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Interactive Fracture Criterion for SGF-PP:

Validation on Lower Bumper Support

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LYB Materials in Opel Cars: Material Meets Engineering

On *BUMPERS*
e.g. Mokka X, Meriva, Corsa: *Hifax* TRC779 XLDE

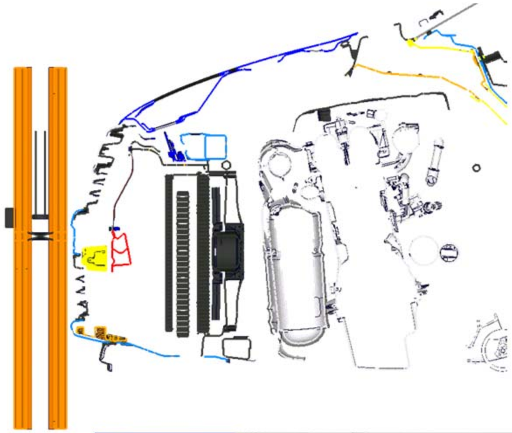
Source: http://media.opel.com

On *EXTERIORS*
e.g. Adam Rocks skid plate: *Hifax* TRC134P

On *INSTRUMENT PANELS and INTERIORS*
e.g. Adam: *Softell* TKG300N, *Hostacom* HKG339N

Source: http://media.opel.com

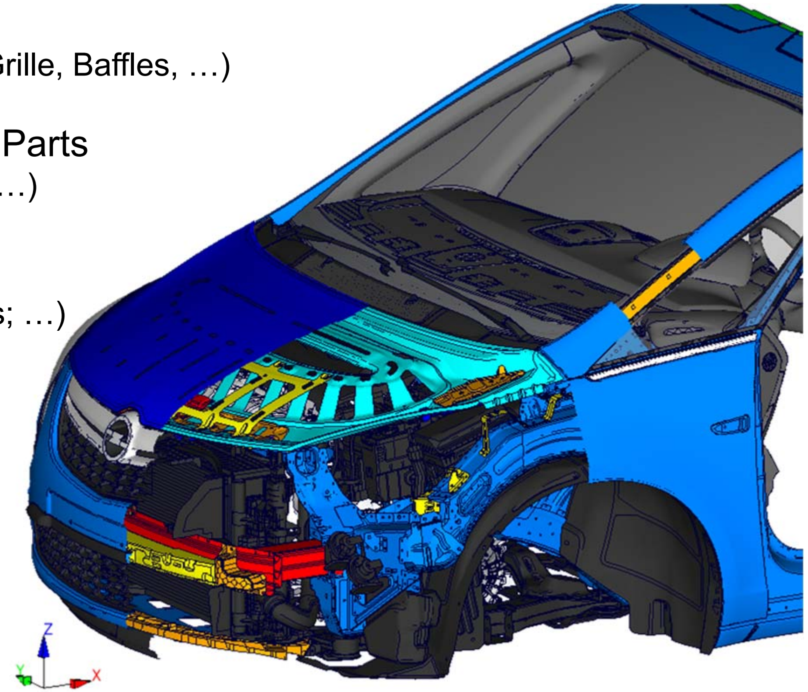
Component Performance and Material Fracture

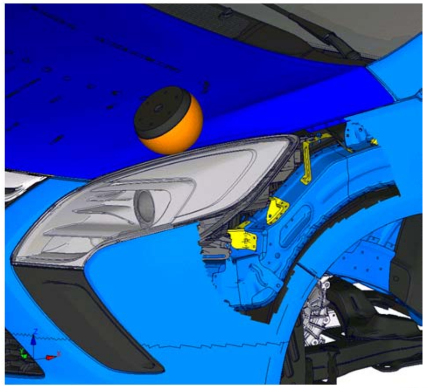


Front Fascia ASM
(Fascia, Reinforcements, Grille, Baffles, …)

Front Fascia Structural Parts
(Lower Support, Absorber, …)

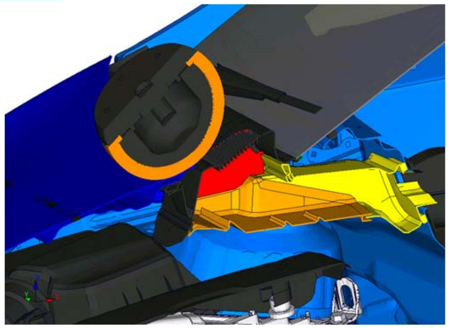
Engine Compartment
(Air Filter, Covers, Brackets; …)

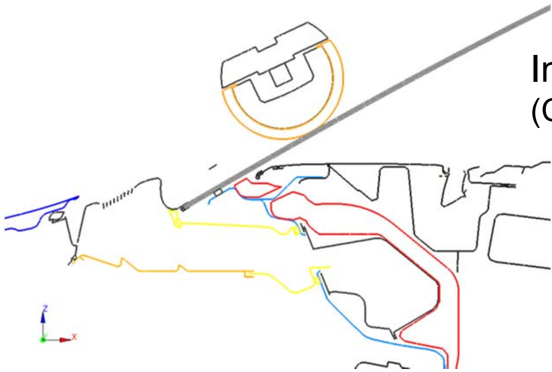




Head Lamp
(Housing, Brackets, …)

Cowl
(Water Deflection Panel, Air Inlet Panel, …)





Instrument Panel
(Carrier, Reinforcements, …)

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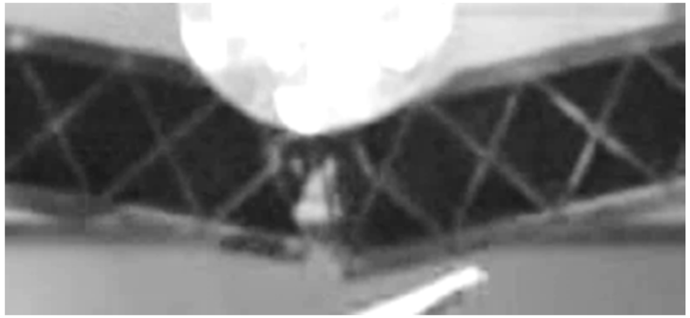
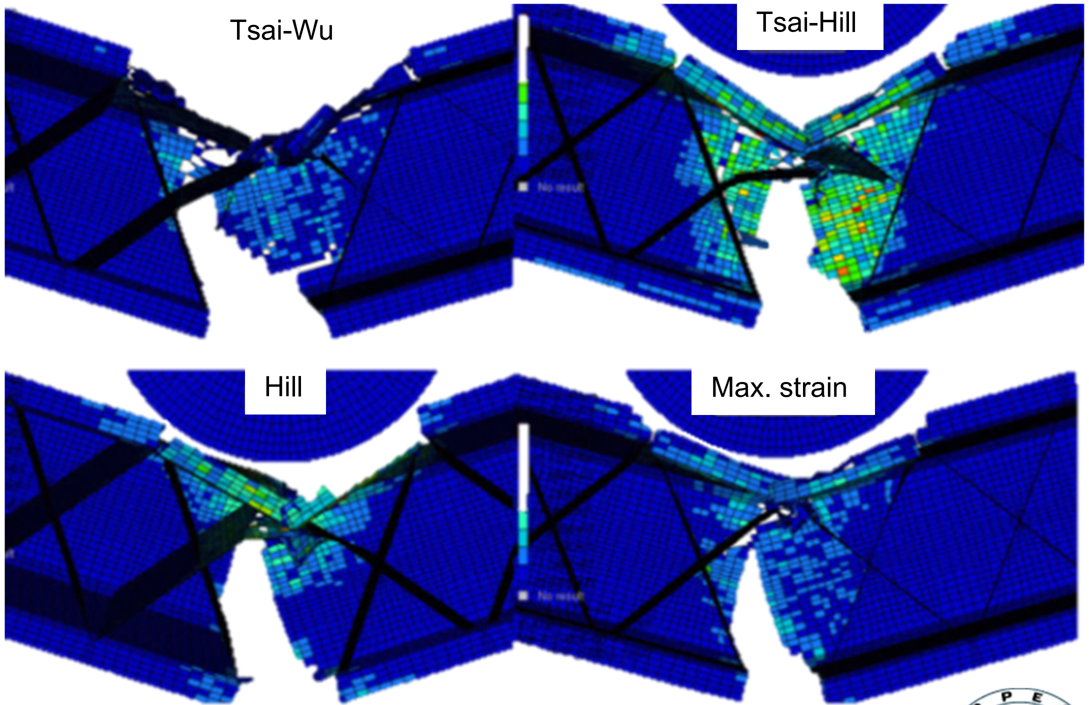
Fracture modeling

The subject is still at the center of the debates in the technical and scientific literature:

There is no evidence of criteria better performing than others.

Different fracture criteria in general provide different predictions.





Source: M.Nutini, M.Vitali, “Simulating failure with Ls-dyna in Glass Reinforced, Polypropylene-Based Components”, Ls-dyna German Forum, 2012

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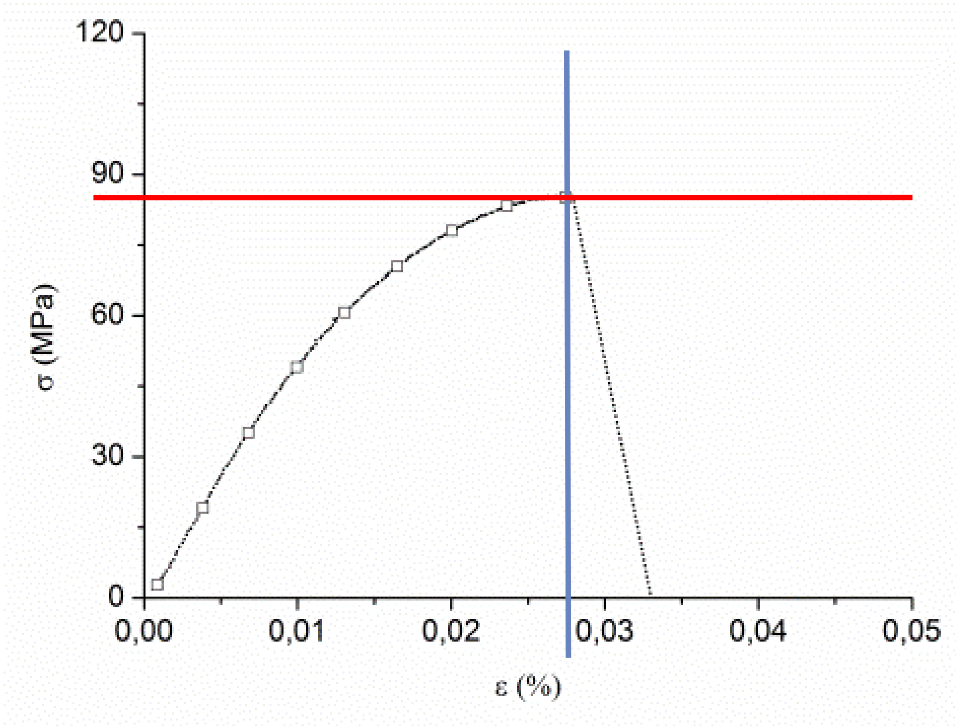
Fracture modeling

Fracture criteria: Determine when an element fails in an Finite Element Simulation.

Basic criteria used:

- Fracture mode-based criteria: max. strain, max. stress

- Interactive criteria: modeling the interaction between the stress components



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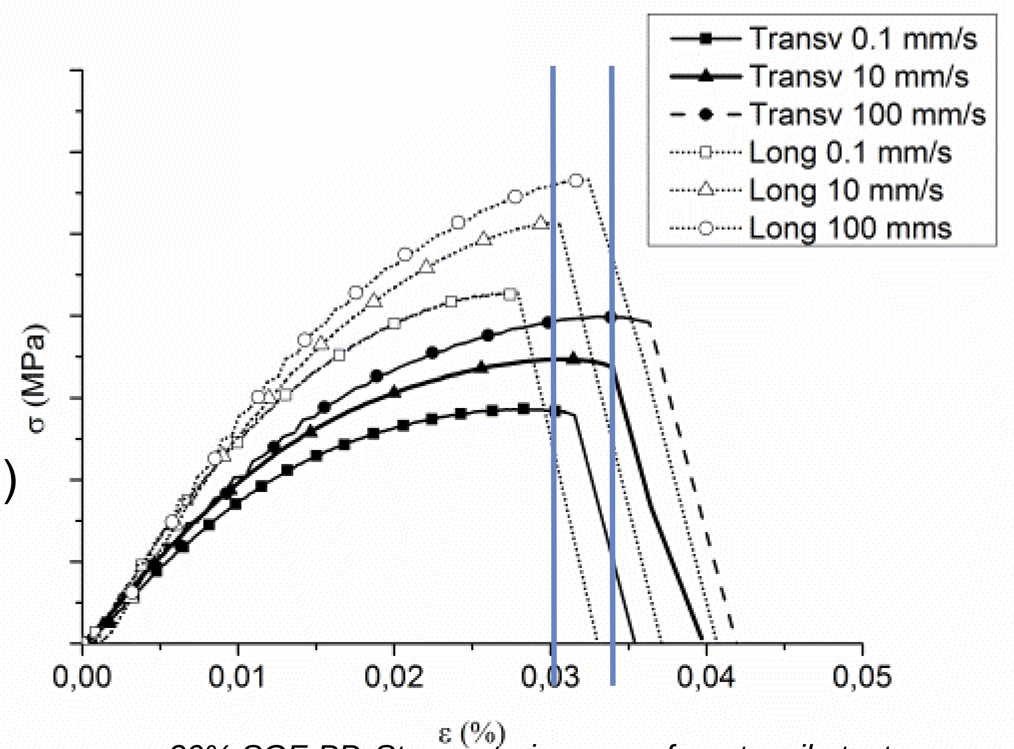
Fracture criteria for Polypropylene Compounds

For SGF-PP materials fracture depends on:

- Strain rate
- Temperature
- Pressure
(asymmetry tension / compression)
- Material (fiber) orientation



30% SGF-PP. Stress-strain curves from tensile tests

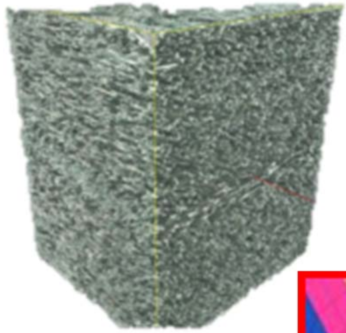
Due to the low sensitivity on strain rate and orientation:
stress values have been preferred for the fracture criterion.

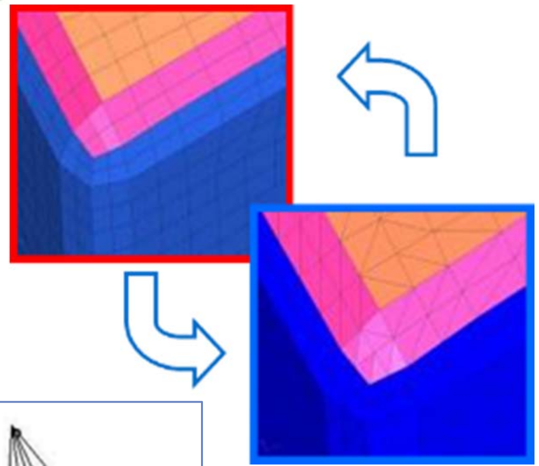
Fracture criteria and anisotropy

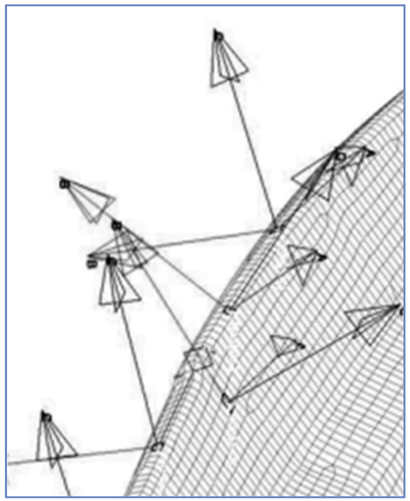
Fracture criteria need to be coupled with anisotropic material laws.

Process information is transferred to the structural analysis, e.g. fiber orientation or flow/material direction, which determine the local material properties. Moldfilling code: Moldflow by Autodesk, RSC model for fiber orientation.

Transversally isotropic laws: e.g. Lsdyna MAT_103: plane stress, orthotropic symmetry, material principal directions determined by flow direction in the mold.







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Interactive fracture criteria

Interactive criteria define parameterized quadratic functions of the stress tensor components. The parameters are determined based on the experimental values of the material strengths.

Features/Model	HILL	TSAI-HILL	TSAI-WU
anisotropy	√	√	√
strain rate dependency	√	√	√
tension/compression asymmetry	-	√	√

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Interactive fracture criteria: Some mathematics

General formulation:

$$\emptyset = F_i \sigma_i + F_{ij} \sigma_i \sigma_j = 1$$

$$\sigma = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{zx} \\ \sigma_{zy} \end{bmatrix}$$

Isosensitive materials (tension = compression): HILL criterion

$$\emptyset = F\,(\sigma_1 - \sigma_2)^2 + G\,(\sigma_2 - \sigma_3)^2 + H\,(\sigma_3 - \sigma_1)^2 + 2\,L\,\sigma_4^2 + 2\,M\,\sigma_5^2 + 2\,N\,\sigma_6^2 = 1$$

Transversally isotropic material (anisotropy direction: fiber direction):
TSAI-WU criterion

$$\emptyset = F_1\sigma_1 + F_2(\sigma_2 + \sigma_3) + F_{11}\sigma_1^2 + 2F_{12}\sigma_1(\sigma_2 + \sigma_3) + F_{22}(\sigma_2^2 + \sigma_3^2) + F_{23}\sigma_2\sigma_3 + F_{44}\sigma_4^2 + F_{55}\left(\sigma_5^2 + \sigma_6^2\right) = 1$$

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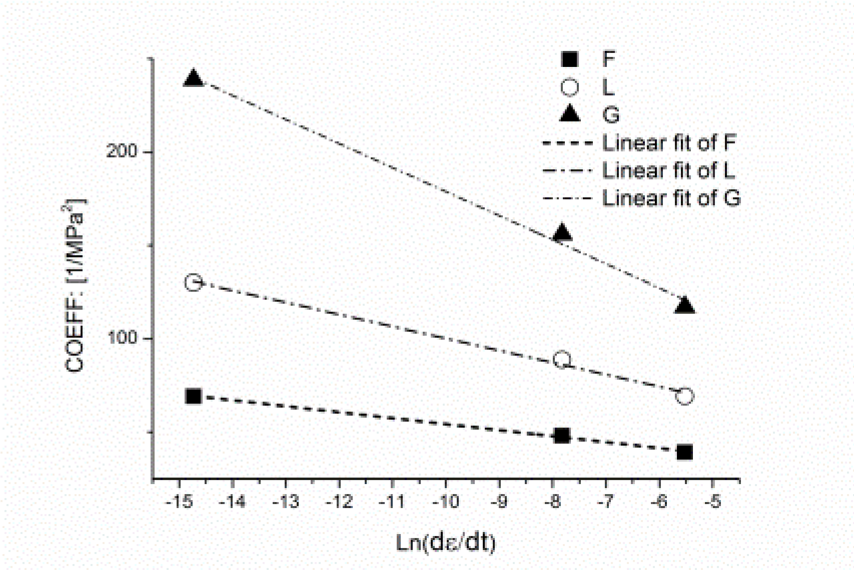
Interactive fracture criteria: Simplified (2D) implementation

HILL criterion:

$$\emptyset = 2F\,{\sigma_1}^2 + G\,{\sigma_2}^2 + 2\,L\,\sigma_4^2 = 1$$

The parameters are function of the material strengths in the principal directions:

$$F = \frac{1}{2X_i^2}\;; \qquad G = \frac{1}{Y_i^2} - \frac{1}{2X_i^2}\;; \qquad L = \frac{1}{2\,S^2}$$



Measurements suggest logarithmic-function to interpolate between known values and extrapolate therefrom.

Interactive fracture criteria: Simplified (2D) implementation

TSAI-HILL criterion:

$$\emptyset = 2F\,{\sigma_1}^2 + G\,{\sigma_2}^2 + 2\,L\,\sigma_4^2 = 1$$

The parameters are function of the material strengths in the principal directions:

$$F = \frac{1}{2X_i^2}\ ; \qquad G = \frac{1}{Y_i^2} - \frac{1}{2X_i^2}\ ; \qquad L = \frac{1}{2\,S^2}$$

The coefficients are chosen according to the sign of the stress tensor component ("isosensitive modification") with the suffix *i* = *t* or *c* depending on the sign of the stress.

Compression and shear values were obtained through appropriate scaling coefficients from those measured under tensile loading, as in the typical situation for "early stage" design when no all the material data are available.
Scaling factors used: 1.3 for compression, 0.8 for shear according to literature(*,**). Other values were tested as well, with less satisfactory results.

(*) M.Nutini and M.Vitali, 12th Ls-dyna German Forum, Filderstadt, 2013
(**) M.Nutini, M.Vitali, S.Bianco, D.Brancadoro, D.Marino, A.Luera, 10th European Ls-dyna Conference, Wuerzburg (D), 2015

Interactive fracture criteria: Simplified (2D) implementation

TSAI-WU criterion:

Interaction coefficient

$$\emptyset = F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + 2F_{12}\sigma_1\sigma_2 + F_{22}\sigma_2^2 + F_{44}\sigma_4^2 = 1$$

The parameters are function of the material strengths in the principal directions:

$$F_1 = \frac{1}{X_t} - \frac{1}{|X_C|}; \quad F_2 = \frac{1}{Y_t} - \frac{1}{|Y_C|}; \quad F_{11} = \frac{1}{X_t|X_C|}\ ; \ \mathrm{F}_{22} = \frac{1}{\mathrm{Y_t|Y_C|}}\ ; \ \mathrm{F}_{44} = \frac{1}{\mathrm{S}^2}$$

Compression and shear values were obtained through appropriate scaling coefficients from those measured under tensile loading
Scaling factors: 1.3 for compression, 0.8 for shear as those used for Tsai-Hill criterion.

$$F_{12} = -\frac{0.5}{\sqrt{X_t \cdot X_C \cdot Y_t \cdot Y_C}}$$

Basic Tsai-Wu

Alternative formulations:
De Teresa: $F_{12} = -F_{11}/4$.
Narayanaswami: $F_{12} = 0$.

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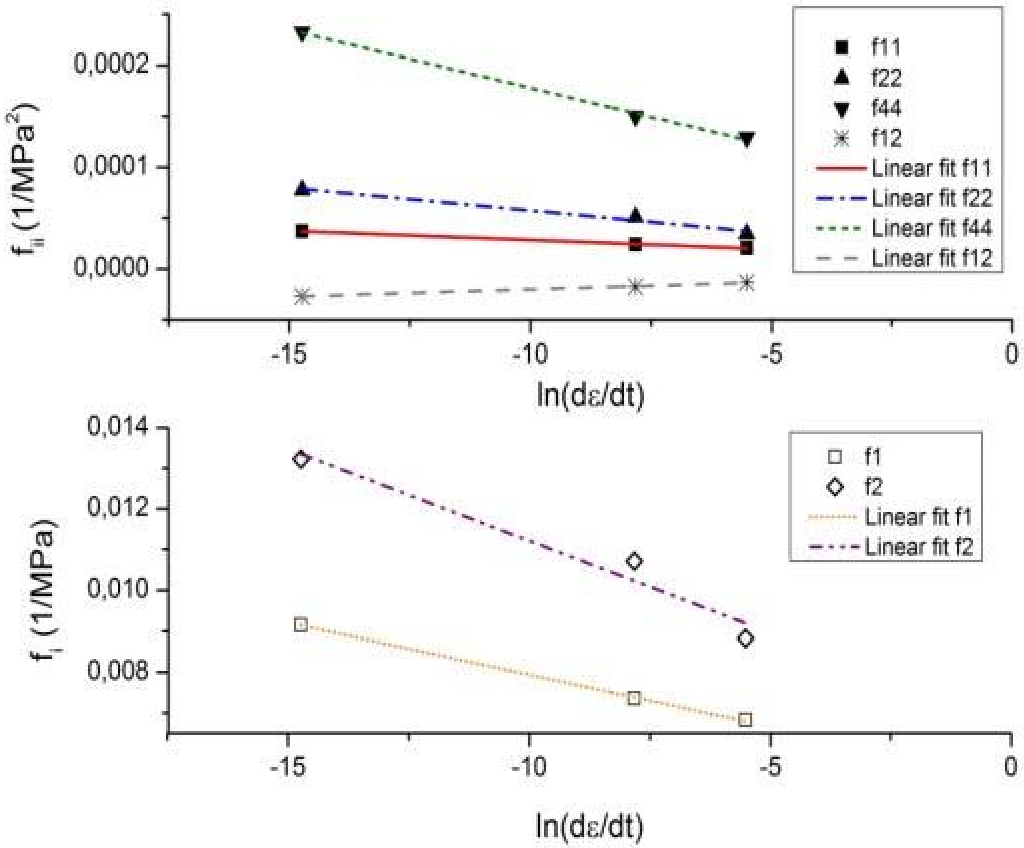
Interactive fracture criteria: Simplified (2D) implementation

TSAI-WU criterion:

$$\emptyset = F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + 2F_{12}\sigma_1\sigma_2 + F_{22}\sigma_2^2 + F_{44}\sigma_4^2 = 1$$



Measurements suggest logarithmic- function to interpolate between known values and extrapolate therefrom.

Validation on Component Level: Lower Bumper Support

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Validation on Component Level: Motivation

Regulations and assessment protocols from consumer organizations (e.g. Euro NCAP) describe test procedures and injury risks for pedestrian protection. The behavior of the lower bumper support is essential to protect pedestrian's lower leg from injuries in a collision with a vehicle front.

In automotive safety engineering CAE methods became the predominant tool for development. Physical testing conducted for product validation, rather than for development iterations.

CAE material modelling for lower bumper support component must sufficiently capture mechanical properties for loading and unloading conditions, including strain rate dependency and fracture.

Complex vehicle CAE simulations require model validation on different levels: material characterization on specimen level, component and full vehicle validation.

Glass fiber reinforced polymers are of particular interest for this part. Material stiffness enables mass effective solutions, but limited ductility bears the risk of fracture.

CAE material modelling must sufficiently capture fracture.

Validation on Component Level: Test Setup Definition

For material validation on component level a test set up was developed addressing all relevant characteristics close to full vehicle conditions (limitations to available test facilities had to be considered):

- Loading
- Unloading
- Strain rate dependency
- Fracture

Experimental try outs were conducted to find three significant loading conditions:

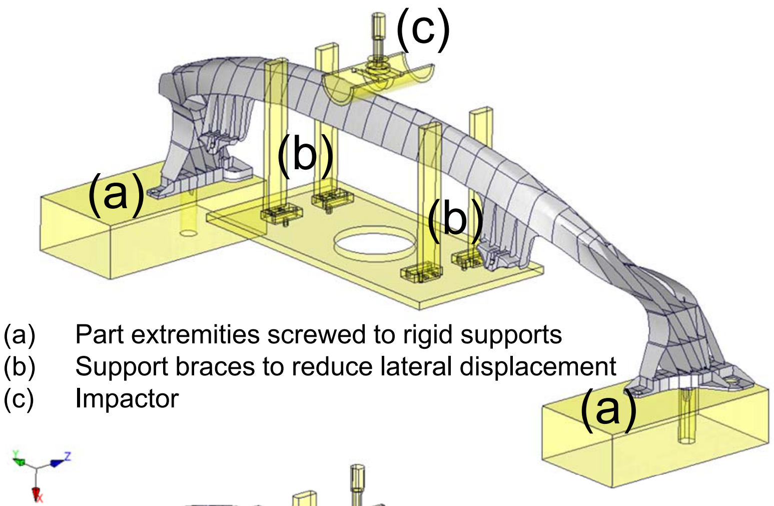
- Quasi static loading above fracture (v = 50 mm/min)
- Dynamic loading just below fracture (v = 5.5 m/s)
- Dynamic loading just above fracture (v = 6.5 m/s)

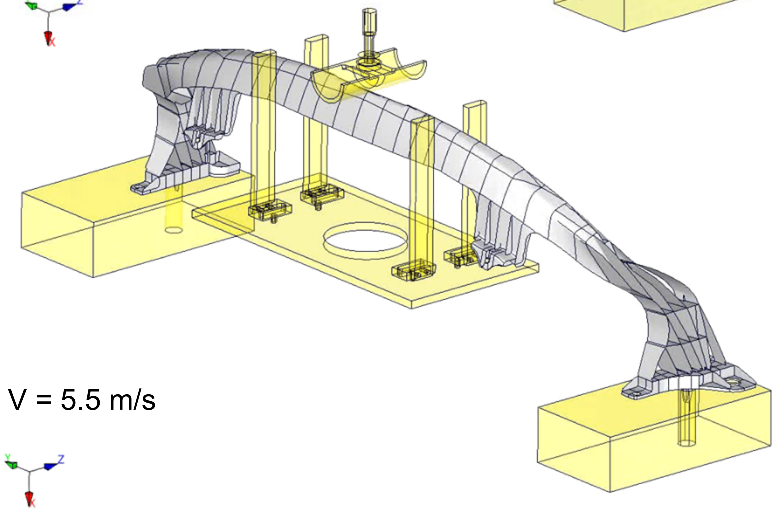
High speed videos for evaluation of fracture localization were recorded.

Time history data for force and displacement were recorded.

Validation on Component Level: Test Setup Definition

Test set up for validation on component level: Dynamic drop tower test.





V = 5.5 m/s

Impact velocities: 5.5 m/s and 6.5 m/s.

Force measurement in Impactor with load cell.

Displacement measurement with laser system.

Iterations for identification of impact velocities (fracture / no fracture).

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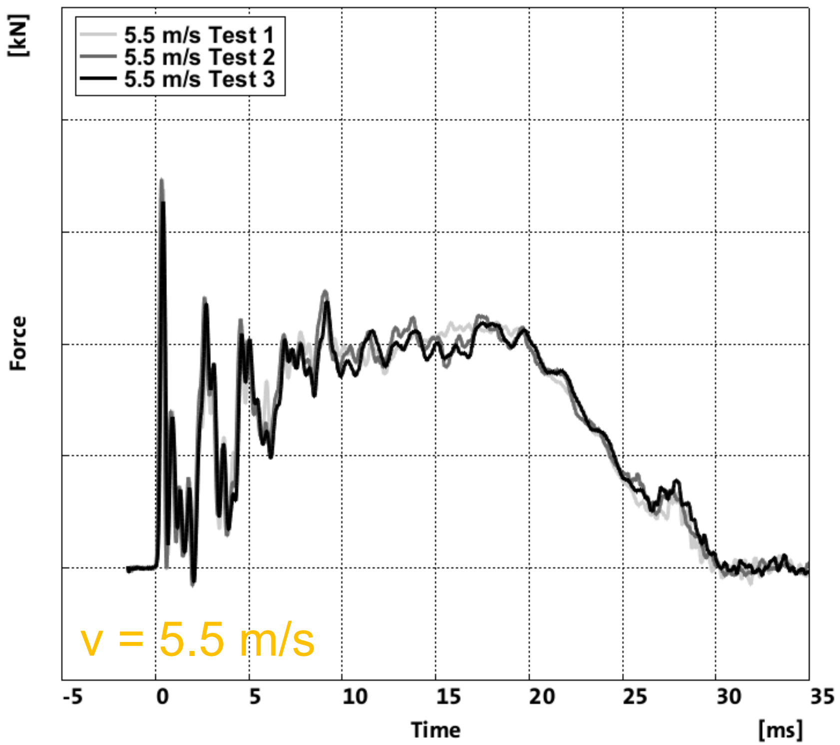
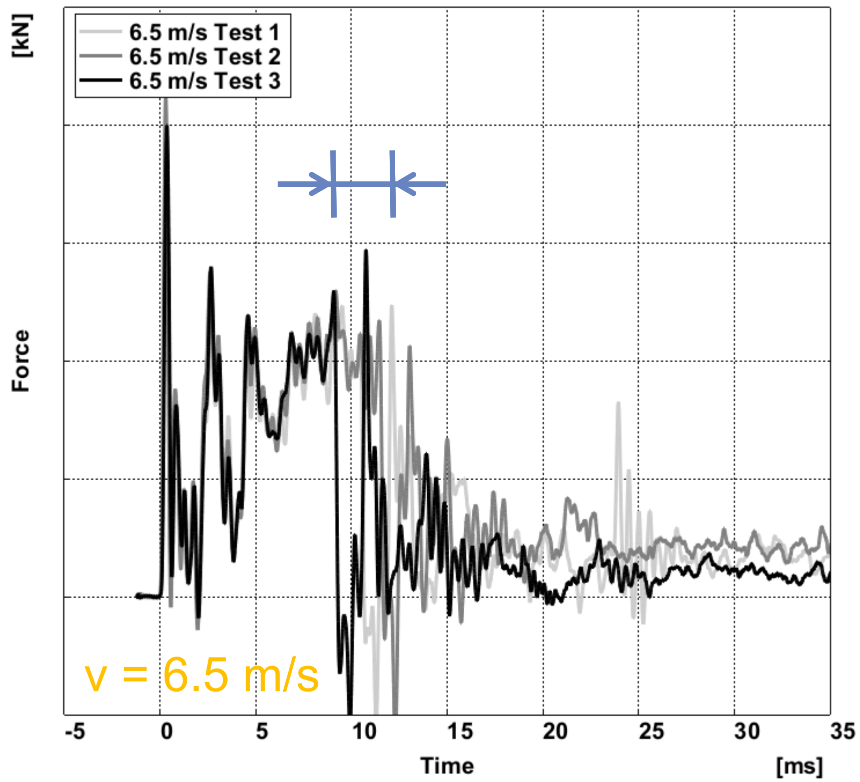
Validation on Component Level: Test Results

Dynamic loading: Fracture evaluation and repeatability.





Experiment shows good repeatability in stiffness, but some variation in fracture.

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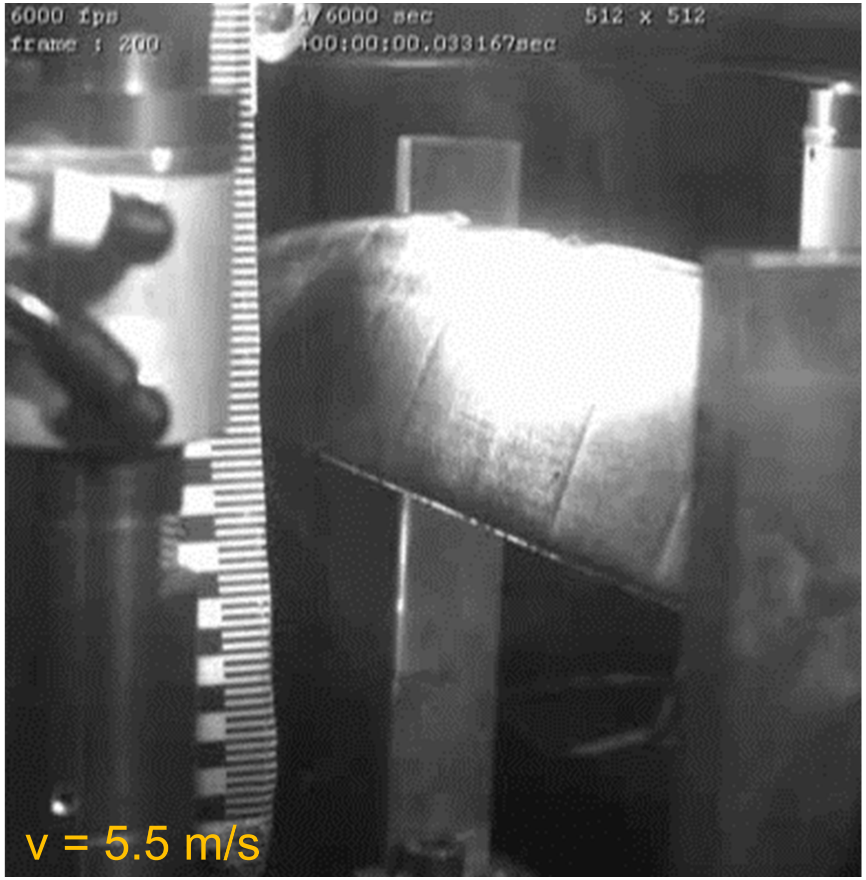
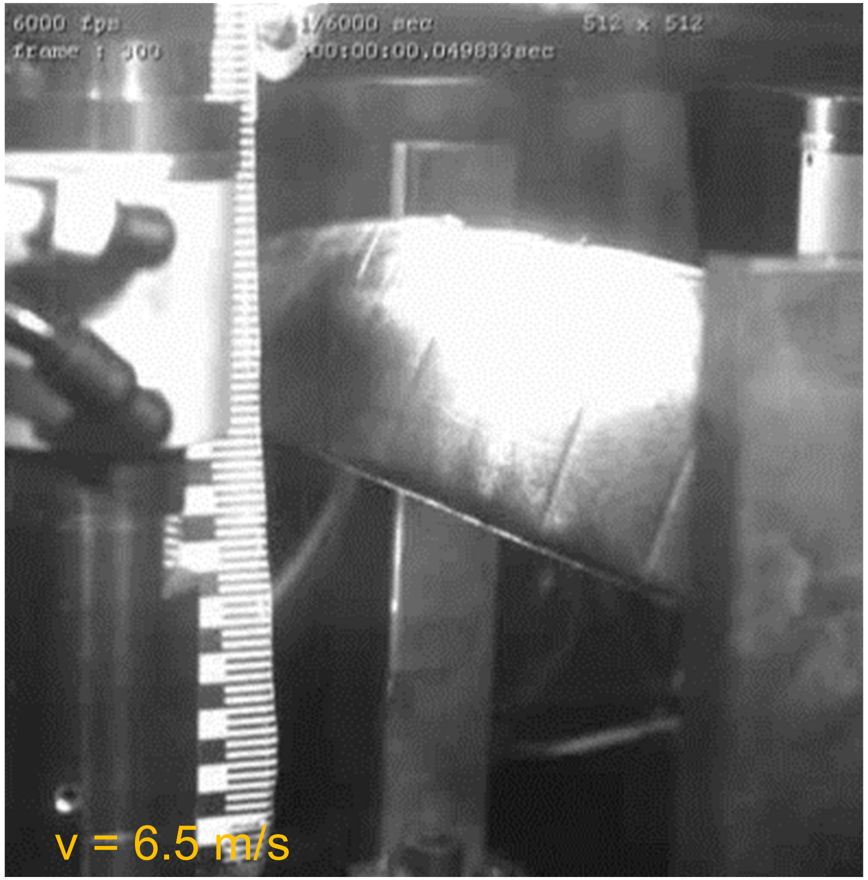
Validation on Component Level: Test Results

High speed video recording for 5.5 m/s and 6.5 m/s test set up.





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Validation on Component Level: Test Results

Frames from high speed video recording for 6.5 m/s test set up.

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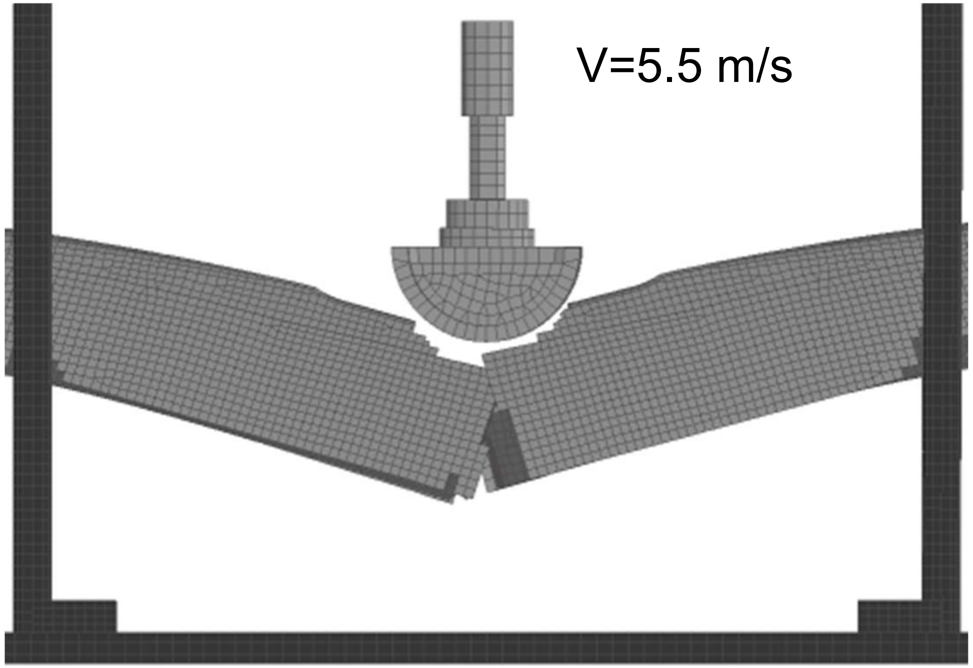
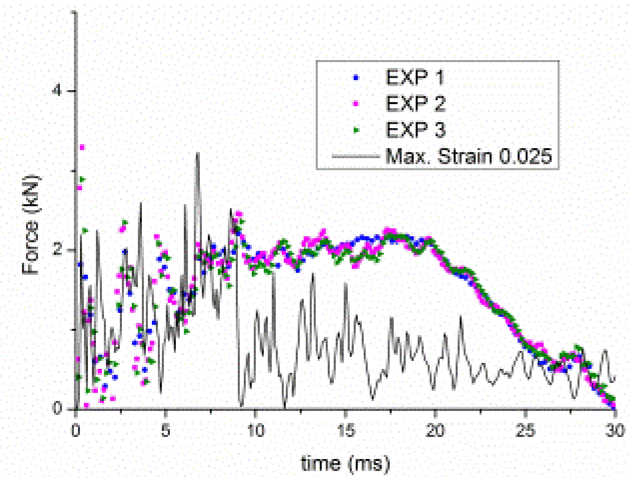
Simulations results: maximum strain criterion

Simulation with “traditional” fracture criteria (max. strain)





Fracture predicted in the simulation, not occurring in the experiment.

Wide material fracture in the contact between impactor and part, not occurring in the experiment

Earlier fracture and consequent excessive drop in the curves force- displacement

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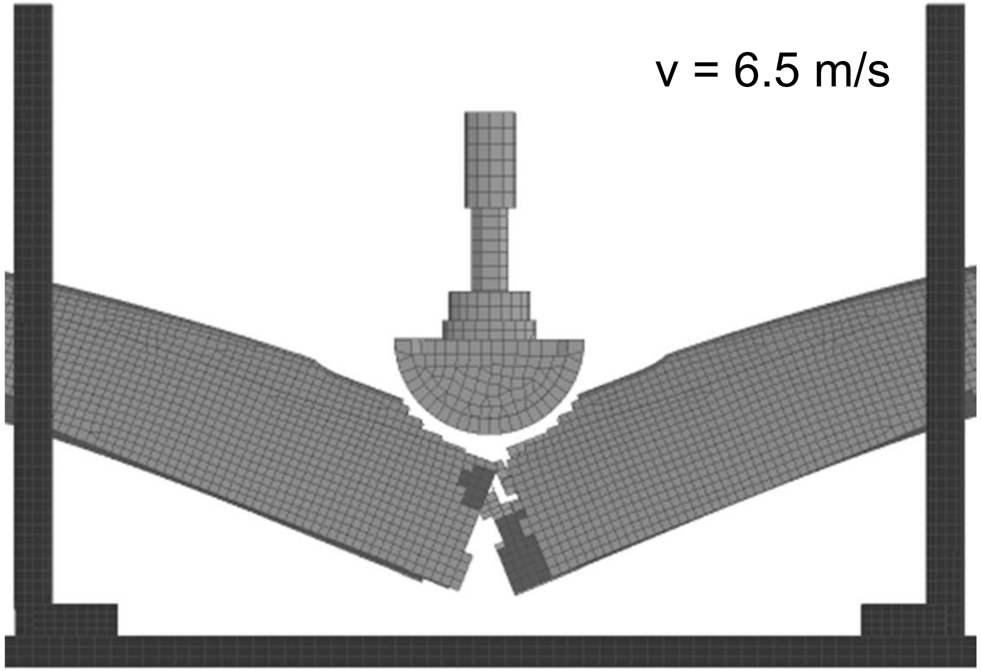
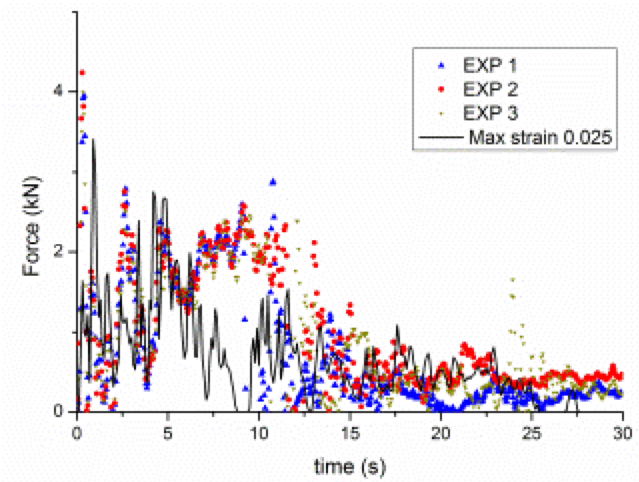
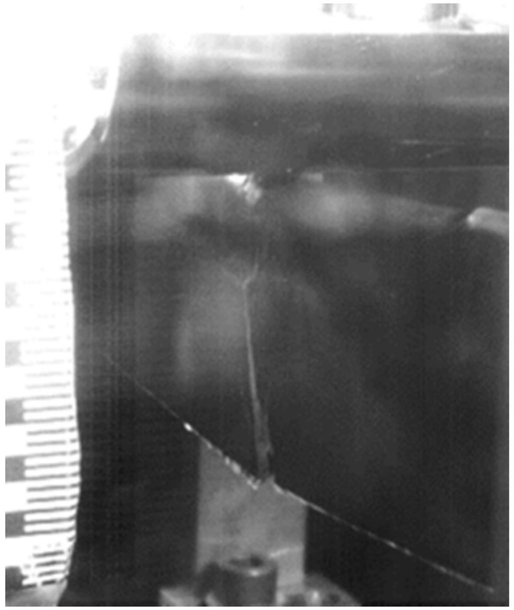
Simulation with “traditional” fracture criteria (max. strain)



Wide material fracture in the contact between impactor and part, not occurring in the experiment.

Earlier fracture and consequent excessive drop in the curves force- displacement.





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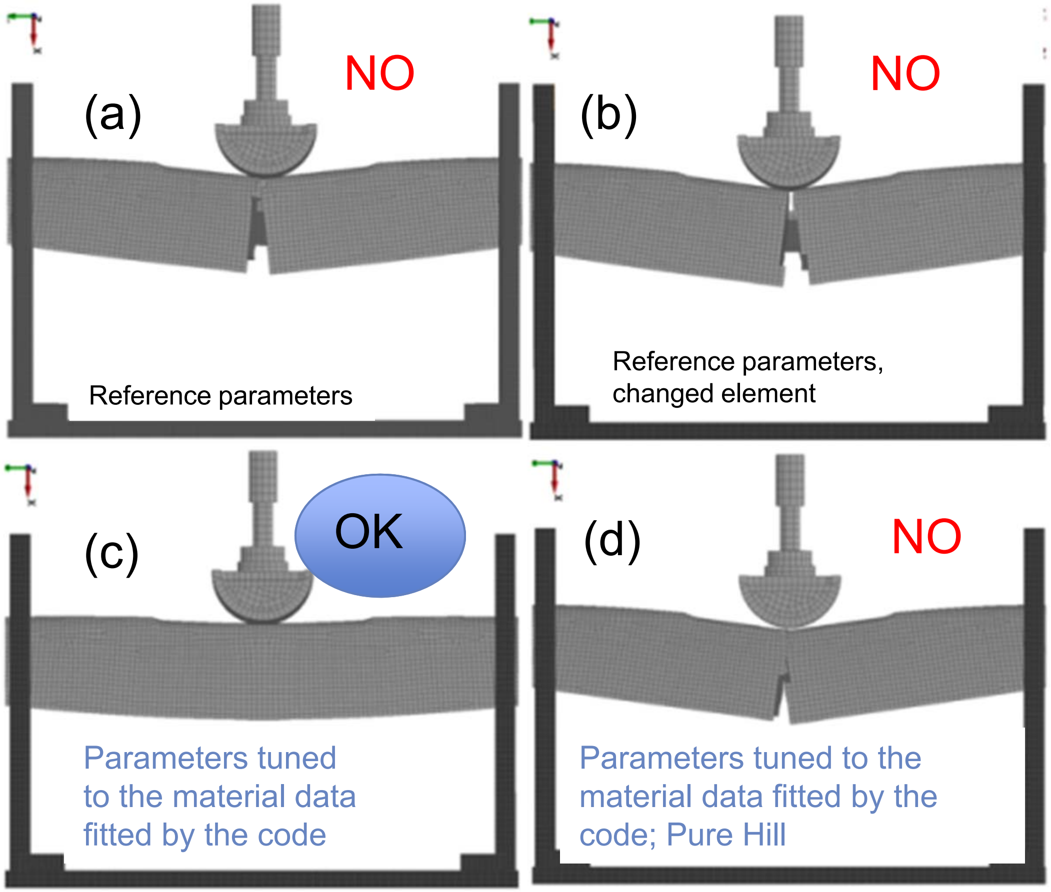
Simulations results: Hill / Tsai-Hill

Results with Hill / Tsai-Hill criterion: Test at v= 5.5 m/s



The simple introduction of parameters as based on material characterization caused wrong prediction: fracture predicted in simulation, not in reality (a).

Changing F.E. parameters did not result in significant improvements: e.g. element formulation (b).

Using material parameters tuned to the material law as internally fitted by the code provides reasonable results : no fracture predicted (c).

However, neglecting compression/tension differentiation causes wrong prediction (d).

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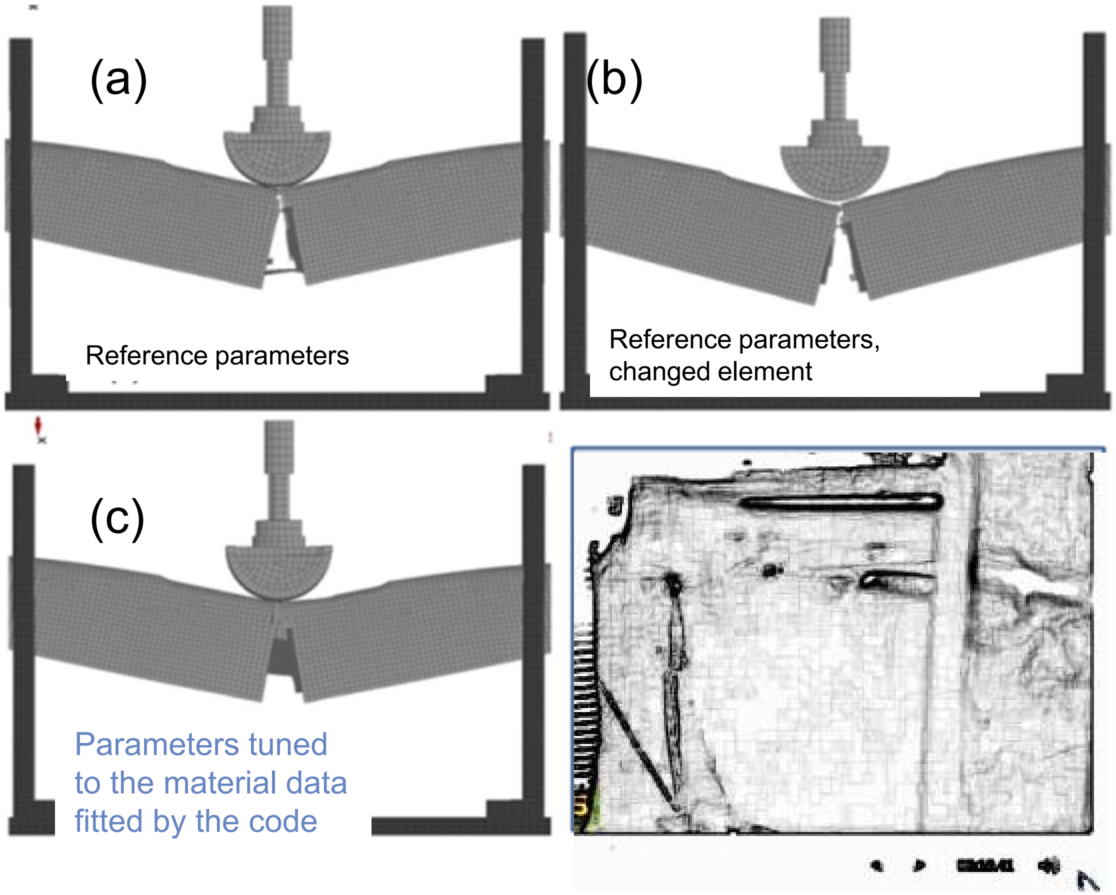
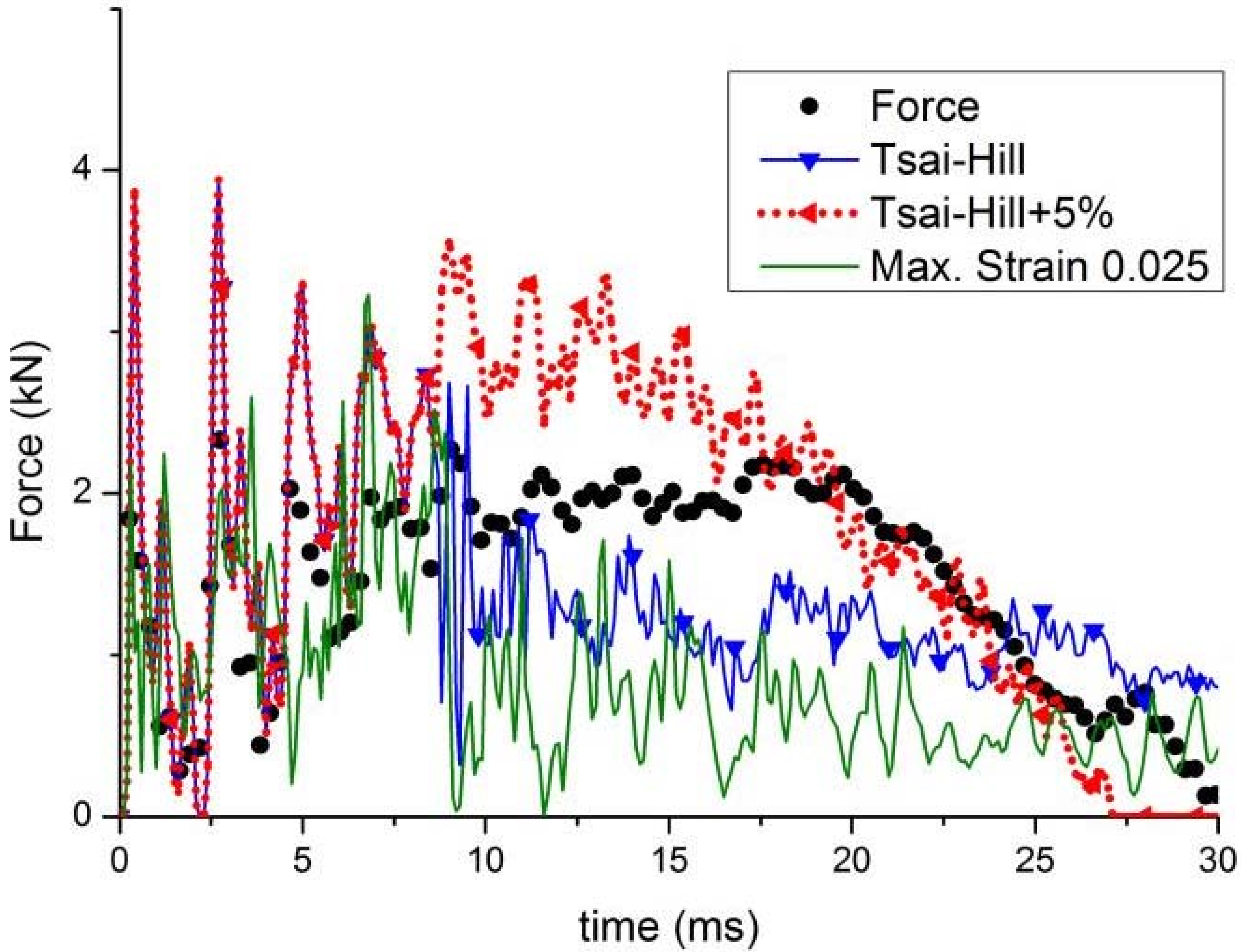
Results with Hill / Tsai-Hill criterion: Test at v= 6.5 m/s



The Tsai-Hill configurations examined for the test at low speed could all reproduce the fracture in the test at 6.5 m/s.

Using material parameters tuned to the material law as internally fitted by the code provides reasonable results, with fracture localization and extension aligned to what observed.

Results with Hill / Tsai-Hill criterion: Test at v= 5.5 m/s



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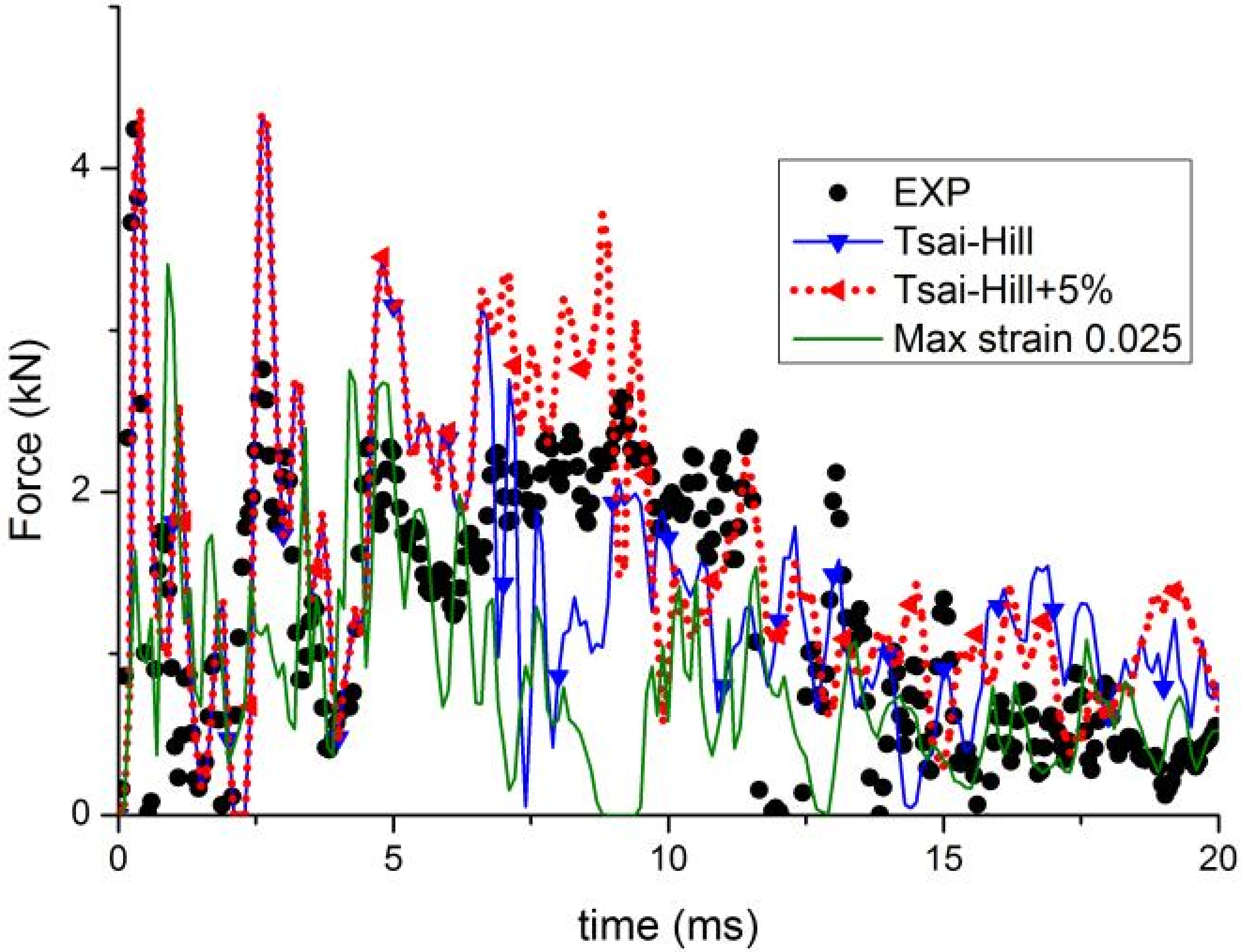
Results with Hill / Tsai-Hill criterion: Test at v= 6.5 m/s



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Conclusions from using Hill / Tsai-Hill fracture criteria

The Tsai-Hill criterion can be used to reasonably predict the component fracture better than the simple “max-strain” criterion.

The criterion is definitely sensitive to its parameters selection, in particular to the material strengths. They need to be tuned to the stresses effectively used by the code in its internal regularizations.

Once this is done, the localization of the fracture - when it occurs - is reasonable; no fracture is predicted when it is not experimentally observed.

The force levels sensed by the impactor are aligned with the experimental data.

The “pure” Hill criterion (no compression-sensitive) predict instead fracture occurring when it does not in the real test.

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Simulations results: Tsai-Wu

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Results with Tsai-Wu: Test at 5.5 m/s

Record No.	Failure Criterion	Element Formulation	NPT1	Failure type	Failure localization
0	EXPERIMENT			NO FAILURE OBSERVED	
1	Tsai-Wu	16	3	none	OK
2	Tsai-Wu	2	3	none	
3	Tsai-Wu compression sensitive	16	3	none	
4	Tsai-Wu / De Teresa	16	3	Complete	*Side and Support*
5	Tsai-Wu / Narayanaswami	16	3	Complete	*Side and Support*
6	Tsai-Wu AND max stress	16	3	none	

The simple introduction of parameters as based on material characterization leads to prediction in the test at low speed in agreement with the experimental evidence when using basic Tsai-Wu implementation.

Alternative formulations for the interaction coefficient lead to results not aligned with the experimental evidence.

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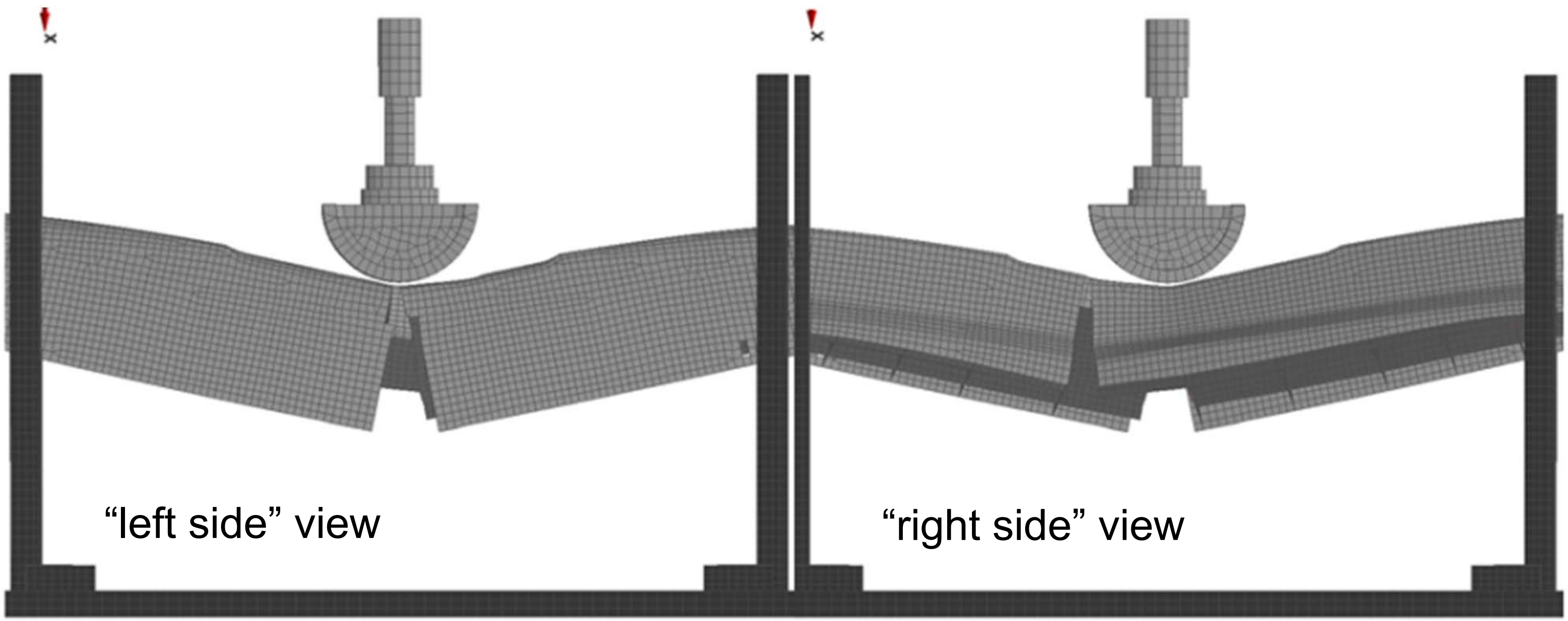
Results with Tsai-Wu: Test at 6.5 m/s



Tsai-Wu, reference parameters:

Simply introducing the material data as from material characterization leads to reasonable prediction of the fracture localization and extension in the test at high speed when using basic Tsai-Wu formulation.

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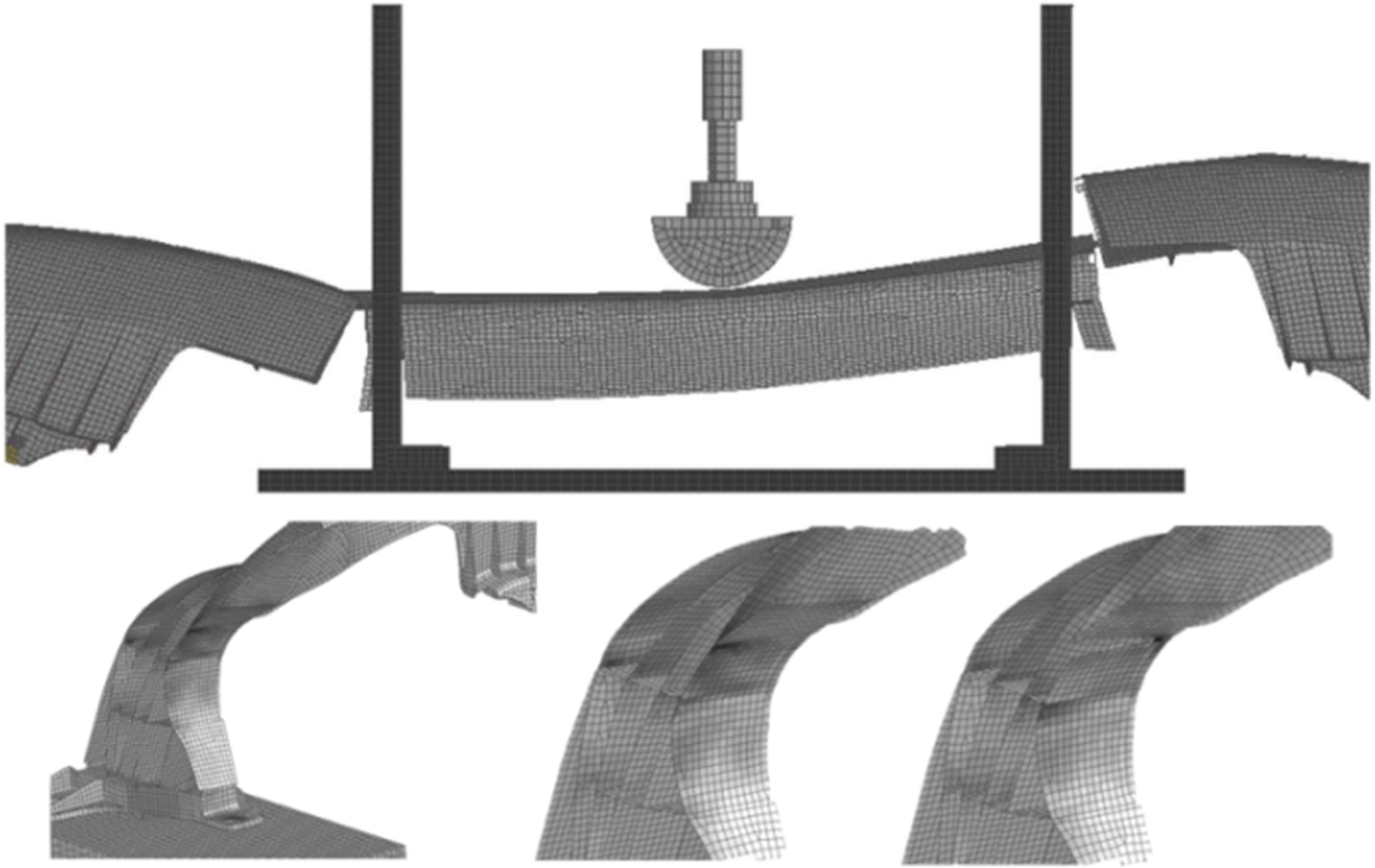
Results with Tsai-Wu: Test at 6.5 m/s



Tsai-Wu interaction coefficient as per De Teresa.

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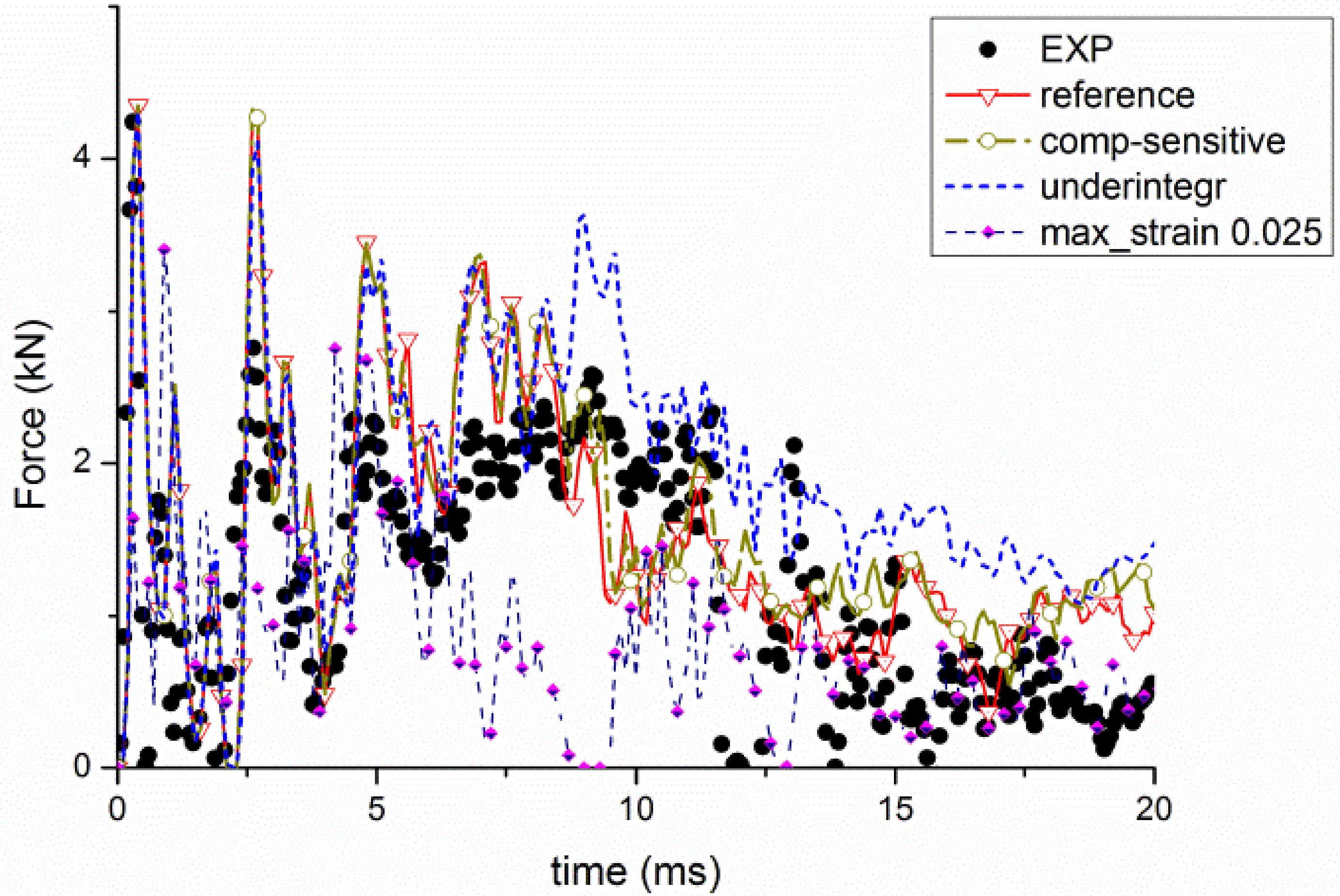
Results with Tsai-Wu: Test at 6.5 m/s



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Conclusions from using Tsai-Wu fracture criteria

The Tsai-Wu criterion can be used to reasonably predict the component fracture better than the simple “max-strain” criterion.

The criterion is not as sensitive as the Tsai-Hill criterion to the material strengths. Experimental values can be directly used.

The compression-to-tension ratio used from literature can be used. Values far from reality give however wrong predictions. Ideally, compression tests - if available - would give more accurate results.

The interaction coefficient modeled according to Tsai-Wu give sensible results. Weird results have been obtained using other formulations.

Other FEM parameters are relevant for the accuracy of the results, e.g. as element formulation.

The force levels sensed by the impactor are aligned with the experimental data.

A material law differentiating tension from compression is expected to provide even more accurate results.

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Conclusions

For GF-reinforced PP, the “interactive” fracture criteria used here proved to provide results better aligned to the experimental evidence, rather than using simple criteria based on maximum strain.

The prediction of the fracture, its localization and the force levels sensed by the impactor were sufficiently accurate for an early design stage.

Among the criteria tested, preference is given to the Tsai-Wu criterion since it seems less affected by variations or uncertainties in the input parameters.

Higher accuracy in the prediction is expected when such criteria would be coupled with more advanced anisotropic material laws, as those based on micromechanics or compression-tension sensitive laws.

In any case the implementation of these criteria is very simple and they do not require complex experimental data sets for identifying their parameters.

The validity of the approach here presented needs to be assessed on the basis of additional experimental evidence, by varying loading conditions, materials and also considering different parts.

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