Material Model for Deformation and Failure of Cast Iron for High-Speed Impacts

S. Edelmann / M. Walter / H. Chladek
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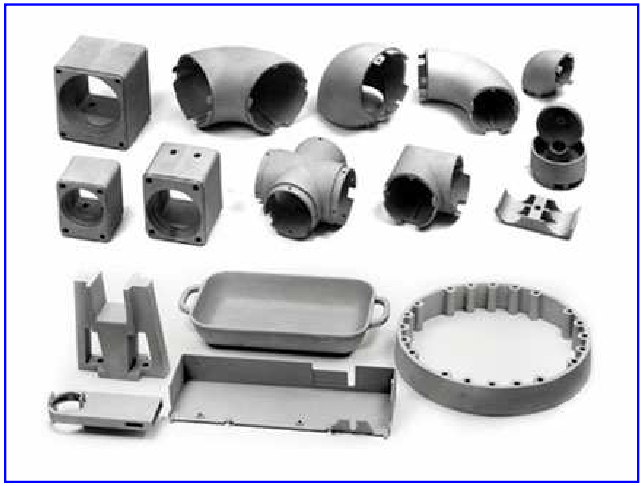
Overview

- Introduction
  - Use of cast iron / Highly dynamic loading
- Specimen Test
  - Material data basing on tension and compression tests
- Implementation
  - Use of the standard and enhanced material implementation
- Impact Test
  - Verification of the enhanced material implementation
- Summary

Introduction

- Use of cast iron
  - Cast iron parts have been used for a wide range of applications in mechanical engineering for a long time
  - Previously cast iron parts have often been used for simple parts only

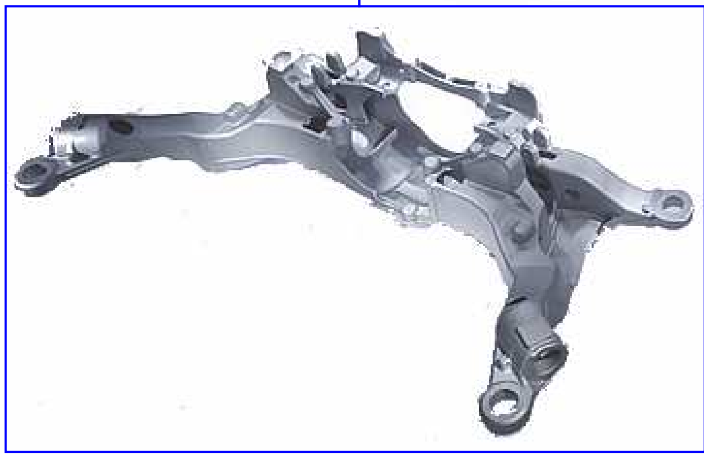
    e.g. fittings, wheels, exhaust manifolds, pipes, gates, ovens, boiler, pans, etc.

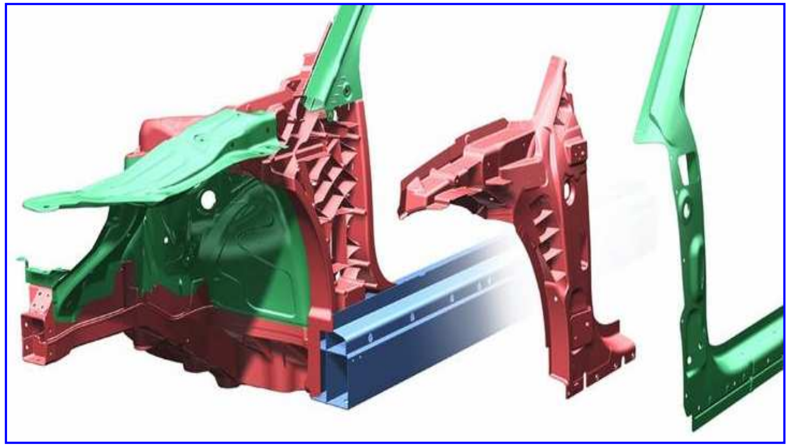


Introduction

- Use of cast iron
  - Today cast iron parts are very common in automotive and aircraft industry, turbo machinery, wind energy and generating plants
  - Due to their design flexibility cast parts are increasingly utilised for very high loadings

    e.g. axis, components of automotive space frames, subframes, turbine casings, etc.

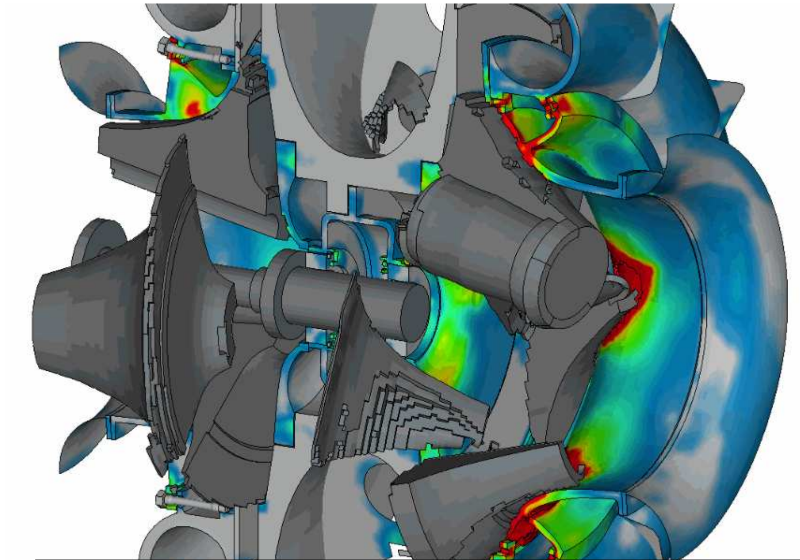




Introduction

- Highly dynamic loading due to misuse or failure
  - In case of an accident such as a car crash, an aircraft emergency landing, a turbine burst, etc. highly dynamic impacts occur
  - These highly dynamic impacts of cast parts can be analysed by an explicit simulation code such as RADIOSS
- Example: Turbocharger

Common turbocharger design with cast iron casings



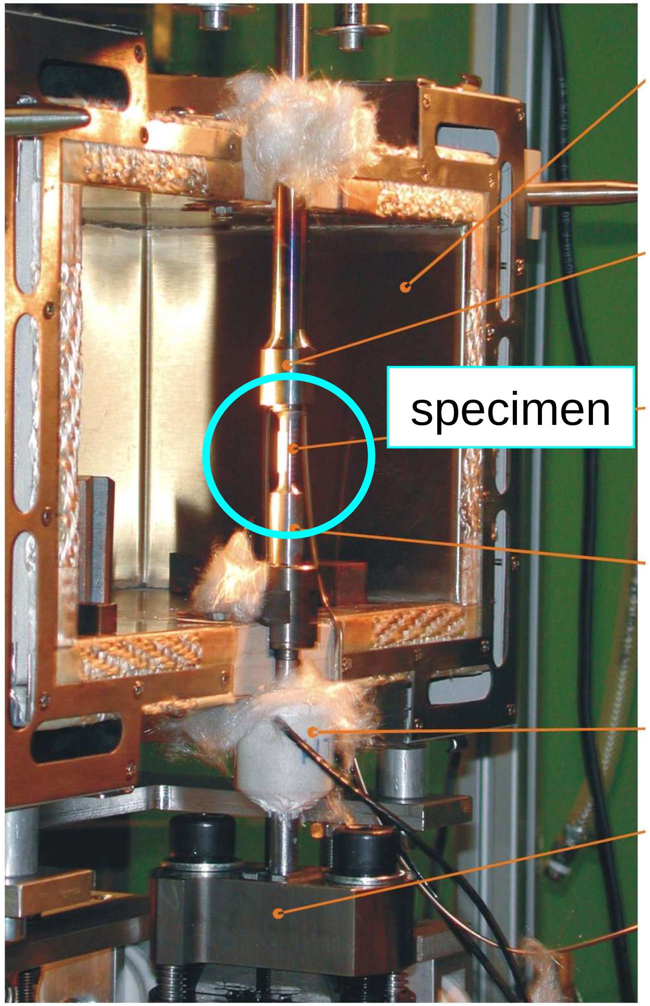
Display model of a containment simulation of a turbocharger

Specimen Tests

- Overview
  - Specimen tests are required to determine the material properties
  - The most common tests are tension tests with quasi-static and dynamic loading, sometimes also considering the temperature
- Tension Test
  - Tension tests are well known in the industry, nonetheless often missing in practice due to time and costs
  - Anyway, the description of an isotropic elastoplastic material behaviour requires a stress-strain-curve input
- Compression Test
  - In addition compression tests are required for the analysis of a possible interrelation of behaviour under tension and compression

Specimen Tests

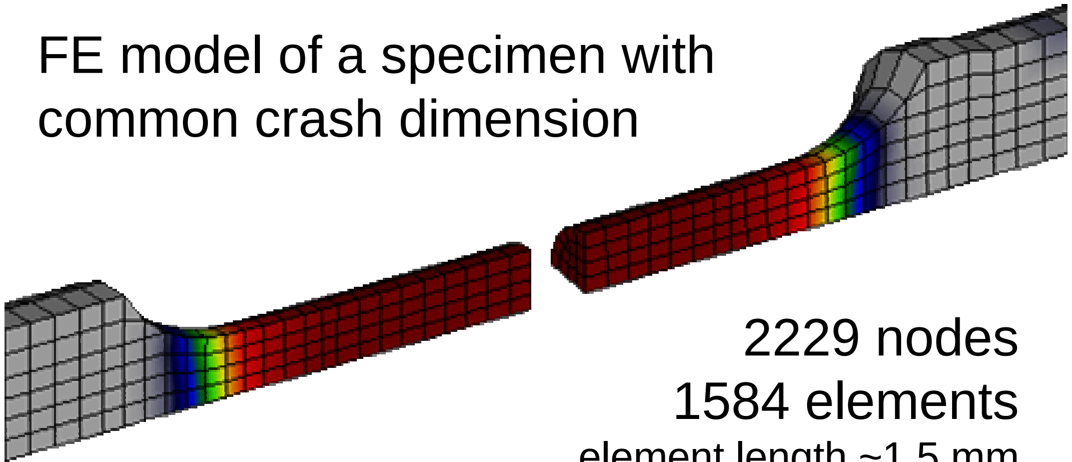
- Tension test of a specimen
  - Nowadays servo-hydraulic test rigs are very common for tension tests
  - These test rigs can be controlled by load and by strain for different speeds
  - The measurement system comprises load cells and strain gauges
  - A heating system allows testing at different temperatures
  - Test results are given as engineering data (force vs. displacement)
  - The use for simulation requires a transfer to true stress-strain data



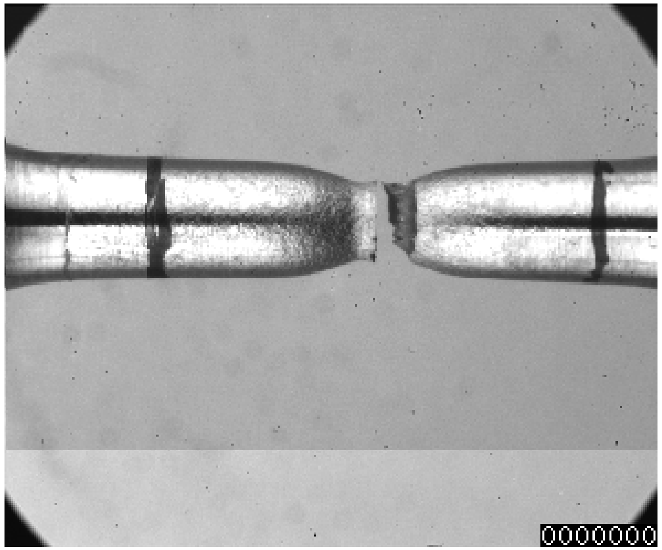
Specimen Tests

- Tension test of a specimen
  - For a sufficient set of input data, the tension test has to be performed with different strain rates, e.g. 10E^{-4} 1/s (quasi-static) as well as 5, 100, 500 1/s (dynamic loading)
  - Depending on the intended use different temperature are required also, e.g. 20 ℃ (ambient temperature), 200, 400, 6 00 ℃
  - In the simulation a ¼ specimen model is very common

FE model of a specimen with common crash dimension

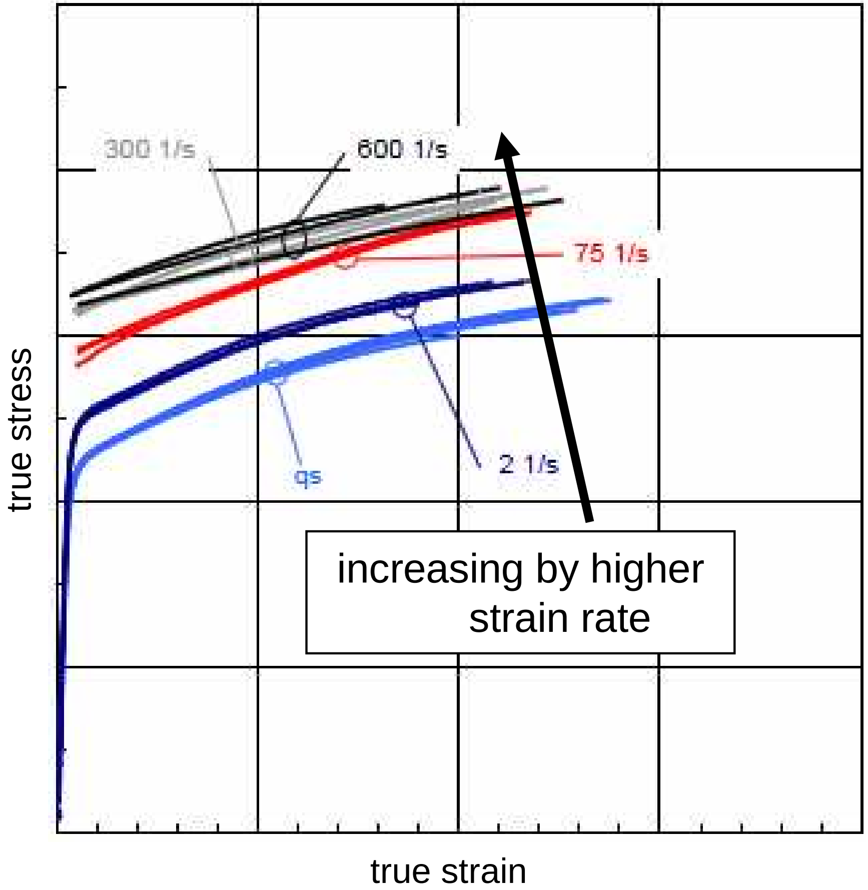


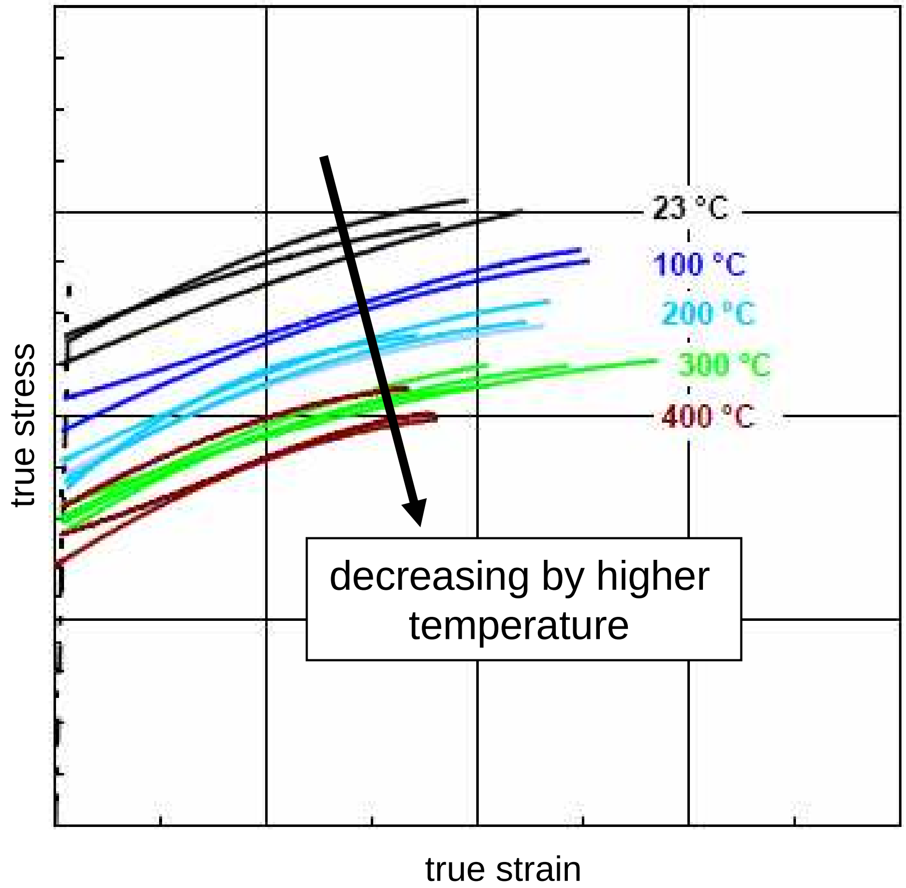
2229 nodes
1584 elements
element length ~1.5 mm



Specimen Tests

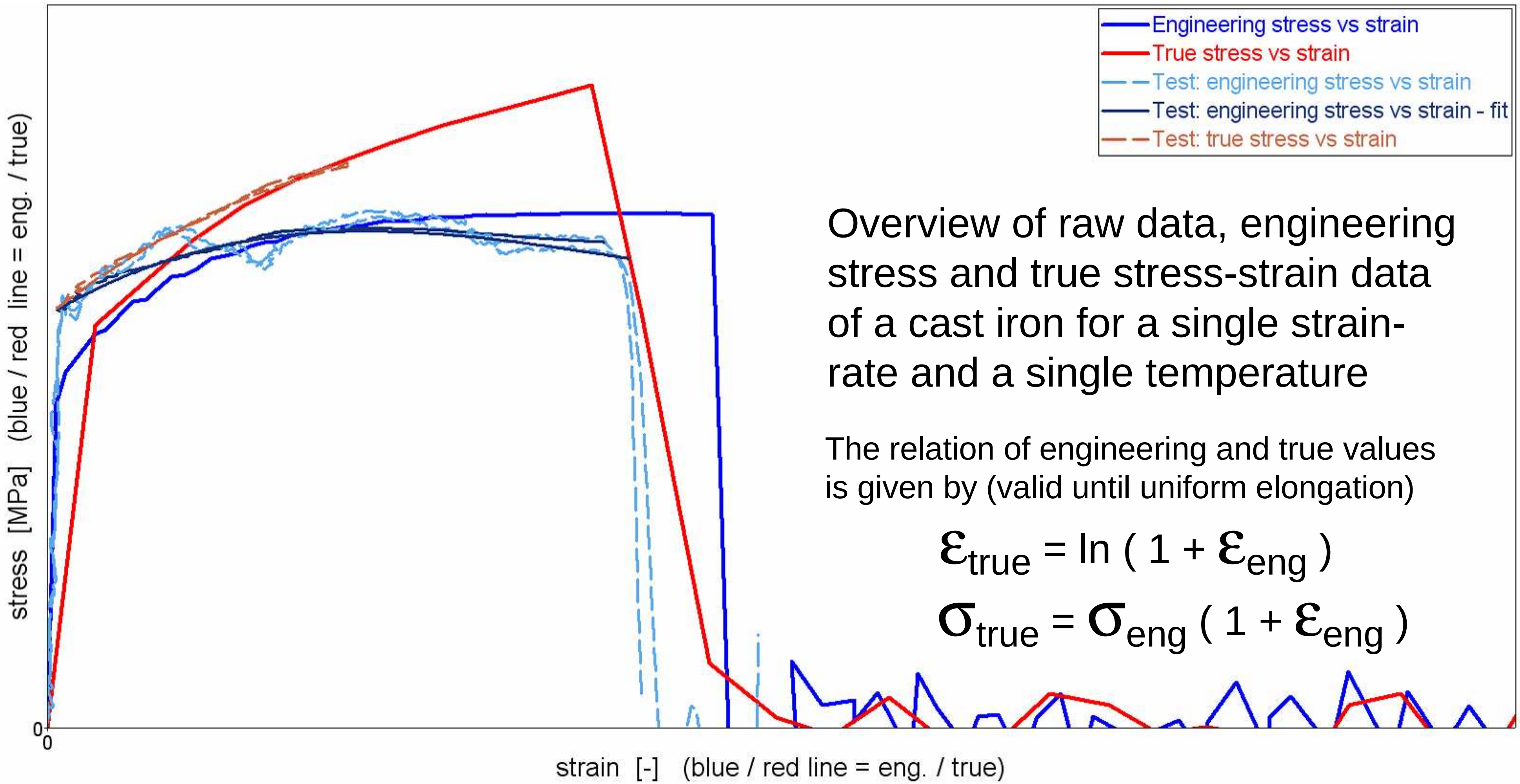
- Tension test of a specimen
  - Typical effects of higher strain rate and higher temperature





Specimen Tests

- Tension test of a specimen, comparison of simulation/test



Overview of raw data, engineering stress and true stress-strain data of a cast iron for a single strain-rate and a single temperature

The relation of engineering and true values is given by (valid until uniform elongation)

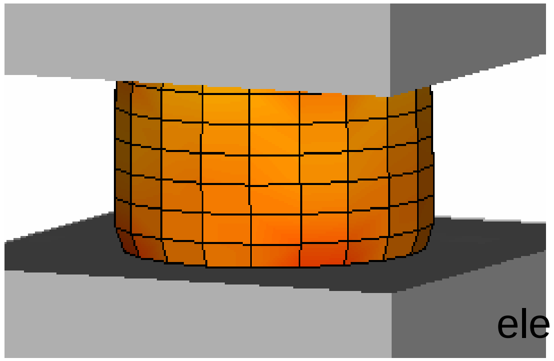
$$\varepsilon_{true} = \ln(1 + \varepsilon_{eng})$$

$$\sigma_{true} = \sigma_{eng}(1 + \varepsilon_{eng})$$

Specimen Tests

- Compression Test
  - An additional compression test allows the analysis of a possible interrelation of material behaviour under tension and compression
  - But as testing under highly dynamic loading is very difficult, normally this test is done with quasi-static loading
  - There is a significant influence of the friction between the specimen and the plates of the test rig

FE model of a specimen with common crash dimension

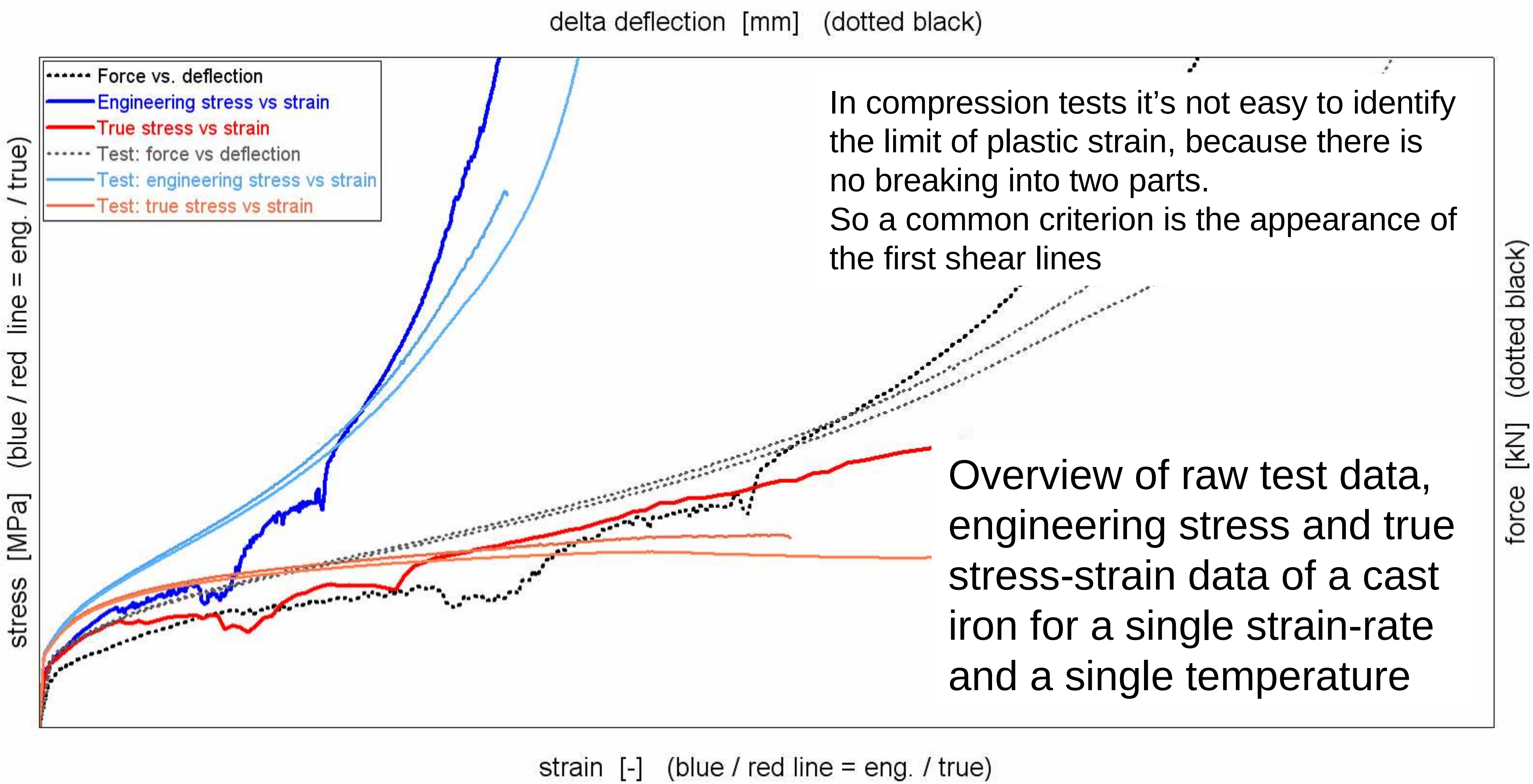


1929 nodes
1604 elements
element length ~0.8 mm

Specimen before and after test

Specimen Tests

- Compression Test



In compression tests it's not easy to identify the limit of plastic strain, because there is no breaking into two parts.
So a common criterion is the appearance of the first shear lines

Overview of raw test data, engineering stress and true stress-strain data of a cast iron for a single strain-rate and a single temperature

Implementation

- Overview
  - RADIOSS offers a wide range of different material laws that are very common in explicit respectively crash simulation
  - Examples are /MAT/LAW2 (Johnson-Cook) with polynomial input or /MAT/LAW36 with tabulated input, which is preferred today
- Standard material implementation
  - Using /MAT/LAW36 as a standard crash material for a common description of an isotropic elastoplastic material law
- Enhanced material implementation
  - Different stress-strain-curves for tension and compression
  - Different failure modes for tension and compression (triaxiality)

Implementation

- Standard material implementation
  - Using /MAT/LAW36 as a standard material description for crash simulation with an isotropic elastoplastic material law
- Common input data
  - Physical data e.g. bulk modulus, density, Poisson's ration, etc.
  - Maximum plastic strain (element eroding if this limit is reached)
  - Isotropic / kinematic hardening formulation
  - Yield stress functions for different strain rates
    - The first curve represents the lower limit of strain-rates (quasi-static)
    - Extrapolation for higher strain rates using the two last curves
    - Linear interpolation between two strain-rates
  - Remark: stress-strain-curves are based on tension tests

- /MAT/LAW36 - Standard
  - Isotropic elastoplastic material law using a user defined function for the plastic stress-strain-curve

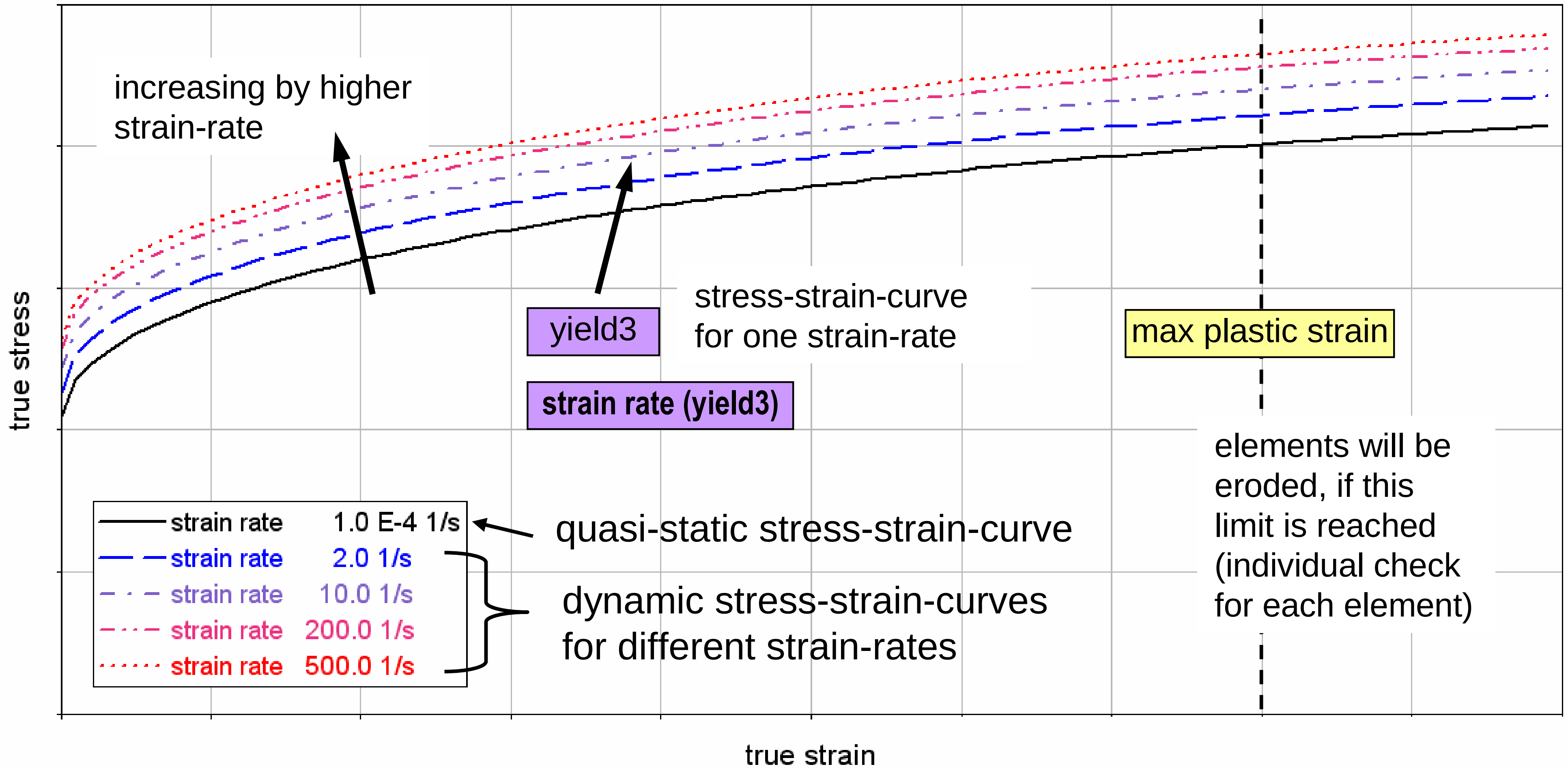
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
/MAT/LAW36/mat_ID/unit_ID or /MAT/PLAS_TAB/mat_ID/unit_ID									
mat_title									
density									
bulk modulus		Poisson's ratio		max plastic strain		ε_{t1}		ε_{t2}	
N_{funct}	F_{smooth}	C_{hard}		F_{cut}		ε_f			
$funct\_ID_p$	Fscale								
yield1	yield2	yield3	yield4	yield5					
$Fscale_1$		$Fscale_2$		$Fscale_3$		$Fscale_4$		$Fscale_5$	
strain rate (yield1)		strain rate (yield2)		strain rate (yield3)		strain rate (yield4)		strain rate (yield5)	

yield1 — ID number of the stress-strain-curve 1 to 5 which are associated to the

strain rate (yield1) — strain rate value 1 to 5 of the stress-strain-curve

Implementation

- /MAT/LAW36 - Standard
  - Common stress-strain-curves for /MAT/LAW36



Implementation

- Enhanced material implementation
  - Using /MAT/LAW36 as a standard material description for crash simulation with an isotropic elastoplastic material law

- Additional feature - Enhancement 1
  - Different stress-strain-curves for tension and compression
- Physical background
  - Most cast iron materials have significant differences in the stress-strain-curves for tension and for compression
  - This has to be taken into account for 3D-structures especially
  - This can be implemented directly into the standard material card /MAT/LAW36, no extra card is needed

Implementation

- /MAT/LAW36 - Enhancement 1
  - Enhanced material implementation for the relationship of compression and tension by using the standard card

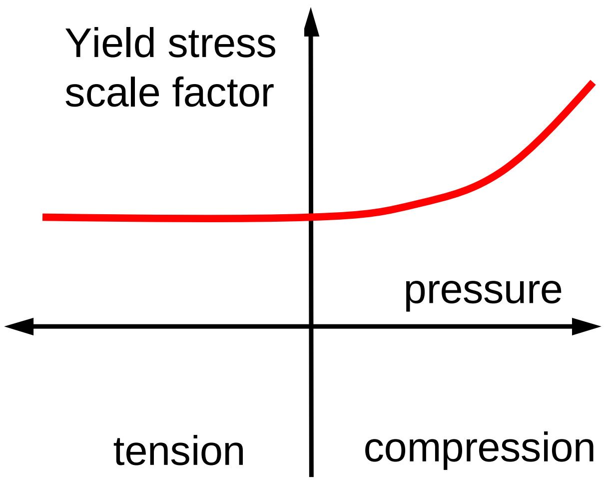
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
/MAT/LAW36/mat_ID/unit_ID or /MAT/PLAS_TAB/mat_ID/unit_ID									
mat_title									
density									
bulk modulus		poisson's ratio		max plastic strain		ε_{t1}		ε_{t2}	
N_{funct}	F_{smooth}	C_{hard}		F_{cut}		ε_{f}			
pressure	**scale**								
yield1	yield2	yield3	yield4	yield5					
$Fscale_1$		$Fscale_2$		$Fscale_3$		$Fscale_4$		$Fscale_5$	
strain rate (yield1)		**strain rate (yield2)**		**strain rate (yield3)**		**strain rate (yield4)**		**strain rate (yield5)**	

pressure ID number of the compression / tension relationship

scale scaling factor for the relationship

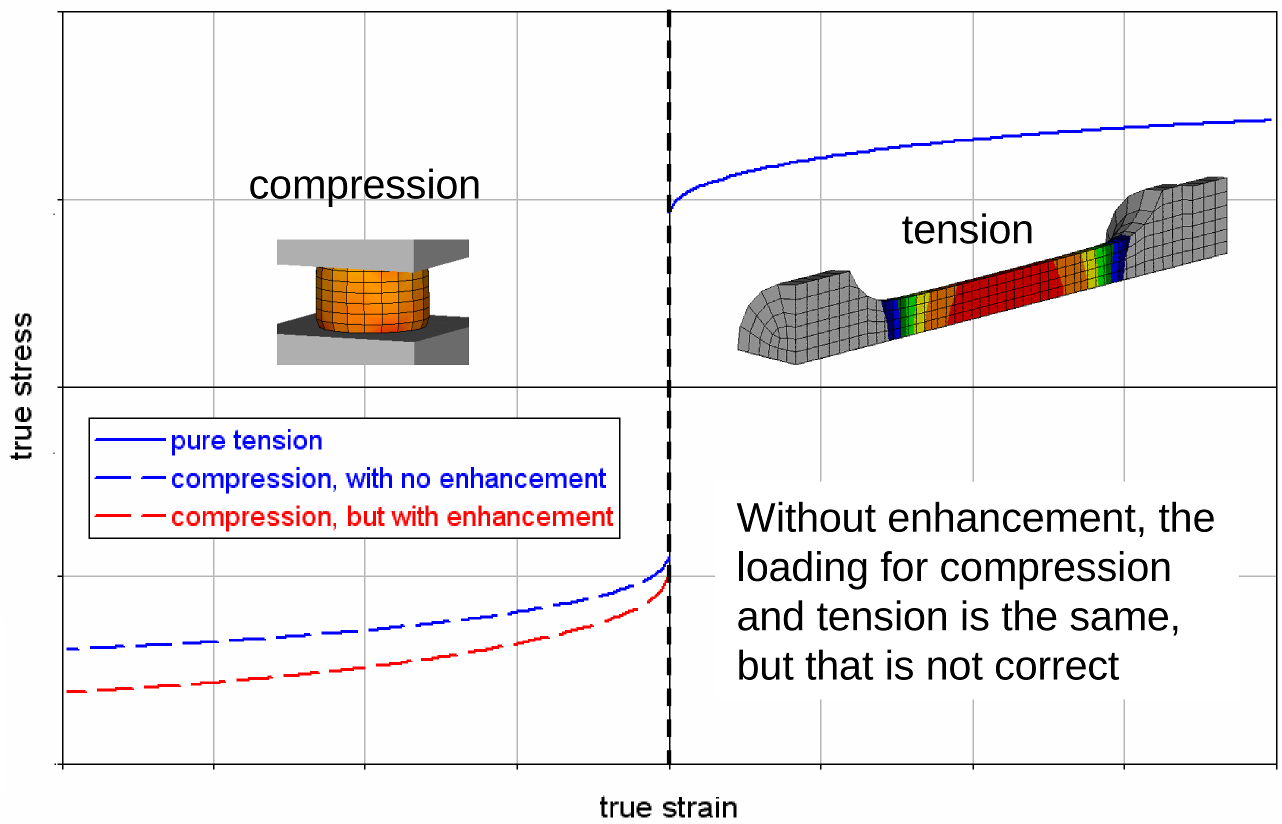
Implementation

- /MAT/LAW36 - Enhancement 1
  - Enhanced material implementation for the relationship of compression and tension by using the standard card



pressure | scale

Yield stress factor vs. pressure for defining the difference of tension and compression



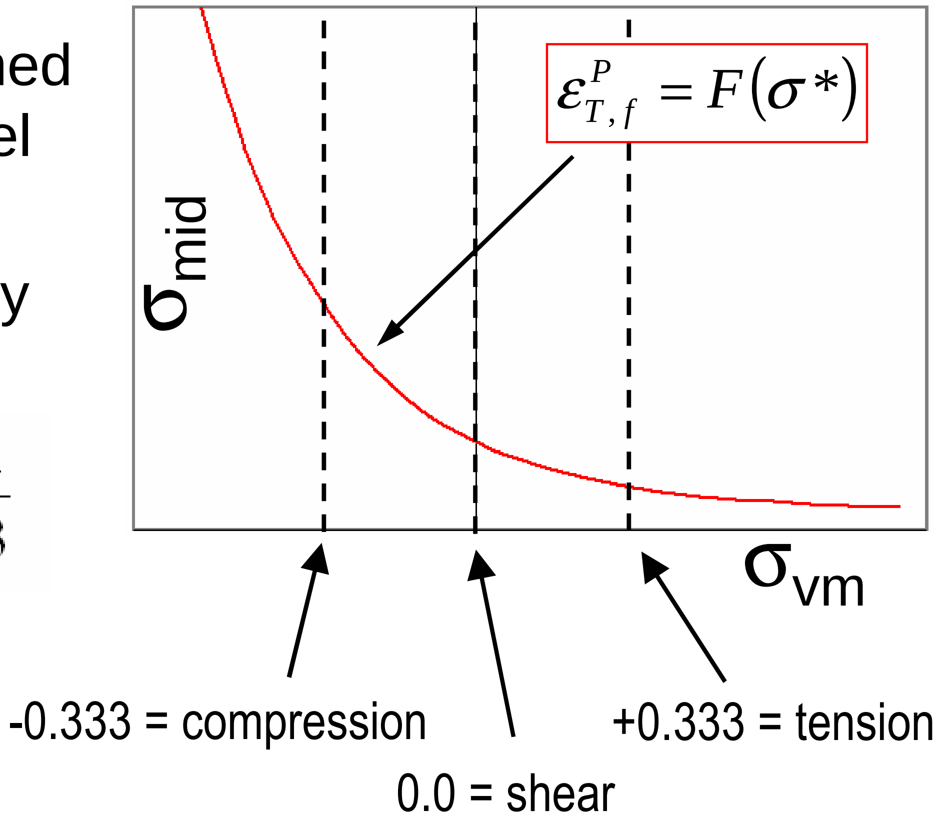
Implementation

- Enhanced material implementation
  - Using /MAT/LAW36 as a standard material description for crash simulation with an isotropic elastoplastic material law
- Additional feature - Enhancement 2
  - Different failure modes for tension and for compression (triaxiality)
- Physical background
  - Most cast iron materials also have significant differences in the failure mode due to tension and due to compression
  - This has to be taken into account for all simulation with fracture
  - This effect can be described by an additional failure card which can be associated to the used material card

- Enhancement 2 /FAIL/JOHNSON - physical background
  - Enhanced material implementation for the failure relationship of compression and tension using the additional /FAIL card
  - The failure relationship is defined by a function of mid-stress level to von-Mises stress
  - This relation is named triaxiality

$$\sigma^*_{Tension/compression} = \frac{\sigma_M}{\sigma_{VM}} = \frac{\sigma/3}{|\sigma|} = \pm\frac{1}{3}$$

$$\sigma^*_{Shear} = \frac{\sigma_M}{\sigma_{VM}} = \frac{0}{\sigma_{VM}} = 0$$



- Enhancement 2 / FAIL/JOHNSON
  - Enhanced material implementation for the failure relationship of compression and tension using the additional /FAIL card

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
/FAIL/JOHNSON/mat_ID/unit_ID									
Damage Factor 1		Damage Factor 2		Damage Factor 3		Damage Factor 4		Damage Factor 5	
$\dot{\varepsilon}_0$		I_{shell}	I_{solid}						

  - The relationship (failure curve) is defined by at least three failure parameters D1 to D3, D4 and D5 can be added optionally

$$\varepsilon^P_{T,f} = [D_1 + D_2.\exp(D_3.\sigma^*)].\left[1 + D_4.\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right].[1 + D_5.T^*]$$

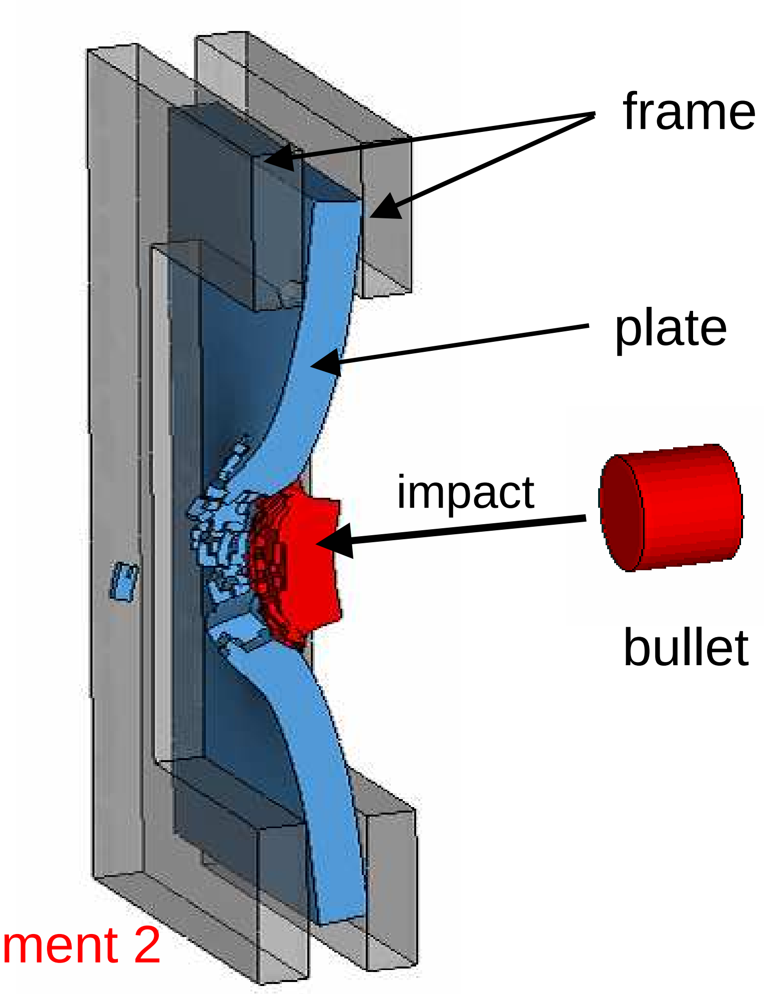
-> therefore normalized mean stress $\sigma^* = \sigma_M / \sigma_{VM}$

Impact Test

- Overview
  - The impact test is a simple but repeatable test for analysing a multiaxial stress combination under highly dynamic loading
  - Thus in this presentation the impact test is used for demonstrating the qualities of the material implementations described above
- Verification / Comparison of test and simulation
  - The calculations were carried out using different initial speeds of the bullet when hitting the plate
  - This allows to determine the limit of specific energy needed for a full penetration and to compare it for test and simulation
  - The simulation compares the standard material law versus the optimised i.e. the enhanced material implementation with the additional failure specification

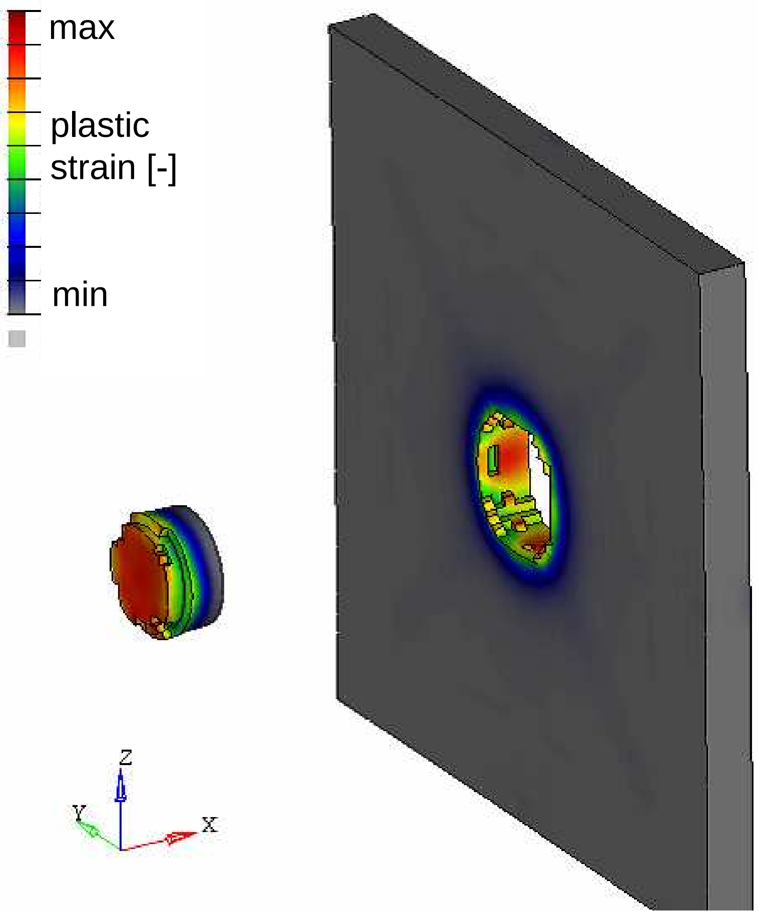
- Impact Test
  - For this impact test the same cast iron material is used for the plate and for the bullet
  - The plate is clamped by a rigid steel frame
  - The bullet has different initial speeds
- Simulation
  - Comparison of standard material and optimised material implementation
    - Standard = /MAT/LAW36
    - Optimised = /MAT/LAW36 + /FAIL/JC

Enhancement 1 + Enhancement 2

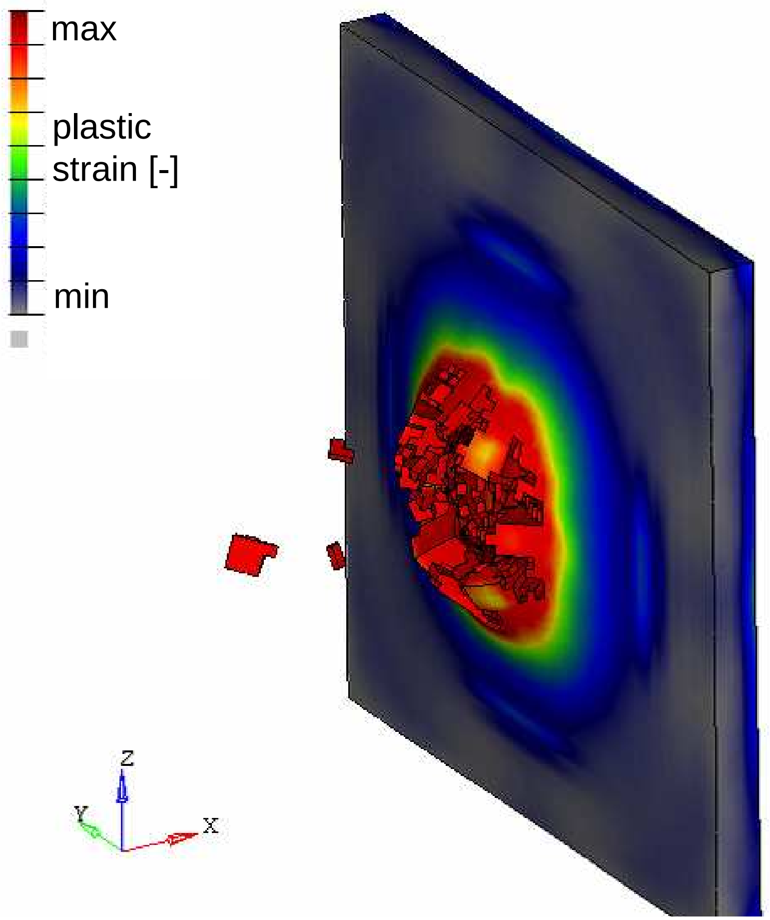


Impact Test

- Comparison of both material implementations

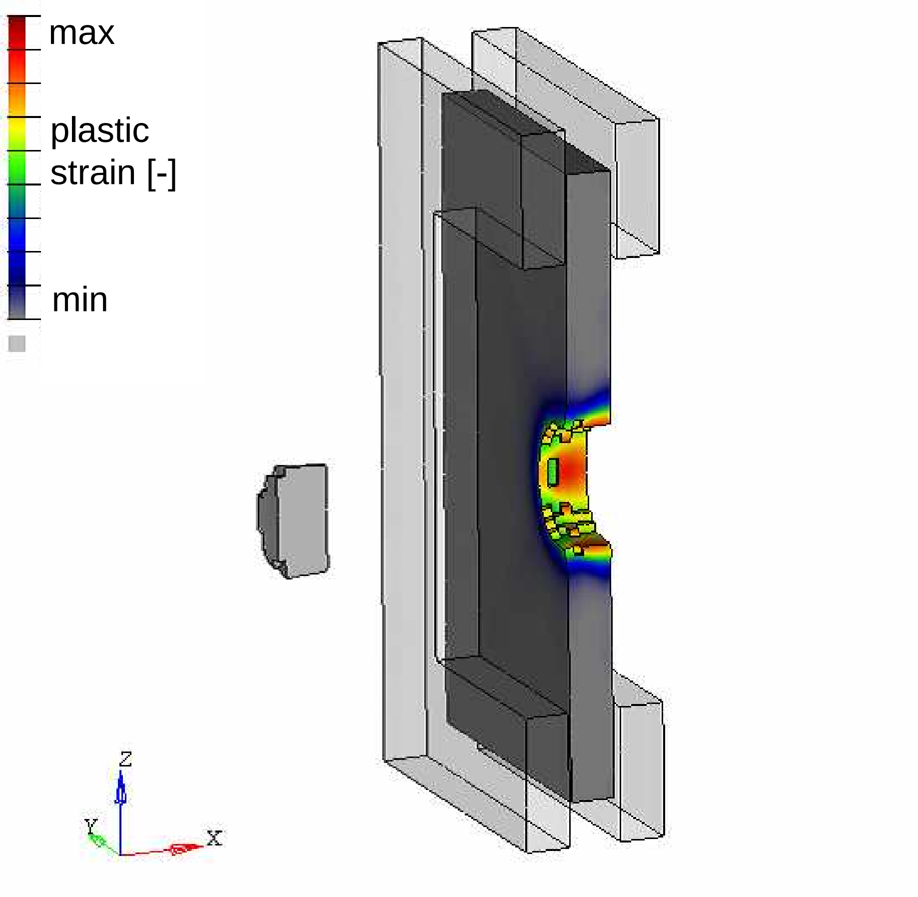


Standard Material Implementation

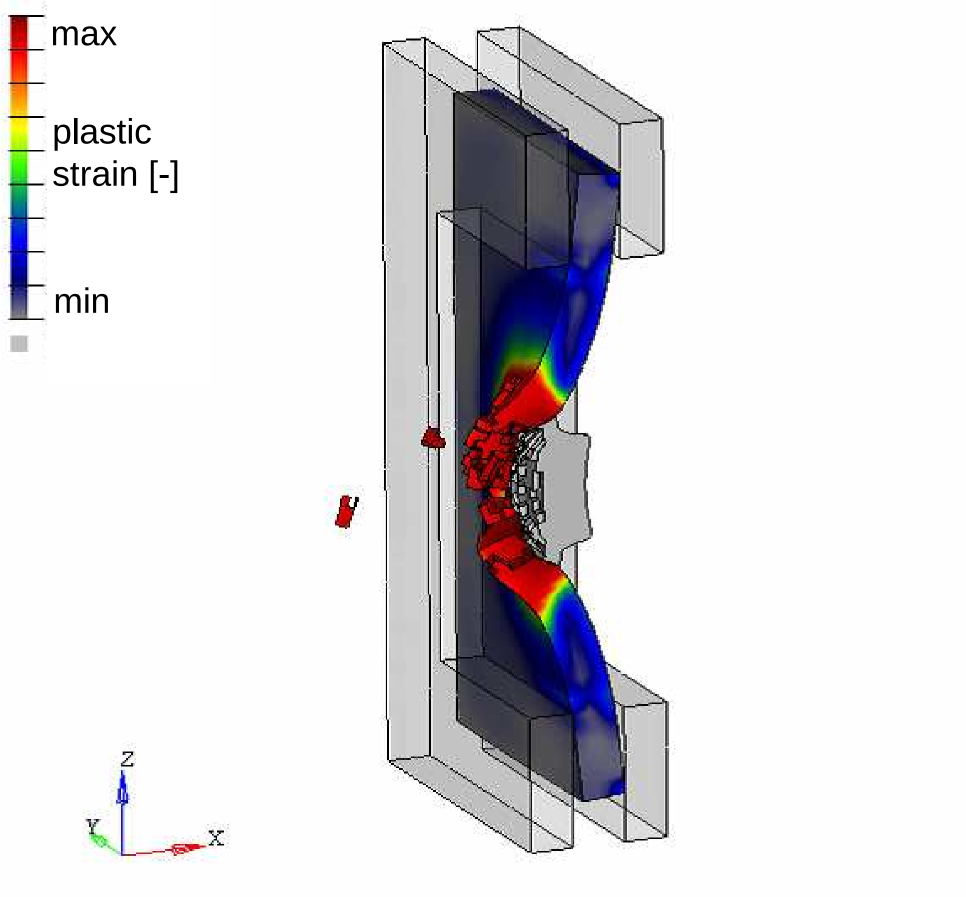


Optimised Material Implementation

- Comparison of both material implementations



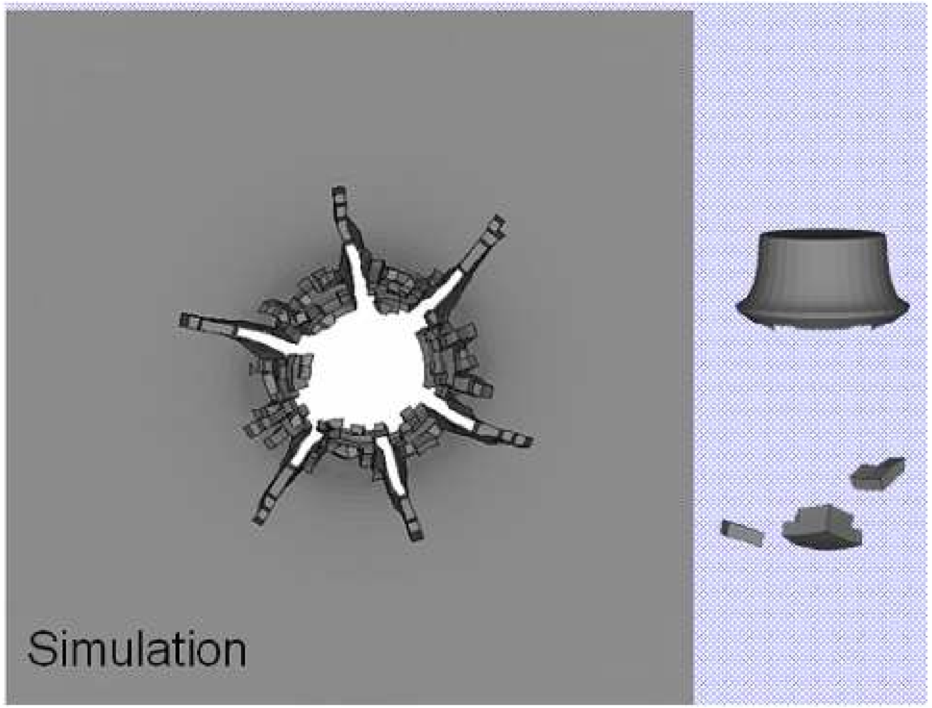
Standard Material Implementation



Optimised Material Implementation

Impact Test

- Comparison of impact test and simulation



The optimised material law with the enhanced material and the additional failure specification leads to an excellent correlation of deformation and failure behaviour and meets the specific energy which is needed for a full penetration

Summary

- Cast Iron Parts
  - Due to design flexibility and low costs, cast iron parts are used increasingly for very high loadings in a wide range of applications
  - But for highly dynamic loads with a significant failure behaviour, e.g. in a car crash, an impeller burst, etc. a standard material law defined only by a tension test is no longer sufficient
  - In particular for cast iron parts, the different behaviour under tension and compression in the stress-strain curves as well as in the failure behaviour have to be taken into account

- CAE Simulation / Process
  - RADIOSS Explicit can handle this by using common crash material laws, which can enhanced very comfortably with specific parameters and with an add-on of given failure criteria cards

Appendix

- Acknowledgement / References
  - German Research Association for Combustion Engines (FVV)
    - for allowing to attend sophisticated research programs, in particular, the research program FVV 0936 (Containment safety)
  - Federal Institute for Materials Research and Testing (BAM)
    - for their activity on a specimen test programme for cast iron
  - Fraunhofer Institute for Mechanics of Materials (IWM)
    - for their research for a better cast iron material description
- References / Internet
  - www.de.wikipedia.org www.konstruktionspraxis.vogel.de
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  - www.claasguss.de/html/home.html www.audia2museum.de/54.html
  - www.svrider.de/Homepage/SV1000FAQ/SV1000FAQ_rahmen.jpg