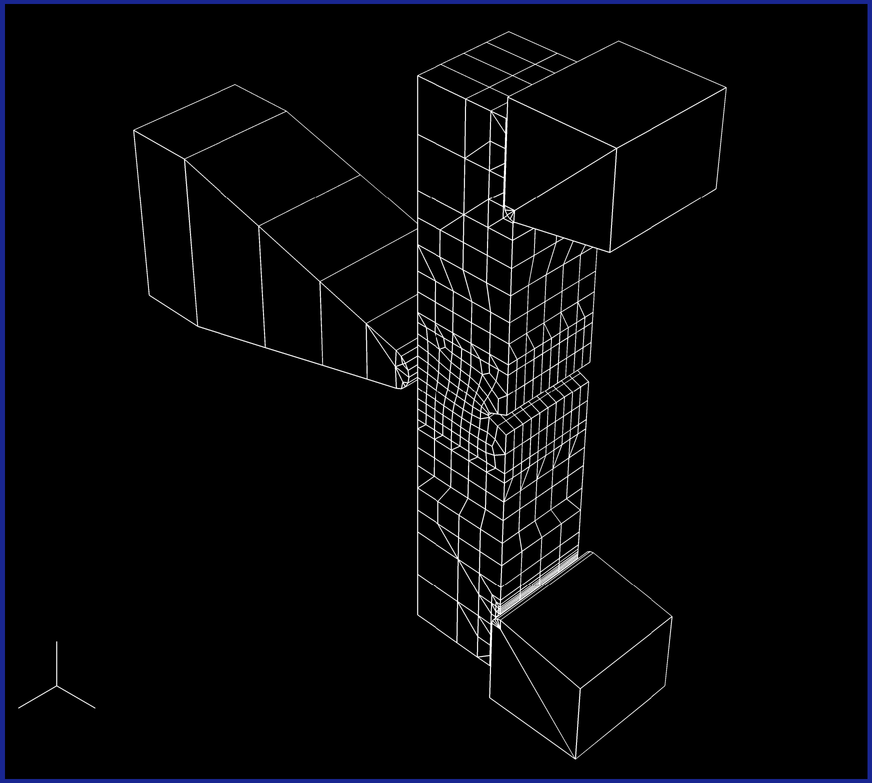
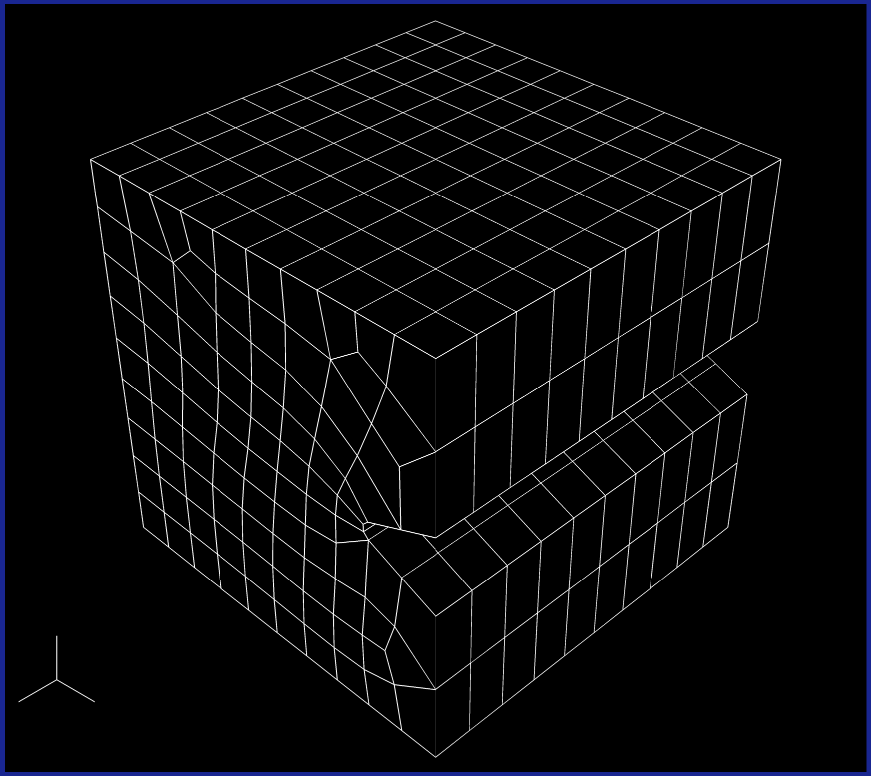
Example: the Charpy test



Full FE model

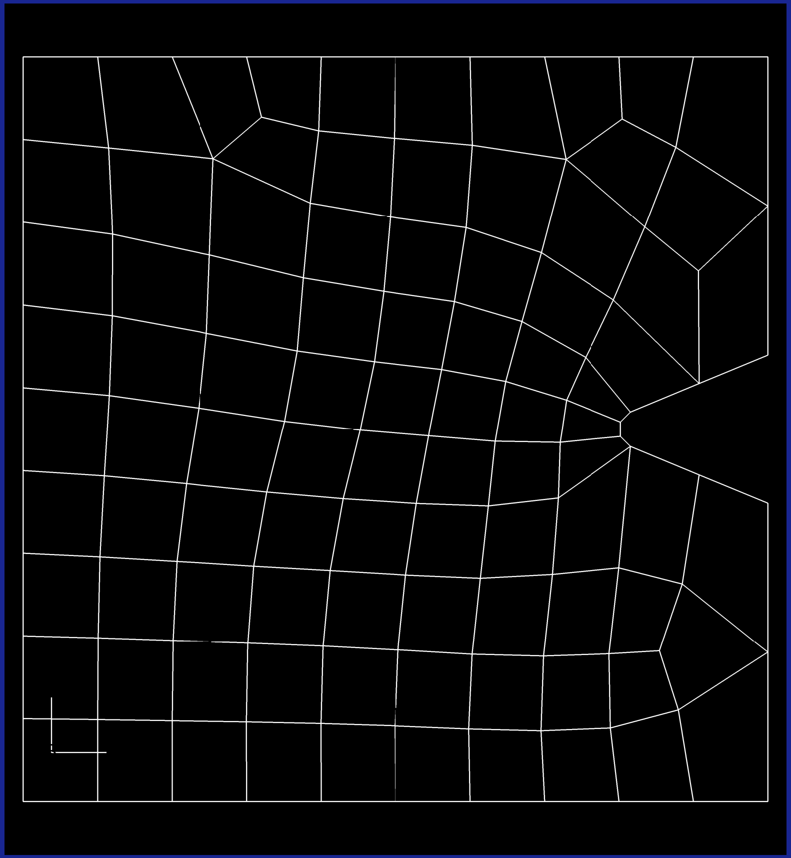


The damage zone, 900 FEs

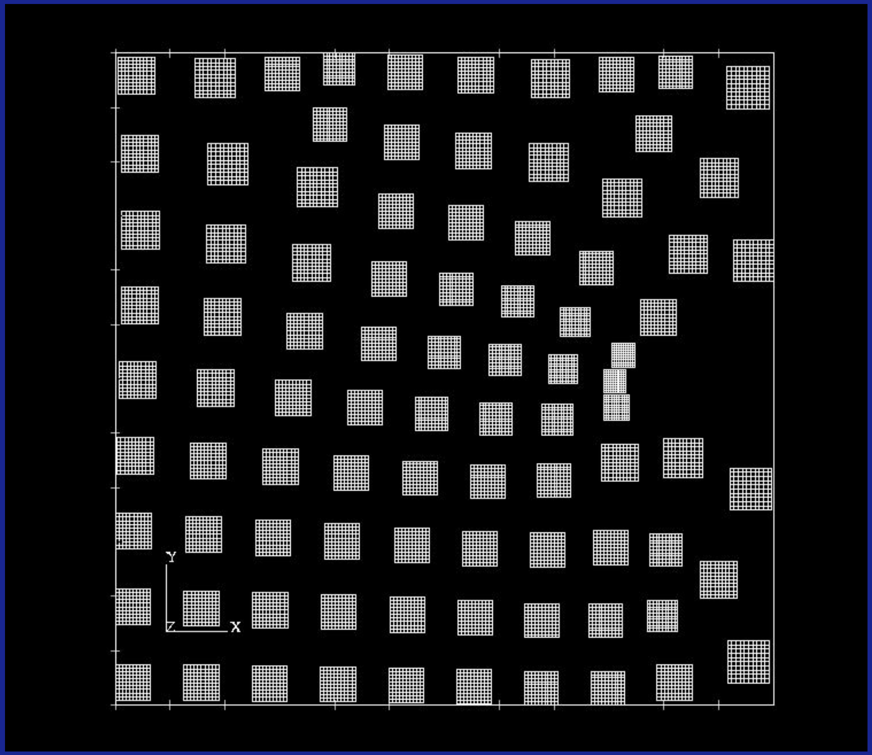
112,500 ductile and 900,000 brittle cells

Takes 3 hours on Pentium 4, 2.4 GHz

Modelling results on the CA scale

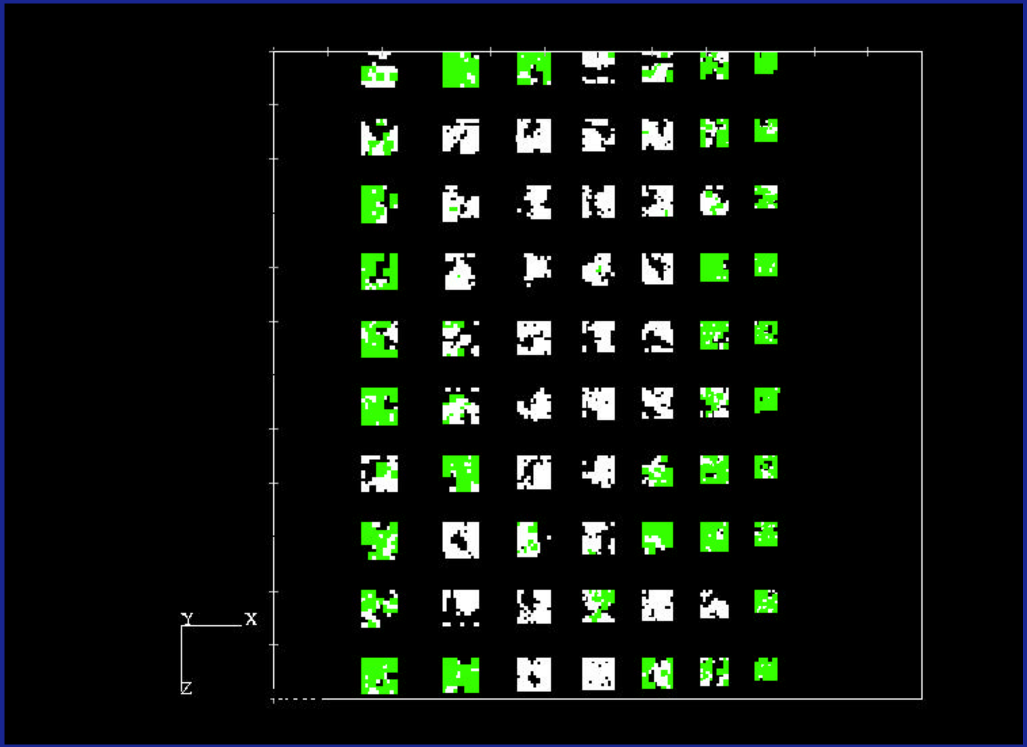


FE mesh of the damage zone

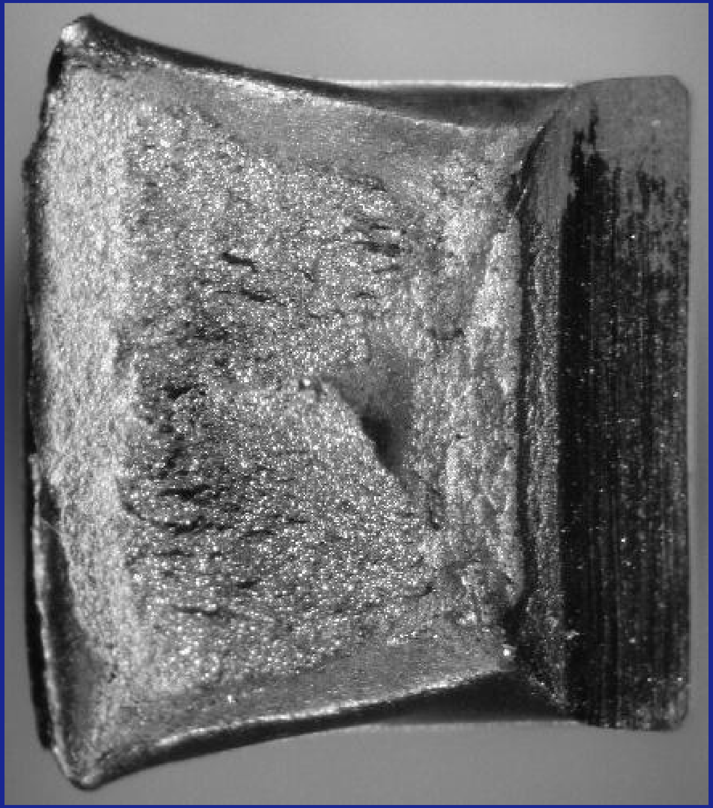


Corresponding brittle CA blocks

Fracture surface at T=$-50°$C

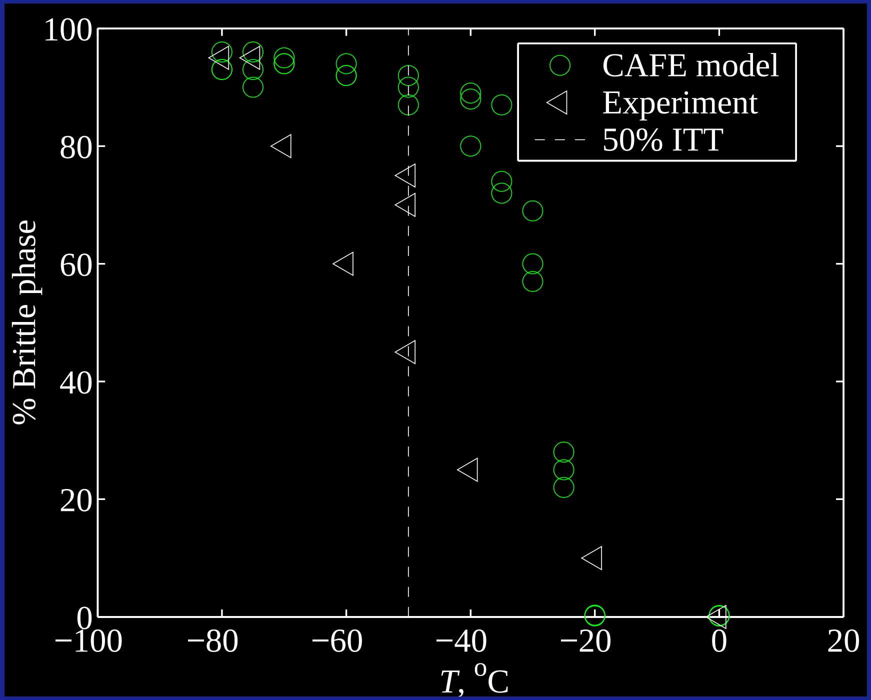


CAFE model
Brittle phase is 54%

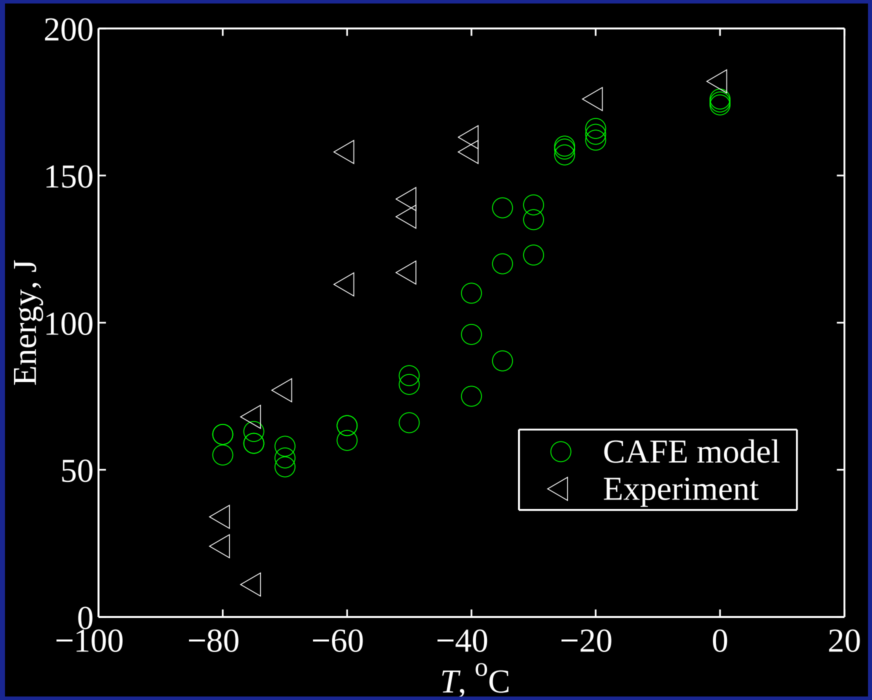


Experiment
Brittle phase is 70%

Modelling results on the FE scale

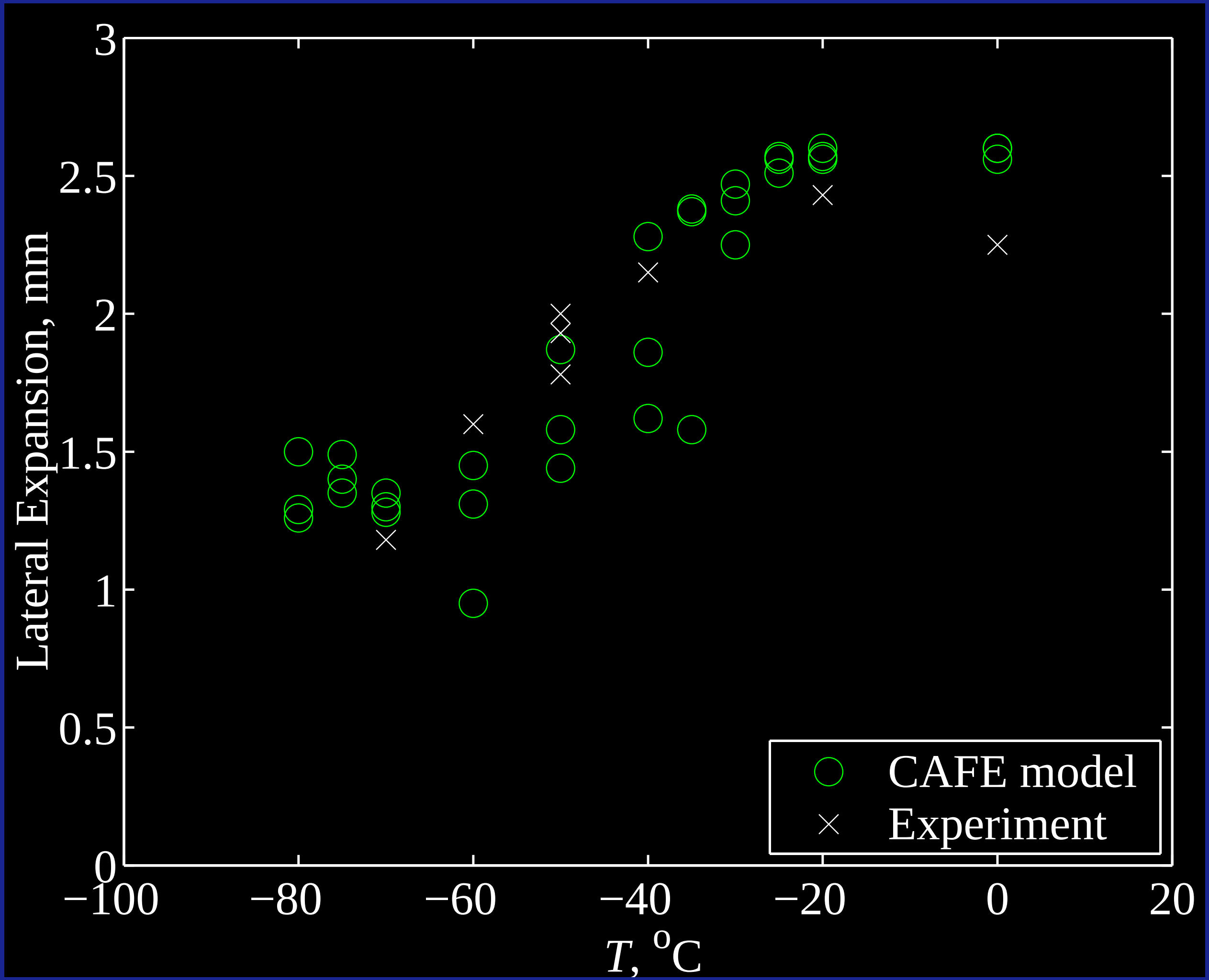


Brittle phase



Energy absorbed

Modelling results on the FE scale



Charpy lateral expansion data

Conclusions

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- can predict crack arrest
- can simulate scatter in experimental data