TECHNISCHE HOCHSCHULE MITTELHESSEN

Institute of Mechanics and Materials

Notes on Simulating Head Impact on Windshields

Stefan Kolling, Christopher Brokmann, Christian Alter

Introduction and Content

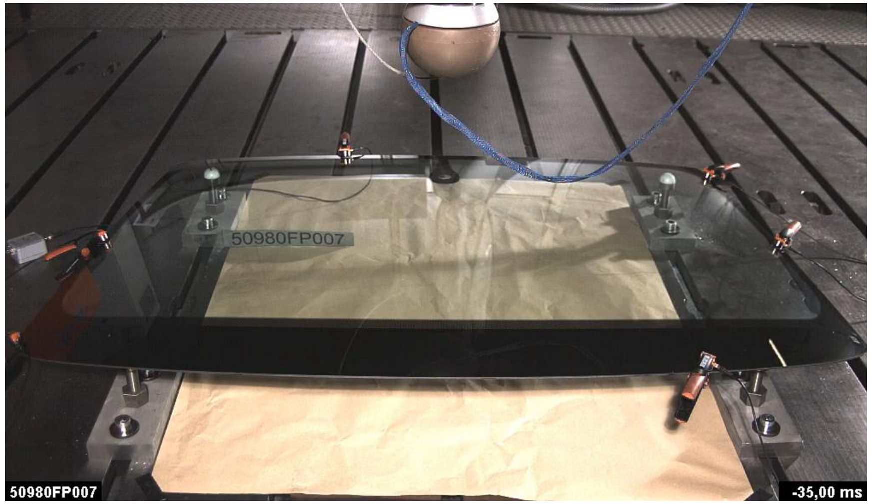
Source: hondanews.com

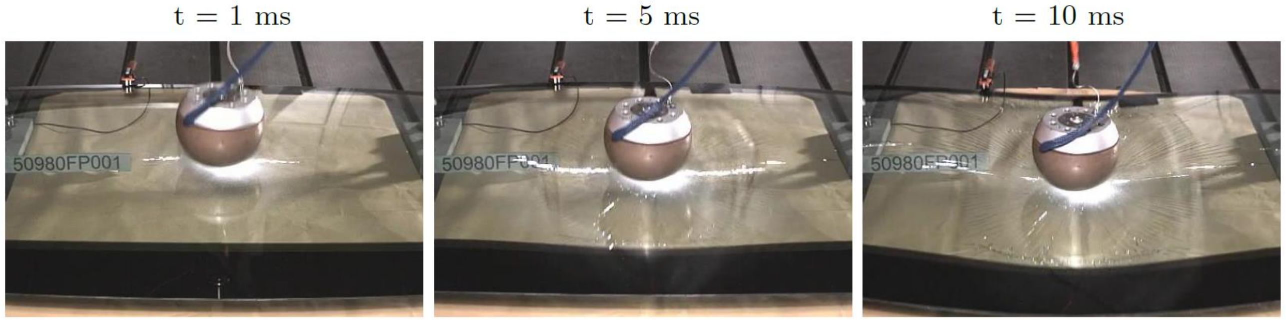
- Reproducibility of head impact tests on windshields
- Probability of glass fracture
- FE-modelling of laminated glass
- Stochastic simulation

Source: BGS Böhme & Gehring GmbH

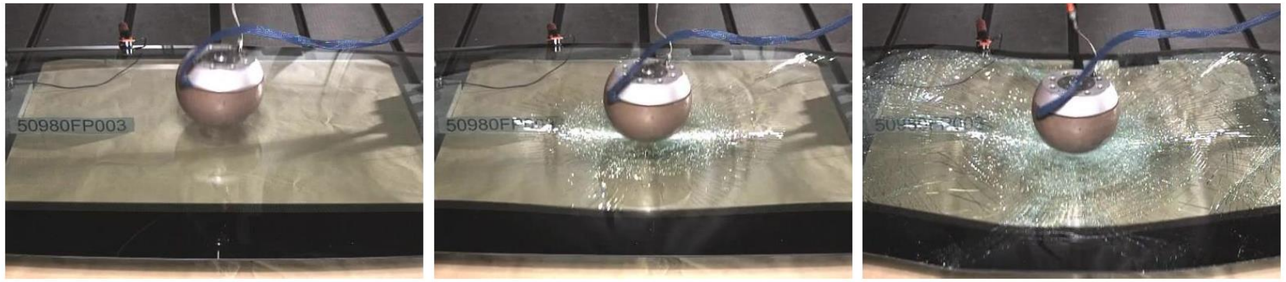
Motivation: How Reproducible are Head Impact Tests?

- Audi A3 windshields
- Free-flying head
- 10 m/s, centric, 10 tests
- Euro NCAP adult head
- Four-point support

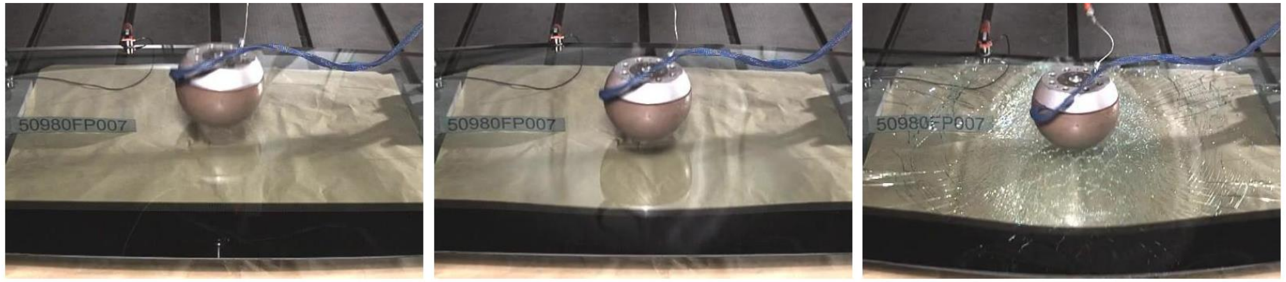




(a) Initial fracture of test number 1 between 0 and 1 ms.



(b) Initial fracture of test number 3 between 2 and 3 ms.



(c) Initial fracture of test number 7 between 8 and 9 ms.

Motivation: How Reproducible are Head Impact Tests?

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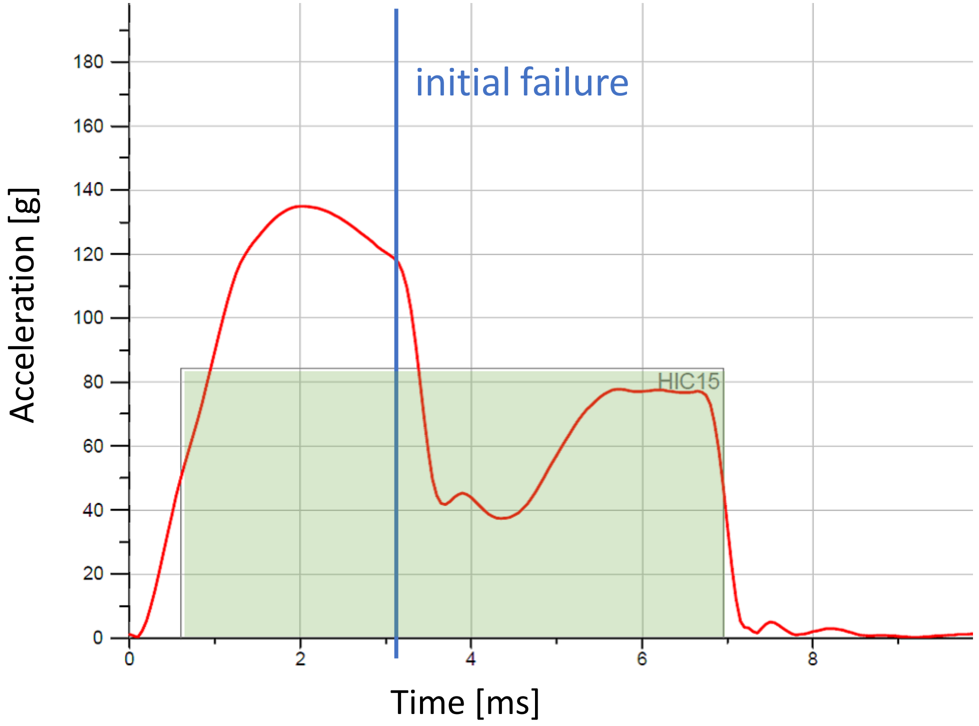
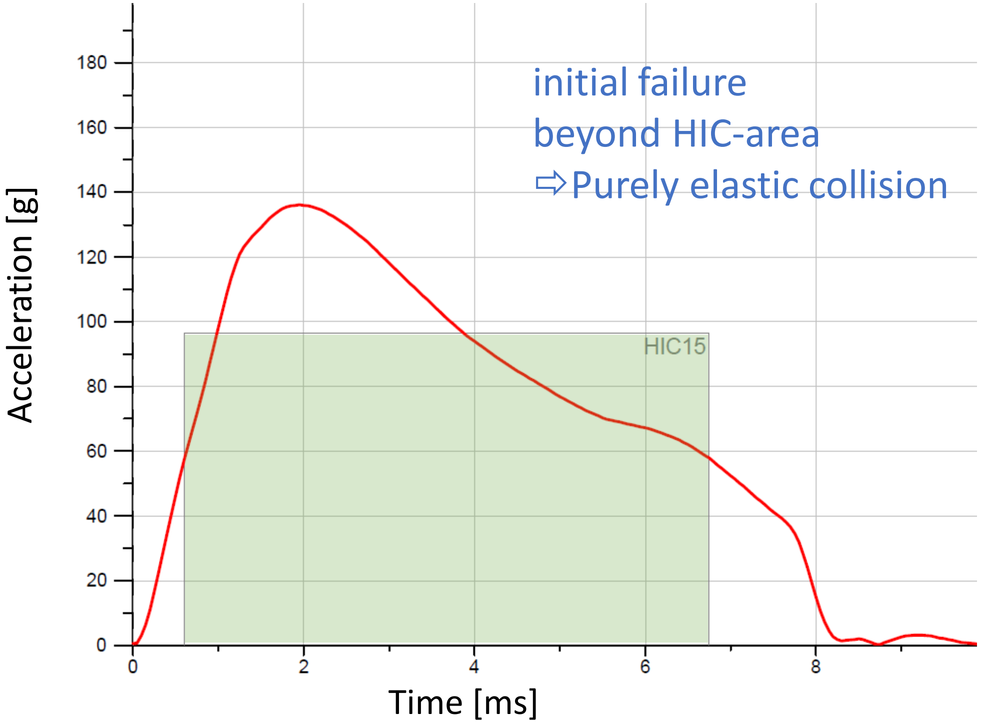
- Head Injury Criterion
- HIC15 = 418 … 566 in 10 identical tests
- Accelerations are completely different

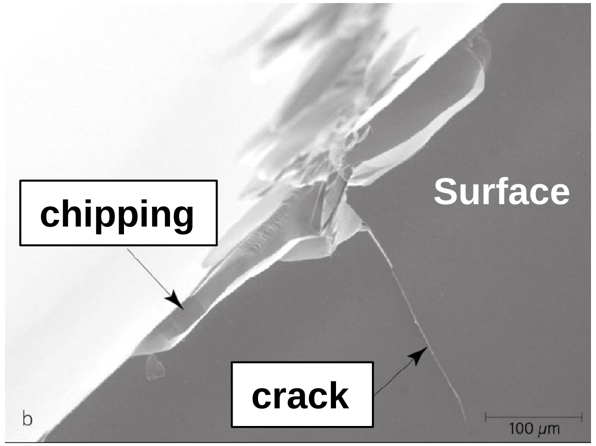
$$\mathrm{HIC} = \max\left\{\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)\mathrm{d}t\right]^{2.5}(t_2-t_1)\right\} < 1000$$

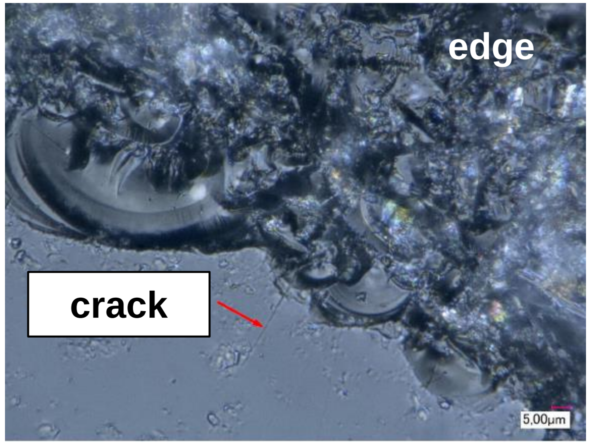


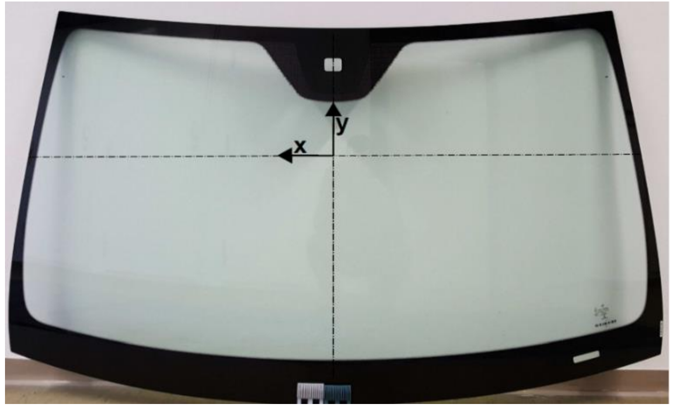


Where does this Scatter come from?

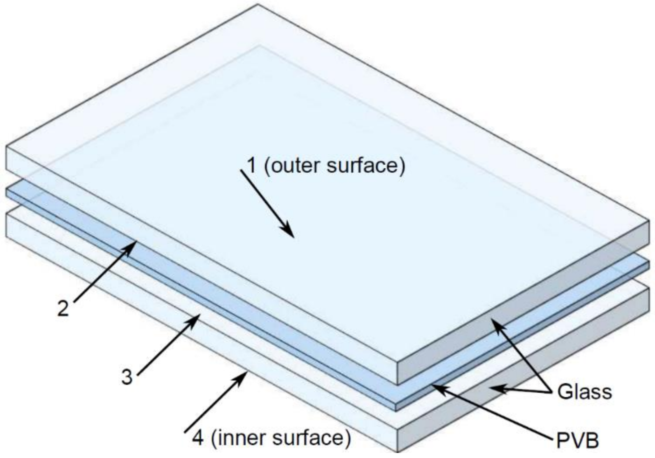
➢ The reasons are microcracks in the surface / edge of the glass







➢ These are production and handling related:
- Edge processing
- Silkscreen
- Transportation



➢ Different stress at failure for all 4 surfaces, edges and screen-printing area must be considered in the simulation

How to determine the probability of fracture?

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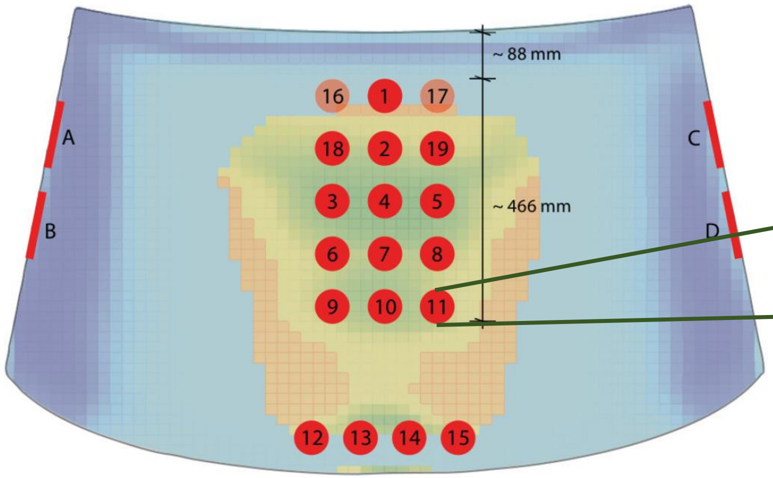
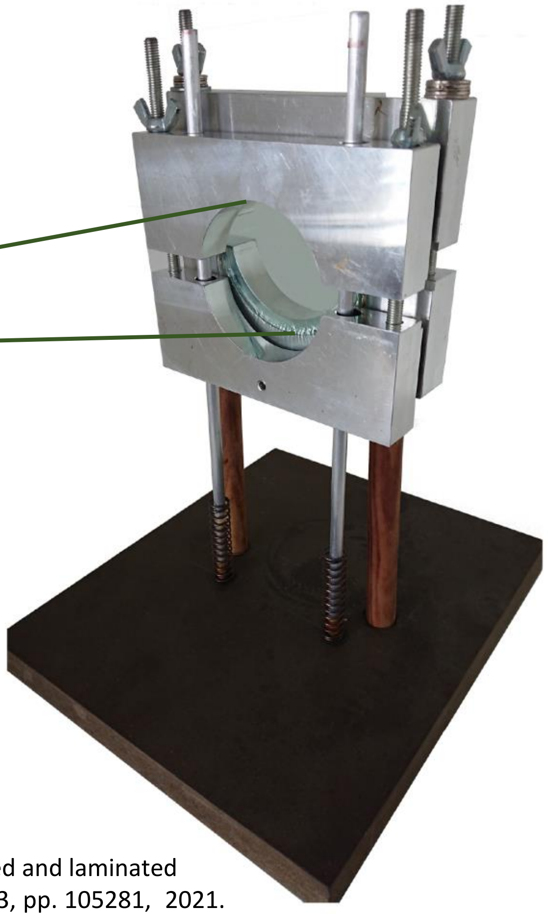
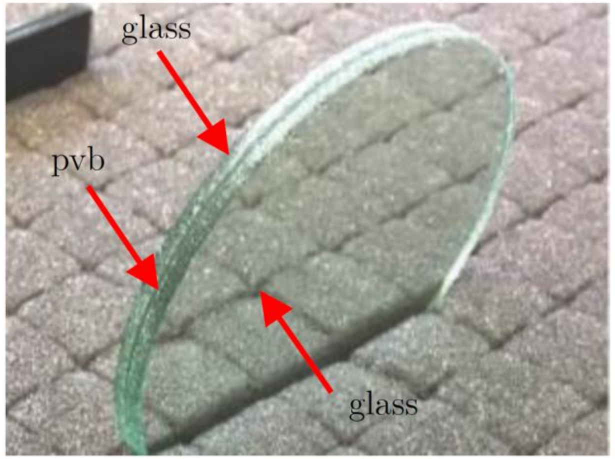
- Specimen preparation[1)]

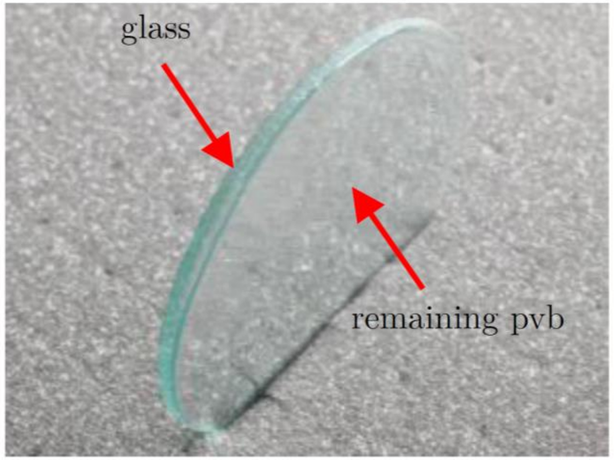


Audi A3 windshield





(a) before separation

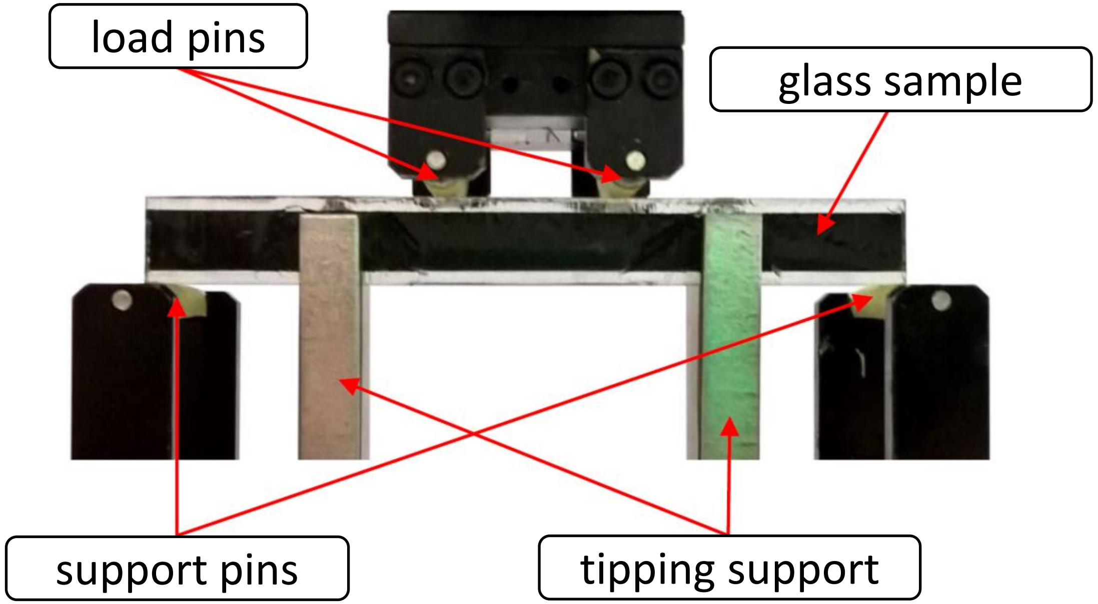


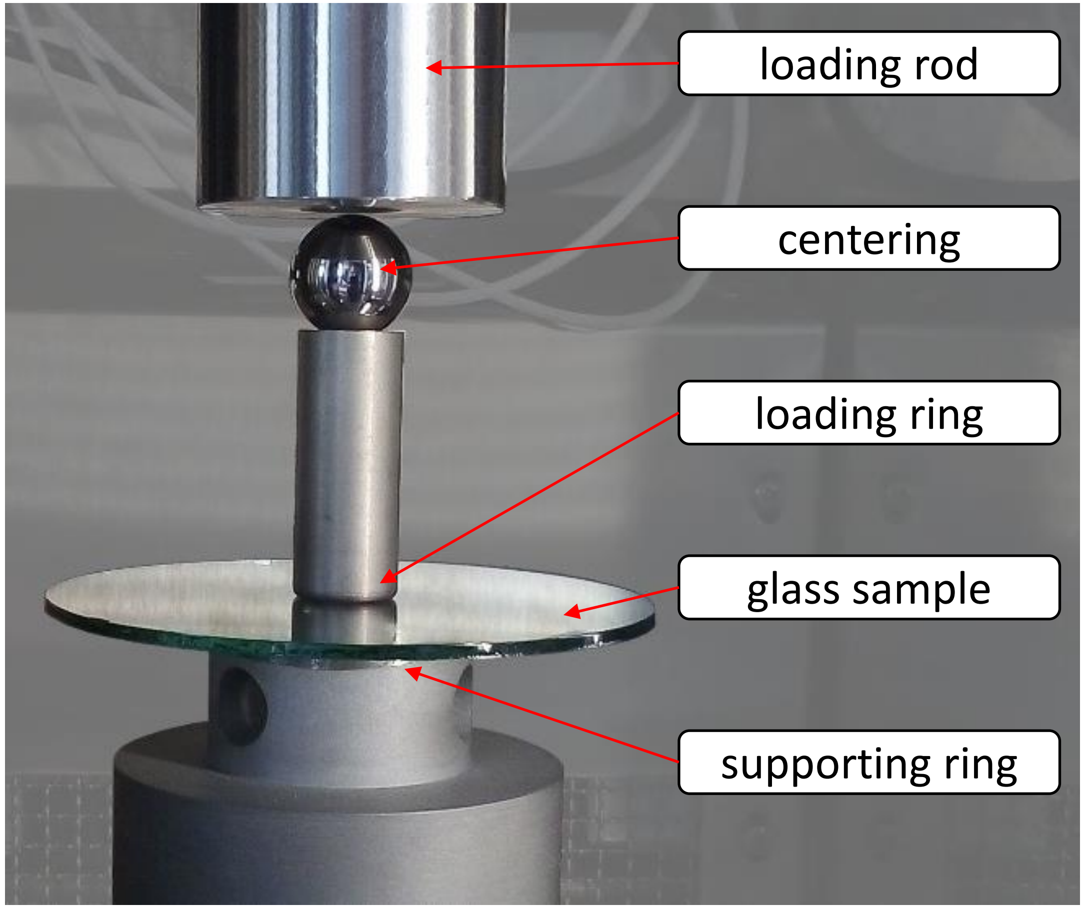
(b) after separation

[1)] S. Müller-Braun et al.: Strength of the individual glasses of curved, annealed and laminated glass used in automotive windscreens, Engineering Failure Analysis, Vol 123, pp. 105281, 2021.

How to Determine the Probability of Fracture?

- Small specimens (quasi-static)[1]:
  - waterjet cutting / separation
  - coaxial ring-on-ring tests (surface)
  - four-point bending (edges)





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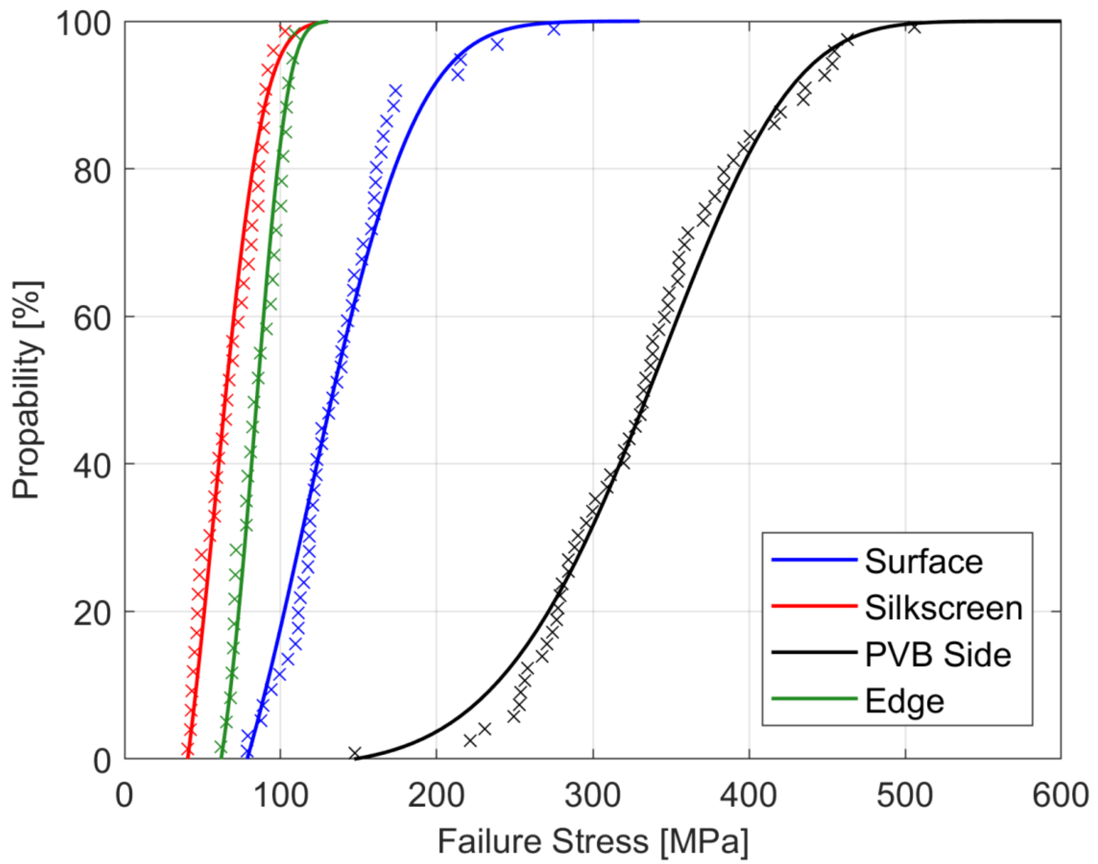
Probability Distribution – Critical Crack Lengths

- Statistical evaluation[1)]
- Left truncated Weibull distribution

$$P(x) = 1 - \exp\left[\left(\frac{\tau}{\eta}\right)^{\beta} - \left(\frac{x}{\eta}\right)^{\beta}\right]$$

- Scale parameter η
- shape parameter β
- Truncation point τ
  τ =0 yields the well-known two-parameter Weibull distribution

- So far, we obtained the critical and not the initial crack lengths from this distributions !



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How to Determine the Initial Crack Lengths?

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- For subcritical crack growth, the crack velocity can be expressed by the stress intensity

$$K_{\mathrm{I}} = Y\sigma\sqrt{\pi a} \quad \text{and} \quad K_{\mathrm{IC}} = Y\sigma_f\sqrt{\pi a_f} \quad \text{at fracture}$$

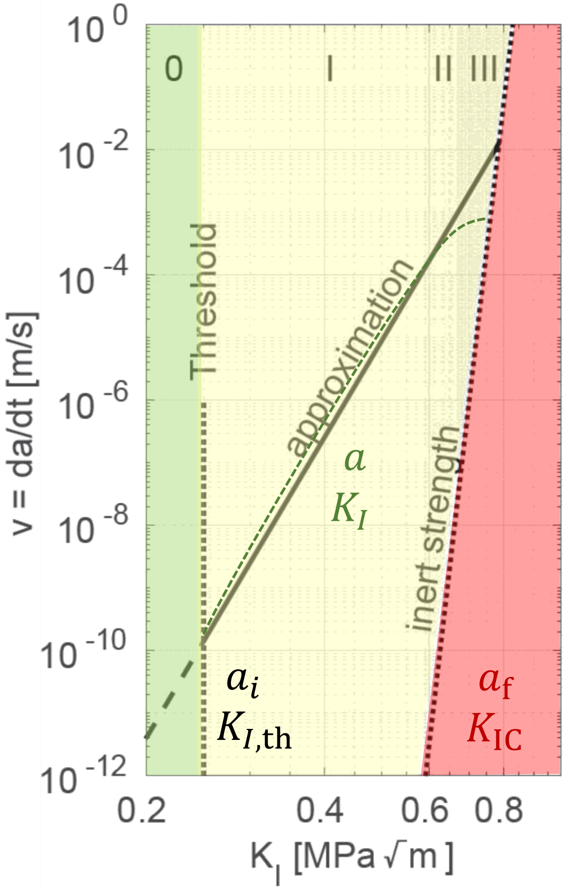
- Linear approximation by parameters n and v_0 yields

$$v = \frac{da}{dt} = v_0 \left(\frac{K_I}{K_{IC}}\right)^n$$

from which the initial crack length a_i can be computed reversely by integration.

- Crack grow parameters[1]:

H [%rh], 25°C	30	40	50	60	70
n	15.43	15.10	14.75	12.96	12.26
v_0	9.54	10.22	10.47	13.95	15.99



[1] C. Brokmann et al.: Subcritical crack growth parameters in glass as a function of environmental conditions. Glass Structures & Engineering 6:89–101, 2021.

What About the Rate Dependence of Glass?

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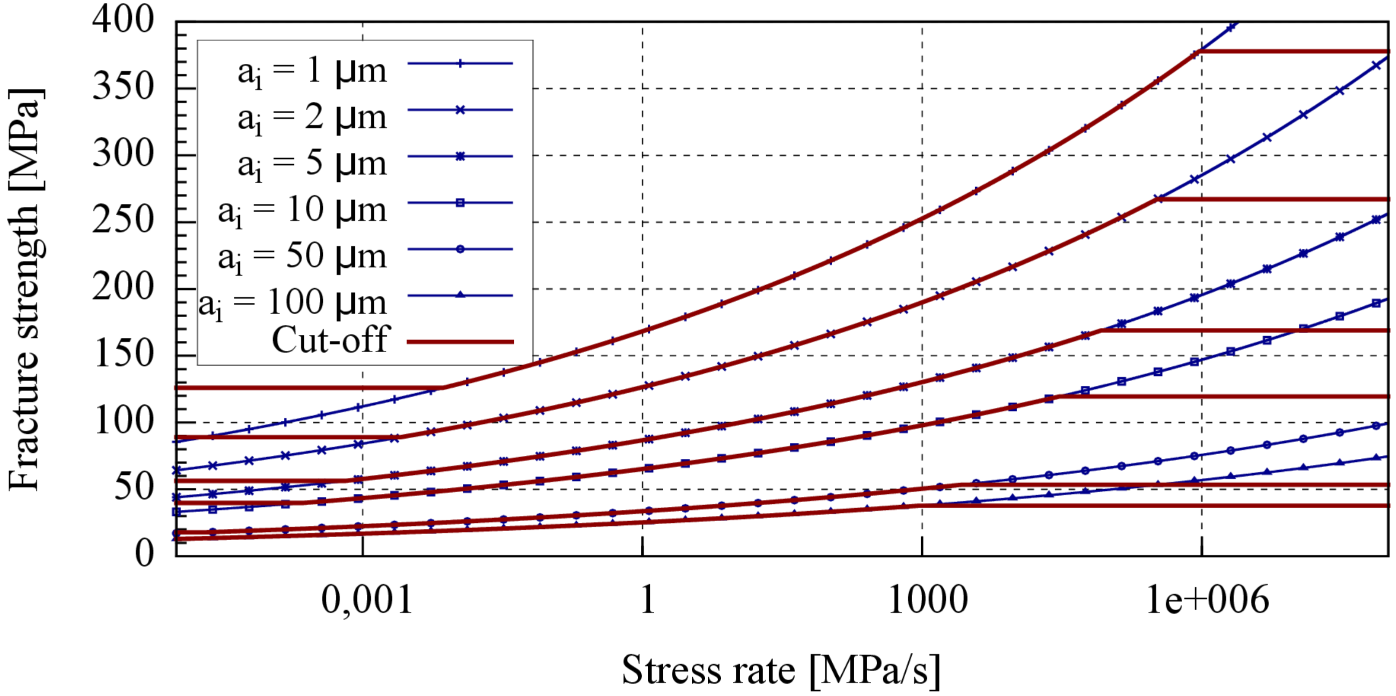
Fracture strength in dependency of the stress rate: $\sigma_{crit.} = \left(\frac{2(n+1)K_{Ic}^{n}}{v_0(n-2)(Y\sqrt{\pi})^n a_i^{\frac{n-2}{2}}} \right)^{1/(1+n)} \dot{\sigma}^{1/(1+n)}$

with $v_0 \approx 6\ mm/s$ and $n \approx 16$

Lower limit

$$K_I = \sigma\sqrt{\pi a}\,Y$$

$$\sigma_{TH} = \frac{K_{TH}}{\sqrt{\pi a}Y}$$



Upper limit

$$K_I = \sigma\sqrt{\pi a}\,Y$$

$$\sigma_{Ic} = \frac{K_{Ic}}{\sqrt{\pi a}Y}$$

Non-Local Failure Model for Glass – Regularization

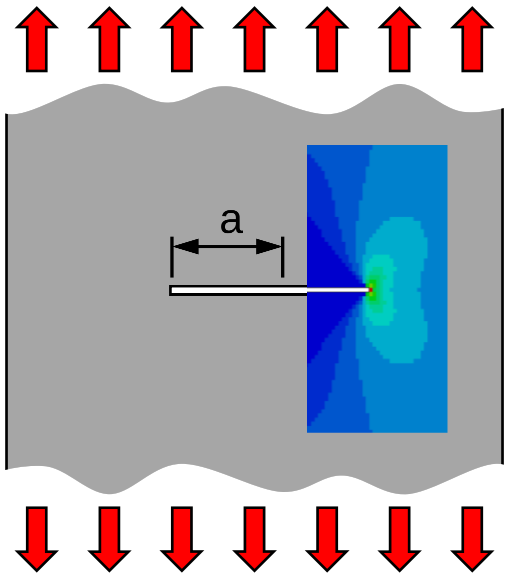
<u>Reduction of strength</u>

- Griffith crack
  - Element size: 10 mm, 5 mm, 2,5 mm, 1 mm
  - Element at the crack tip
- Stress depends on element size
- Stress decreases proportional to $1/\sqrt{l_{el}}$
- Combination of
  - Stress field
  - Element geometry
  - Major stress
- Regularized stress intensity

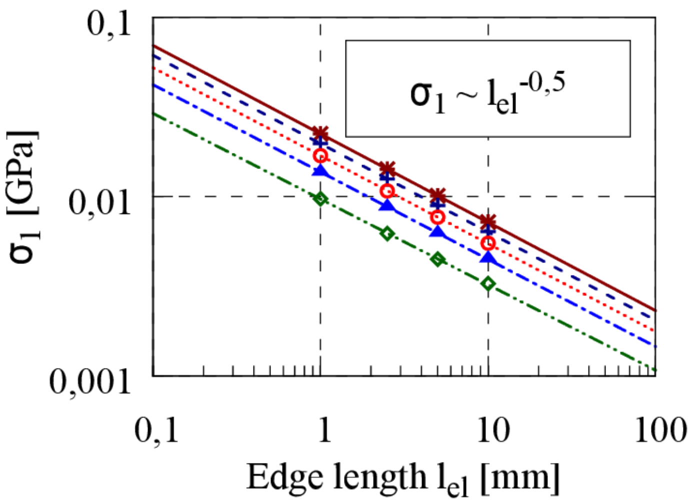
$$K_I^{\text{Num.}} = \sigma_1 \sqrt{\pi\, l_{el}}\, f_{\text{geo}}$$

$$K_I^{\text{Analyt.}} \sim K_I^{\text{Num.}}$$

$\sigma = 1\ \text{MPa}$



$\sigma = 1\ \text{MPa}$



Non-Local Failure Model for Glass[1)]

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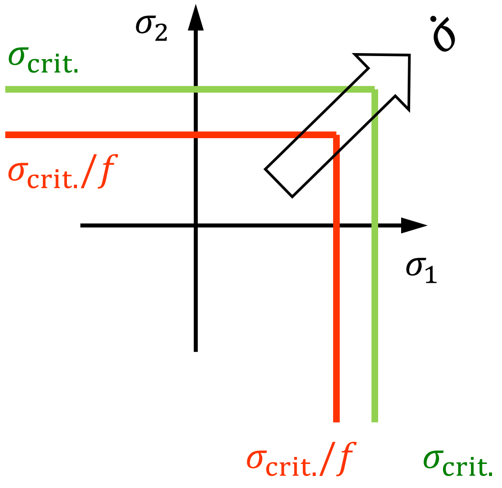
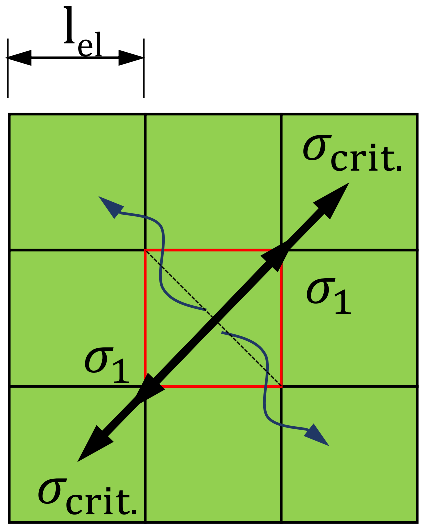
- Major stress criterion
  - $\sigma_{1,2} \geq \sigma_{crit.}$
- Strength depends on stress rate
  - $\sigma_{1,2} \geq \sigma_{crit.}(\dot{\sigma})$
- Crack orthogonal to principal stress
  - Linear stress reduction
  - $n = \text{int}\left[\frac{l_{el}}{v\,\Delta t}\right]$, v =1,520m/s
- Reduction of strength in crack direction
  - Reduction depends on neighboring fracture state (⇨ non-local)
  - $\sigma_{crit.} = \begin{cases} \sigma_{crit.} & \text{without neighboring crack} \\ \sigma_{crit.}/f(l_{el}) & \text{with neighboring crack} \end{cases}$
- Element erosion after second element perpendicular to first crack failed



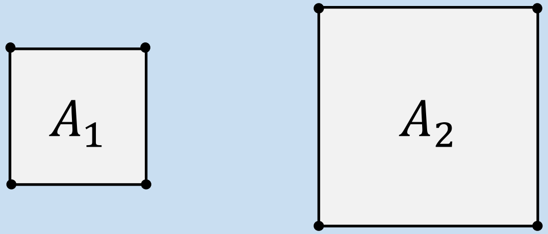


1) C. Alter et al. : An enhanced non-local failure criterion for laminated glass under low velocity impact. Int. J. Imp. Eng. 109:342–353, 2017.

Numerical Treatment [1)]

initialization

1. Assign stress at fracture to the Gauss points according to the distribution functions separately for edges, each side of the surface and screen-printing area
2. Regularization of the fracture stress

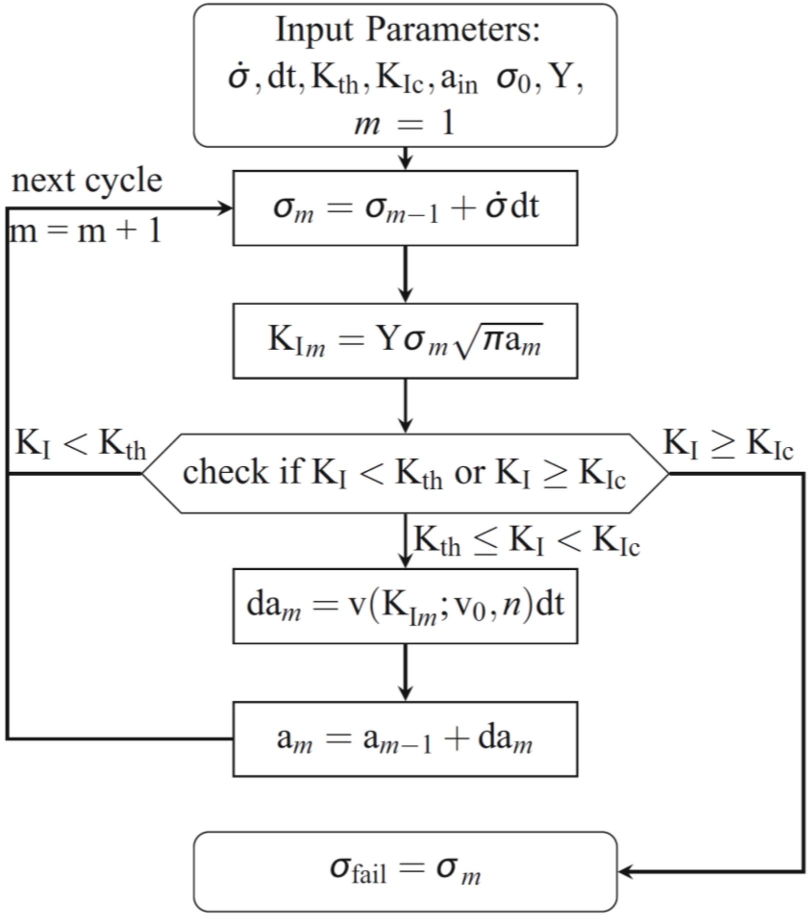


$$\sigma_2 = \sigma_1 \left(\frac{A_1}{A_2}\right)^{-\frac{1}{\beta}}$$

3. Calculate the initial crack length in each Gauss point

simulation

4. Compute subcritical crack growth
5. Activate (non-local) failure criterion



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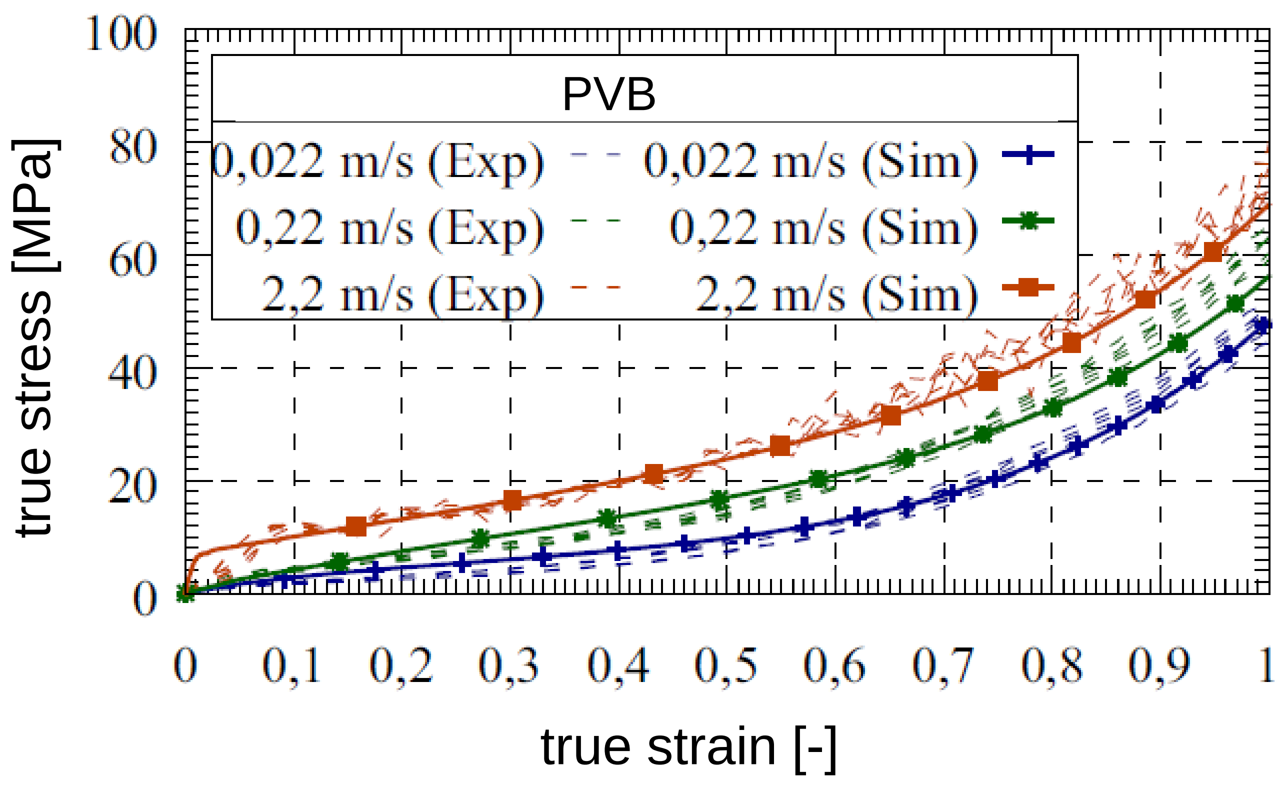
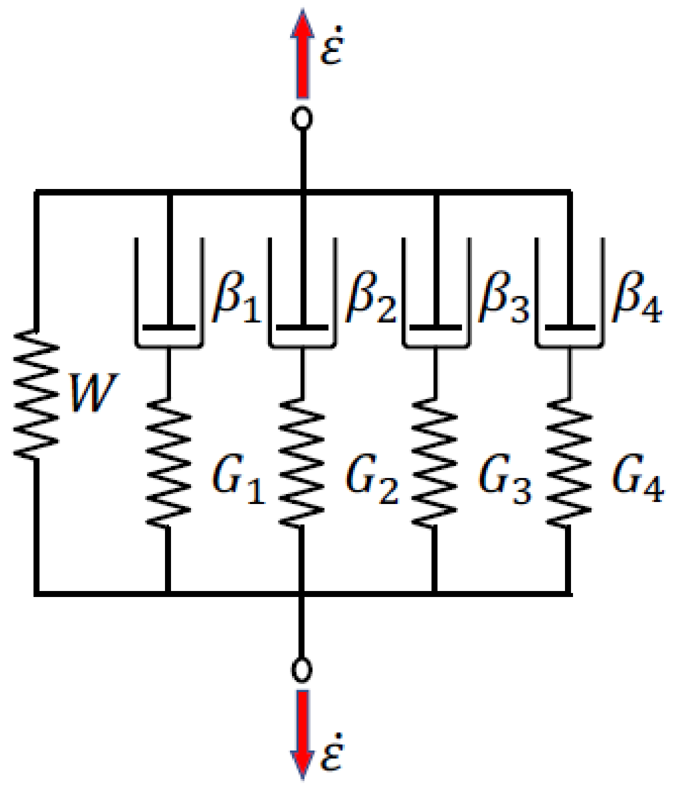
PVB – Interlayer: *MAT_GENERAL_HYPERELASTIC





$$W_{DEV}(I_C, II_C) = \sum_{i,j=0}^{n} A_{ij}(I_C - 3)^i (II_C - 3)^j$$

FE-Model for Laminated Glass

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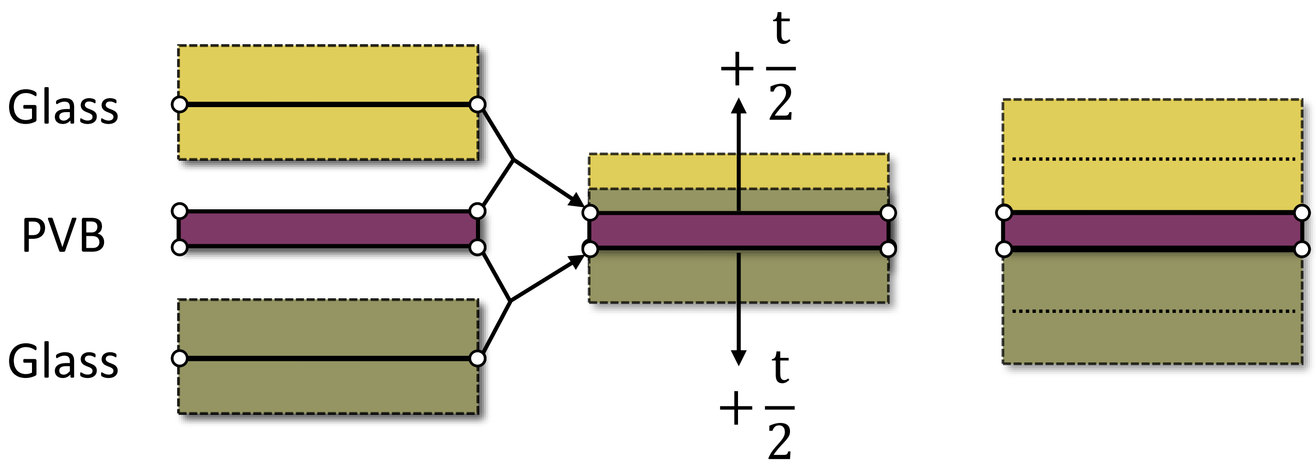
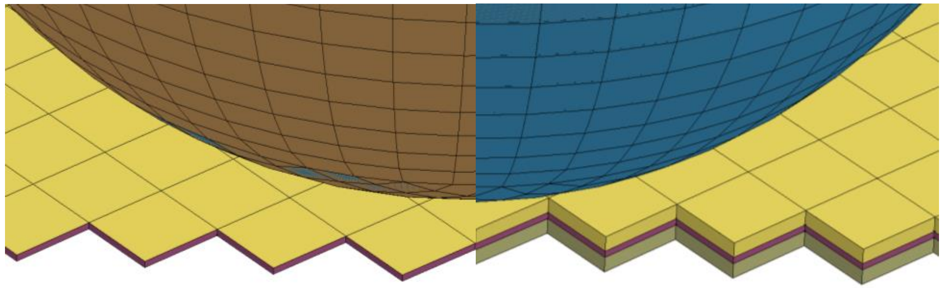
- Element types
  - Glass: Shell elements
    linear elastic
    non-local failure criterion
  - PVB: Solid elements
    hyperelastic
- Coincident coupling
- Shift of shell
  and contact thickness



Visualization of shifted shell thickness



- Regular mesh for the windscreen (2.5 - 10mm)
- Commercial model of the impactor from Lasso
- User subroutines in the explicit
  FE packages Radioss and LS-DYNA

Validation of the Laminated Glass Model

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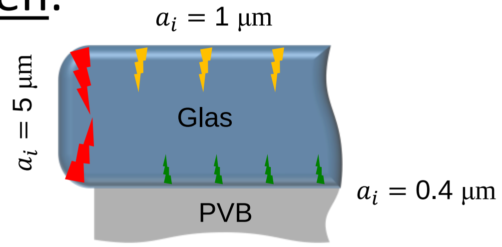
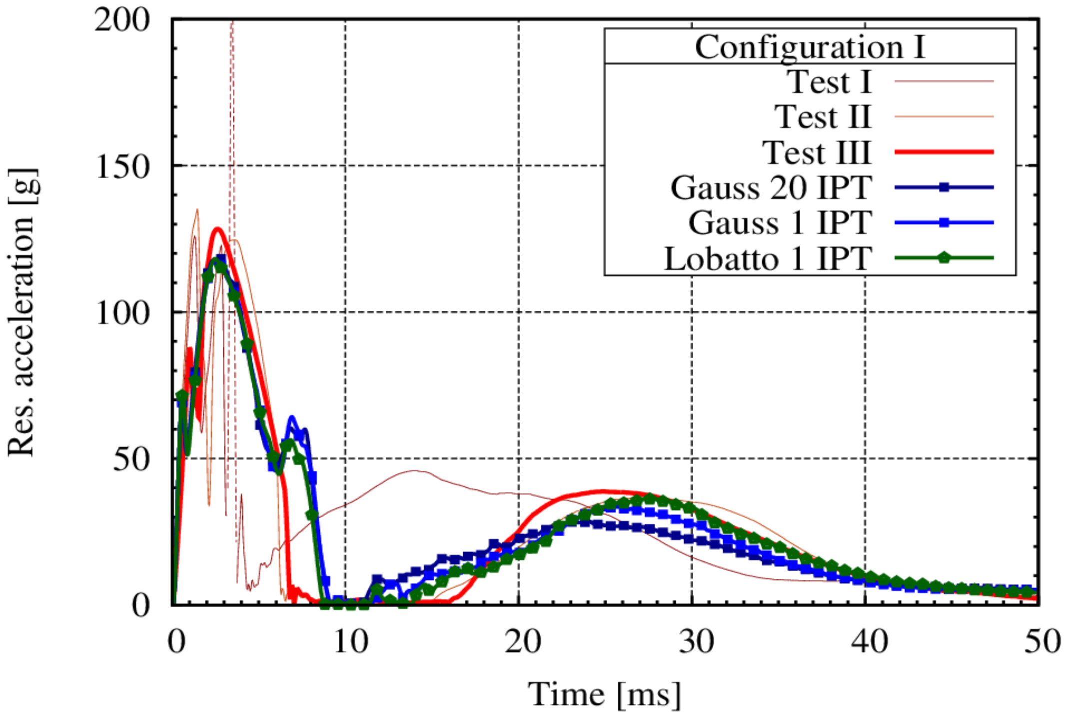
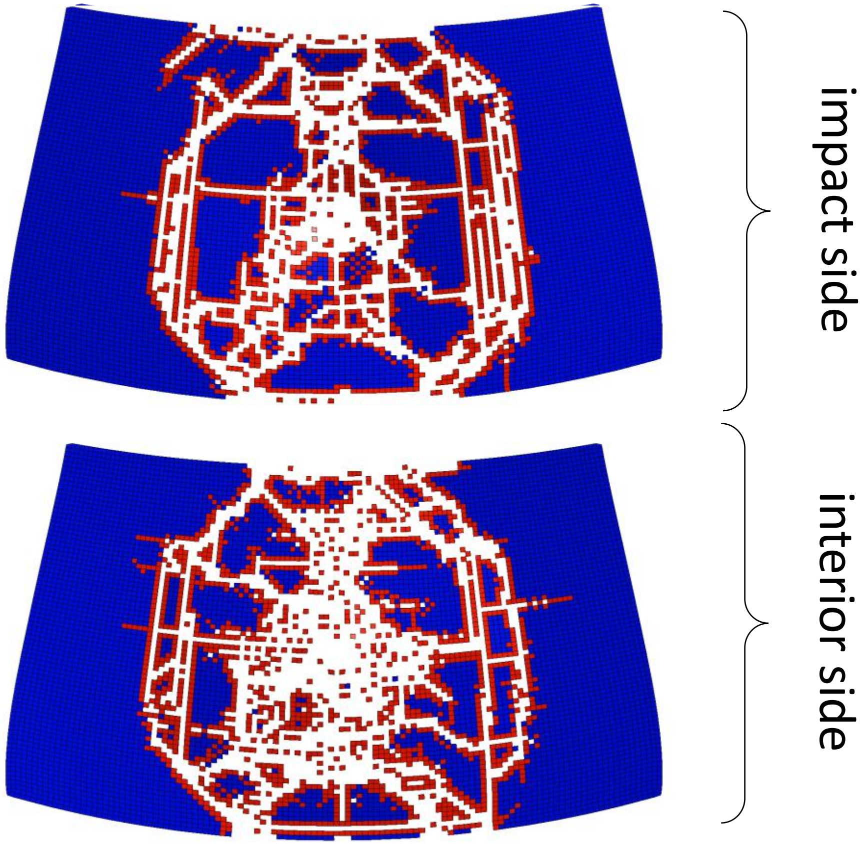
Head impact on center of the windscreen:

- Integration points at the glass surface
- Element erosion if one integration point fulfills the crack criteria

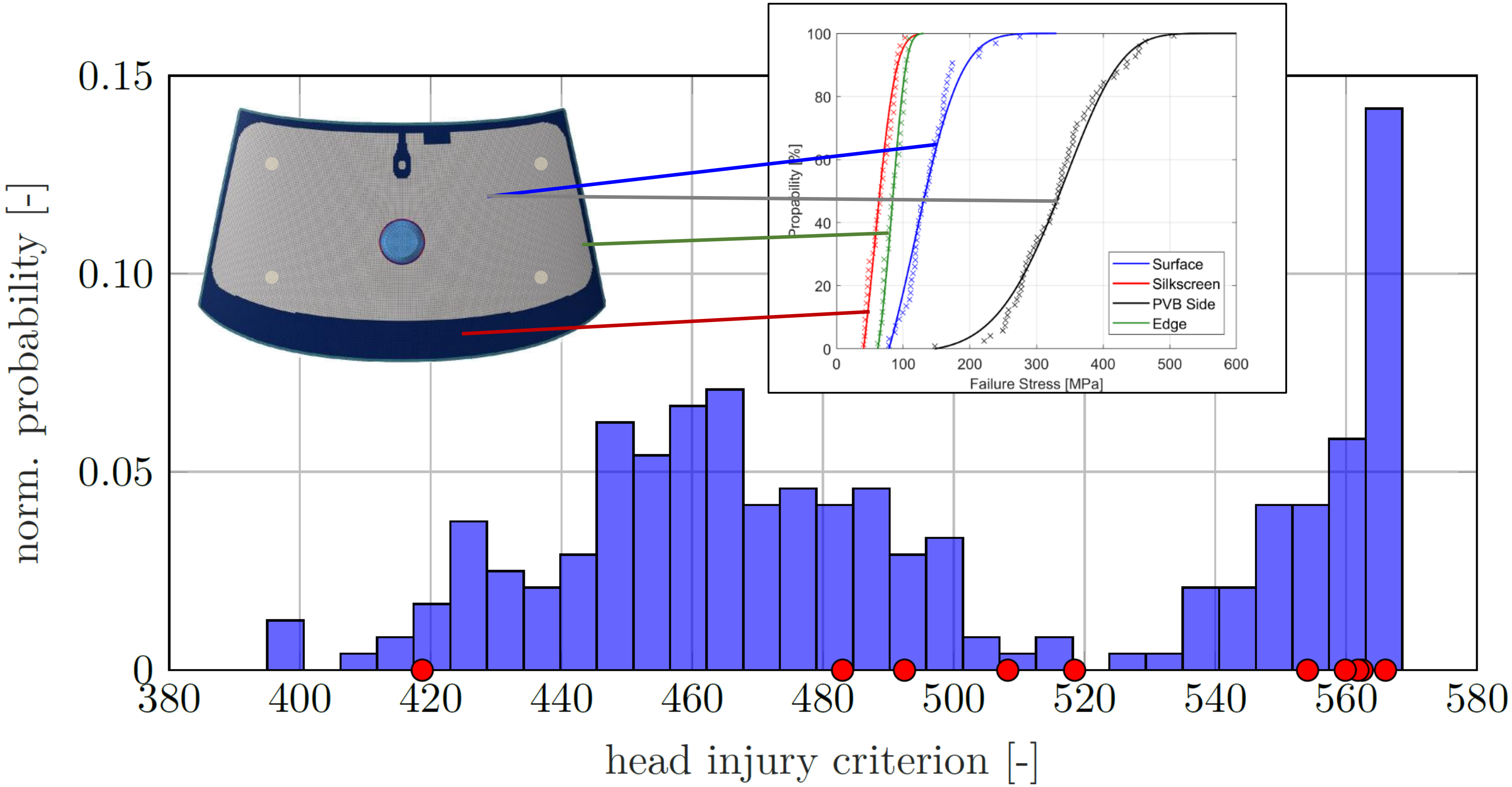






Stochastic Simulation: HIC as a Probability Value

- Stochastic simulation, four-point support (250 runs)



Test No.	HIC
1	492
2	483
3	419
4	554
5	562
6	562
7	560
8	566
9	518
10	508

Stochastic Simulation: HIC as a Probability Value

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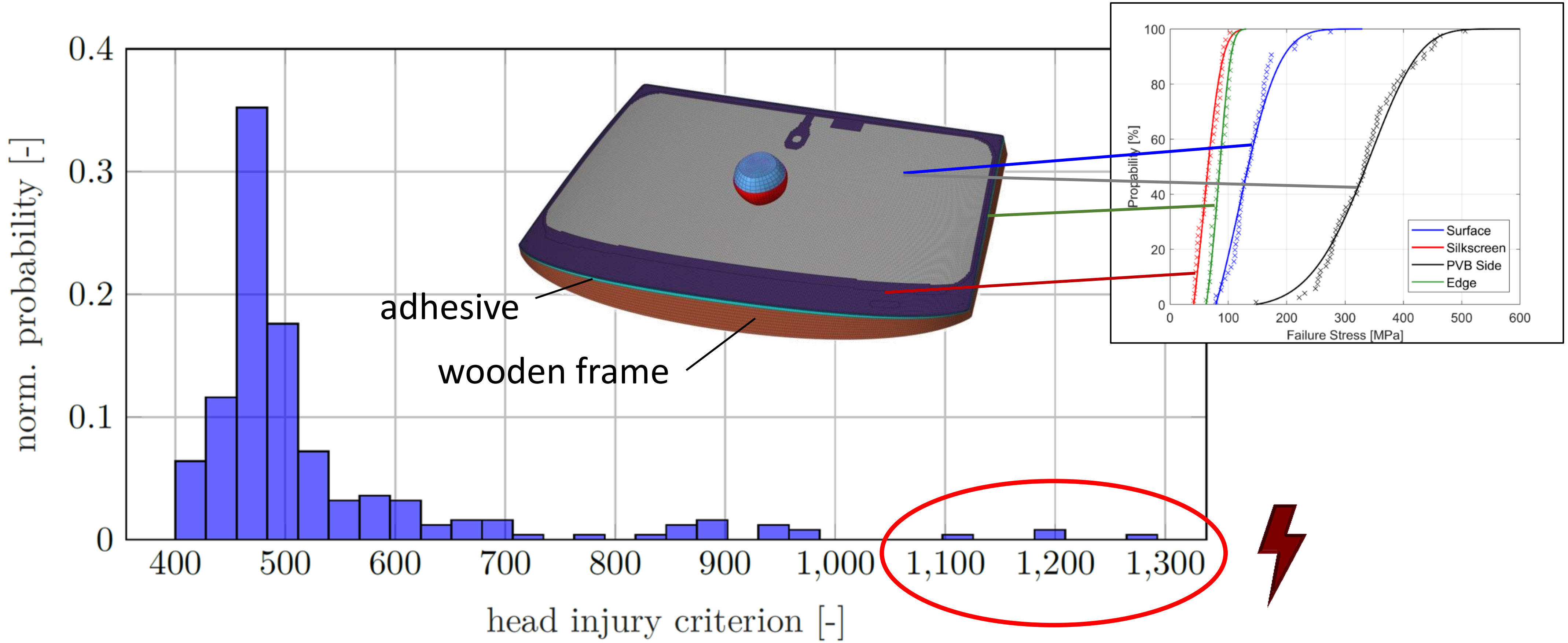
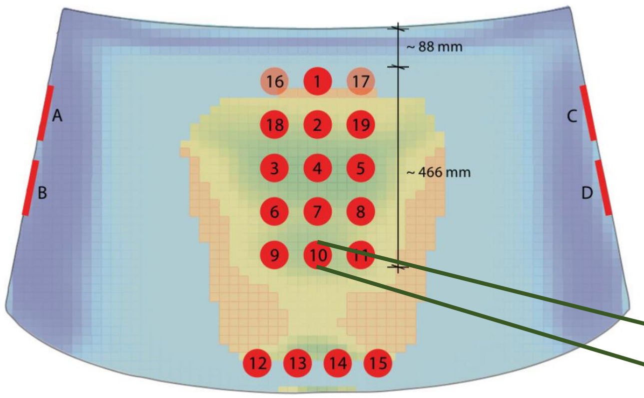
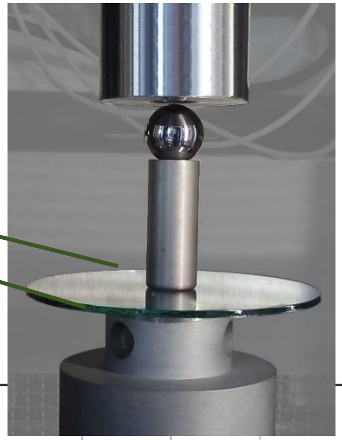
- Test setup close to the car and stochastic simulation (250 runs)

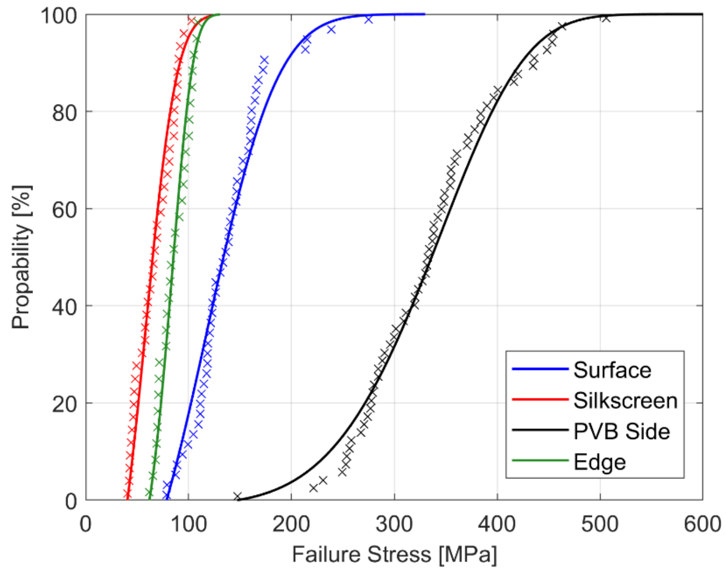


Summary: The Methodology in a Nutshell



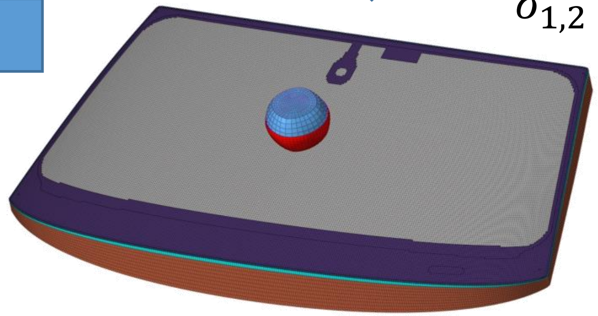


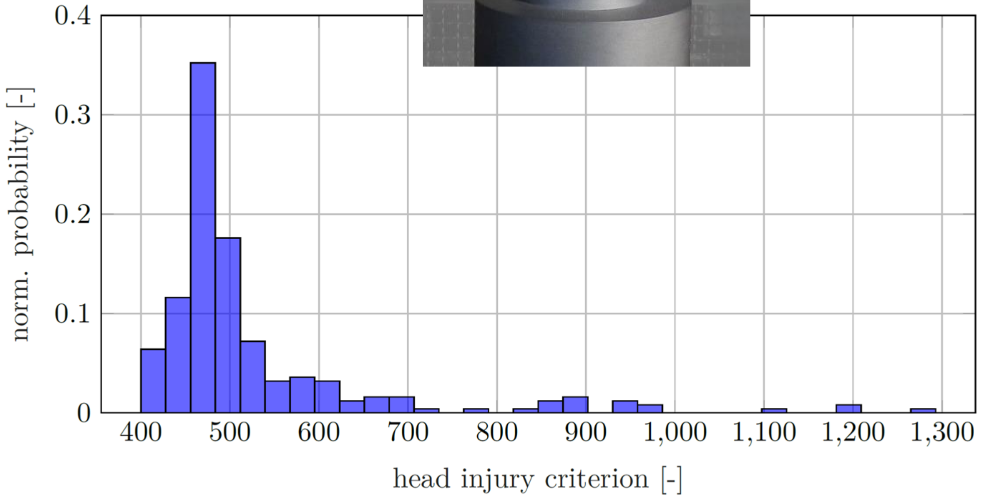
$P(x)$



$$a_i = \int \left(\frac{K_I}{K_{IC}} \right)^n dt$$

$$\sigma_{1,2} \geq \sigma_{\text{krit.}} \, (\dot{\sigma})$$





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Thank you

for your attention!

Federal Ministry
for Economic Affairs
and Climate Action