INSTITUT FÜR KRAFT-FAHR-ZEUGE
RWTH AACHEN UNIVERSITY

13. LS-Dyna Forum 2014

Effect of the Non-Local Failure Criterion on the Acceleration Signal of Head Impactors at Impact in the Windscreen Centre

Bamberg, 8. October 2014

Dipl.-Ing. Frederic Nuß, Dipl.-Ing. Andreas Herkenhoff,
Univ.-Prof. Dr.-Ing. Lutz Eckstein

Institut für Kraftfahrzeuge
RWTH Aachen University

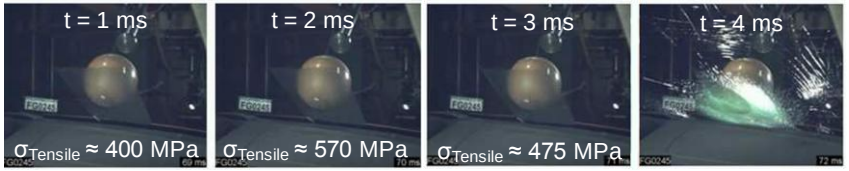
Agenda

- Motivation
- Basic Mechanical Material Properties of Glass
- Experimental Results of Head Impact Test with Reference Vehicle
- Analysis of Non-Local Failure Criterion Based on Simulations
- Summary and Outlook

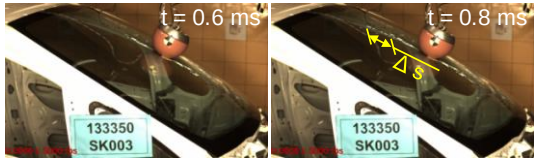
Motivation

Non-local Failure Criterion (RADIOSS)

- Criterion for modelling failure behaviour of glass (developed by [PYT11,PYT13]):
  - Elastic deformation without failure despite high tensile stresses
  - Sudden failure combined with fast crack propagation (≈ 2.000 m/s)
  - Failure initiation depending on curvature

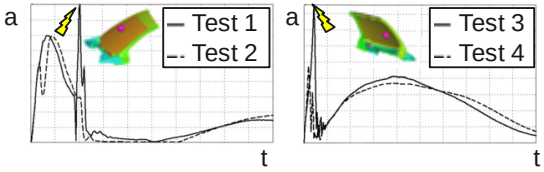


Chronological sequence of impactor test (picture from [RIE05], stresses from internal simulations)



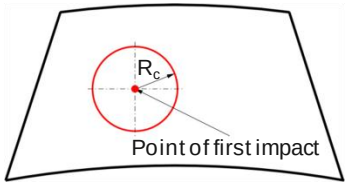
Crack propagation during impactor test
(v = Δ s / Δ t ≈ 150 mm / 0,2 ms = 750 m/s)

- Modelling of failure criterion [PYT11]:
  1. Internal energy in certain area $\mathbf{r_{crit}}$ reaching critical energy $\mathbf{E_{crit}}$
  2. Deletion of elements, which principal stress exceeds $\boldsymbol{\sigma_{crit}}$
- Values given in [PYT11] for r_{crit} = 210 mm, E_{crit} = 22,3 J and σ_{crit} = 60 MPa



Comparison of impactor accelerations at exterior and interior impact (after [PYT11])

- **BUT:** σ_{crit} for glass is a value range, not a fixed value



Parameter of non-local failure criterion [PYT11]

Motivation - cont‘d

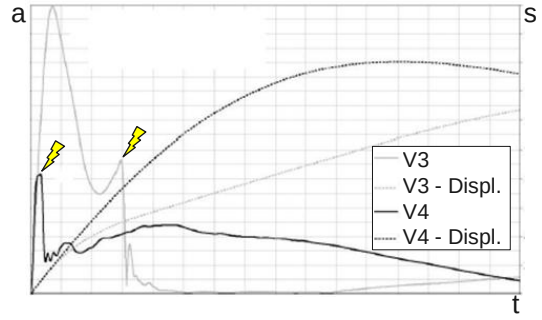
Non-local Failure Criterion (RADIOSS)

- Values given for r_{crit}, E_{crit} and σ_{crit}
- **BUT:** σ_{crit} for glass is a value range, not a fixed value

Modelling of Different Failure Mechanisms

- Implementation in LS-DYNA since R7.0.0 (*MAT_ADD_EROSION)
- Modelling different failure mechanisms in [HAU13] based on non-local failure criterion in LS-DYNA probably by variation of σ_{crit}

- **BUT:** no values given for r_{crit}, E_{crit} and σ_{crit}



Effect of different fracture mechanisms on acceleration signal [HAU13]

Goal

- Analysis of modelling potentials of non-local failure criterion in LS-DYNA
- Sensitization of influence of fracture mechanics and probabilistic fracture mechanics for glass

Agenda

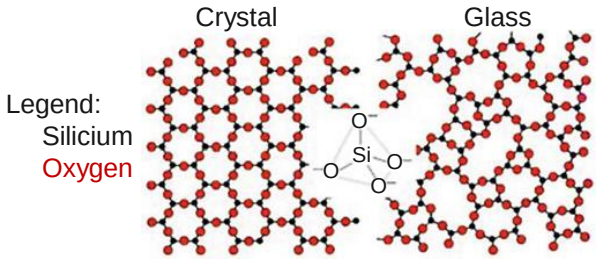
- Motivation
- Basic Mechanical Material Properties of Glass
- Experimental Results of Head Impact Test with Reference Vehicle
- Analysis of Non-Local Failure Criterion Based on Simulations
- Summary and Outlook

Basic Mechanical Material Properties of Glass

Crystal Structure [SCH14]

- Tetrahedral structure based on SiO_4-units
- Same near-order like crystals, but no far order

- Existing structural orders not sufficient for characterization
  - order not as stringent as in crystallite hypothesis
  - order not as statistically random as in network hypothesis



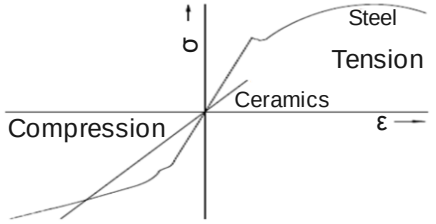
Schematic diagram of SiO_2 network of quartz and quartz glass [SCH14]

Mechanical Behaviour of Glass

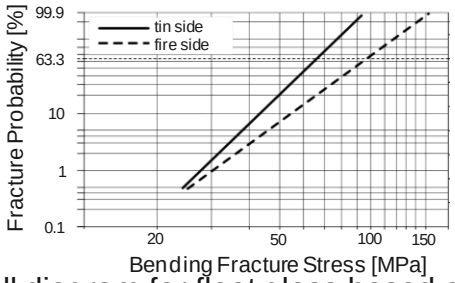
- In contrast to metals no elastic-plastic, but purely elastic behaviour
- Sudden fracture in case of excessive loading

- Fracture stress depending on defect size (Griffith)
  - Defects at component surface or
  - Stochastically distributed defects at crystal structure

- Fracture stress not a fixed value, but value range [VAR01]
- Description of fracture stress in Weibull diagram
- Production caused differences for each glass surface
- Statistic relevant number of repetition (30 or more) for scientific investigations necessary [VAR01]



Stress-strain-diagram for ceramics and steel [BAR08]



Weibull diagram for float glass based on double ring bending tests [FEL12, SED99]

Agenda

- Motivation
- Basic Mechanical Material Properties of Glass
- Experimental Results of Head Impact Test with Reference Vehicle
- Analysis of Non-Local Failure Criterion Based on Simulations
- Summary and Outlook

Experimental Results of Head Impact Test with Reference Vehicle

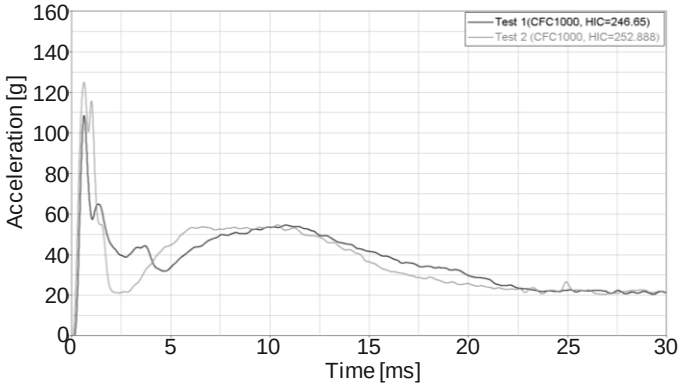
Boundary Conditions

- Head impact at windscreen centre
- Impact with adult head impactor (4.5 kg), a velocity of 40 km/h and an impact angle of 65°
- New head impactor skin
- Certified windscreen (as spare part) attached with 2-component adhesive 24 h before test
- Two repetitions

Test set-up before test

Test Results

- Similar acceleration signal
- Maximum acceleration between 105 and 125 g
- HIC between 247 and 253
- Fracture initiation between 0.2 ms (test 1) and 0.6 ms (test 2)
- Significant stiffness reduction after 1 to 1.5 ms



Acceleration signal of impact test

Fracture pattern after test

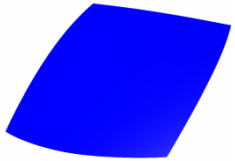
Agenda

- Motivation
- Basic Mechanical Material Properties of Glass
- Experimental Results of Head Impact Test with Reference Vehicle
- Analysis of Non-Local Failure Criterion Based on Simulations
- Summary and Outlook

Set-Up of Simulation Model

Geometry

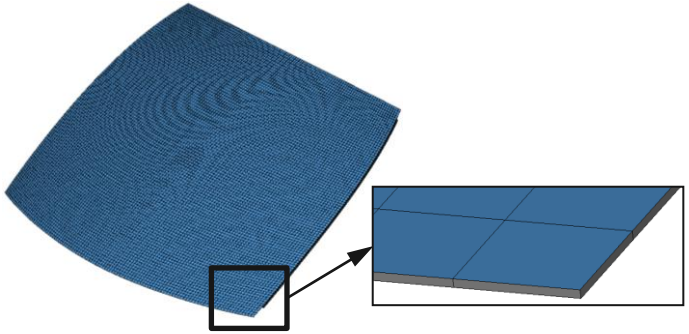
- Based on 3D-data from online provider
- Surfaces re-designed in CATIA and validated with spare part windscreen



Catia Model

Meshing

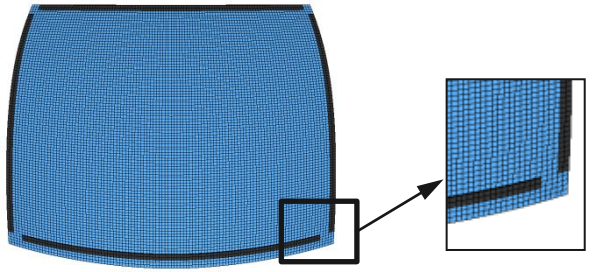
- Symmetric meshing using quad elements
- Shell-Solid-Shell modelling of laminated safety glass (glass - PVB - glass) using coincident nodes and NLOC
- Glass: MAT_123, ρ = 2,500 kg/m³, E = 70 GPa, PR = 0.22, SigY = 1,000 Mpa, ETan = 10 with MAT_ADD_EROSION
- PVB: MAT_27, ρ = 1,100 kg/m³, PR = 0.495, A = 1.6, B = 0.06



Windscreen Model

Adhesive Modelling

- Adhesive at interior side
- Solid elements
- Adhesive side fixed using BOUNDARY_SPC at connection to A-pillar and windscreen frame



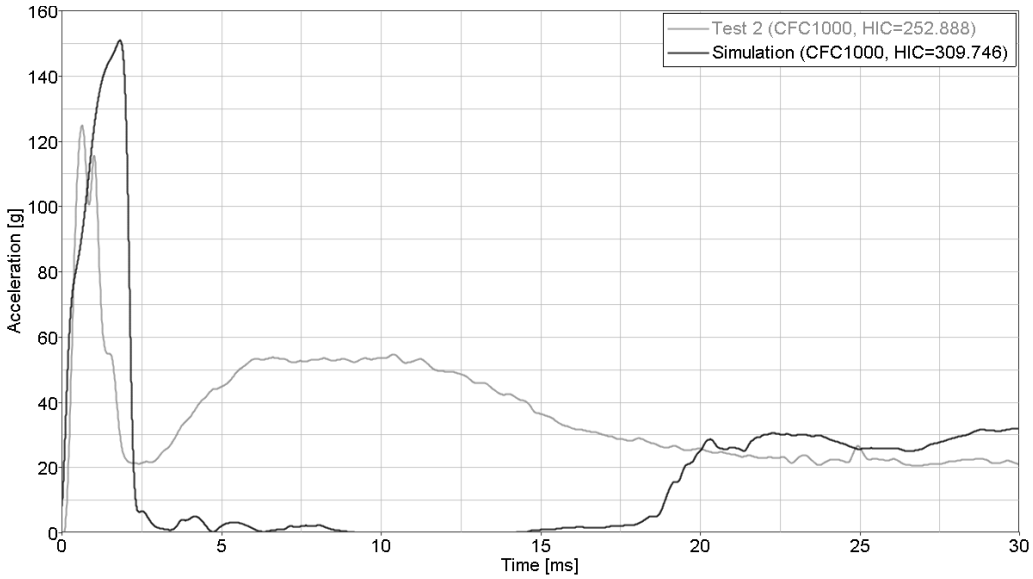
Adhesive at windscreen Interior side

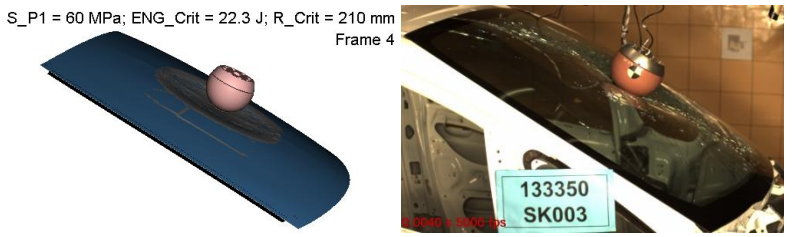
Head Impact Simulations Using Non-Local-Failure Criteria

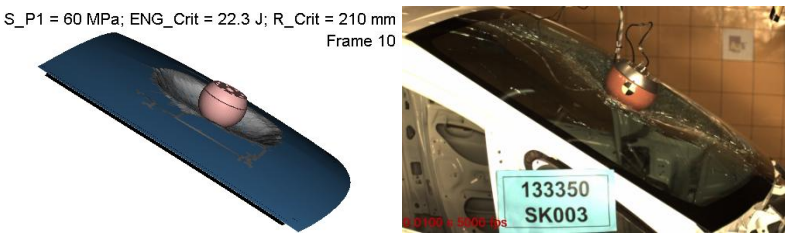
INSTITUT FÜR KRAFT-FAHR-ZEUGE
RWTH AACHEN UNIVERSITY

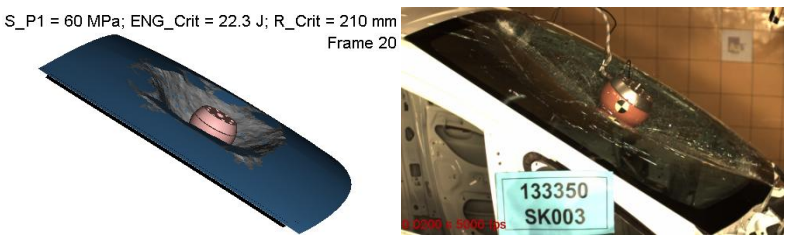
Parameter from [PYT11]

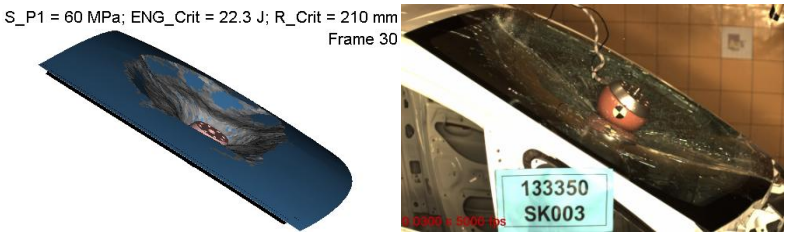
- First stiffness reduction too late
- Crack propagation locally limited
- Deletion of nearly all elements in impact area
- Acceleration of head impactor after first stiffness reduction (from 3 until 18 ms) too low









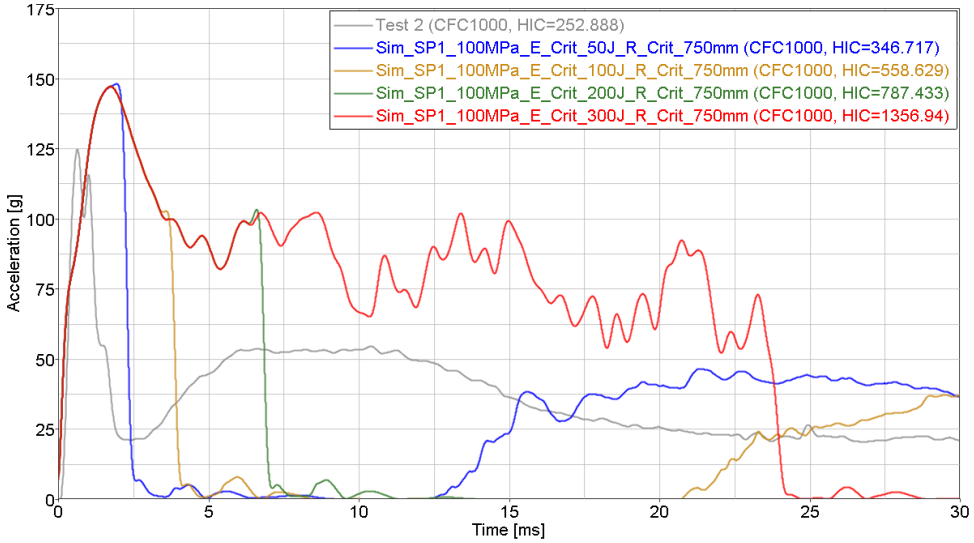


Head Impact Simulations Using Non-Local-Failure Criteria

INSTITUT FÜR KRAFT-FAHR-ZEUGE
RWTH AACHEN UNIVERSITY

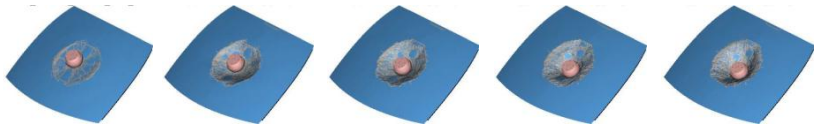
Variation of parameter E_{crit}

With increasing E_{crit}
- Later first stiffness reduction until lack of cracking possible
- Locally increasing crack or element deletion area



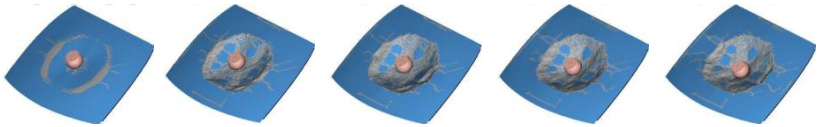
S_{P1} = 100 MPa; **E_{crit} = 50 J**; r_{crit} = 750 mm

t_{crack} ≈ 3 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



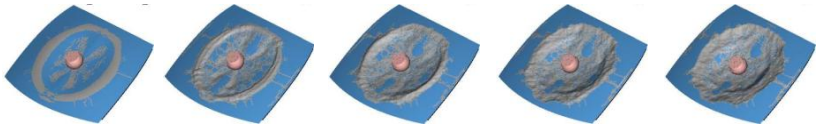
S_{P1} = 100 MPa; **E_{crit} = 100 J**; r_{crit} = 750 mm

t_{crack} ≈ 4 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



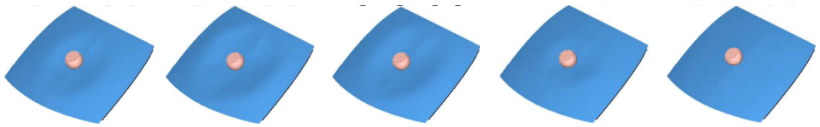
S_{P1} = 100 MPa; **E_{crit} = 200 J**; r_{crit} = 750 mm

t_{crack} ≈ 7 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



S_{P1} = 100 MPa; **E_{crit} = 300 J**; r_{crit} = 750 mm

t = 5 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms

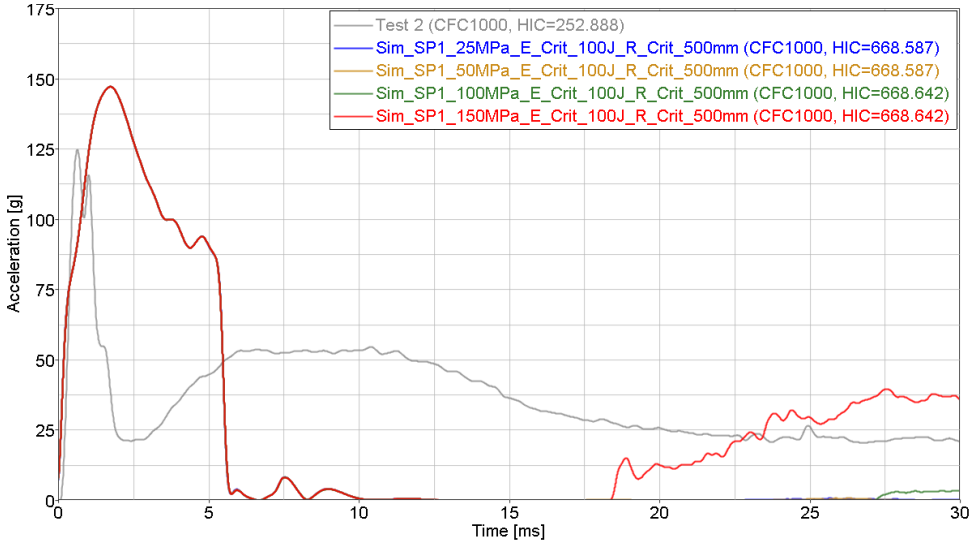


Head Impact Simulations Using Non-Local-Failure Criteria

INSTITUT FÜR KRAFT-FAHR-ZEUGE
RWTH AACHEN UNIVERSITY

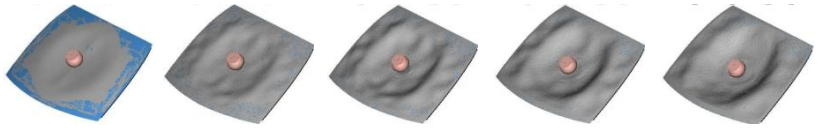
Variation of parameter σ_{crit} (S_{P1})

With increasing σ_{crit}
- Smaller number of deleted elements
- Locally limited crack distribution
- No effect on first stiffness reduction



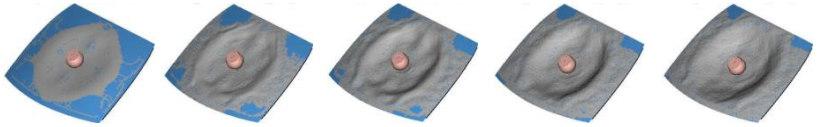
S_{P1} = 25 MPa; E_{crit} = 100 J; r_{crit} = 500 mm

t_{crack} ≈ 5 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



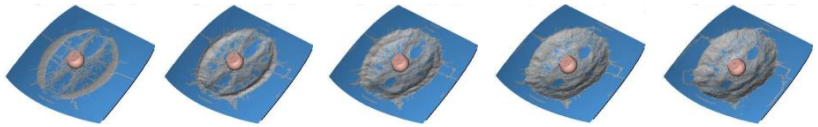
S_{P1} = 50 MPa; E_{crit} = 100 J; r_{crit} = 500 mm

t_{crack} ≈ 5 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



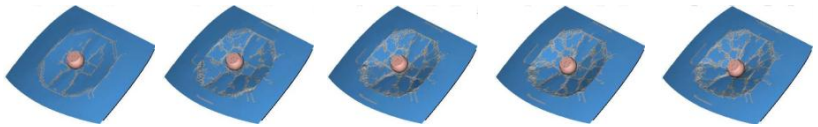
S_{P1} = 100 MPa; E_{crit} = 100 J; r_{crit} = 500 mm

t_{crack} ≈ 5 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



S_{P1} = 150 MPa; E_{crit} = 100 J; r_{crit} = 500 mm

t_{crack} ≈ 5 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



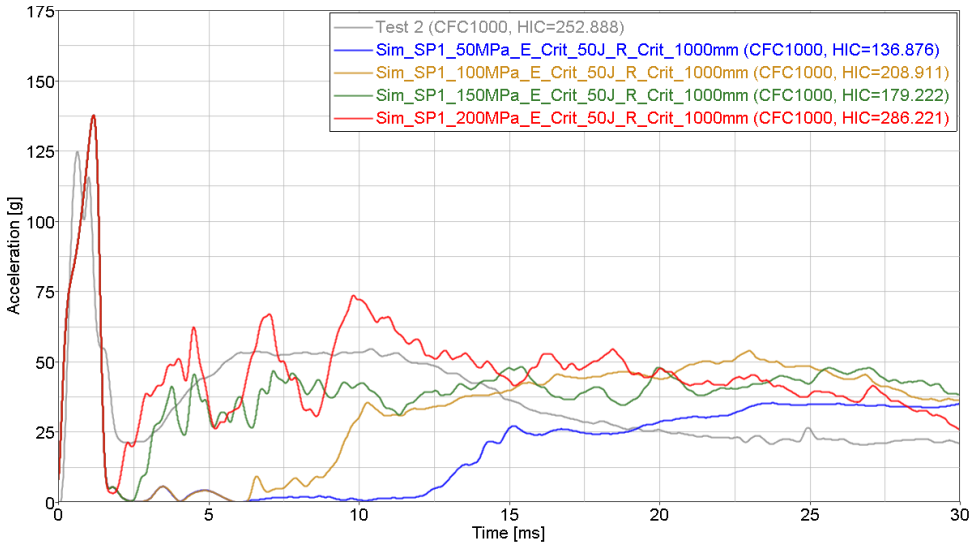
Head Impact Simulations Using Non-Local-Failure Criteria

INSTITUT FÜR KRAFT-FAHR-ZEUGE
RWTH AACHEN UNIVERSITY

Variation of parameter σ_{crit} (S_{P1}) cont'd

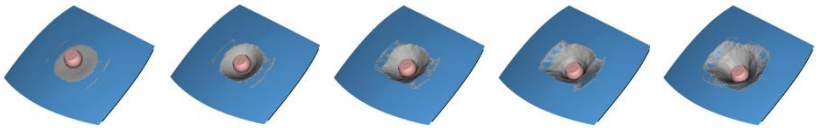
With increasing σ_{crit}

- Smaller number of deleted elements
- Locally limited crack distribution
- No effect on first stiffness reduction
- Higher stiffness of cracked windscreen



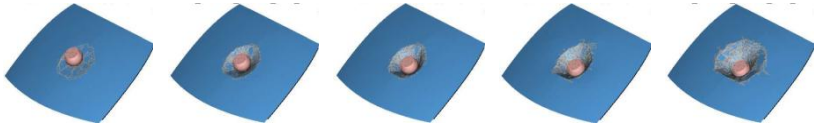
S_{P1} = 50 MPa; E_{crit} = 50 J; r_{crit} = 1000 mm

t_{crack} ≈ 2 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



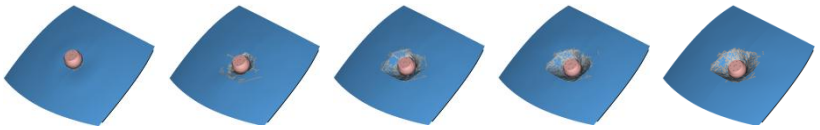
S_{P1} = 100 MPa; E_{crit} = 50 J; r_{crit} = 1000 mm

t_{crack} ≈ 2 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



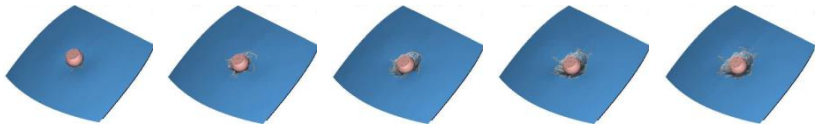
S_{P1} = 150 MPa; E_{crit} = 50 J; r_{crit} = 1000 mm

t_{crack} ≈ 2 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



S_{P1} = 200 MPa; E_{crit} = 50 J; r_{crit} = 1000 mm

t_{crack} ≈ 2 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



Head Impact Simulations Using Non-Local-Failure Criteria

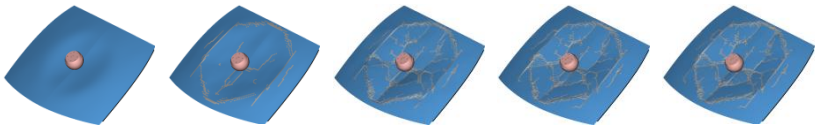
INSTITUT FÜR KRAFT-FAHR-ZEUGE
RWTH AACHEN UNIVERSITY

Variation of parameter r_{Crit}

With increasing r_{Crit}
- Earlier first stiffness reduction
- Locally limited element deletion
- Higher stiffness of cracked windscreen

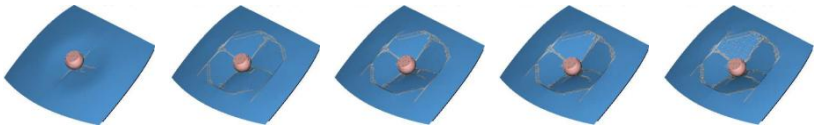
S_{P1} = 200 MPa; E_{crit} = 50 J; **r_{crit} = 250 mm**

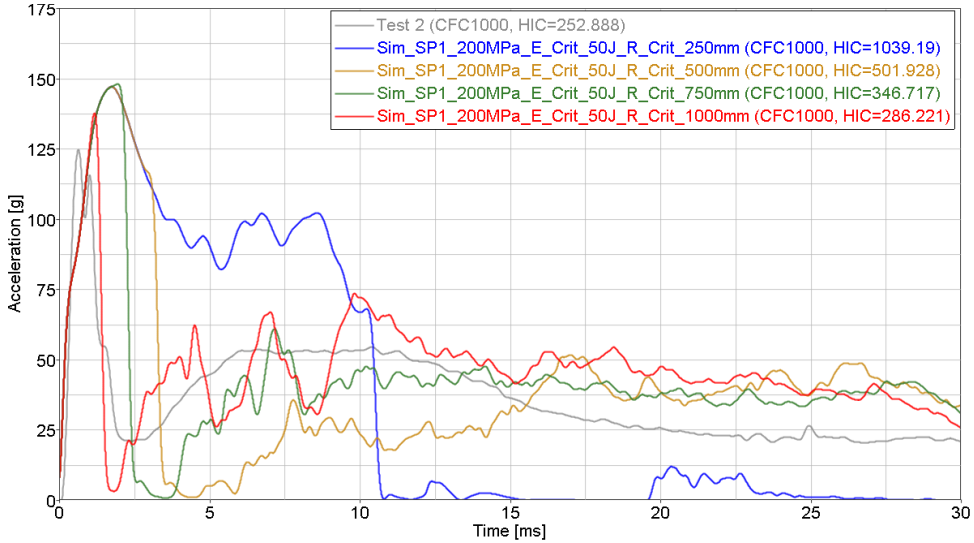
t ≈ 5 ms t_{crack} = 10 ms t = 15 ms t = 20 ms t = 25 ms



S_{P1} = 200 MPa; E_{crit} = 50 J; **r_{crit} = 500 mm**

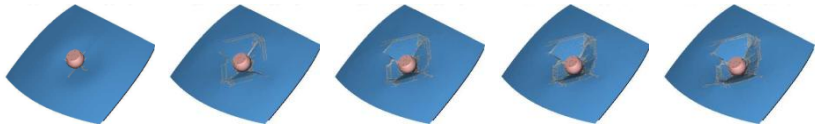
t_{crack} ≈ 3 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms





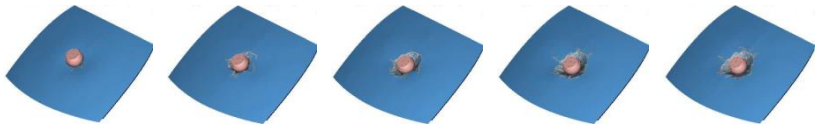
S_{P1} = 200 MPa; E_{crit} = 50 J; **r_{crit} = 750 mm**

t_{crack} ≈ 2.5 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms



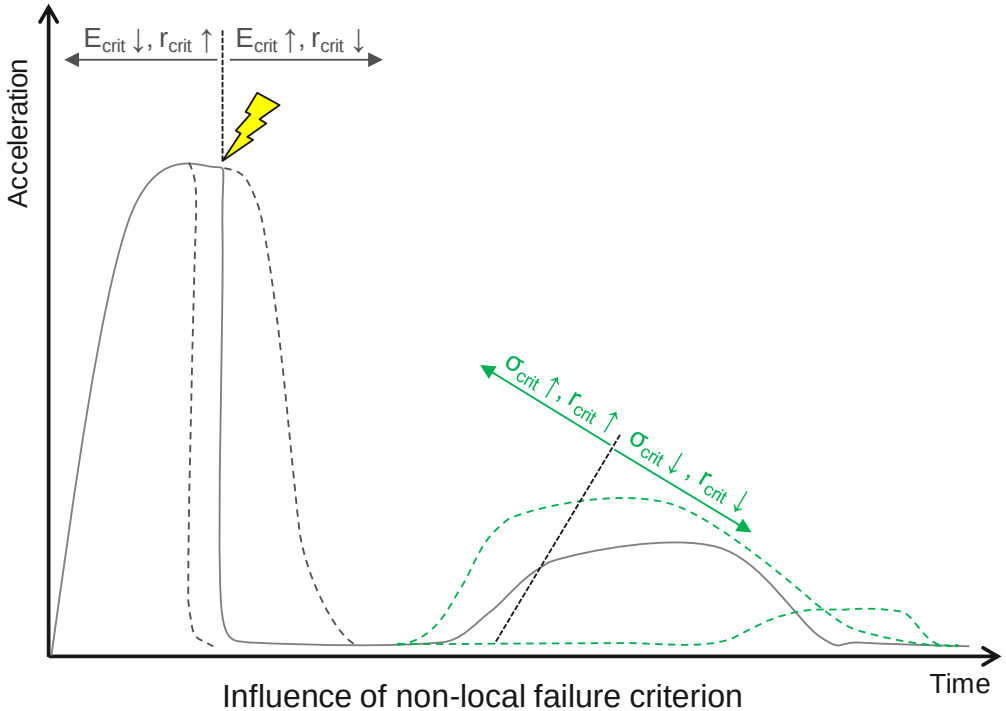
S_{P1} = 200 MPa; E_{crit} = 50 J; **r_{crit} = 1000 mm**

t_{crack} ≈ 2 ms t = 10 ms t = 15 ms t = 20 ms t = 25 ms

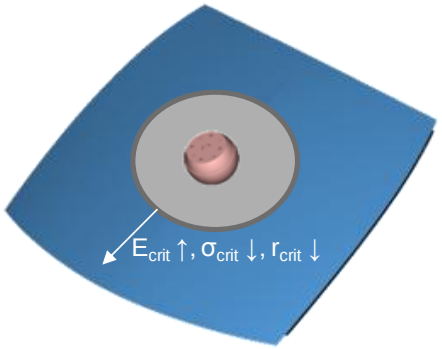


Influence of Non-Local Failure Criterion Parameters

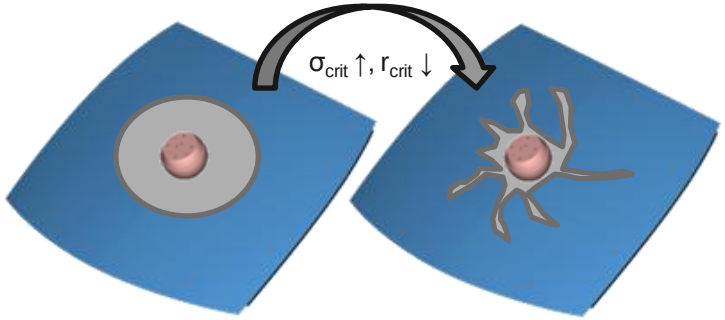
Influence Shown Based on Simulation Results



Influence of non-local failure criterion parameters on acceleration signal



Influence of non-local failure criterion parameters on element deletion area



Influence of non-local failure criterion parameters on crack pattern

Optimization of Simulation Results Based on Parameter Variation

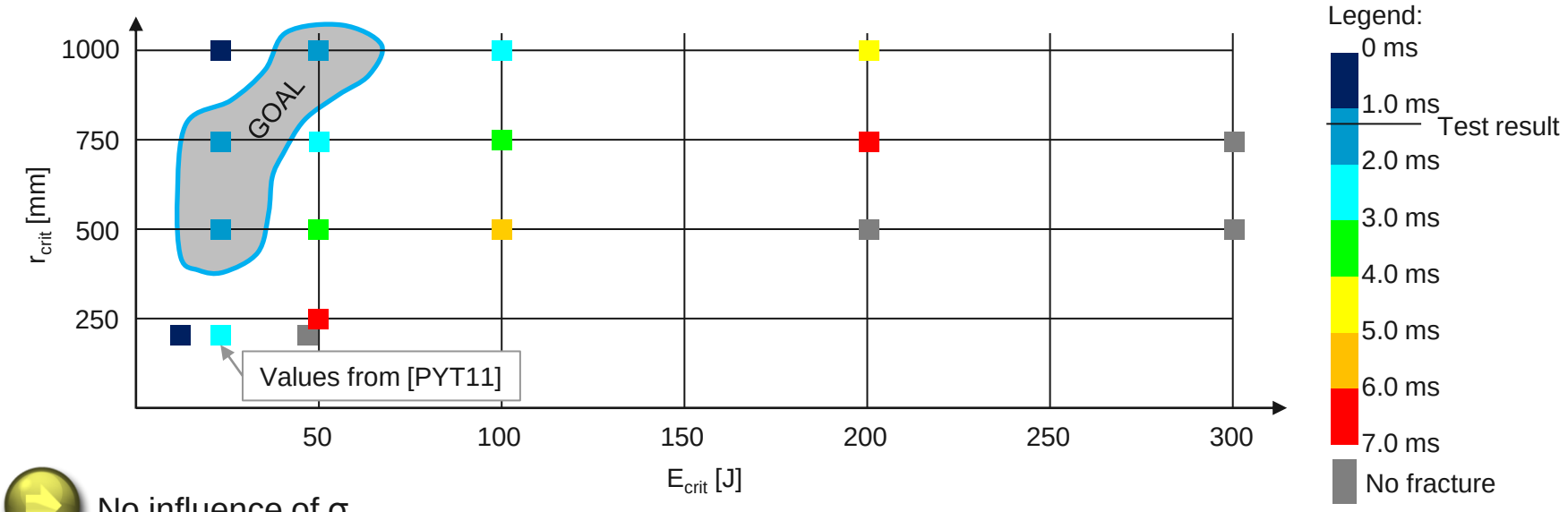
Possible Optimization Parameters

- Model set-up including layer structure, contact modelling, material parameter, etc.
- **BUT:** focus on parameter of non-local failure criterion

Validation Criteria

- Comparing differences in acceleration signal (validation metric, e.g. CORA [GAR12]), time of head impactor velocity equals zero (in test ca 36 ms)
- **BUT:** focus on first stiffness reduction, begin 2nd peak and crack pattern

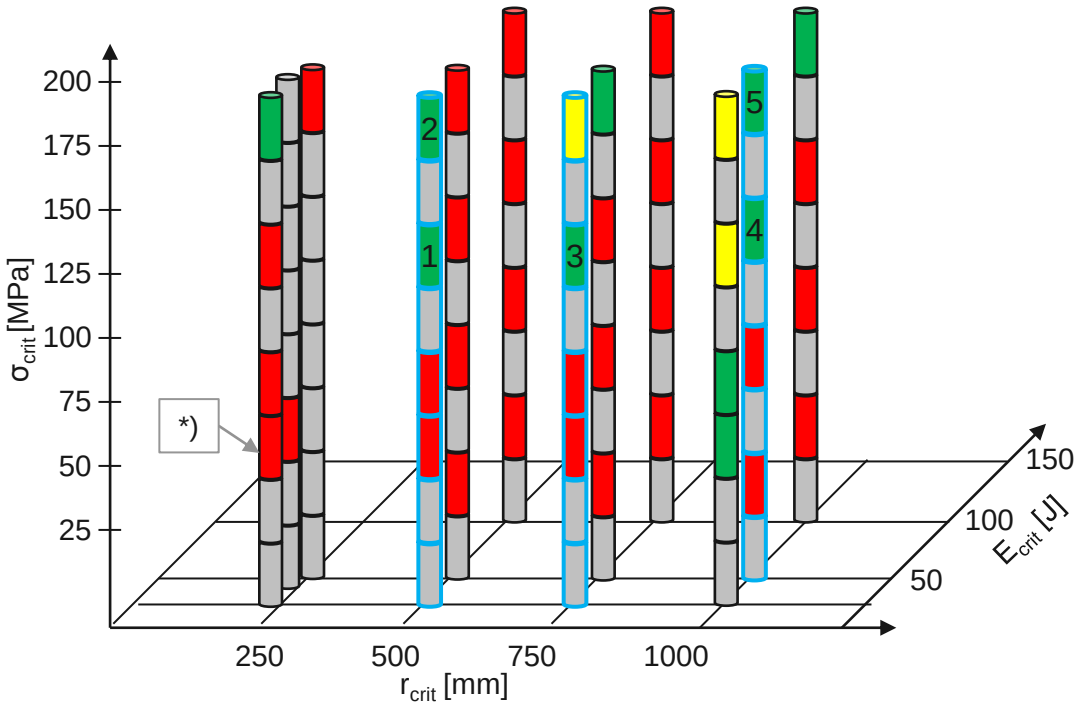
Time of First Stiffness Reduction as Function of r_{crit} and E_{crit}



No influence of σ_{crit}

Optimization of Simulation Results Based on Parameter Variation

Beginning of 2nd Peak as Function of σ_{crit}, r_{crit} and E_{crit}



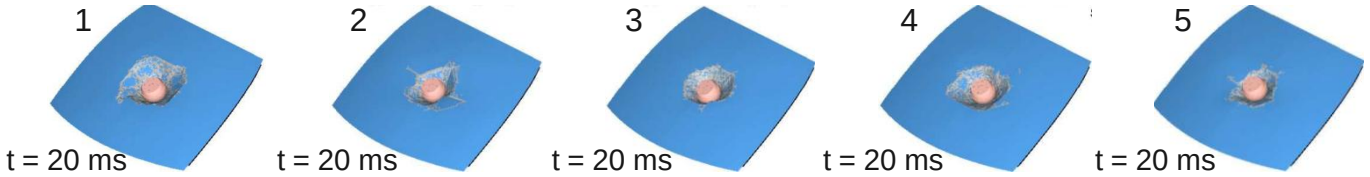
Legend:

- Earlier than in test
- Same than intest
- Later than in test
- No simulation
- Incorrect time of first stiffness reduction
- Correct time of first stiffness reduction

* Values from [PYT11]

1 Numbering of simulations used for crack pattern analysis (see below)

Analysis of Crack Pattern

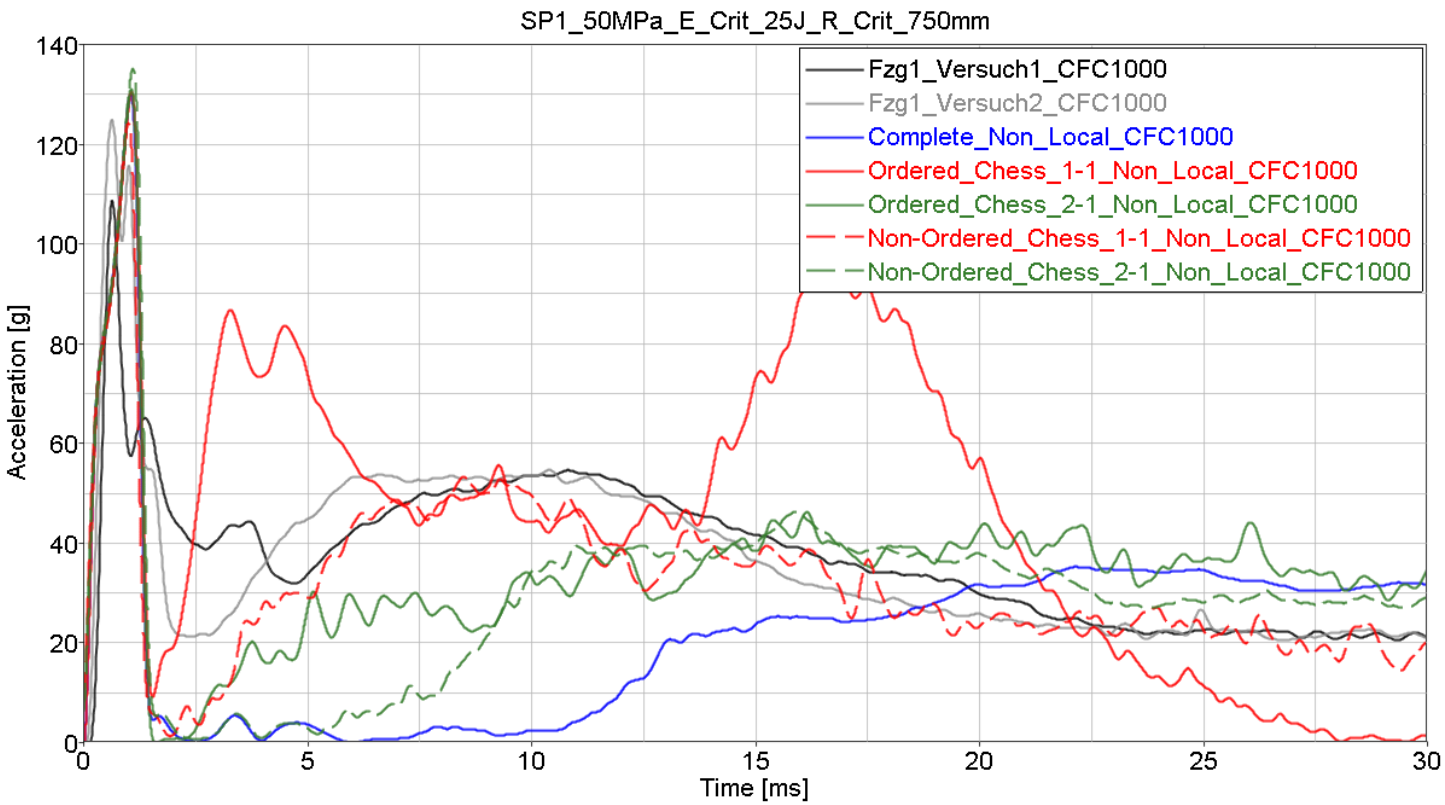


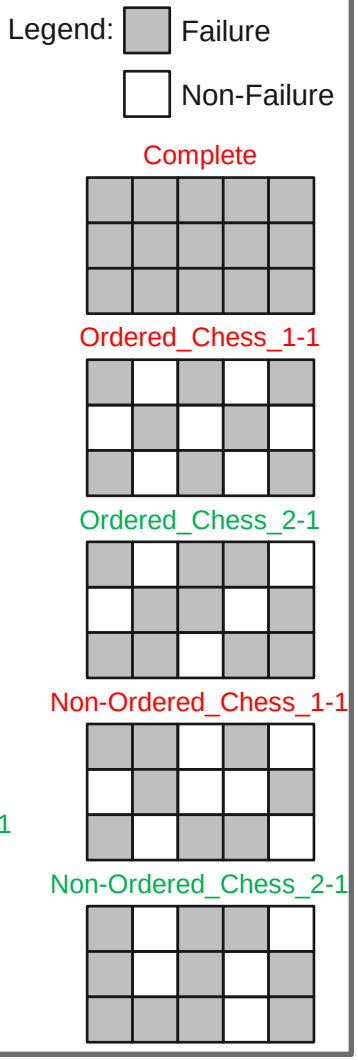
Crack pattern less global distributed compared to test

Optimization of Simulation Results Based on Chess-Meshing

INSTITUT FÜR KRAFT-FAHR-ZEUGE
RWTH AACHEN UNIVERSITY

Reducing Amount of Deleted Elements by Integration Second Non-Failure Material Model





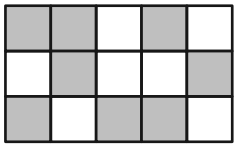
Variation of Parameters for Modelling Later Crack Initiation

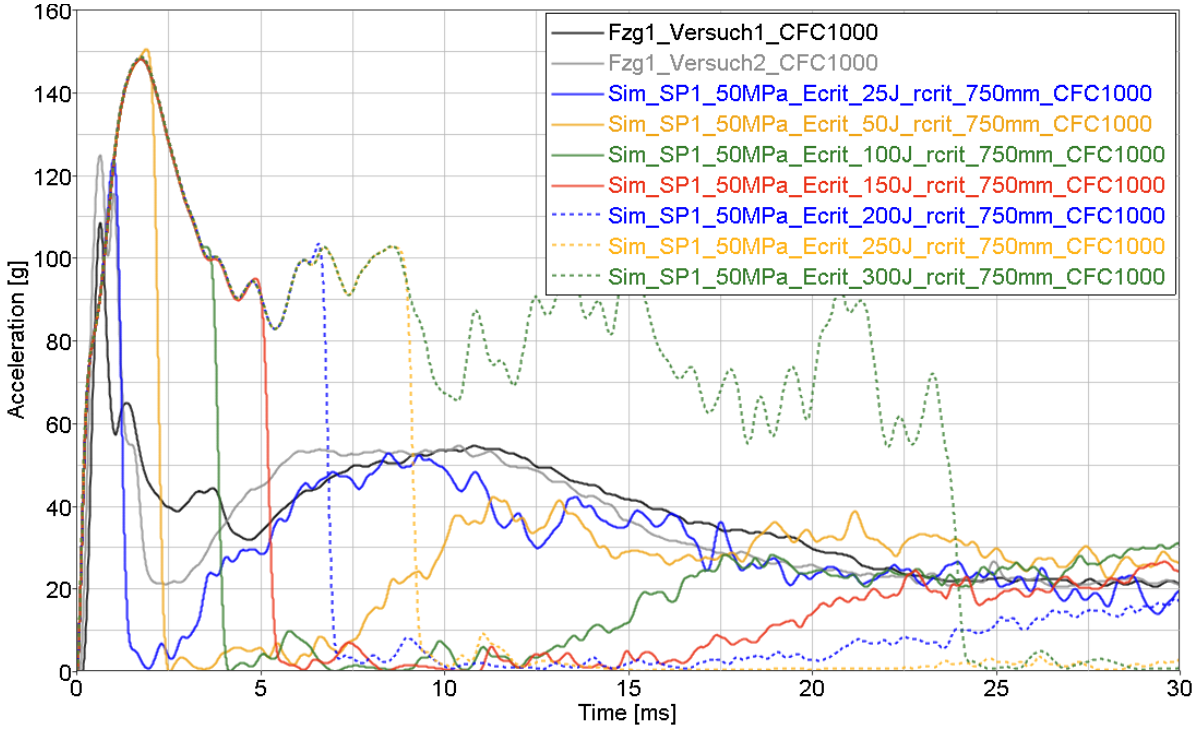
Adaptation of E_{crit}

GOAL

Effect of different fracture mechanisms on acceleration signal [HAU13]

Non-Ordered_Chess_1-1





Agenda

- Motivation
- Basic Mechanical Material Properties of Glass
- Experimental Results of Head Impact Test with Reference Vehicle
- Analysis of Non-Local Failure Criterion Based on Simulations
- Summary and Outlook

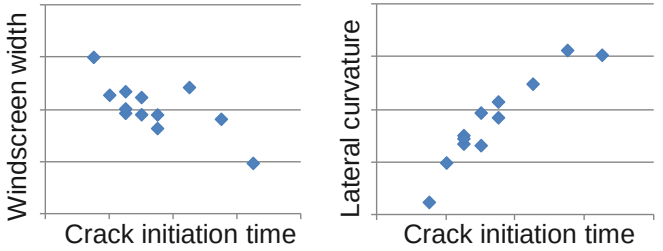
Summary and Outlook

Summary

- Analysis of non-local failure criterion for modelling glass failure during head impact in windscreen area
- In [PYT11] given values combined with shell-solid-shell modelling results in late first stiffness reduction combined with a too global deletion of glass elements and thus a too soft after fracture behaviour
- Solution was not possible just by a variation of parameters
- Integration of a non-ordered chess meshing approach with equal numbers of failing and not failing elements showed good correspondence for acceleration signal, crack propagation and deformation
- Later first stiffness reduction could be modelled by increasing E_{crit}

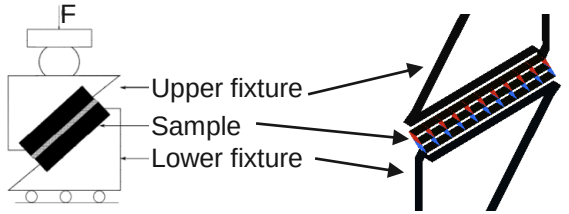
Outlook

- Prediction of fracture probability and crack initiation time based on statistically distributed defects (results will be published within SIMVEC in November 2014)
- Development of design guidelines for pedestrian friendly windscreen geometries based on fracture probability



Crack initiation time for different windscreen geometries

- Consideration of delamination results from compression-shear test (CST)



CST - Drawing after [CHAXX] and simulation model

Literatur

[BAR08] BARGEL,H.-J.
Werkstoffkunde
Springer Verlag Berlin Heidelberg, 10th Edition, 2008

[CHAXX] CHAPUIS, V.; PELISSET, S.; TRACHSEL, V.; RAEIS-BARNEOUD, M.
The right way to characterize adhesion of polymers in PV modules
Ecole Polytechnique Fédérale de Lausanne (EPFL)

[FEL12] FELDMANN, M.; KASPER, R.; LANGOSCH, K.
Glas für tragende Bauteile
Werner Verlag, Köln, Deutschland, 2012

[GAR12] GARCIA POLANCO, J.A,
Head impact protection, simulation model validation, activities and documentation; validation corridor development
Final Event Documentation of IMVITER, 2012

[HAU13] HAUFE, A.; CELIC, Z.; LIEBOLD, C.
Potential modeling techniques of laminated glass for pedestrian protection and ‘Ejection Mitigation’
Automotive-CAE Grand Challenge, Aschaffenburg, 2013

[PYT11] PYTTEL, T.; LIEBERTZ, H.; CAI, J.
Failure criterion for laminated glass under impact loading and its application in finite element simulation
International Journal of Impact Engineering 38 (2011) 252-263

[PYT13] PYTTEL, T.; LIEBERTZ, H.; CAI, J.
Non-local failure criterion for laminated glass under impact loading
Automotive-CAE Grand Challenge, Aschaffenburg, 2013

[RIE05] RIES, O.;
PS/164 - (OICA) Observation of different windscreen glass fracturemodes during headform impactor tests
http://www.unece.org/fileadmin/DAM/trans/doc/2005/wp29grsp/ps-164e.pdf
Informal Document of OICA w.r.t. Informal Group on Pedestrian Safety 2005

[SCH14] SCHAEFFER, H.A.; LANGFELD, R.
Werkstoff Glas - Alter Werkstoff mit großer Zukunft
Springer-Verlag Berlin Heidelberg 2014

[SED99] SEDLACEK, G.; BLANK, K.; LAUFS, W.; GUESGEN, J.
Glas im konstruktiven Ingenieurbau
Ernst & Sohn Verlag, Berlin, 1999

[VAR01] VARNER, J. R.
Festigkeit und Bruchmechanik von Glas
Festigkeit von Glas, Grundlagen und Messverfahren
Fortbildungskurs der Hüttentechnischen Vereinigung der Deutschen Glasindustrie (HVG), 2001

Contact

Dipl.-Ing. Frederic Nuß

Institut für Kraftfahrzeuge
RWTH Aachen University
Steinbachstraße 7
52074 Aachen
Germany

Phone +49 241 80 25663
Fax +49 241 80 22147

Email nuss@ika.rwth-aachen.de
Internet www.ika.rwth-aachen.de