

J-R curve prediction using cohesive model and its sensitivity to a material curve

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ABSTRACT

Cohesive crack models are nowadays widely used to analyze cracking processes in the materials. The importance of the cohesive zone approach is emphasized to analyze the localization and failure in engineering materials. The micromechanical modeling encounters a new problem that is different from assumption of continuum mechanics. The material is not uniform on the microscale but a material element has its own complex microstructure. The concept of a representative volume element (RVE) has been introduced a few years ago. The material separation and damage of the structure is described by the interface element. Using this technique the behavior of the material is split into two parts: the damage of the free continuum with arbitrary material law and the cohesive interface between the continuum elements. The general advantage, compared to classical fracture mechanics, is that, in principle, the parameters of the respective models depend only on the material and not on the geometry. These concepts guarantee transferability from specimen to components over a wide range of sizes and geometries. The paper is focused on prediction of *J-R* curve by 3D FEM cohesive elements. The corresponding true stress – true strain curve (material curve) appear to be a key problem of this approach application. For forged 42CrMo4 steel the ductile fracture was predicted. *J-R* curve is calculated by cohesive elements using Warp3D and Abaqus codes. Crack propagation is based on the cohesive element extinction algorithm. The ductile tearing process consisting of initiation, growth and coalescence of voids has been represented by a traction separation law. Interface elements (cohesive elements) representing the damage are implemented between the classical continuum elements representing elastic-plastic properties of the material.

KEY WORDS: cohesive zone model, representative volume element, ductile fracture, *J-R* curve prediction, material curve.

INTRODUCTION

Damage may lead to the initiation and growth of macro cracks in a component and to the final fracture. The crack tip, the term used very often in the fracture mechanics, is a mathematical idealization. In reality, there is a region of material degradation in some process zone. In this zone the behaviour of the micro level becomes important for constitutive modelling. Three different approaches exist to model damage, material separation, and the fracture phenomena on level of the component:

- (i) No damage evolution is modelled and conventional material model, e.g. elastic plastic constitutive equations are applied. The process zone is assumed as infinitesimally small, specific fracture criteria, e.g. based on K , J , C^* for crack extension are required.
- (ii) Separation of surfaces is admitted if some critical value is reached locally, whereas the material outside the surface behaves conventionally; fracture criterion is a cohesive law.
- (iii) Softening behaviour is introduced into constitutive model; accumulation of damage is described by additional internal variables.

The identification and determination of the micromechanical parameters require a hybrid approach based on testing and numerical simulation. Micromechanical modelling encounters a new problem, the material is not uniform on the microscale and the material element has its own microstructure. The concept of a representative volume element (RVE) has been introduced by Hill and others [1]. Many constitutive models for damage evolution exist, e.g.: (i) formation of microcracks and their extension with small global plastic deformation (cleavage fracture), (ii) nucleation, growth and coalescence of microvoids (ductile rupture). The crack propagation within a structure can be simulated using several different methods [2, 3 and 4]: (i) node release technique controlled by any fracture mechanics parameter, (ii) constitutive equation including damage (Gurson), (iii) continuum damage concepts based on the theory of Kachanov, Lemaitre etc., or (iv) on the cohesive zone approach realised by the cohesive elements. Numerical representations of cohesive zone model suffer from certain mesh bias.

In present time the extensive effort is concentrated to the application of cohesive models in 3D modelling and to experimental determination of input parameters for models used in FEM. There is also a strong need to standardize the simulation techniques and the experimental determination of the base data.

The aim of this paper can be seen in verification of the application of the cohesive model based on the exponential traction separation law, experimental and calibration procedure inevitable for the determination of the cohesive parameters for the modelling of the ductile fracture.

COHESIVE MODEL AND TRACTION-SEPARATION LAW

Since the cohesive model is a phenomenological model, there is no evidence, which form is to be taken for the cohesive law, $T(\delta)$. Thus cohesive law has to be assumed independently of specific material as a model of the separation process. Most authors take their own formulation for the dependence of the traction on the separation. The exponential model is used by many authors for both the ductile and the cleavage fracture. An exponential relationship between the effective traction (δ) provides a decohesion model. The T - δ response follows an irreversible path with unloading always direct to origin. This model represents all the features of the separation process by: (1) the shape of the cohesive traction/separation curve (T - δ), (2) the local material strength by the peak traction (T_0), and, the local ductility defined by the work of separation (Γ_0) given by the area under (T - δ) curve.

For the determination of the cohesive stress, T_0 , in the case of normal fracture a hybrid technique has been developed. Using conventional elastic-plastic analysis, the distribution of the axial stress across the notch section of the specimen geometry is determined for the moment of the crack initiation in the centre of specimen. At that event, the axial stress exhibits a maximum in the centre of specimen, which is supposed to be equal to T_0 .

The cohesive energy, Γ_0 can be determined in a fracture mechanics test by assuming that Γ_0 equals the J -integral at initiation of stable crack extension, J_i . The procedure can be taken by the standard test methods [3].

MATERIAL; EXPERIMENTAL AND CALCULATION PROCEDURES

Mirone – La Rosa – Risitano (MLR) Model

To determine material curve for characterization of the elastoplastic behaviour of tested material the standard tensile experiments have been using for many years. The relation $\sigma_{ekv}(\varepsilon_{ekv})$ is found but the problem is the validity of this relation after necking. According to many experimental observations in [5] the new approximate curve in Eq. 1 was received for standard tensile specimens (see Fig.1) and modified tensile specimens – waisted specimens (Fig.2). This Eq. 1 was used in our prediction of the material curve. At least 10 specimens were used in both cases, the third curve was determined by standard procedure and the higher values of deformation are the fitted values.

$$MLR\sigma(\varepsilon_{ekv} - \varepsilon_N) = 1 - 0,6058(\varepsilon_{ekv} - \varepsilon_N)^2 + 0,6317(\varepsilon_{ekv} - \varepsilon_N)^3 - 0,2107(\varepsilon_{ekv} - \varepsilon_N)^4 \quad (1)$$

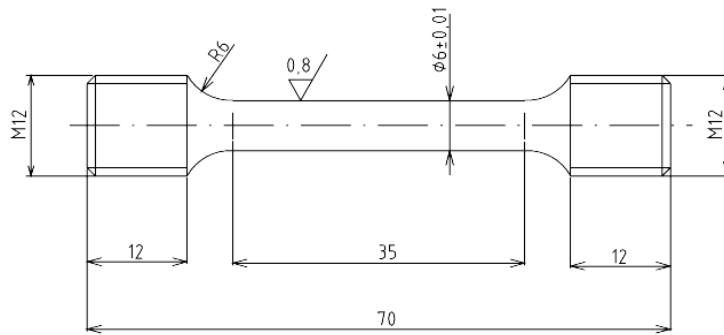


Fig. 1 Standard tensile specimen

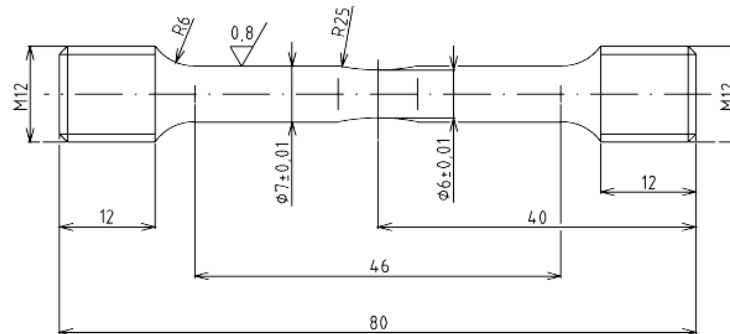


Fig.2 Modified tensile specimen – waisted

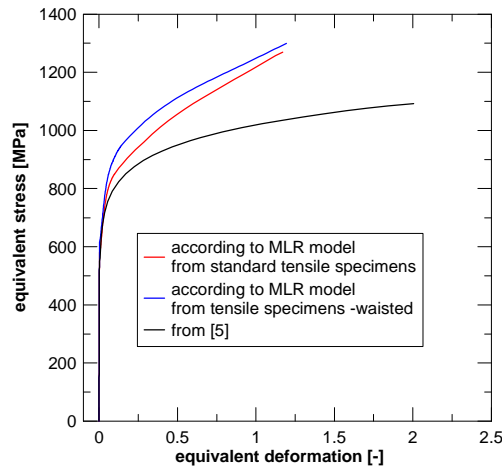


Fig. 3 Material curves used for modelling

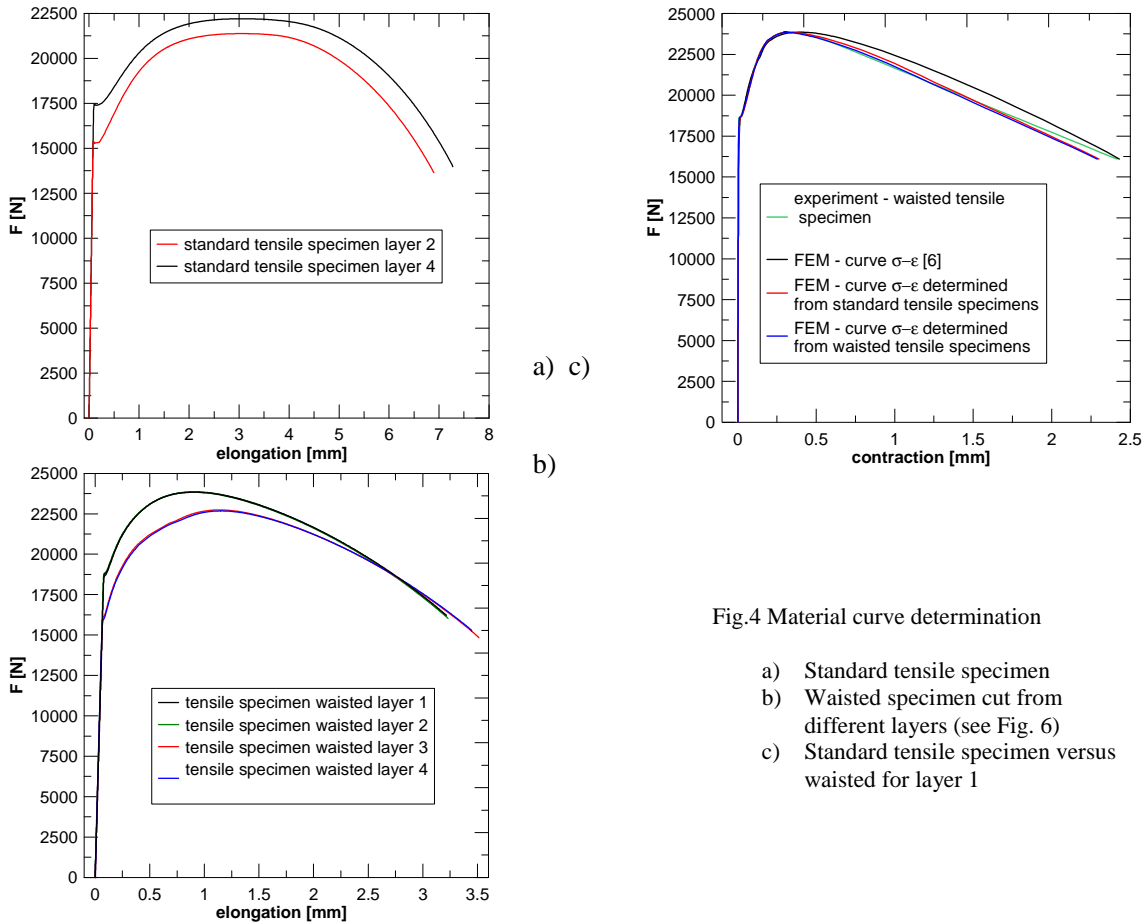


Fig.4 Material curve determination

- a) Standard tensile specimen
- b) Waisted specimen cut from different layers (see Fig. 6)
- c) Standard tensile specimen versus waisted for layer 1

Cohesive Model Parameters Determination

For the determination of the cohesive stress, T_0 , in the case of normal fracture (mode I) a set of twelve experiments for tensile notched bars was done. The dimension of this specimen can be seen on the following Fig. 5.

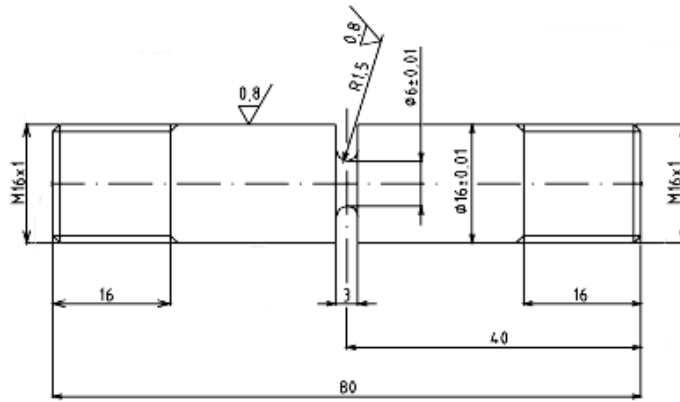


Fig. 5 Notched tensile specimen

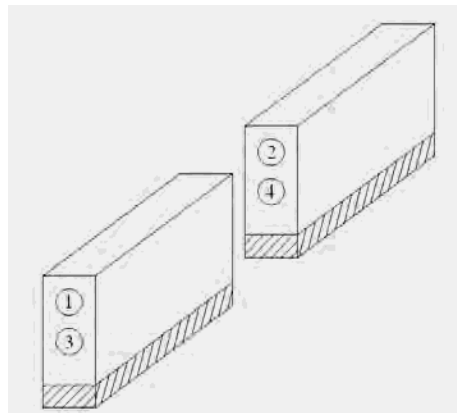


Fig. 6 Explanation of the term “layer”

An elongation was measured using transducer Zwick TC-EXMACRO.001; contraction by MTS extensometer, type.: 632. 19F – 21. The mean value of the cohesive stress T_o was determined from the above mentioned set of twelve experiments and from the computations for the material curve received from the waisted tensile specimens; T_o is then 2000 MPa. For determination of the stress- strain distribution the standard FEM Abaqus package with CAX4 elements was used.

Step	3	6	10	13	16	24
F [N]	2504,2	8000,53	16003,4	22003,6	25001,9	29002,4
Step	31	34	37	43	45	
F [N]	32502	33675,4	33217,3	31149,1	29999,7	

Table 1 Load steps used in Fig. 7

The standard CT specimens were used for J -integral determination according the ASTM 1820-99a procedure (based on measurement of the J - Δa curve). The experimentally determined value of J_i was found to be $J_i = 115 \pm 5$ MPa.mm. This value was calibrated (tests for data from the predicted interval) using numerical procedure in WARP3D.

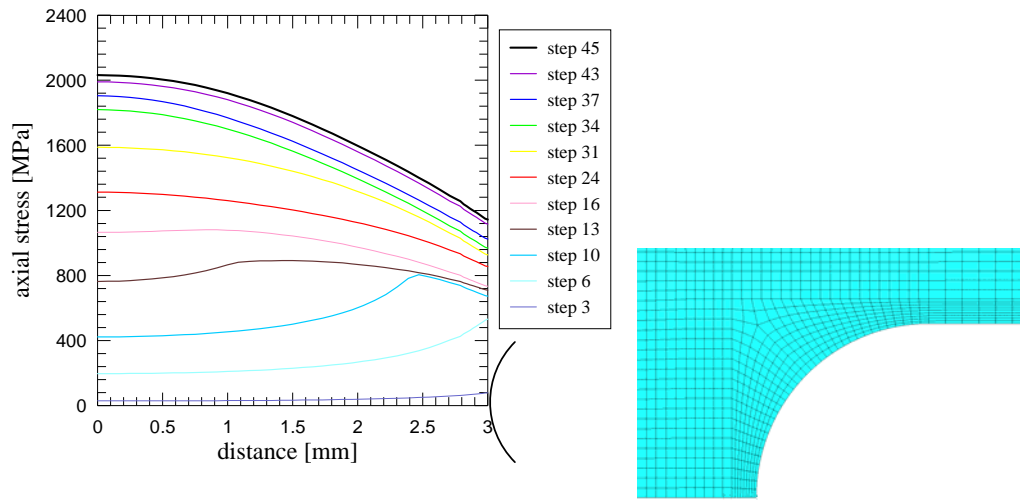


Fig. 7 Axial stress – T_0 and crack tip mesh for notched specimen used for FEM modelling

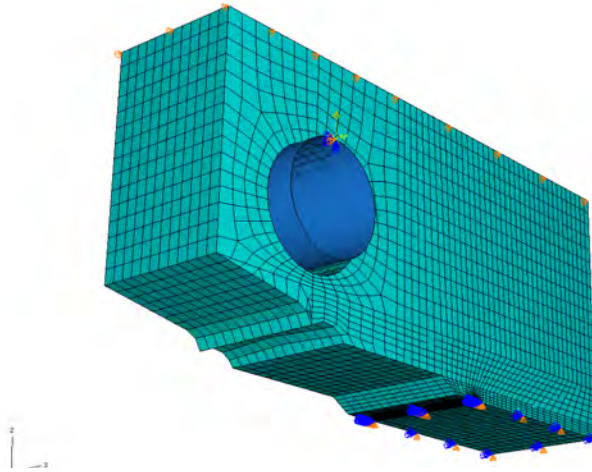


Fig. 8 FE mesh for CT specimen

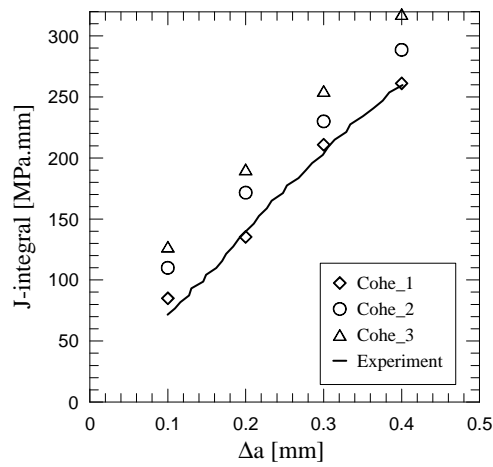


Fig. 9 J_i calibration

The material properties are given by relations true stress-true strain (the material curve). The numerical modeling was realized with all three material curves, see Fig. 3 and Fig 4c. Finding that the best results have been obtained using data generated on the waisted tensile specimens, this curve was used in all subsequent predictions. The standard FEM package ABAQUS has been utilized. Set of computations were applied to the calibration of the cohesive parameters used for J - R curve prediction (T_0 , J_i). Various combinations for T_0 and J_i were tested. In the Fig. 9 the values J_i are marked as Cohe_1, Cohe_2 a Cohe_3, ($J_i = 110, 120, 130$) and received data were compared with the experimental values. The best correlation was found for first value of $J_i=110$ MPa.mm. From the above analyses follows the prime combination of the cohesive parameters.

- $T_0=2000$ MPa
- $J_i=110$ MPa.mm

J-R Curve Prediction

Single three point bend specimen SE(B) has been used for experimental prediction of the J - R curve by the multiple specimen method. Using the cohesive parameters received on the notched specimens (T_0) and J_i on the CT specimens the numerical simulation of the stable crack growth was simulated and J - R curve was predicted. By utilization of two symmetry planes (plane xy and yz) for SE(B) specimen with $a/W = 0.5$ only one quarter of the real body was modelled, see in Fig. 10. The FE mesh consists from 8560 nodes and 7155 element C3D8 (Abaqus). For application of nonlinear cohesive element, the package Warp3D was necessary to use. In the same mesh generated in Abaqus the next 180 cohesive elements *inter_8* were added. Owing to numerical instability the loading increment from one step was decreased from 0,025mm to 0,0025mm (therefore more than 1000 loading steps were applied). The predicted values of the curve F versus $CTOD$ can be seen in Fig. 11 and the final prediction of the J - R curve in the Fig. 12.

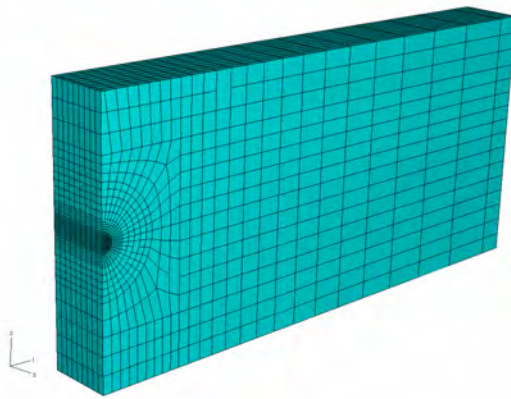


Fig. 10 FE mesh for SE(B) specimen

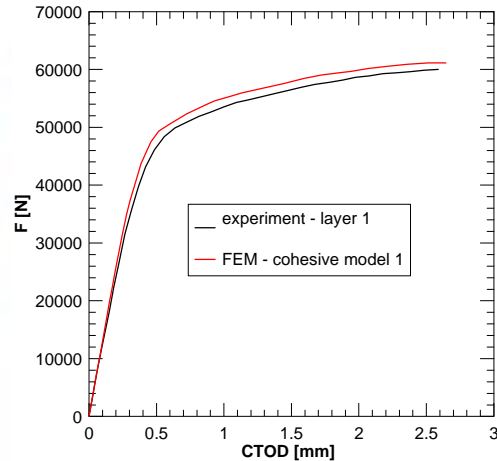


Fig. 11 Applied force versus CTOD

Calculating the stable crack propagation in SE(B) body the strong dependence of numeric convergence of the solution and numerical stability on the quality of the mesh was found. Especially the dependence on the mesh density in the direction of width of the body was observed in the calculations. Simulation is a bit time consuming and approximately at least 20 FE meshes were tested, mainly to find comparison with sooner obtained data for modelling of the stable crack growth using GTN model [6]. There is strong need to make some numerical test making relationships between shape of the traction separation law and shape of generated mesh for application of the finite elements method. It has been found for GTN model that the bevel edge of the elements in the crack tip is the best way how to receive to convergent solution, on other hand for application of the cohesive elements it is vice versa, no bevel edge is convenient to use.

CONCLUSIONS

The summary of this study can be drawn:

- Three separate tensile geometries were investigated, including waisted and notched specimens. Waisted samples and standard tensile specimens were used to determine the material curve. The notched specimens have been found very suitable for the verification of the measured material curves. The shallow notch of the waisted tensile specimen allows monitoring of the diametral contraction during testing, so that the true stress could be accurately monitored. Agreement of the computed curve (using Abaqus) force - deflection and force -

contraction for notched specimen was excellent. Notched specimens were used for T_0 determination and calibration.

- The standard CT specimens were used for J -integral determination according the ASTM 1820-99a procedure and J_i value has been calibrated through the best fit of the calculated and measured J - R curve.
- Received cohesive parameters were applied for the J - R curve prediction on the SE(B) specimen with $a/W=0.5$. Strong dependence of the convergence and the numerical stability of the crack growth modelling on the mesh was found, especially for the mesh density in the direction of thickness of the body.
- The shape of the J - R curve is more determined by the material curve than by the shape of the traction separation law. The exact determination of the material curve is the key point for proper application of the cohesive zone model used for the ductile fracture.

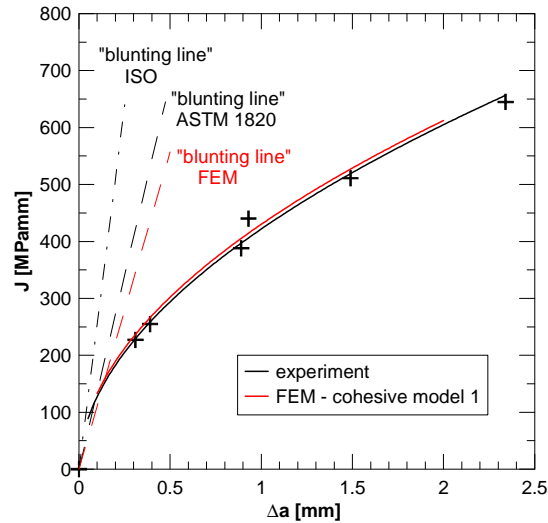


Fig. 12 J-R curve received on the SE(B) specimen

NOMENCLATURE

a/W	[-]	crack length to width ratio
B	[mm]	thickness of the bend specimen
$CTOA$	[°]	crack tip opening angle
$CTOD$	[°]	crack tip opening displacement
E	[MPa]	Young's modulus
F	[N]	force
J	[MPa·mm]	J -integral
J_i	[MPa·mm]	fracture toughness for crack initiation, expressed by J -integral
K	[MPa·m ^{0.5}]	stress-intensity factor
K_{IC}	[MPa·m ^{0.5}]	fracture toughness, expressed by the stress-intensity factor
T_0	[MPa]	maximum traction
Γ_0	[MPa·mm]	maximum separation work
$T(\delta)$		traction-separation function
W	[mm]	width of bend specimen
μ	[-]	Poisson ratio
δ	[mm]	separation parameter
σ_y	[MPa]	yield strength
σ_{ekv}	[MPa]	equivalent stress
ε_{ekv}	[MPa]	equivalent strain

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