Damage Modeling under Impact Loading in Talc-Filled Polypropylene Compounds

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crashMAT

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Scheme of the presentation

- LyondellBasell: Company at a Glance
- Damage in mineral filled Polypropylene under impact conditions
- Damage modeling and parameter identification: prior art, LyondellBasell contributions, debate in the CAE community
- Experimental and numerical validation
- Next steps

LyondellBasell At A Glance

- One of the largest plastics, chemical and refining companies
- Annual revenues of $44 billion
- 13,300 employees worldwide

	2011	2012	2013
Revenues (USD millions)	**$48,183**	**$45,352**	**$44,062**
EBITDA (USD millions)	**$5,469**	**$5,808**	**$6,311**
Income from Continuing Operations (USD millions)	**$2,472**	**$2,858**	**$3,860**
Diluted EPS from Continuing Operations	**$4.32 per share**	**$4.96 per share**	**$6.76 per share**
Cash from Operating Activities (USD millions)	**$2,860**	**$4,787**	**$4,835**
Cash and Cash Equivalents [1] (USD millions)	**$1,065**	**$2,732**	**$4,450**
EBITDA Margins	**11%**	**13%**	**14%**
Regular Dividend	**$0.55 per share**	**$1.45 per share**	**$2.00 per share**
Special Dividend	**$4.50 share**	**$2.75 share**	**---**
Total Debt/EBITDA [1]	**0.74x**	**0.76x**	**0.92x**
Total Debt/Book Capital [1]	**27%**	**28%**	**32%**

1. Balance sheet items represent end of year data.

What We Make Shapes Tomorrow

We Make Chemicals the World Counts On

Olefins & Polyolefins

- Ethylene
- Propylene
- Polyethylene
- Polypropylene
- *Catalloy* process resins
- PP Compounds
- Polybutene-1

End Uses

•Food Packaging

•Textiles

•Automotive

•Appliances

•Films

•Flexible Piping

Intermediates & Derivatives

- Propylene Oxide
- Styrene Monomer
- PG and PGE
- Acetyls
- Oxyfuels
- Ethylene Oxide
- EG and EOD
- BDO & Derivatives

End Uses

•Insulation

•Home Furnishings

•Adhesives

•Consumer Products

•Coatings

Refining

- Gasoline
- Diesel
- Olefins Feed

End Uses

•Automotive Fuels

•Aviation Fuels

•Heating Oil

•Industrial Engine Lube Oils

Technology

- Process Licensing
- Catalyst Sales
- Technology Services

End Uses

• Polyolefins and Chemical Manufacturers

Global Capacity Positions

- Polypropylene
- Polypropylene Compounds
- Oxygenated Fuels

1st

- Propylene Oxide

2nd

- Polyolefins Licensing

3rd

- Polyethylene
- Ethylene
- Propylene

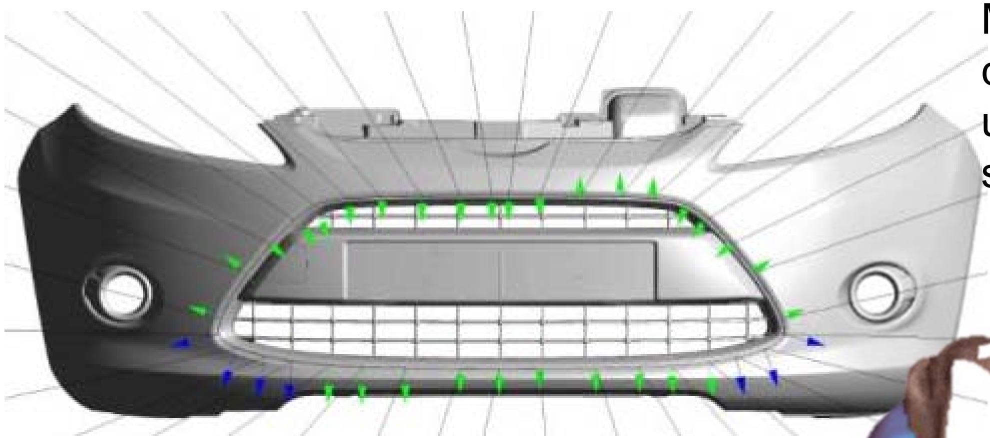
5th

Refining Capacity
268,000
barrels per day

Sources: Third party consultants data.

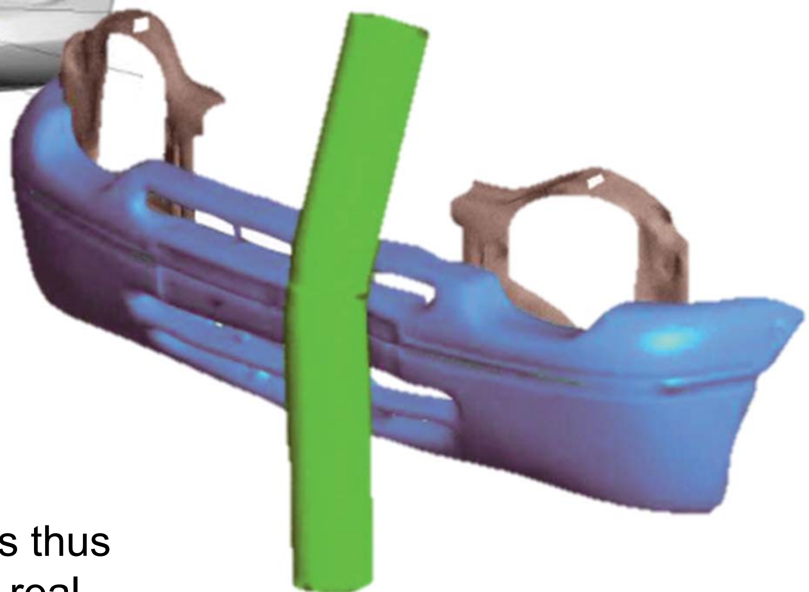
Note: Capacities and worldwide capacity positions are as of December 31, 2012, and include our pro rata share of joint ventures.

Damage in Mineral Filled Polypropylene under Impact Conditions



Mineral filled Polypropylene compounds are typically used in automotive for parts subjected to impact.

Source: LyondellBasell Image Databank



Damage modelling is thus critical for designing real components.

Source: LyondellBasell Image Databank

Damage in Mineral Filled Polypropylene under Impact Conditions

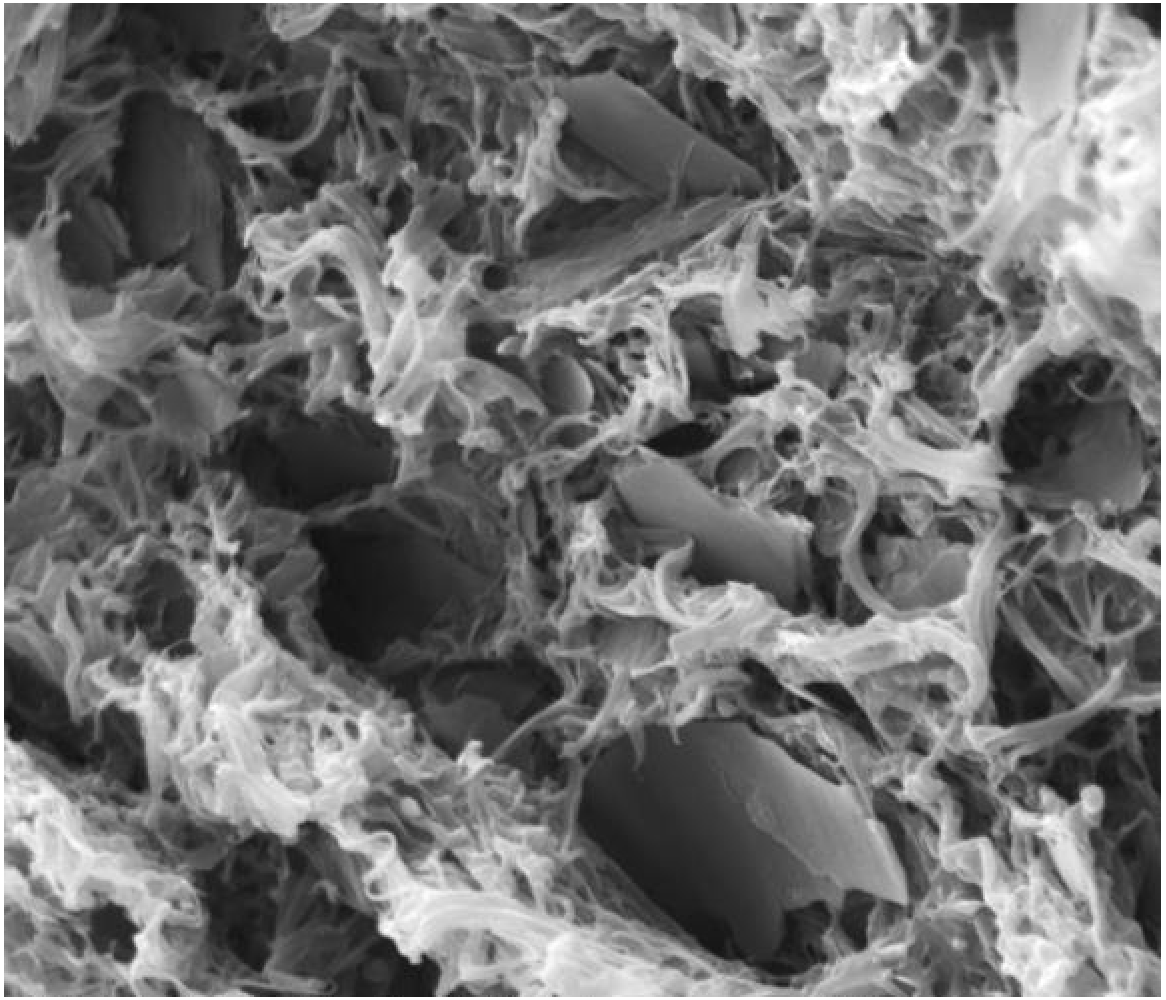
- How can we detect it?

- How can we measure it?

- How can we model it?

- How can we proof it?

Damage in Mineral Filled Polypropylene under Impact Conditions



Source: LyondellBasell

Debonding of (talc) particles from the polymer matrix leads to micro cavities initiation and to the damage of the matrix

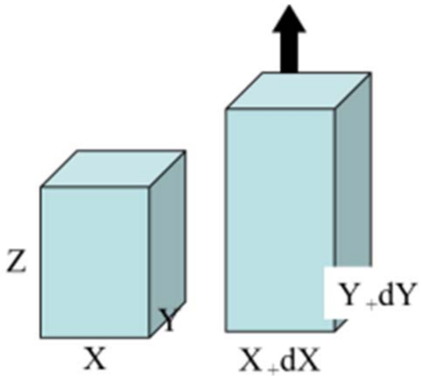
Damage: how can we detect it?

Damage is associated to the volume strain, which is experimentally accessible

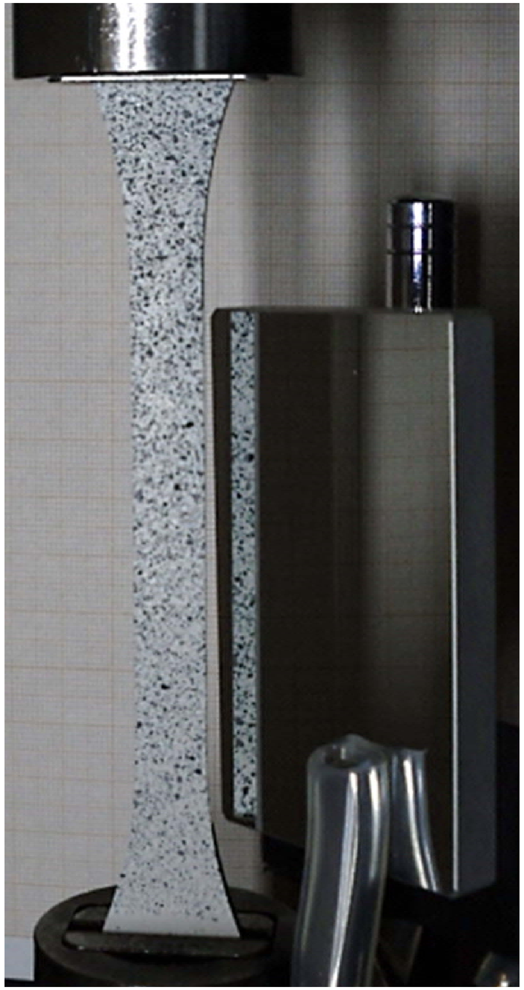
- LyondellBasell Contribution :Proposal for a method based on Local Strain Measurement

M. Nutini, M. Vitali, "Characterization of polyolefins for design under impact: from true stress/ local strain measurement to the F.E. simulation with Ls-dyna Mat. SAMP-1", 7th Ls-dyna German forum, Bamberg 2008

$$\frac{dV}{V} = (\varepsilon_X + \varepsilon_Y + \varepsilon_Z)$$



Damage: how can we detect it?

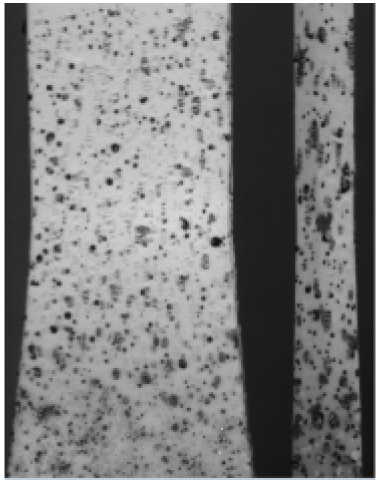


Source: LyondellBasell

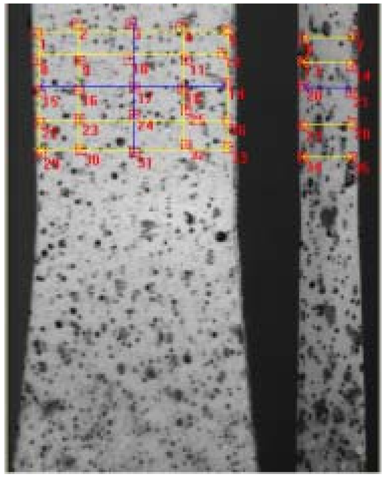
Measuring the volume strain: local strain measurement. DIC (Digital Image correlation), 3D

- Transversal isotropy is not assumed
- Strain along the thickness measured by placing a mirror

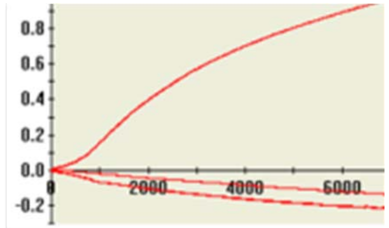
Tensile test filmed through a high-resolution camera



Images elaborated through a 3D DIC dedicated software

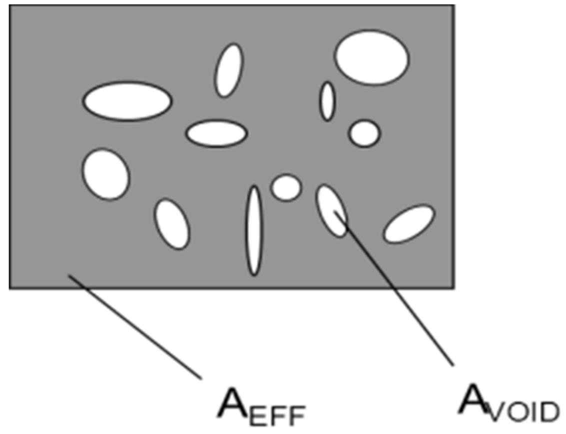


3D local measurement of strains



Damage: how can we measure it?

Damage function implemented according to Chaboche-Lemaitre model: Continuum Damage Mechanics (CDM) approach



Damage variable *D*:
0 (virgin mat.) ≤ *D* ≤ 1 (failure)

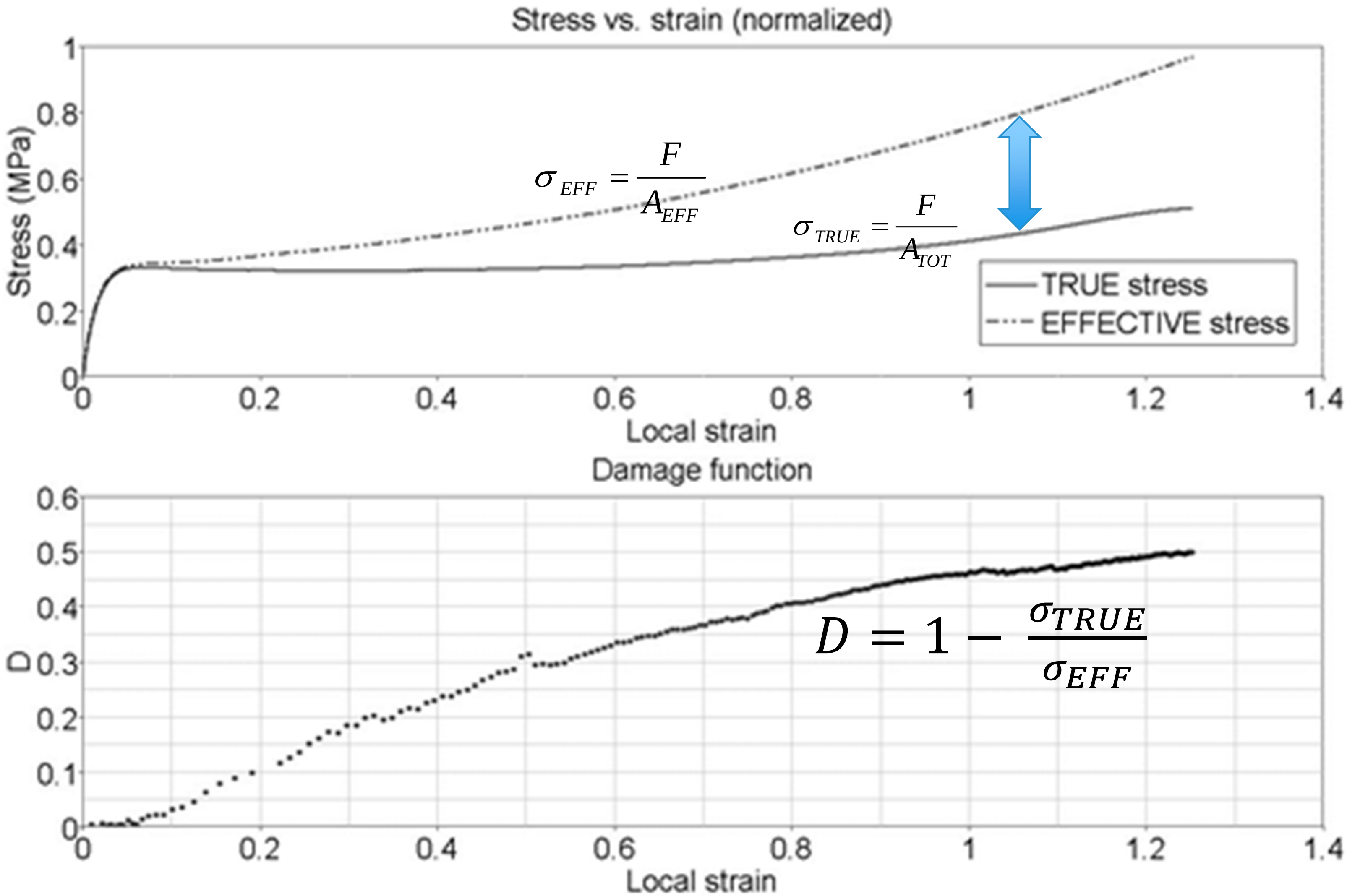
$$D = \frac{A_{VOID}}{A_{TOT}}$$ *Damage function*

$$\sigma_{EFF} = \frac{F}{A_{EFF}}$$ *Effective stress*

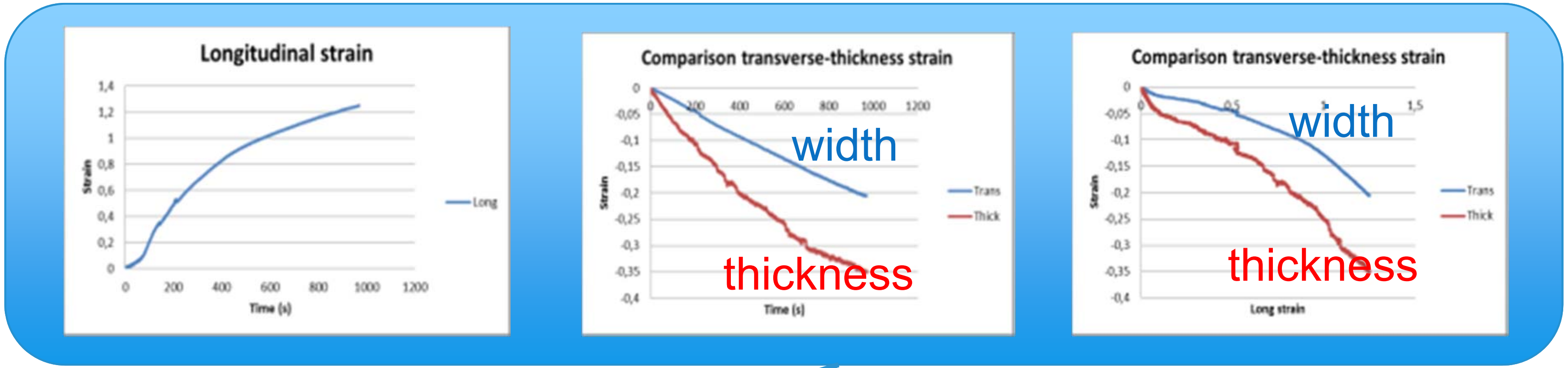
$$\sigma_{TRUE} = \frac{F}{A_{TOT}}$$ *True stress*

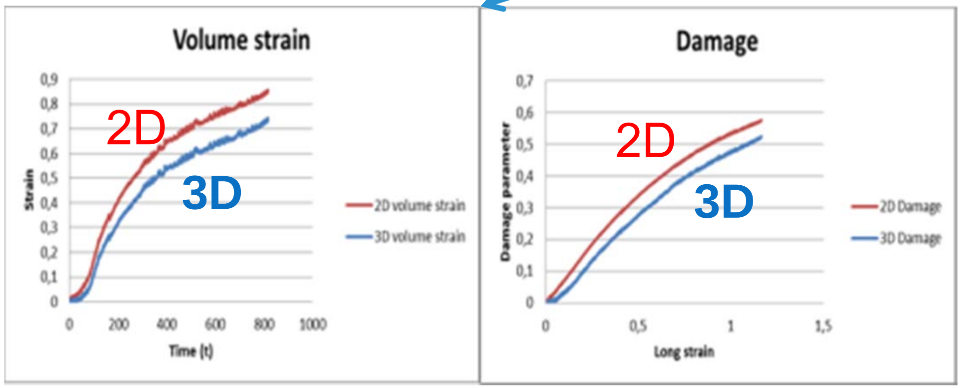
$$D = 1 - \frac{\sigma_{TRUE}}{\sigma_{EFF}}$$

Damage: how can we measure it?



3D local measurement and data elaboration





Parameter identification of damage law according to Chaboche-Lemaitre model

$$A_{TOT} = A_{Eff} + A_{Void}$$

What is “true”? Notes on the Nomenclature

“Stat rosa pristina nomine, nomina nuda tenemus”

$$\sigma_{TRUE} = \frac{F}{A_{TOT}}$$

True stress

- TRUE as far as measured based on the TRUE cross section of the specimen (compared to engineering stress)
- FALSE because the cross section comprises the voids

$$\sigma_{EFF} = \frac{F}{A_{EFF}}$$

Effective stress

- FALSE because based on the assumption of isochoric deformation
- TRUE because it is the stress effectively sustained by the material

Nomenclature might be misleading

We are not running alone …

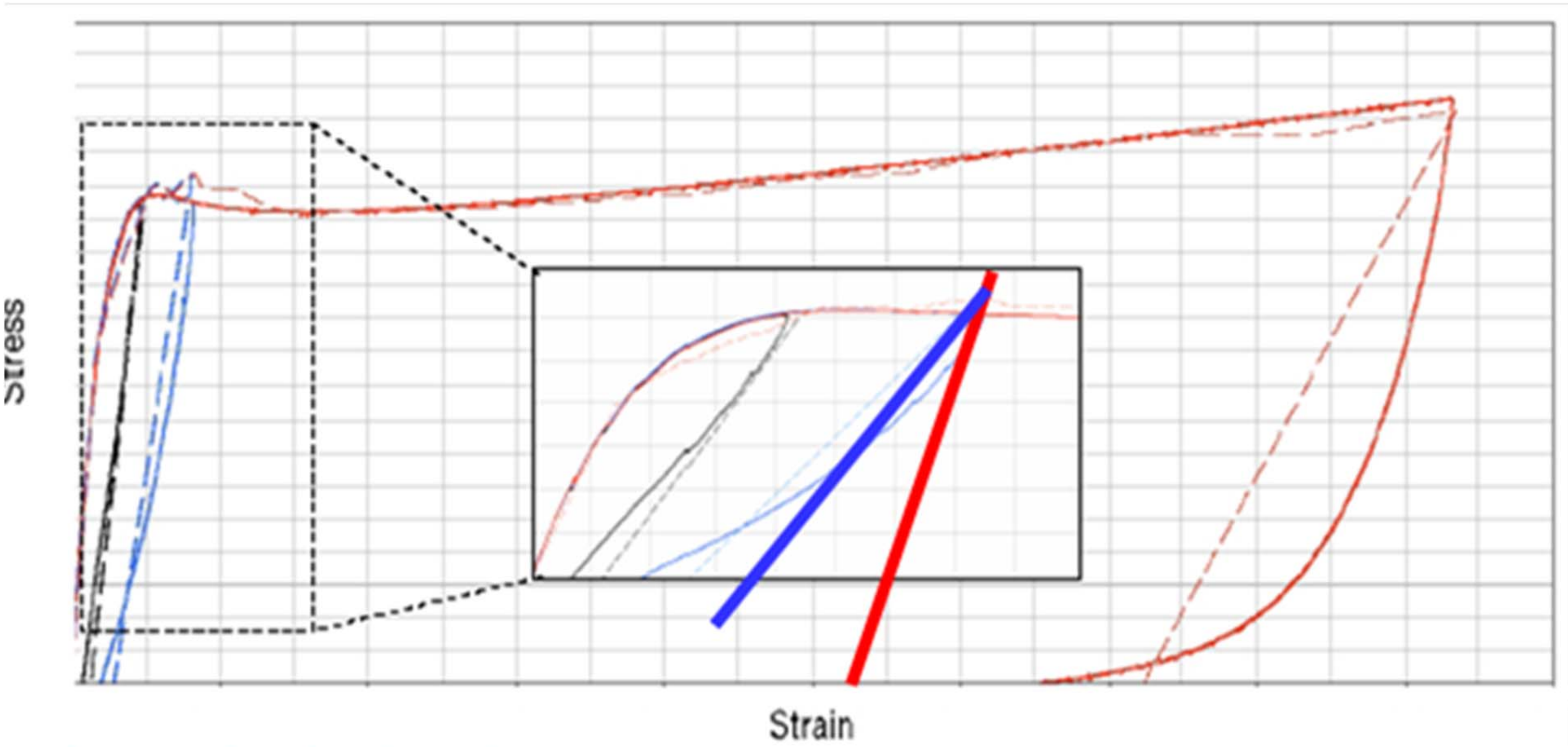
Source: LyondellBasell Image Databank

- Same approach can be found in other more recent publications, e.g.:

- R.Balieu, F.Lauro, B.Bennani, R.Delille, T.Matsumoto, E.Mottola, "A fully coupled elastoviscoplastic damage model at finite strains for mineral filled semi-crystalline polymer, Int. J. Plasticity, (2013)

Other approaches

Other – classical - approaches



Damage function through elastic modulus measurement from uniaxial tensile tests with repeated unloading

Other – classical - approaches

- Gongyao Gu, Yong Xia, Chin-hsu Lin, Shaoting Lin, Yan Meng, Qing Zhou, “Experimental Study on characterizing damage behavior of thermoplastics”, Materials and Design 33 (2013),p. 199-207

Comparison of the results from volume strain and Modulus variation: conflicting responses!

- *Results are different (Gu et al.): Damage underestimated when volume strain is used rather than elastic modulus(D=0.4 vs. D=0.9)*

Open Questions

- Methodologies for measuring the damage give different numerical values (Gu et al.), or similar values (Balieu et al.) .

- Damage values reported to reach values of about 0.8-0.9 when based on stiffness assessment (Gu et al.)
- Damage values according to Chaboche-Lemaitre are supposed to range from 0 (virgin material) to 1 (failure).
- Experienced values from Volume Strain measurement not higher than 0.4-0.5

Questions /Answers

- Experimental answer, reprising the ideas of Delhaye et al. (Int. Journal Impact. Engineering, 2011):
  - SEM observation of fracture surface of tensile specimens

- Numerical answer:
  - Implementing Damage curves in the Finite Element simulation of an impact test

Experimental Answer

Experimental Answer

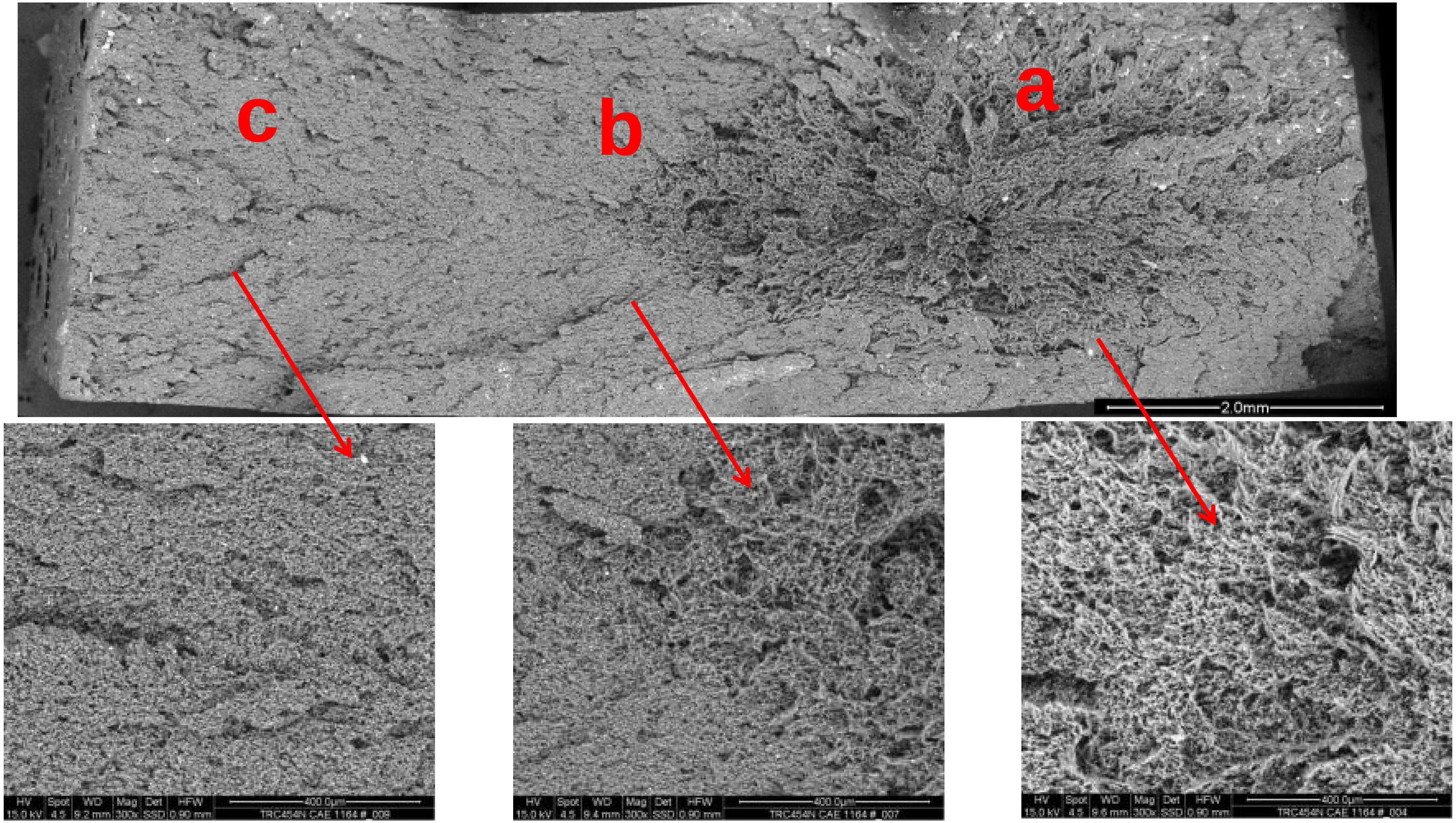
- Fracture surface of tensile specimens analyzed with SEM

- Specimens cut from an injection molded 3 mm thick plaque
- Specimens subjected to tensile test at 100mm/s
- Fracture surfaces cleaned through ultrasounds, then metallized
- Fracture surfaces compared with samples from virgin (= not tested) material

  - Material: mineral filled, impact modified Polypropylene

Analysis at SEM of a Compound Material: Specimen Fracture Surface (SE)

Source: LyondellBasell



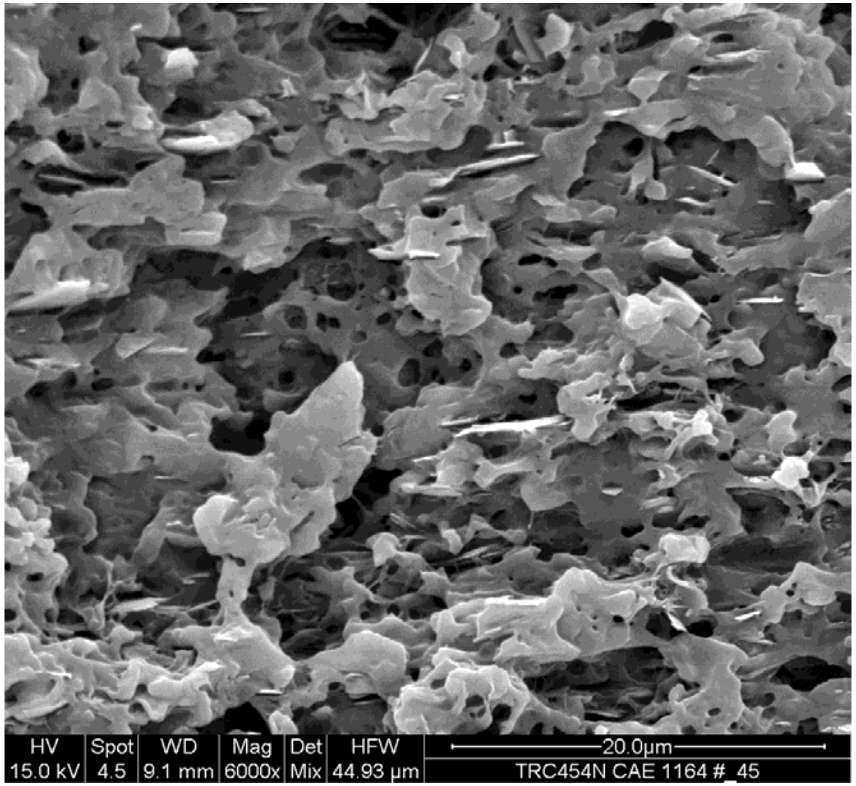
Source: LyondellBasell

Source: LyondellBasell

Source: LyondellBasell

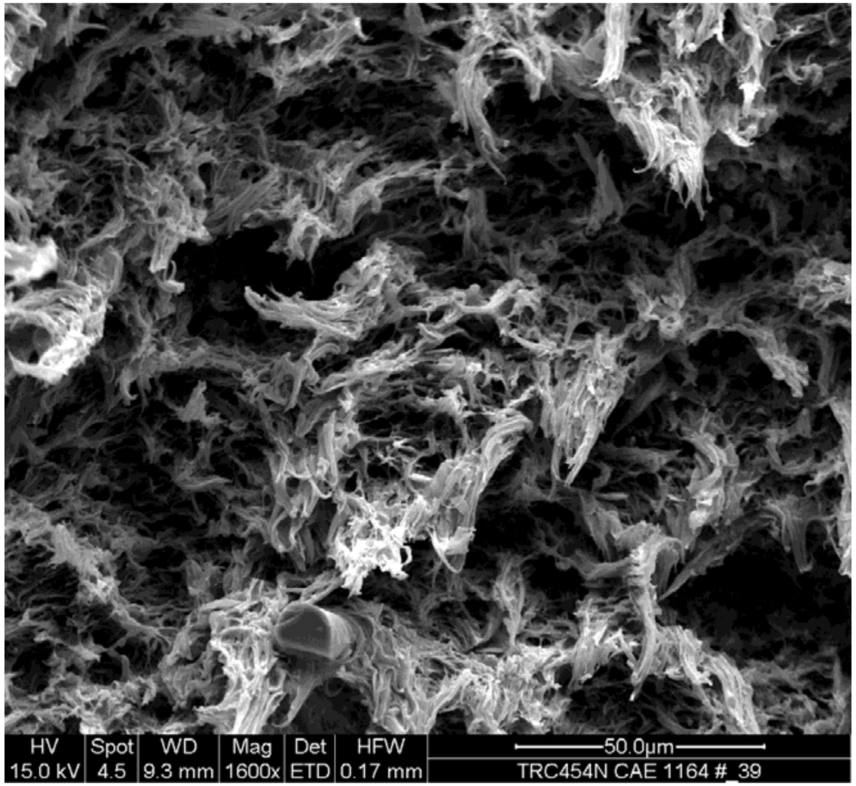
Analysis at SEM of a Compound Material: Specimen Fracture Surface (BS)

c



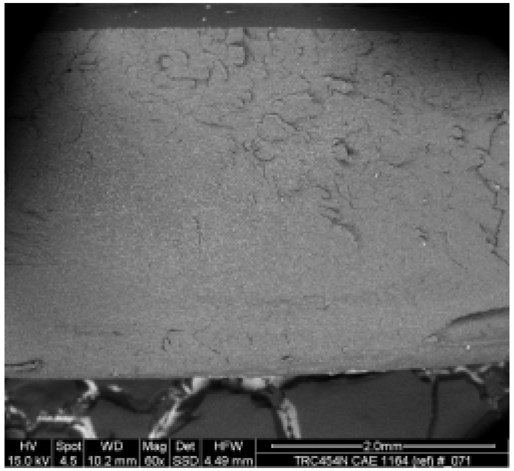
Source: LyondellBasell

a

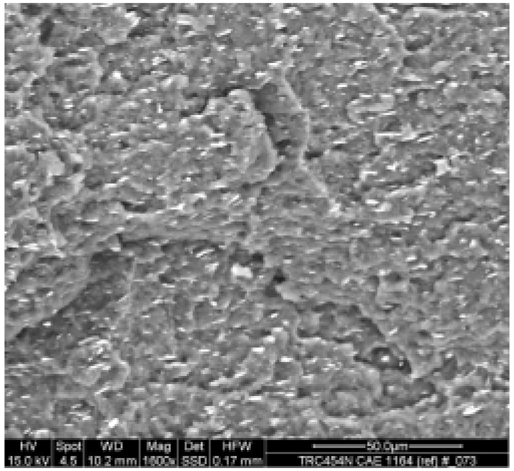


Source: LyondellBasell

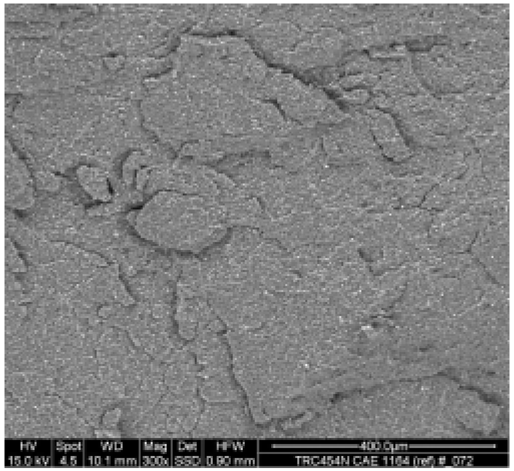
Analysis at SEM of a Compound Material: Virgin Material



Source: LyondellBasell



Source: LyondellBasell



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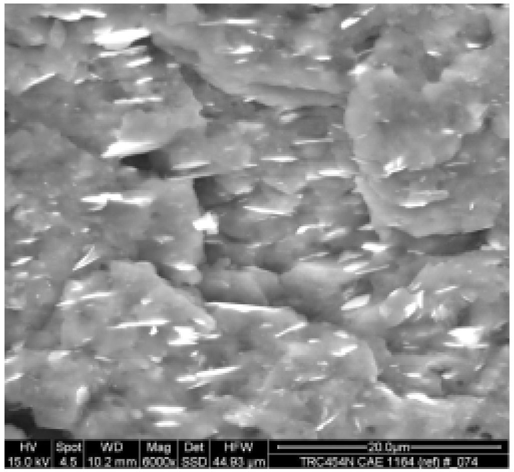


Source: LyondellBasell

- Samples of virgin material broken after cooling in liquid nitrogen.

Analysis at SEM of a compound material (CAE1164)

- Areas with different morphologies can be identified (cfr. Delhaye et al.)
- Area (a): “ductile” area: long stretched ligaments
- Area (c): “brittle” area

- Evidence of NOT UNIFORM damage condition oh the fracture surface.
- The Damage parameter measured with optical tools is then Averaged on the section, in agreement with Continuum approach.
- Higher Damage values could occur more locally but are not visible nor useful when coupled with a TRUE stress/ EFFECTIVE stress measurement

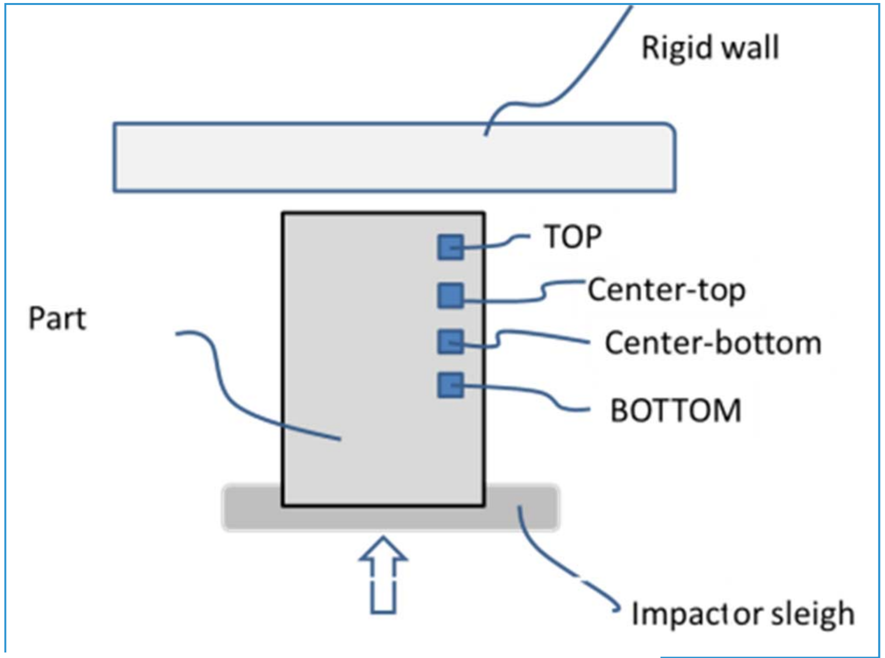
Numerical Answer

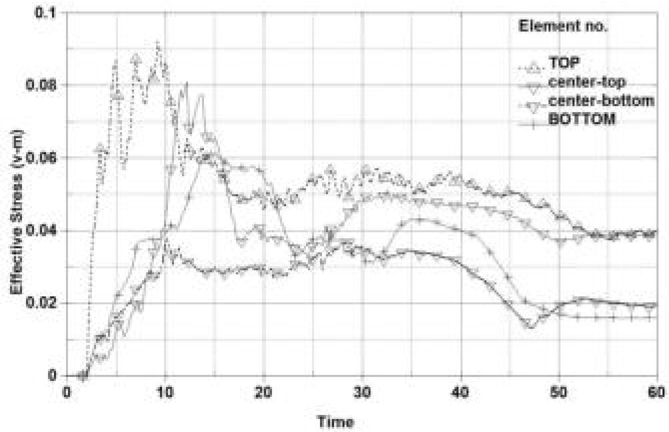
Numerical Answer

Industrial prototypal part (energy absorber), made of talc-filled, impact-modified PP

Material law uses (Ls-dyna SAMP-1):

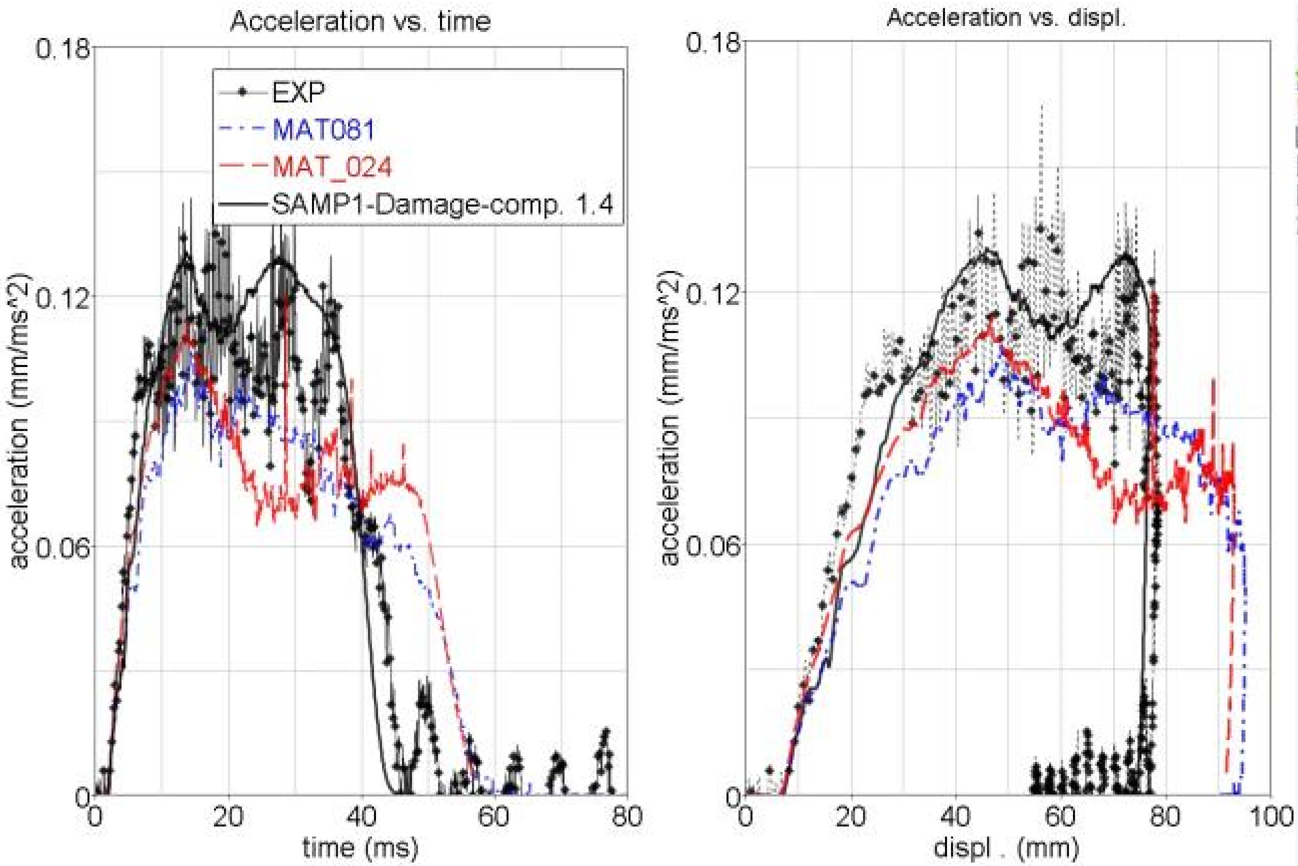
- Pressure-sensitive plasticity
- Strain rate dependence
- Complex loading (Tension , Compression, Bending)
- Damage: portions of the part are subjected to unloading during the impact sequence



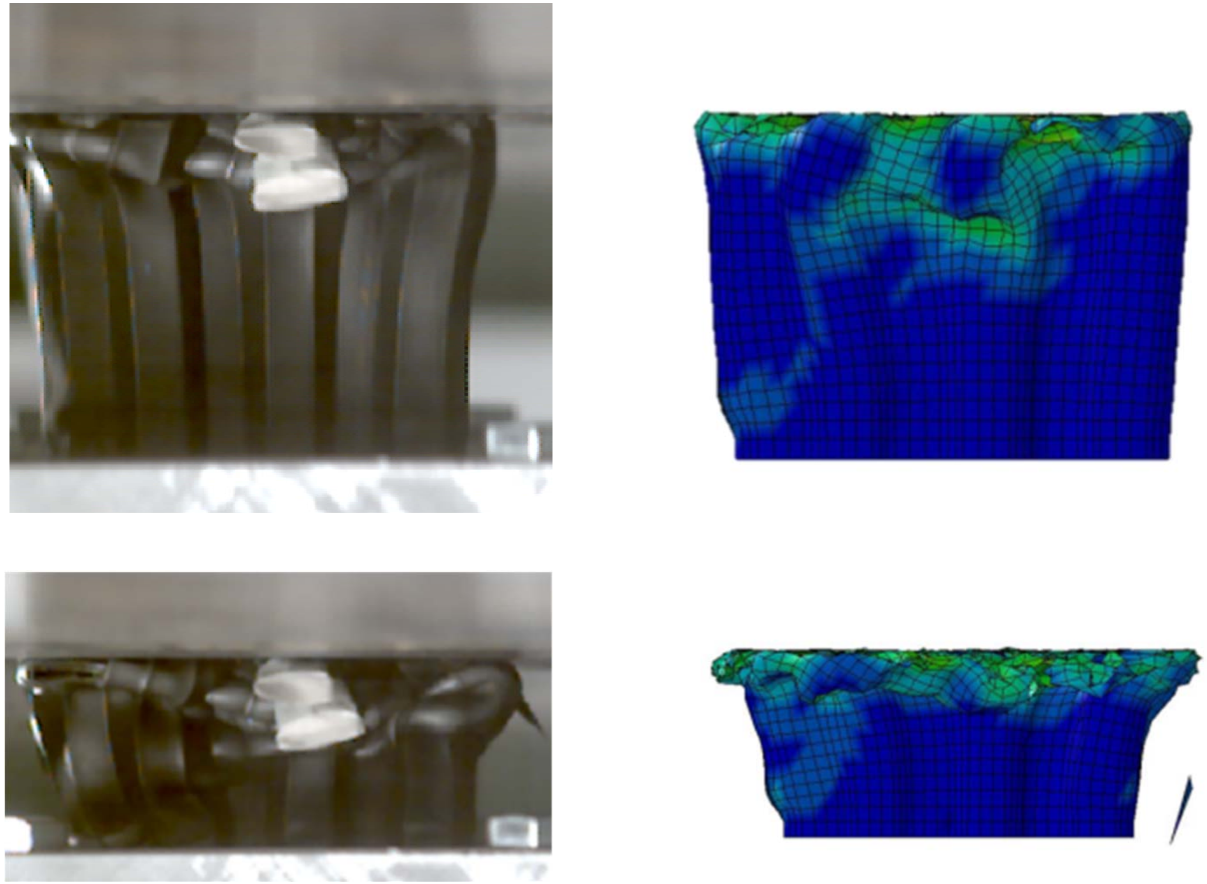


Result: Alternative modeling

- Simulations with SAMP-1 have provided force-displ-time curves in better agreement with the real test than MAT_024 and MAT_081.



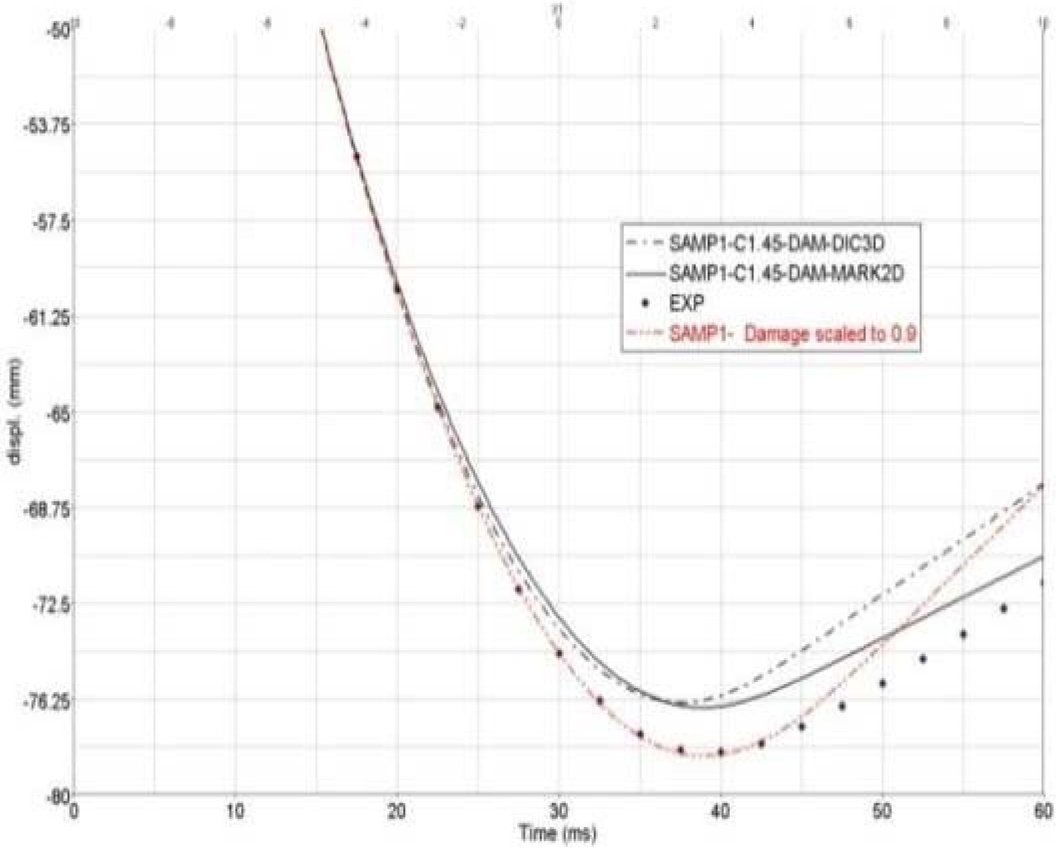
Result: Deformation



Part deformation during the real test (left) and simulated with SAMP-1
t= 15 ms (top) and t=25 ms (bottom)

Result: Damage modeling

- For this class of materials the damage model combined with parameter identification through volume strain give good results (see the <u>slope</u> after motion reversal)
- Arbitrary scaling of damage curves to reach the value 0.9 at failure (to simulate Gu's results) does not give reasonable predictions
- Damage is better evaluated from 3-D strain measurement (curve DIC3D)



Conclusions and next steps

- The damage parameter assessed based on volume strain measurement seems reasonable taking into account the damage localization occurring in the test

- The proposed measurement methodology can be coupled with true stress/ effective stress measured from tensile test which are easily input in an input deck for Finite Element Analysis, in the frame of CDM (Continuum Damage Modeling)

- A further quantitative assessment of damage localization is ongoing

- Watch out! Nomenclature can be misleading, especially regarding “TRUE” variables.

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