"Local approach" to determine fracture toughness from small punch test

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1. Introduction

- History
  - Manahan (1981): first small punch sample
  - Baik (1983): fracture energy; relation T_{sp} vs. FATT
  - Schwant (1985): relation between FATT and K_{IC}
  - Mao (1987): empirical formulas for K_{IC} and J;
  - JAERI (1988): first guideline in SPT
  - Foulds (1995): FEM analyses in EPRI reports
  - Copernicus project (1994-1997): creep SPT in Europe
  - ASTM (2002): first standard F2183
  - CEN (2006): European guideline
- Review existing methods
- Put forward new approach
- Verification using uni-axial tests and CT tests

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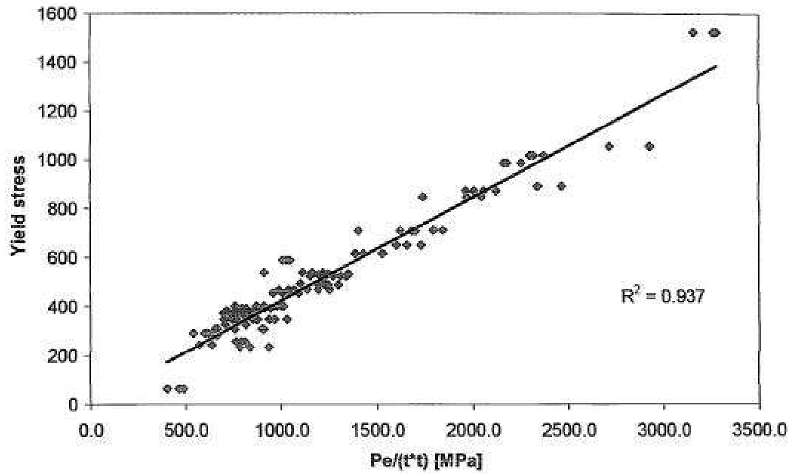
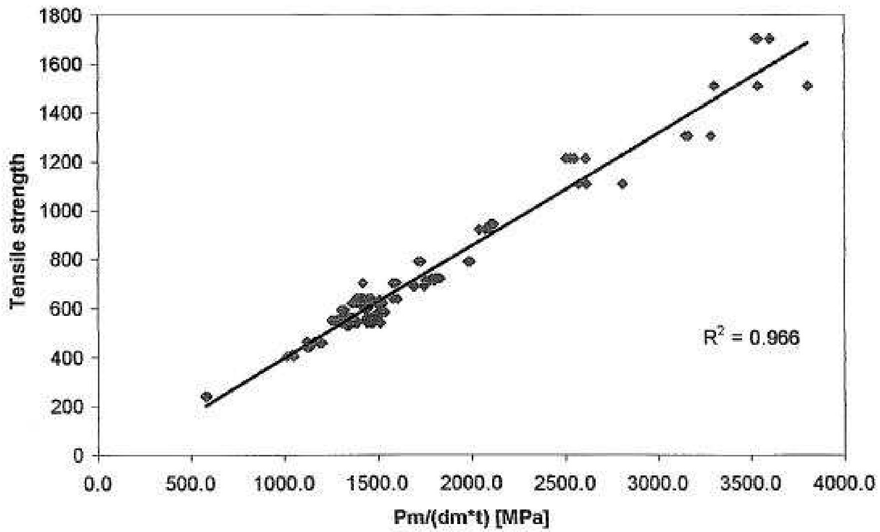
2 Determination of strength/toughness

2.1 Regression approach

2.1.1 Experimental calibration (Eto, 1993; Ostrava, Czech)



$$\sigma_y = f[F_e / t^2]$$



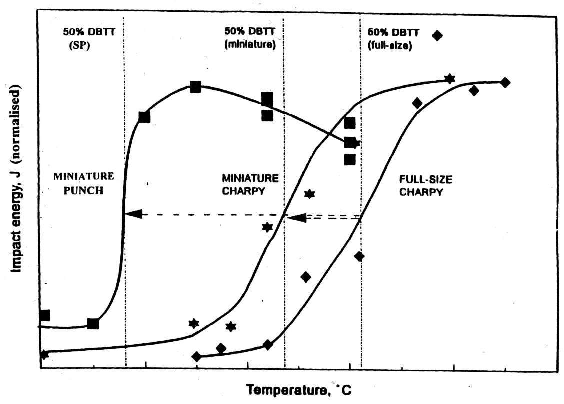
$$\sigma_u = g[F_m / (2a.t)]$$

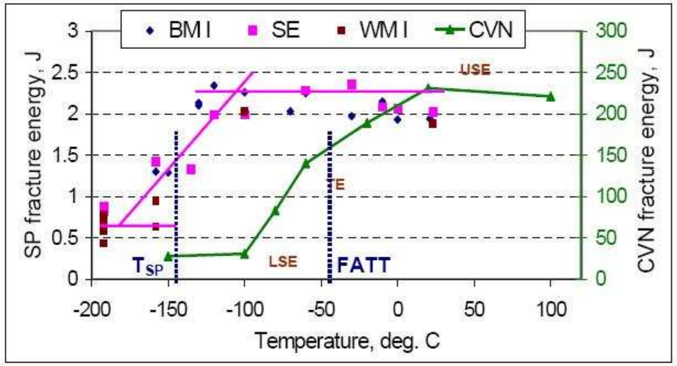
- Comments:

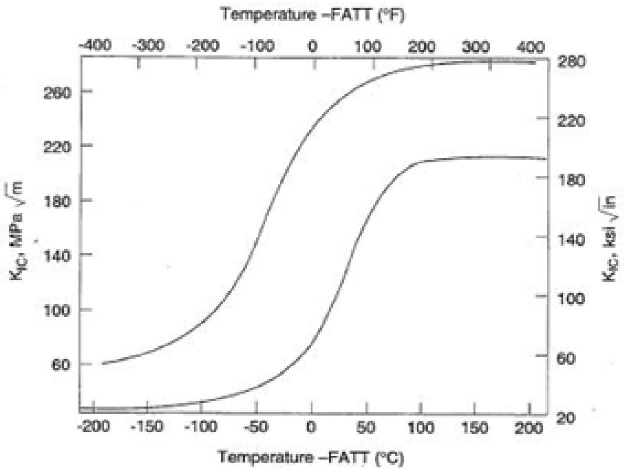
  - large amount of laboratory work

  - Strength determination only

2.1.2 Two step method (Baik, 1983; Schwant ,1985)







$$T_{sp} = \alpha \times FATT$$

- Correlations for steels in power plants (Foulds, Viswanathan, 1995)
- Comments:
  - material dependent
  - scatter bound too big (± 50%)

2.2 JAERI method

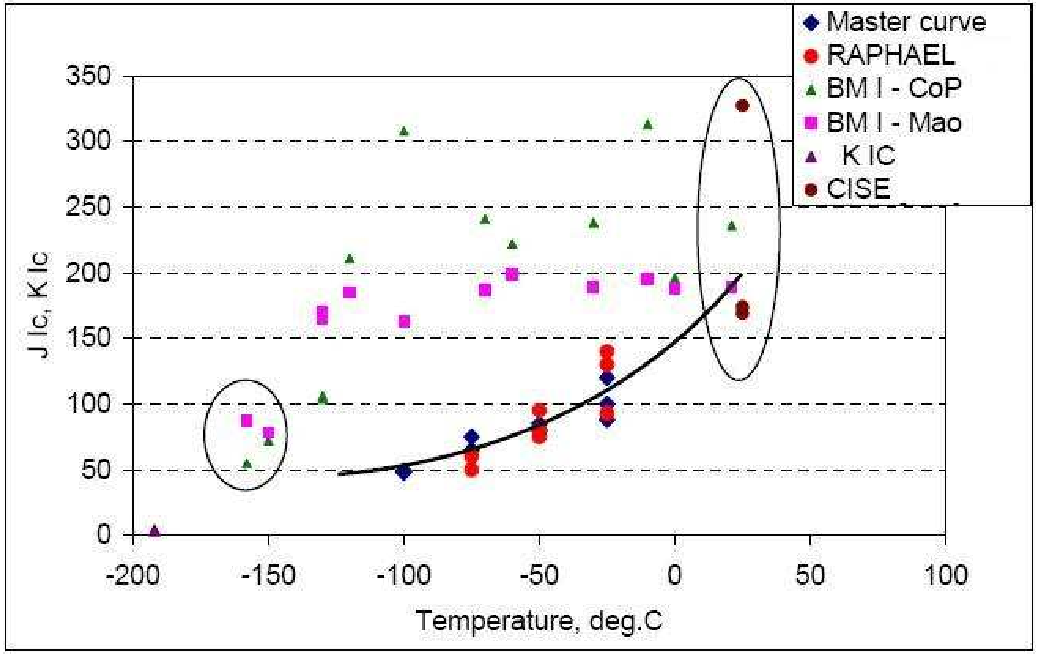
- Based on Bayoumi and Bassim

$$J_{IC} = k\varepsilon_f - J_0$$

$$\varepsilon_f = 0.15(\delta / h_0)^{3/2} \qquad \bar{\varepsilon}_f = \ln(t_0 / t)$$

$$K_{Ic} = C.[\sigma_f^{SP}]^{2/3}$$

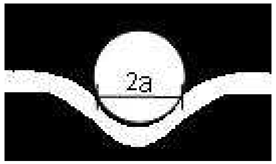
$$\sigma_f = 130(F_m / h_0{}^2) - 320$$

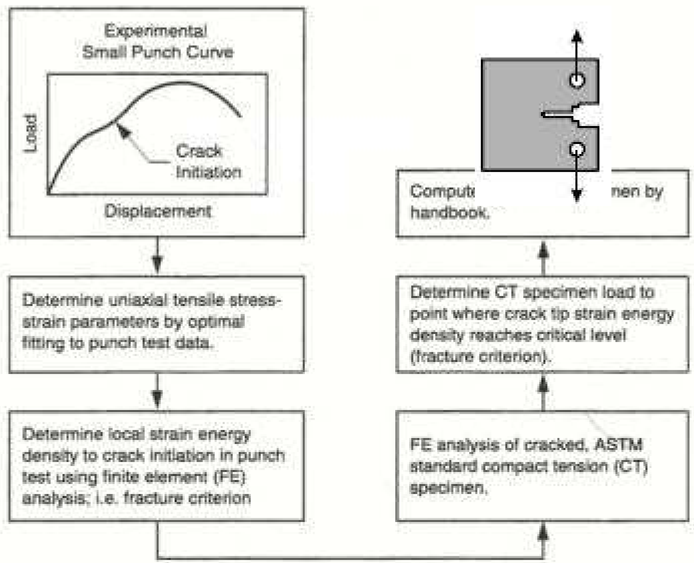


- Foulds' comments
  - Material dependent
  - Load for crack initiation should be used
  - Rupture strain is average
- JRC Petten results support Foulds' comments

2.3 Foulds' analytical approach (EPRI report)

- Criteria: Strain energy density (SED)





- Finite element method is introduced
- Accuracy is improved by a factor of 2, i.e. ±25%
- Comments:
  - The critical SED is derived from un-cracked specimens, an empirical size should be introduced to calculate the average SED
  - Fail to simulate the final rupture of SPT

3 Gurson model and “Local approach”

3.1 Gurson-Needleman-Tvergaard model

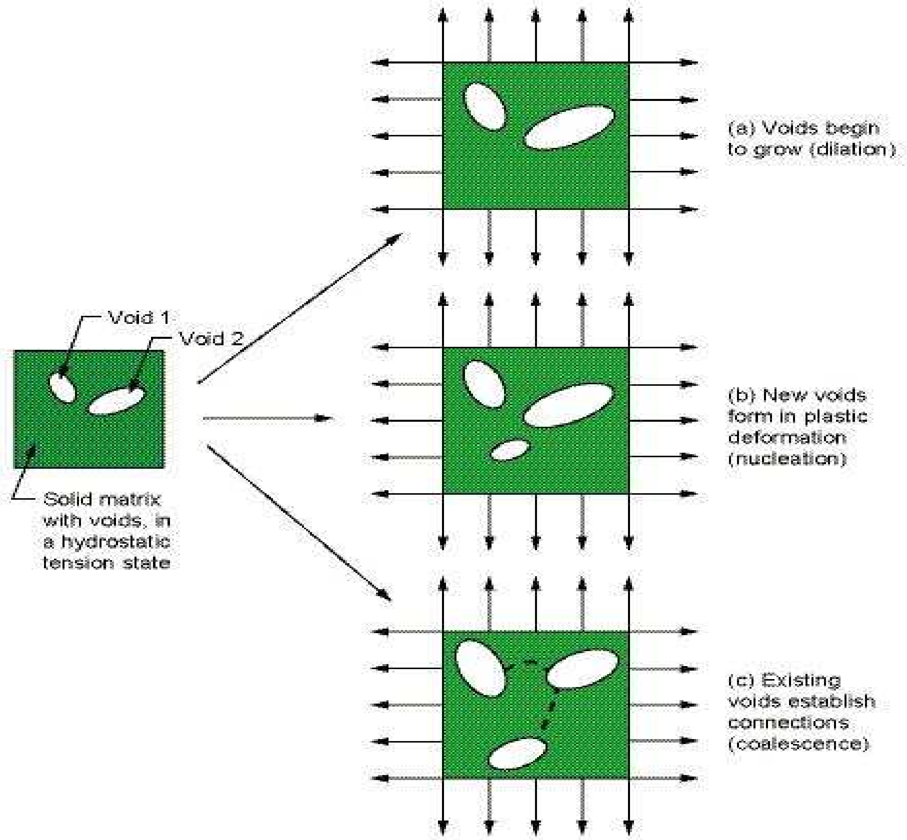
- A plastic potential applicable to porous solid

$$\Phi = \frac{3\sigma'_{ij}\sigma'_{ij}}{2\sigma} + 2qf^*\cosh\left(\frac{\sigma_{kk}}{2\sigma}\right) - [1 + (qf^*)^2] = 0$$

$$f^*(f) = \begin{cases} f & f \le f_c \\ f_c + K(f - f_c) & f > f_c \end{cases}$$

$$f^*(f_F) = 1/q \qquad K = \frac{\frac{1}{q} - f_c}{f_F - f_c}$$

$$\dot{f} = \dot{f}_{growth} + \dot{f}_{nucleation}$$



- ESIS project suggested: q=1.5; K=4.

3.2 Conventional “Local approach” (ESIS project, 1997)

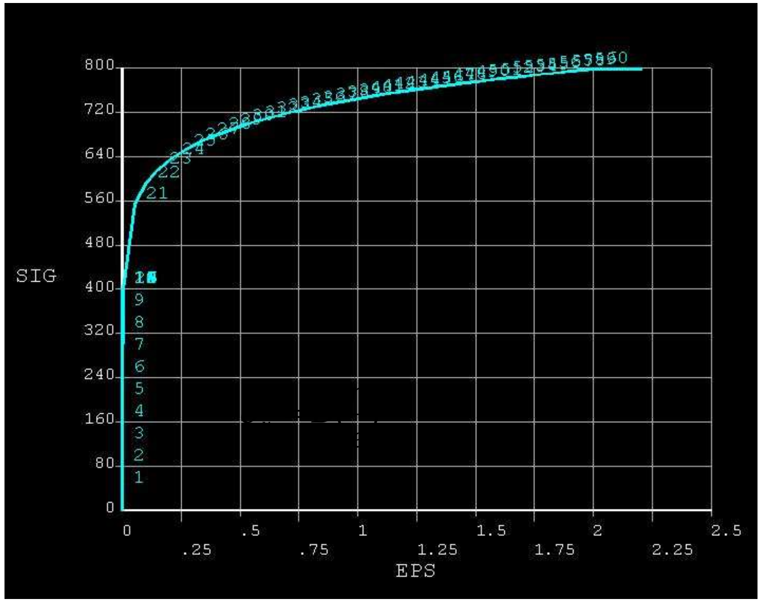
“Local approach” is to simulate macroscopic failure incorporating microscopic rupture processes

- Carry out a standard tensile test, record the true stress - true strain curve and the load-area reduction curve
- Simulation of the tensile test by applying a CDM model, such as the Gurson model, and identify critical damage parameters at the final fracture
- Simulation of ductile crack growth in a CT specimen by applying the derived material constitutive relationships and critical damage parameters
- According to the simulated J-R curve, the J_{IC} value can be derived according to ASTM E 1820-08.

3.3 Local approach for small punch test

(Abendroth, Kuna, 2003; Chang, 2008; Li, Hurst, Matocha, 2010)

- Determine material constitutive relationship and damage parameters from load-deflection curve



- Ramberg-Osgood model

$\sigma = \varepsilon E$ for $\varepsilon < \varepsilon_{ey}$

$\sigma = \sigma y$ for $\varepsilon_{ey} \leq \varepsilon \leq \varepsilon_{ey} + \varepsilon_{py}$

$\sigma = D(\varepsilon - \varepsilon_e)^n$ for $\varepsilon \geq \varepsilon_{ey} + \varepsilon_{py}$

- An optimization procedure that determine the parameters that provide the closest match to the observed load-deflection behavior.

$$F(\chi) = \sum_{i=1}^{N} w_i [P(\delta_i, \chi) - T(\delta_i)]^2$$

- Tensile strength $\sigma_u = D(\frac{n}{e})^n$

3.4 Identification of micro-mechanical parameters

- Micro-mechanical parameters
  - Initial void fraction, f_0
  - Critical void fraction, f_c
  - Void fraction at failure, f_F
  - Volume fraction of inclusion, f_N
  - For nucleation: ε_N, S_N
- Identification (ESIS round robin, Abendroth et al):
  - $f_0 = 0.002$
  - $f_N = 0.01\text{-}0.03$
  - $f_F = 0.2\text{-}0.25$
  - $\varepsilon_N = 0.3$
  - $S_N = 0.1$

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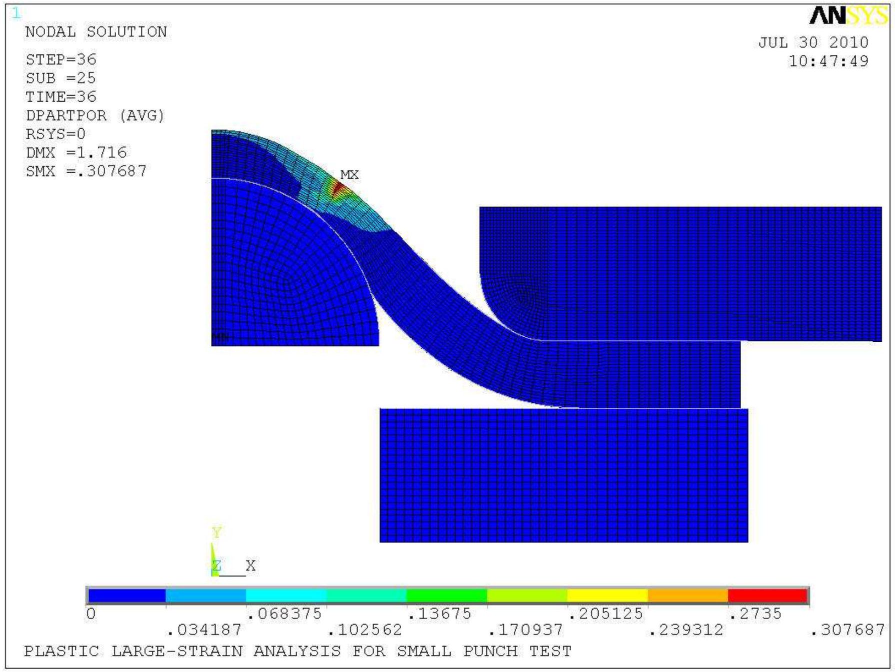
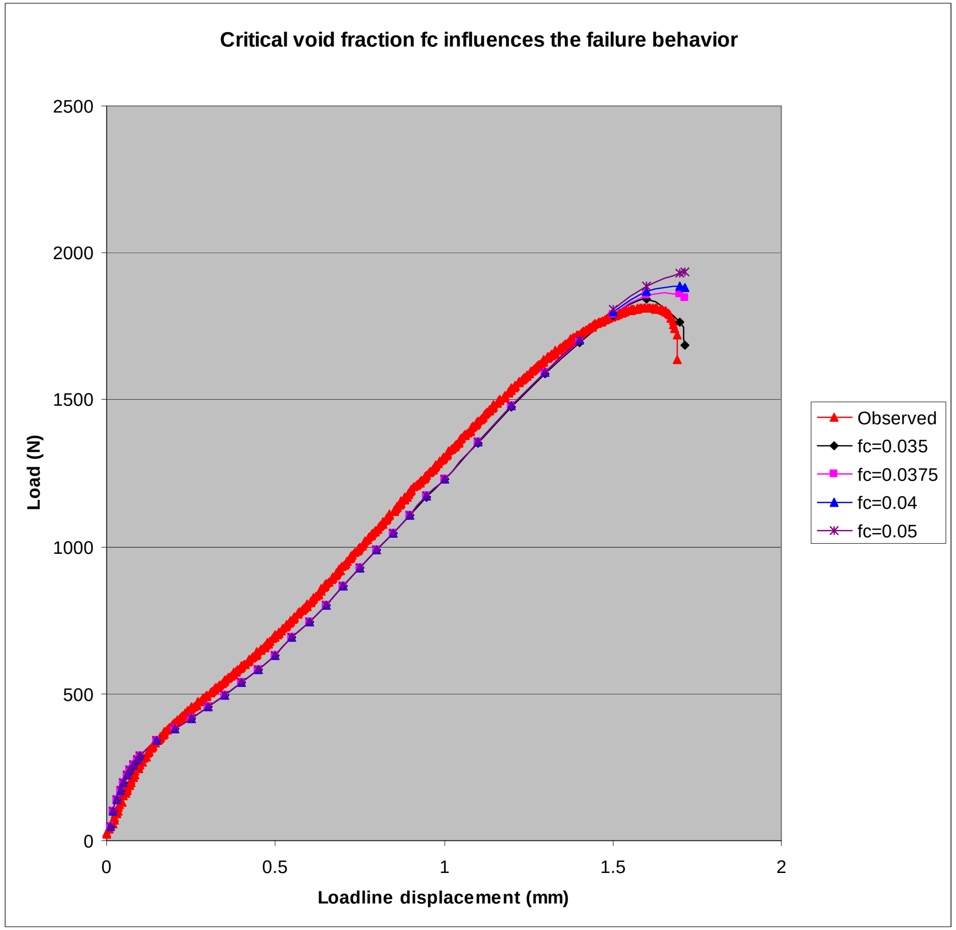
- *fc* is the only one parameter to be derived
- Check the calculated void fraction in SPT simulation and adjust the f_N

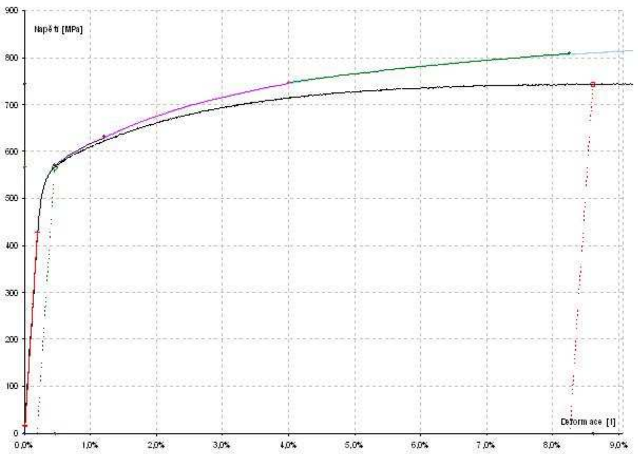




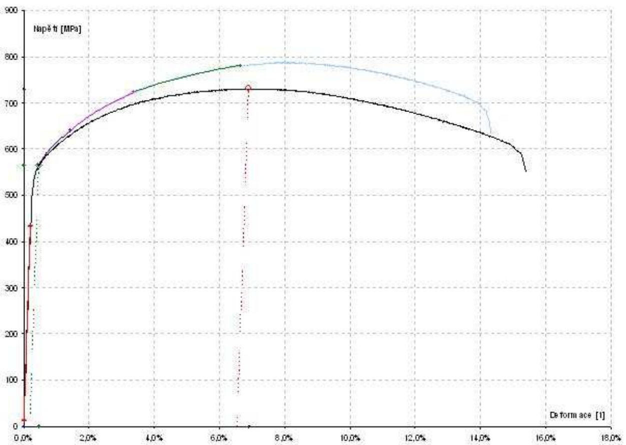
4 Experiments and verification

4.1 Uniaxial and SPT tests (Ostrava, 2010)

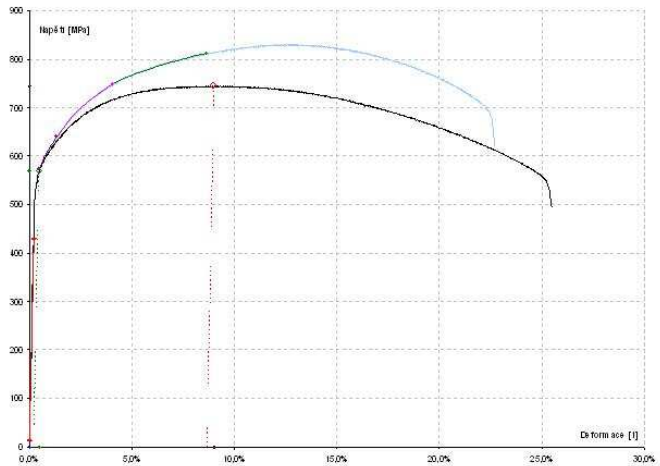
Three uni-axial tensile tests, three SPT tests and six CT tests were performed by Material & Metallurgical Research Ltd., Ostrava



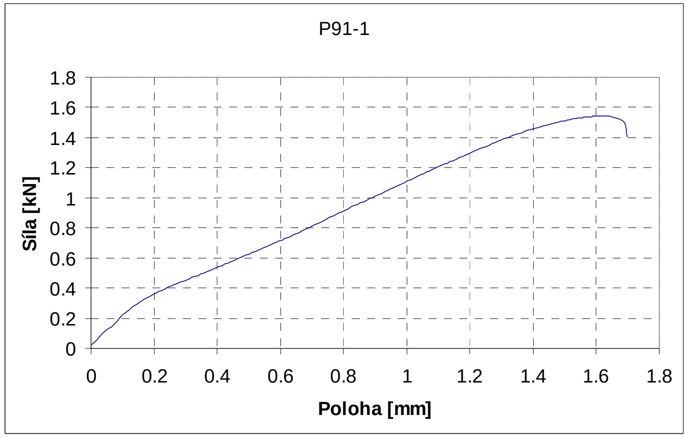
P91-1 uni-axial

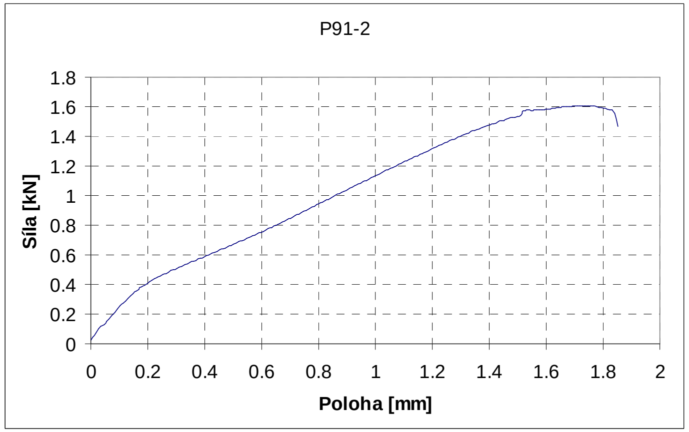


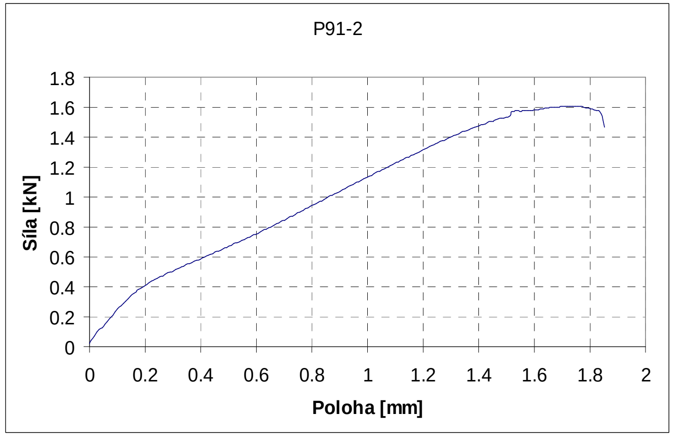
P91-2 uni-axial



P91-3 uni-axial



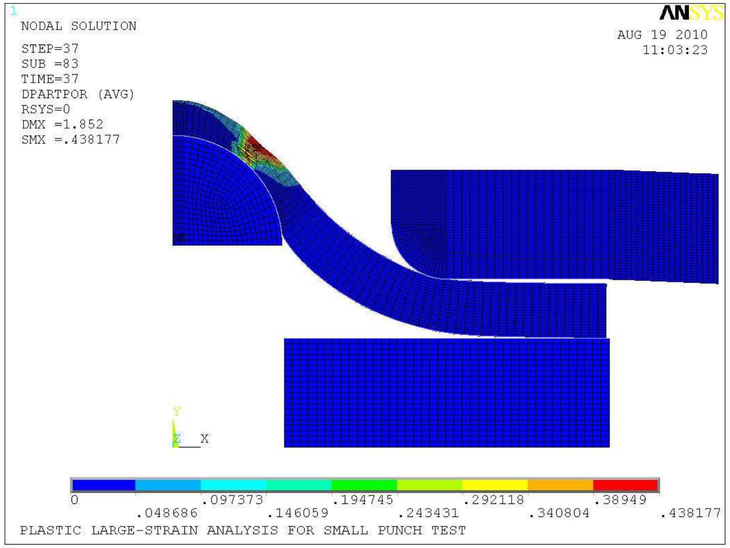


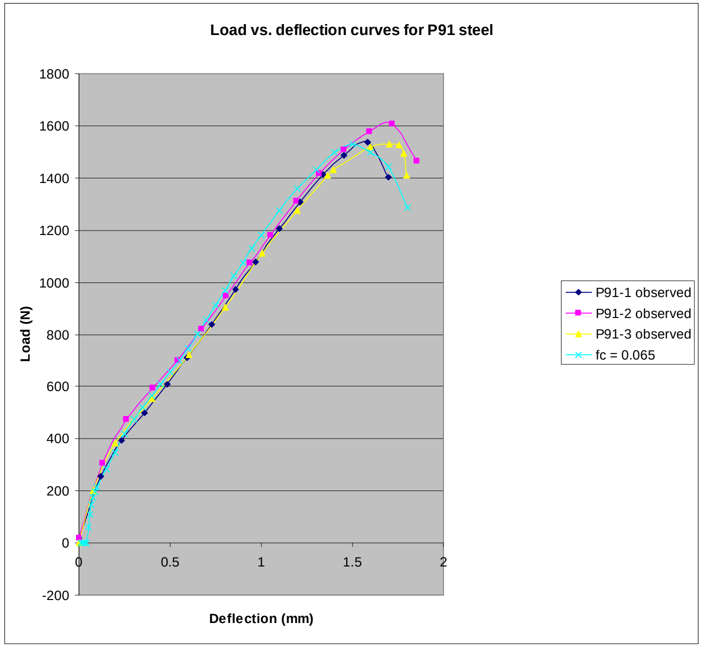


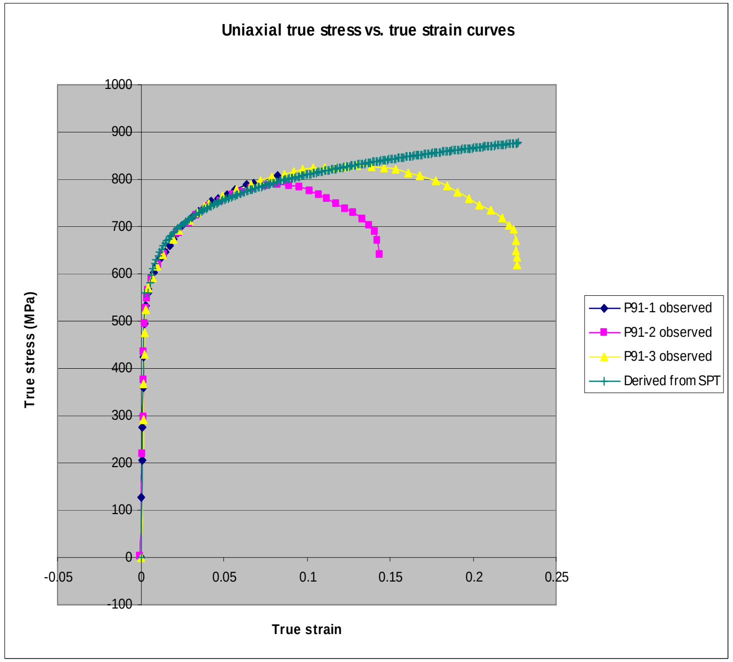
P91-SP-1 P91-SP-2 P91-SP-3

- Test results
  - Yield strength: 563 MPa
  - Tensile strength: 732 MPa
  - J_{IC} (ASTM E 1820): 262.5 N/mm

4.2 Determination of constitutive behavior and damage parameters



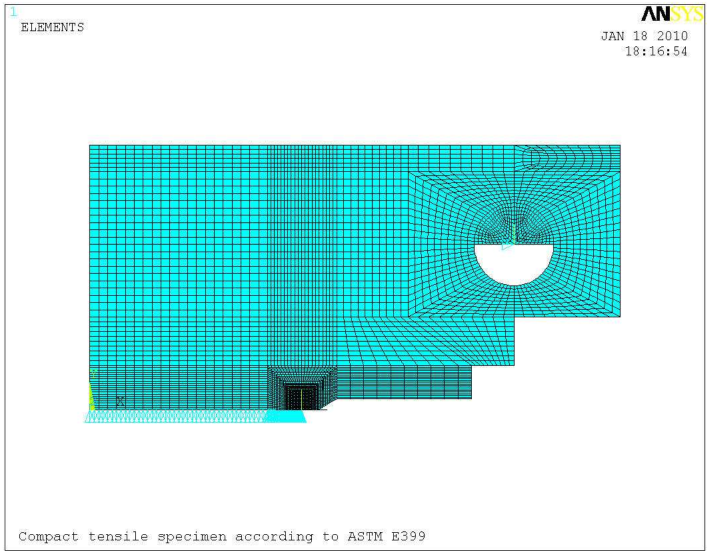


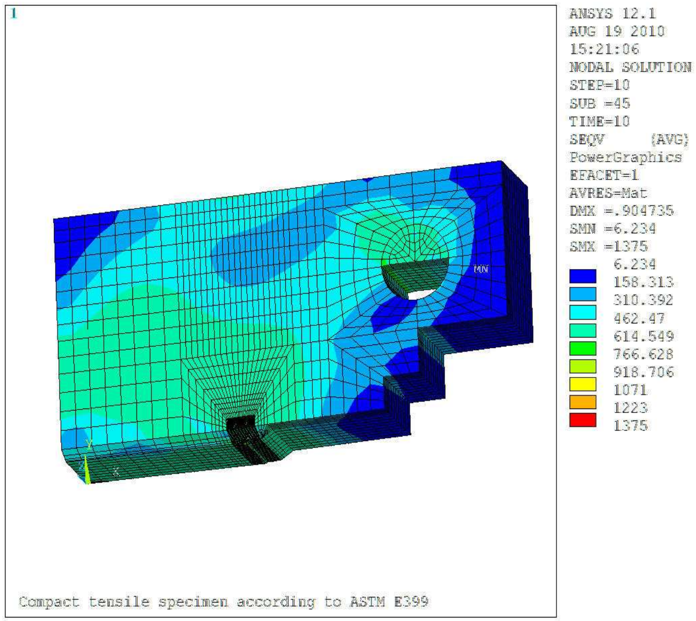


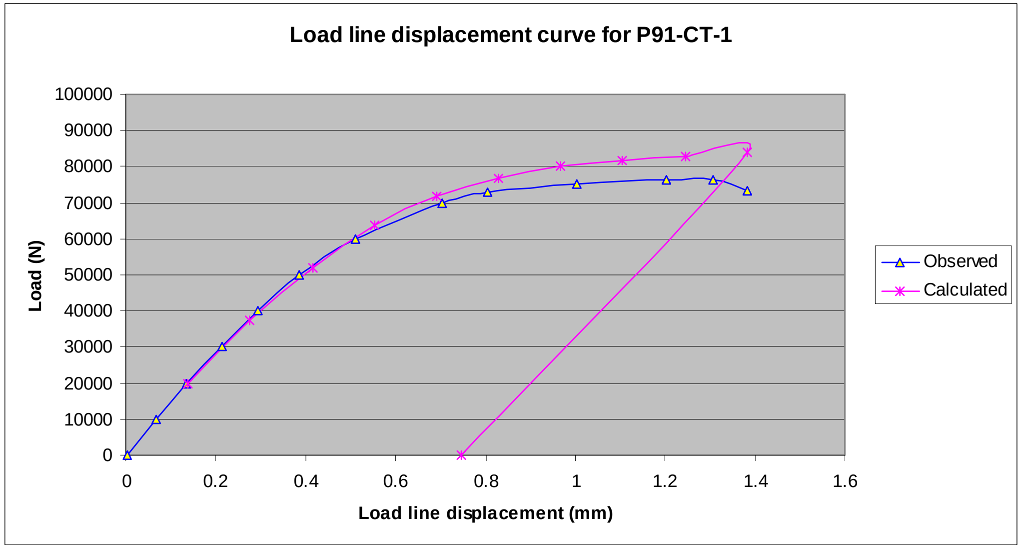
- Predicted results
  - Yield strength: 560 MPa / test 563 MPa
  - Exponent n: 0.095
  - Tensile strength: 738 MPa / test 732 MPa
  - Initial void factor f_0: 0.002
  - Volume fraction of inclusion f_N: 0.02
  - Critical void factor f_c: 0.065 ($f_F = 0.215$)

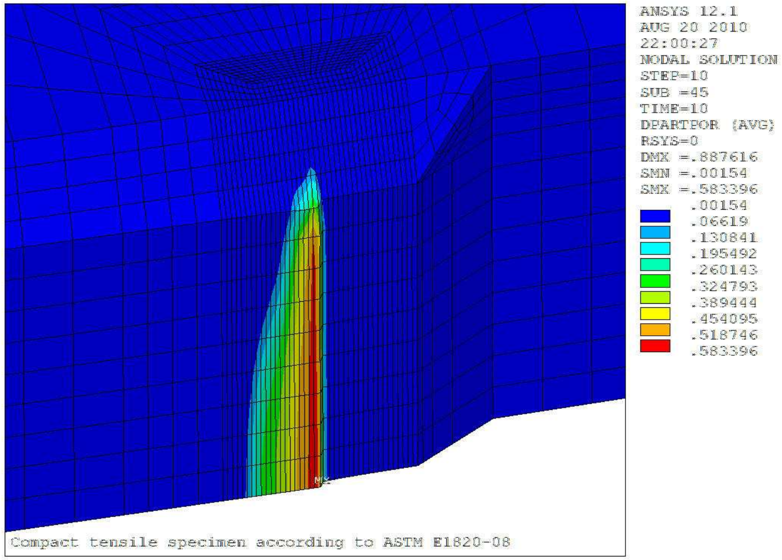
4.3 Determination of J-R resistance curve and J_{IC} value

- Simulation of CT specimen (3D model)
- J integral is derived from load-load line displacement curve
- Crack extension Δa is derived by counting the number of the damaged elements and times element size
- J_{IC} can be determined from J-R curve according to ASTM 1820-08









$$J = J_{el} + J_{pl}$$

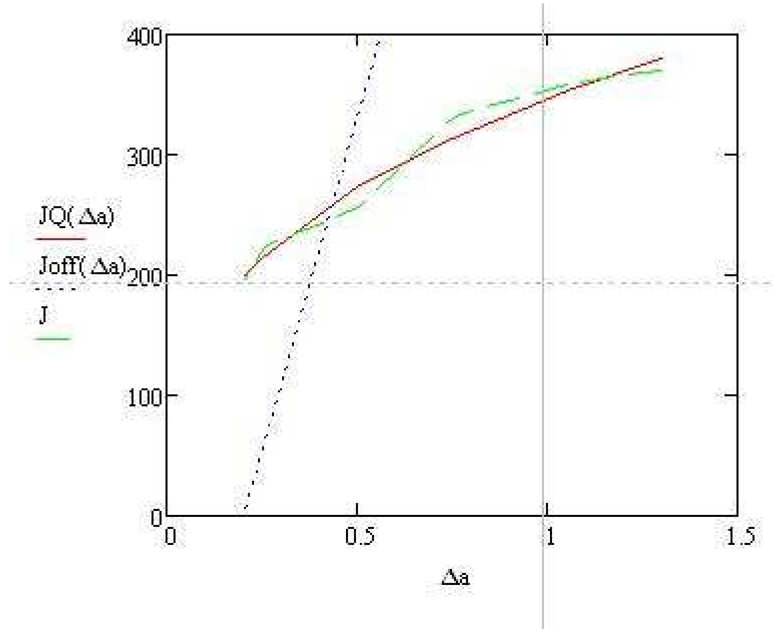
$$J_{el} = \frac{K^2(1-\nu^2)}{E}$$

$$K = [P/(BB_N W)^{1/2}]\, f(a_0/W)$$

$$f(a_0/W) = \frac{(2 + a_0/W)(0.886 + 4.64a_0/W - 13.32(a_0/W)^2 + 14.72(a_0/W)^3 - 5.6(a_0/W)^4]}{(1 - a_0/W)^{3/2}}$$

$$J_{pL} = \frac{\eta A_{pL}}{B_N b_0}$$

$$J_Q = C_1.(\Delta a)^{C2}$$



Predicted results: J_{IC} = 260.0 N/mm / test: 262.5 N/mm

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5. Conclusion

- In comparison of the strengths predicted by SPT and observed from uni-axial tests, the errors are within 5%.
- Standard fracture CT tests are carried out and verification shows that, the predicted toughness J_{IC} are within a scale bound of 5-10 %. In comparison of existing method, the accuracy is improved at least with factor of 2.
- Micro-mechanical parameters, such as f_0, f_N will be chosen such that the model gives best fit to experiments, rather than to replicate microscopic observation. In this sense, the model should be regarded as phenomenological but with a micro-structural basis.

- An error and try procedure is used to identify the micro-mechanical parameters. With assumed f_0, q, K, f_N, ε_N and S_N, the critical void fraction f_c is only one parameter to be derived.
- At crack initiation the calculated void fraction should reach to the void fraction at failure, f_F (about 0.2-0.25). This condition can be used to adjust the assumed f_N.
- A systematic procedure should be set up to speed up the identification process and improve the accuracy.
- Gurson model is only suitable for ductile fracture. For cleavage fracture, the Weilbull stress model should be used . For the transition from ductile to cleavage fracture, another approach was put forward.

End sheet

Thank you for your attention