Simulating Failure With Ls-dyna In Glass Reinforced, Polypropylene-based Components

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Basell Poliolefine Italia srl,,

A LyondellBasell Company

Ls-dyna German Forum 2012

Ulm, 12-14 October, 2012

lyondellbasell

Scheme of the presentation

- LyondellBasell is…
- Short Glass Fiber-reinforced Polypropylene (SGF-PP) examples of applications
- SGF-PP modeling: overview
- Failure criteria, implementation
- Examples of validation (Ribbed beam)
- Conclusions

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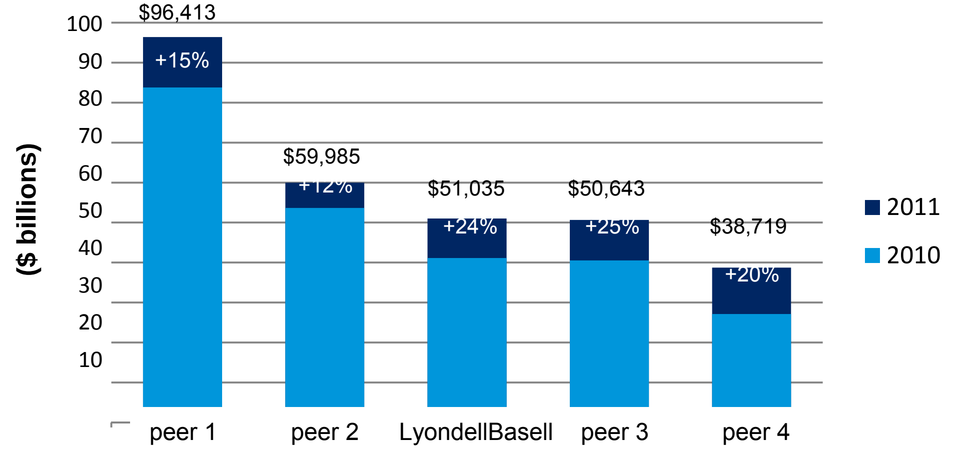
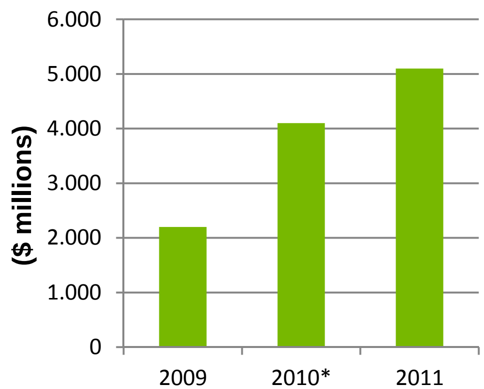
World-Class Scale With Leading Market Positions

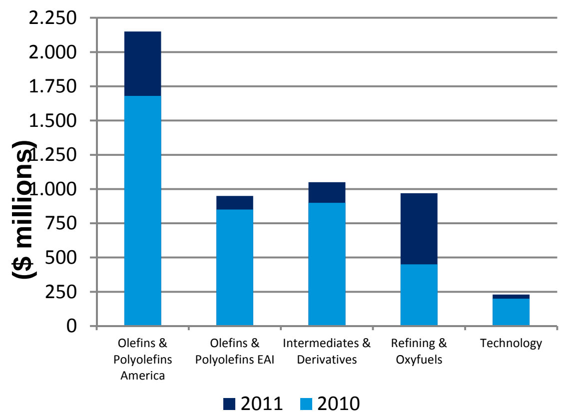
2011 Revenues



2009-2011 EBITDA



2010-2011 Segment EBITDA



LyondellBasell Fast Facts

- One of the world's largest plastics, chemicals and refining companies with revenues of $51billion (2011)
- The global leader in polyolefins technology, production and marketing
- A pioneer in propylene oxide and derivatives
- A producer of fuels and refined products, including biofuels
- Listed on the New York Stock Exchange (NYSE) as a publicly traded company. Ticker symbol: LYB

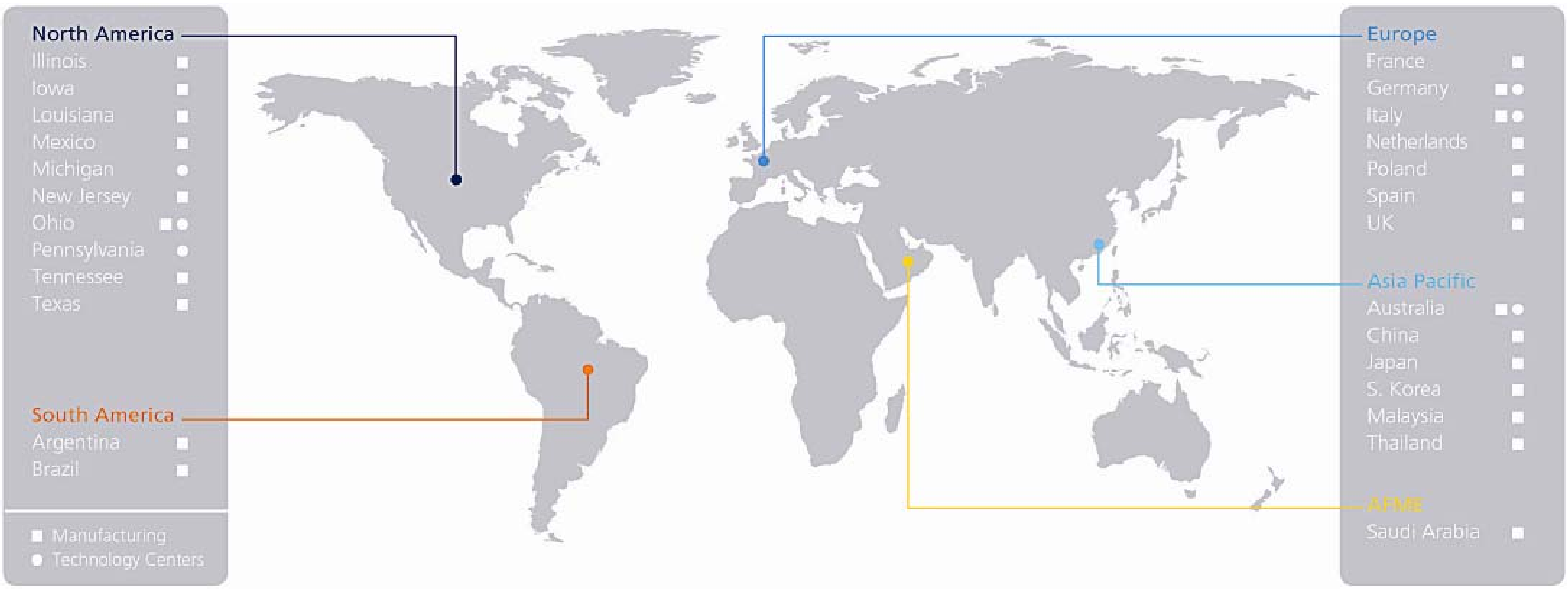

Tarragona, Spain

Global Reach

58 plants in
18 countries

More than
14,000 employees
worldwide

Sales in
more than
100 countries



Owned and operated by LyondellBasell, its subsidiaries and/or joint ventures

Our Product Lines And The End Markets We Serve…

Olefins & Polyolefins

- Americas
- Europe, Asia & Int'l

- 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
- C_4 Chemicals
- Ethylene Oxide
- EG and EOD

End Uses

- Insulation
- Home Furnishings
- Adhesives
- Consumer Products
- Coatings

Refining & Oxyfuels

- Gasoline
- Diesel
- Olefins Feed
- Oxyfuels

End Uses

- Automotive Fuels
- Aviation Fuels
- Heating Oil
- Industrial Engine Lube Oils

Technology

- Process Licensing
- Catalyst Sales
- Technology Services

End Uses

- Polyolefin and Chemical Manufacturers

Global Rated Capacity Rank*

Nr. 1
- Polyolefins
- Oxyfuels
- Polypropylene Compounds
- Polypropylene

Nr. 2
- Propylene Oxide

Nr. 3
- Polyolefins Licensing

Nr. 4
- Polyethylene
- Propylene

Nr. 5
- Ethylene

Refining Capacity

268,000

barrels per day

- LyondellBasell is…
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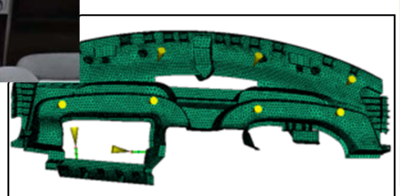
SGF-PP: Examples Of Applications In Automotive

Copyright Citroen Communications

Water boxes

Front Ends



Source: LyondellBasell, 2010

IP carrier,
battery cases,
gear commands

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Simulating An Anisotropic Material

We recognize two main approaches currently available with F.E. analysis

Issue/Approach	Micro-mechanical modeling	Simplified anisotropic
Material Law	Dedicated, based on Mean field homogenization theories (e.g. Digimat by e-Xstream, coupled with most FE codes)	Orthotropic / anisotropic (e.g. Abaqus orthotropic, Ls-dyna MAT_103, Pamcrash Mat 117, Radioss Hill Law)
Input from Process Simulation	Fiber orientation	Flow direction
Experimental data	Tensile test in two or more directions	Tensile test in two or more directions

The choice of the approach depends on the specific problem to be studied and on the “boundaries,” such as resources, requested accuracy and timing .

The considerations and ideas in this presentation about failure modeling are in principle applicable to either approach.

LyondellBasell Contributions

The recent developments by LyondellBasell in either modeling approach are witnessed by publications and presentations at renown conferences on FEM / modeling subjects, as:

- [1] M.Nutini, M.Vitali, “Simulating anisotropy with Ls-dyna in glass-reinforced, polypropylene-based components”, Ls-dyna Anwenderforum, Bamberg 2010
- [2] C.Ferrari, C.Garcia, M.Nutini, “Assessment of Fiber Orientation in Injection-Molded SGF-PP items“, Connect! Moldflow Users Meeting 2011, Frankfurt, 2012
- [3] C.Garcia, M.Nutini, “Fiber Orientation Prediction for Reliable Simulations of Glass-reinforced, Polypropylene-based Components Using DIGIMAT “, Digimat Users Meeting 2010, Luxembourg, 2010
- [4] M.Nutini, “An assessment of fiber orientation in GF-PP compounds by assembling the information from testing, mold filling simulation and Digimat-MF through optimization methods”, Digimat Users Meeting 2011, Munich, 2011

Lyondellbasell Simplified Approach: Background

- A simplified method was presented for modeling anisotropic materials, e.g. GF-reinforced PP (but not limited to), with Ls-dyna

9. LS-DYNA Anwenderforum, Bamberg 2010

Simulating anisotropy with Ls-dyna in glass-reinforced, polypropylene-based components

Massimo Nutini, Mario Vitali

Basell Poliolefine Italia, a Company of LyondellBasell Industries

Summary:

Glass-fiber-reinforced polypropylene (GF PP) materials are increasingly being used by customers to replace metal and engineering polymers in structural automotive applications. Like all glass-fiber-reinforced thermoplastics, GF PP products can show anisotropy caused by fiber orientation that is induced by the injection process. Taking into account fiber orientation in the simulations enables designers to improve the accuracy of the analyses. This can help prevent arbitrary choices and assumptions when setting material parameters, which become mandatory when an isotropic material law is used.

The method proposed in this paper takes advantage of the availability within Ls-dyna of an anisotropic material law (MAT_103), which allows simplified modeling to address critical issues. This law was not developed to address the problem discussed here.

Therefore, this paper illustrates a simplified approach. The presence of glass reinforced fibers is taken into account by running a mold-filling analysis, and then transferring the material flow orientation in to the structural simulation as a material angle. The dependence of the material failure strain on the material orientation can be also easily modeled through a user subroutine. Finally, the approach only requires simple material data based on basic tensile tests; the material law parameters are then identified through optimization techniques.

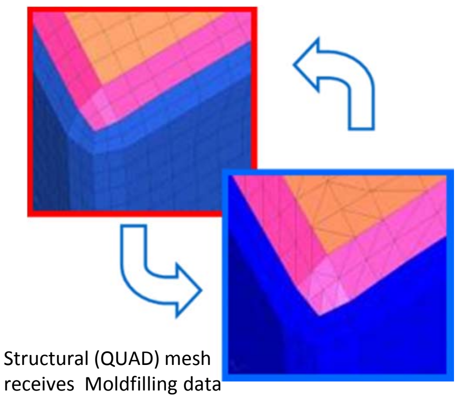
Although this approach is based on some simplifying assumptions, its application is quick and can help the designer obtain more accurate results with respect to the traditional isotropic approach. A selection of validation tests is then proposed that show reliable predictions using limited additional computational effort.

Keywords:

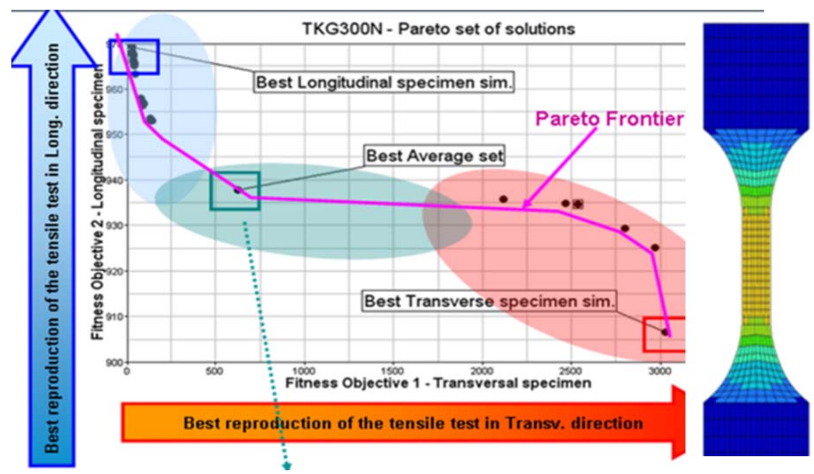
Anisotropy, Fiber Reinforced Polymers, Crash Simulation, Impact, Material Modeling, Material Characterization, Parameter Identification

Basic Elements Of LyondellBasell Simplified Approach

- Use of an orthotropic material law already available in Ls-dyna (MAT_103), reference directions from flow orientation
- Introduction into the structural mesh of the flow orientation, e.g. from moldfilling simulation, through a dedicated interface
- Determination of the material law parameters through reverse engineering, optimizing the simulation of the tensile test to reproduce experimental data
- Experimental data needed: tensile tests on specimen cut from a molded plaque along two different orientations with respect to the flow
- Failure criteria: max. admissible strain, possibility of strain-rate dependent values



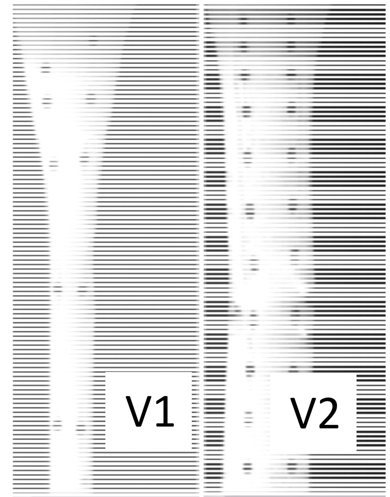
Structural (QUAD) mesh receives Moldfilling data on TRI mesh through a SW interface



Parameter identification is based on the simulation of of the tensile test along two orientations; a Pareto set of solution s then found.

Failure Modeling: Experimental Evidence

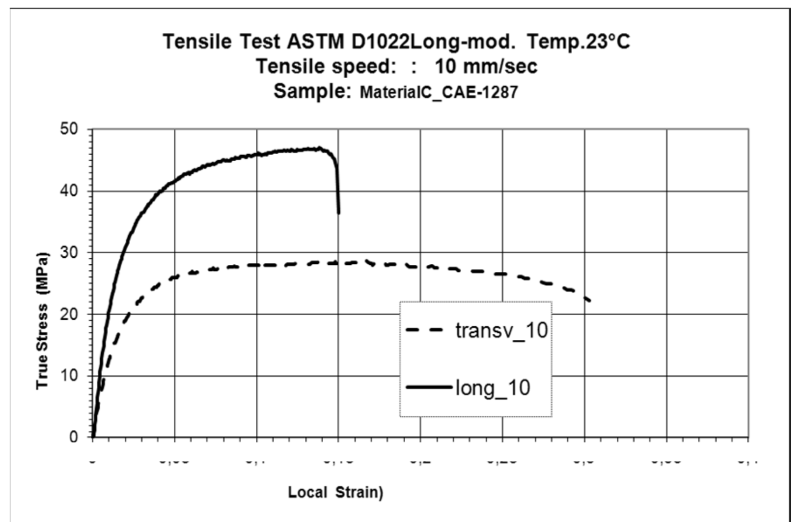
- Typically, in SGF-PP failure is:
  - Strain-rate dependent
  - Orientation-dependent
  - Unequal Compression/tension sensitive



V2 > V1

Source: LyondellBasell, 2012

➢ Although the model was successfully validated on several benchmark tests, more sophisticated failure criteria are now investigated to improve failure prediction



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Failure Modeling: MAT_103 Features

*MAT_ANISOTROPIC_VISCOPLASTIC *MAT_103

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	E	PR	SIGY	FLAG	LCSS	ALPHA
Type	A8	F	F	F	F	F	F	F

Card 2

Variable	QR1	CR1	QR2	CR2	QX1	CX1	QX2	CX2
Type	F	F	F	F	F	F	F	F

Card 3

Variable	VK	VM	R00 or F	R45 or G	R90 or H	L	M	N
Type	F	F	F	F	F	F	F	F

Card 4

Variable	AOPT	FAIL	NUMINT	MACF				
Type	F	F	F	I				

Failure modeling

- Ls-dyna MAT-103 allows using the users-subroutine matusr_103 to implement different failure models

Failure Modeling: Criteria Implemented

- Quadratic (“energetic” or “interactive”) criteria were implemented. These criteria define parameterized quadratic functions of the stress conditions. The parameters are determined based on the experimental values of the material strengths.

- Criteria implemented:

Features/Model	HILL	TSAI-HILL	TSAI-WU
anisotropic	√	√	√
dependence on strain rate	√	√	√
unequal tension/compression	-	√	√

Failure Modeling: Criteria Implementation (1 Of 4)

- HILL criterion
  - Three planes of symmetry defined, defining the principal axes of anisotropy
  - Principal axes identified as the material axes **a,b,c**, assumed as references axes
  - **a,b,c** assumed as the flow directions in the mold, obtained from simulation [1]

$$\Phi=F(\sigma_{11}-\sigma_{22})^2+G(\sigma_{22}-\sigma_{33})^2+H(\sigma_{11}-\sigma_{33})^2+2L\sigma_{12}^2+2M\sigma_{23}^2+2N\sigma_{13}^2$$

- Failure occurs when the functional $\boldsymbol{\Phi}$ of the stress tensor $\boldsymbol{\sigma}$ reaches or exceeds 1

- Parameters identification:

  - All the parameters are identified based on tensile tests of specimens cut from an injection molded plaque:
    - F,G,H: specimens are cut along the reference directions
    - L,M,N: specimens are cut at 45° with respect to reference direction (no shear tests available)

Failure Modeling: Criteria Implementation (2 Of 4)

- TSAI-HILL criterion
  - Implemented as the HILL criterion, but the parameters F, G, H assume different values depending on the sign of the stress tensor component. By so doing, different behavior under tension and compression is modeled.
  - This is achieved with a simple “if” statement in the subroutine matusr_103
  - For the parameters identification, the compression strengths were assumed for simplicity as twice the corresponding tensile strengths (no compression data available)

Failure Modeling: Criteria Implementation (3 Of 4)

- TSAI-Wu criterion
  - Includes in the functional a contribution of linear function of the stress component
  - Implemented – for simplicity – in its 2D form as

$$\Phi = f_1\,\sigma_{11} + f_2\,\sigma_{22} + f_{11}\,\sigma_{11}^2 + f_{22}\,\sigma_{22}^2 + 2\,f_{12}\,\sigma_{11}\,\sigma_{22} + f_{66}\,\sigma_{12}^2$$

- Failure occurs when the functional ***Φ*** of the stress tensor ***σ*** reaches or exceeds 1

- Parameters identification◊ :

$f_{11} = 1/(X_t\,X_c)$ $\quad f_{22} = 1/(Y_t\,Y_c)$ $\quad f_1 = 1/X_t + 1/X_c$ $\quad f_2 = 1/Y_t + 1/Y_c$ $\quad f_{66} = 1/S^2$

$f_{12} = -0.5/(f_{11}\,f_{22})^{1/2}$

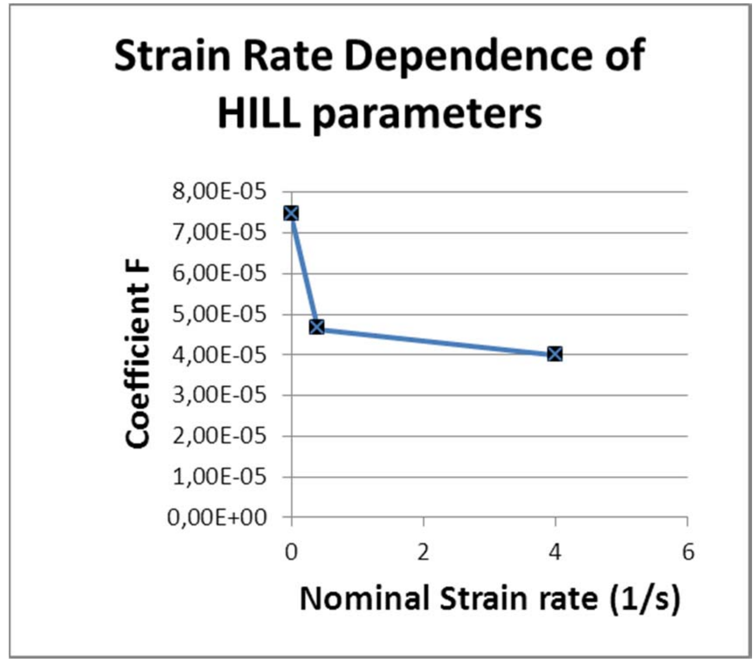
Legenda:
X, Y: strengths in the reference directions; t,c: tension/compression; S: shear
Parameters identified as done for the HILL criterion.

◊ "Lin et al., journal of Composite Materials, Vol. 36, No.12/2002,

Failure Modeling: Criteria Implementation (4 Of 4)

Strain rate dependence

- All the parameters entering in the models implemented are strain-rate dependent, piecewise linearly interpolated
- Tensile tests at least at three different speeds were executed to determine the parameters variability with strain rate



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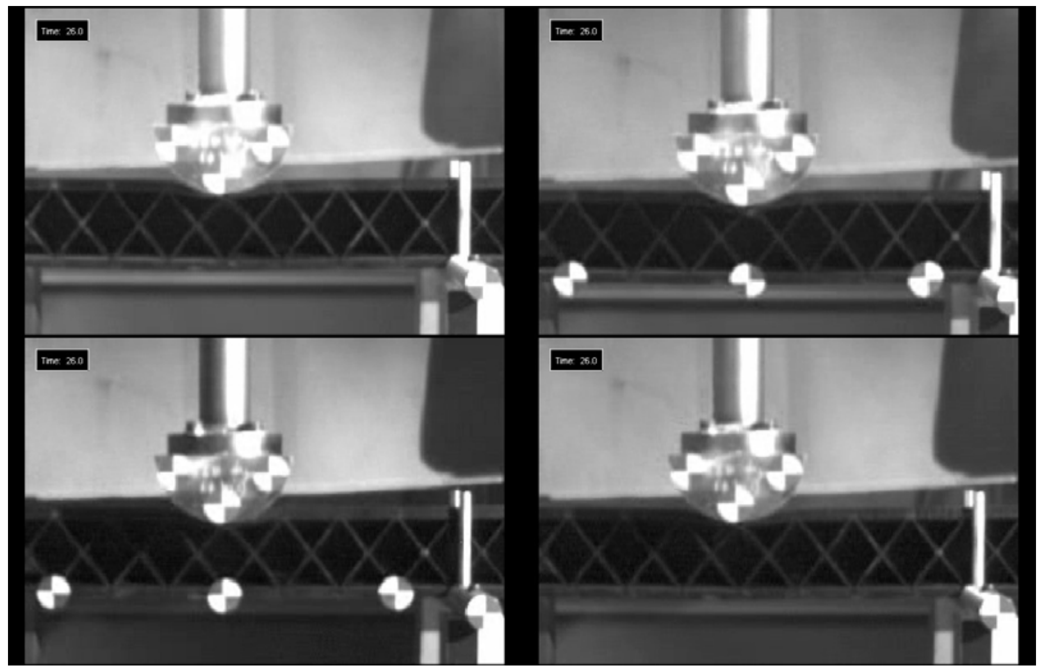
Example Of Validation: Ribbed Beam Impact

- Part molded and tested by a customer: ribbed beam (courtesy from Faurecia Seatings)

Impact test

- Impact speed 2.4 m/s
- Impactor mass 55Kg (rigid)
- Impactor Acceleration recorded, filtered (SAE_180) and unfiltered data available for 5 experiment realizations (4 valid)
- High speed videos available for 4 experiment realizations (4 valid)



Source: courtesy from Faurecia Seatings, 2010

Example Of Validation: Ribbed Beam Impact

"we should look to see what's true and what may not be true, once you start doubting ……which I think, to me, is a very fundamental part of my soul is to doubt and to ask …"

(R.Feynman)

- Due to the complexity of the real material behavior, the previous findings have been further put into discussion, to see if the new approaches can give more accurate predictions

From [1]: "Furthermore, a good accordance between virtual and real experiment is visible in Figure 11, where the deformation and failure behaviors of the assembly are shown at different points in time."

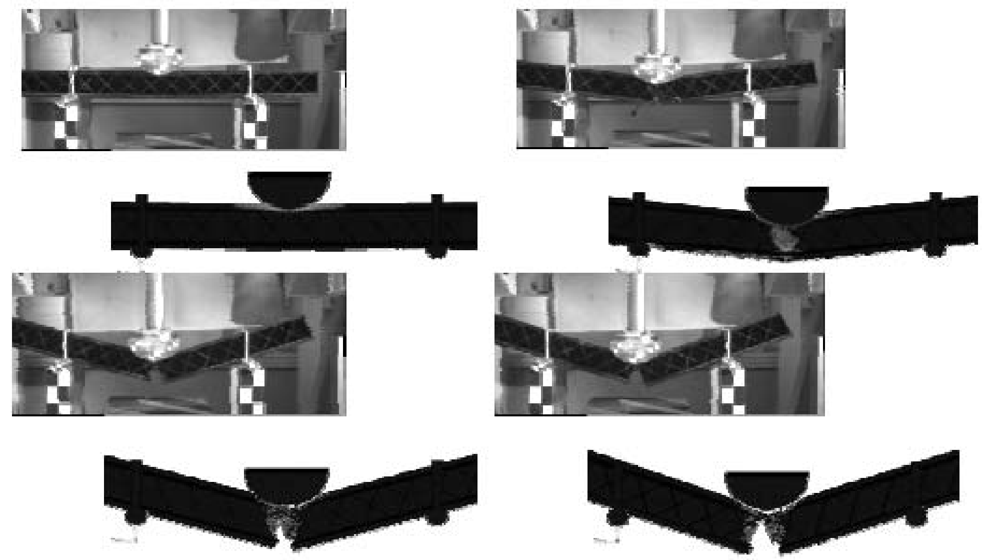
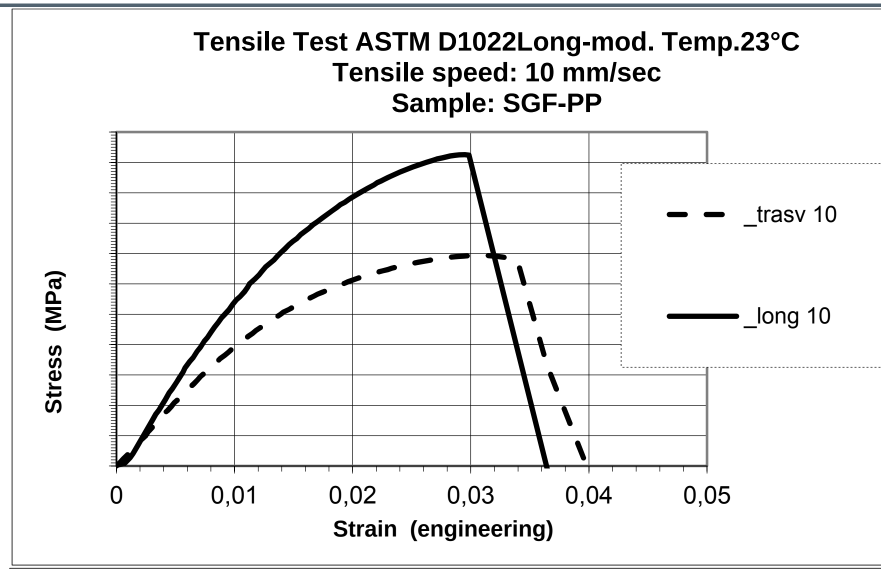
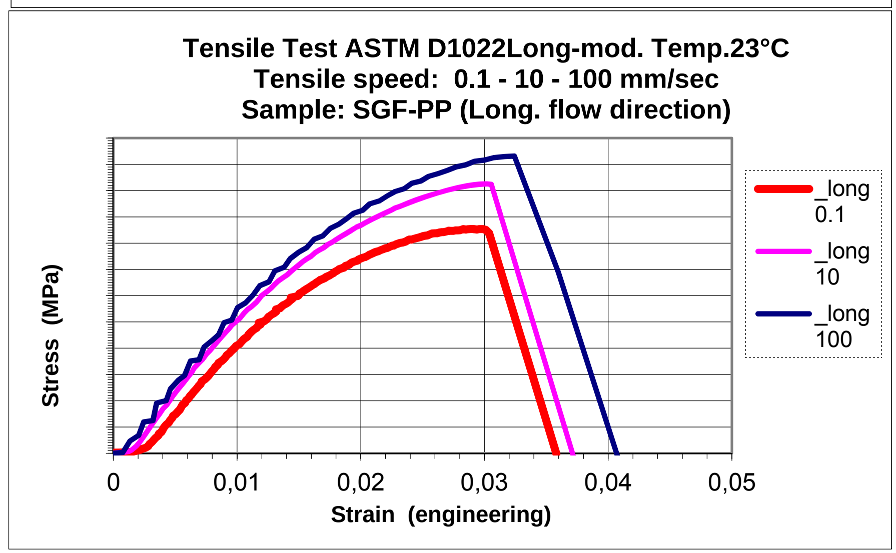


Fig. 11: Real and virtual deformation and failure behaviors of the ribbed beam at different times during the impact sequence. Images from testing courtesy of Faurecia Seatings.

Material Data From Testing

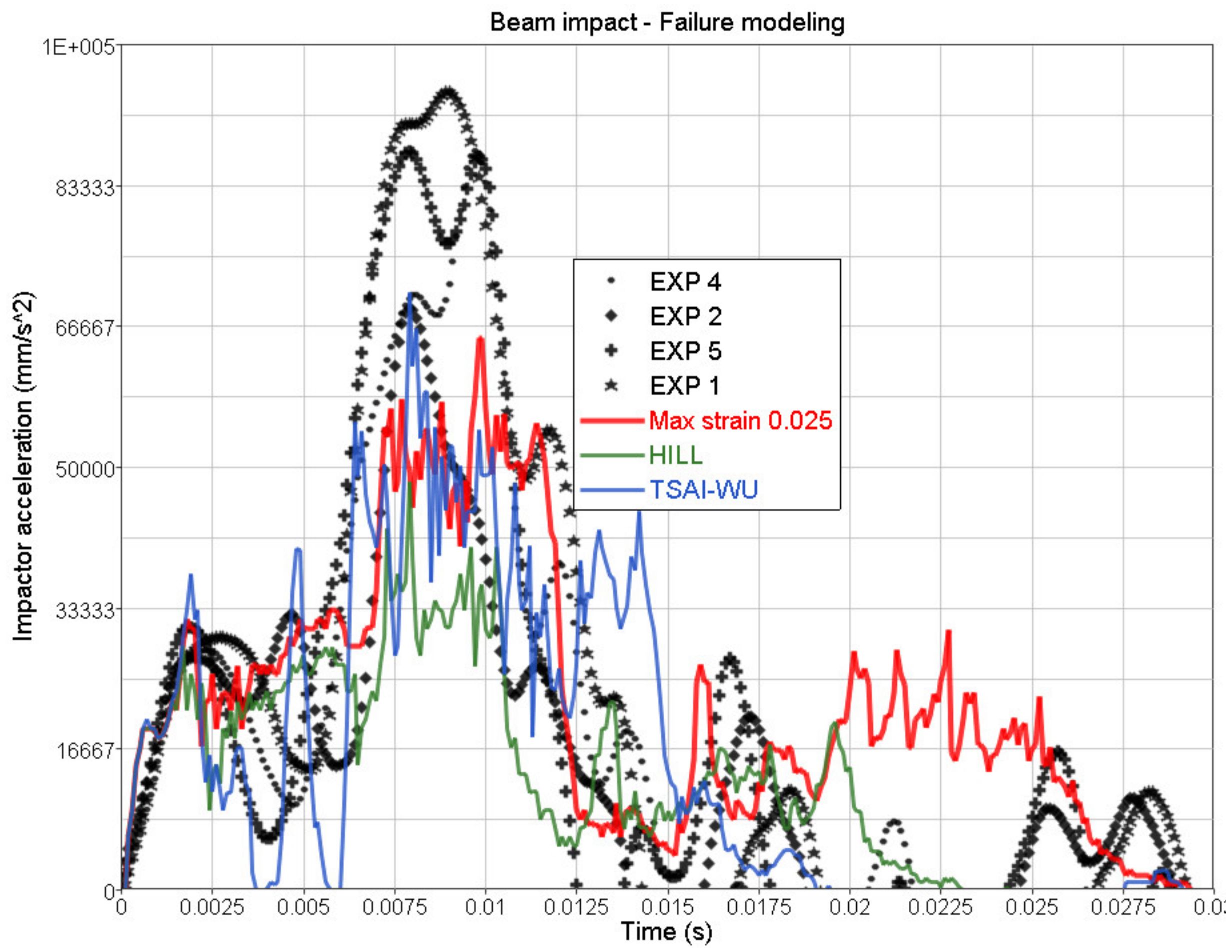
• Material stress-strain curves from tensile tests do not allow introducing a clear dependence on the orientation and on the strain rate when max-strain based criteria are used.





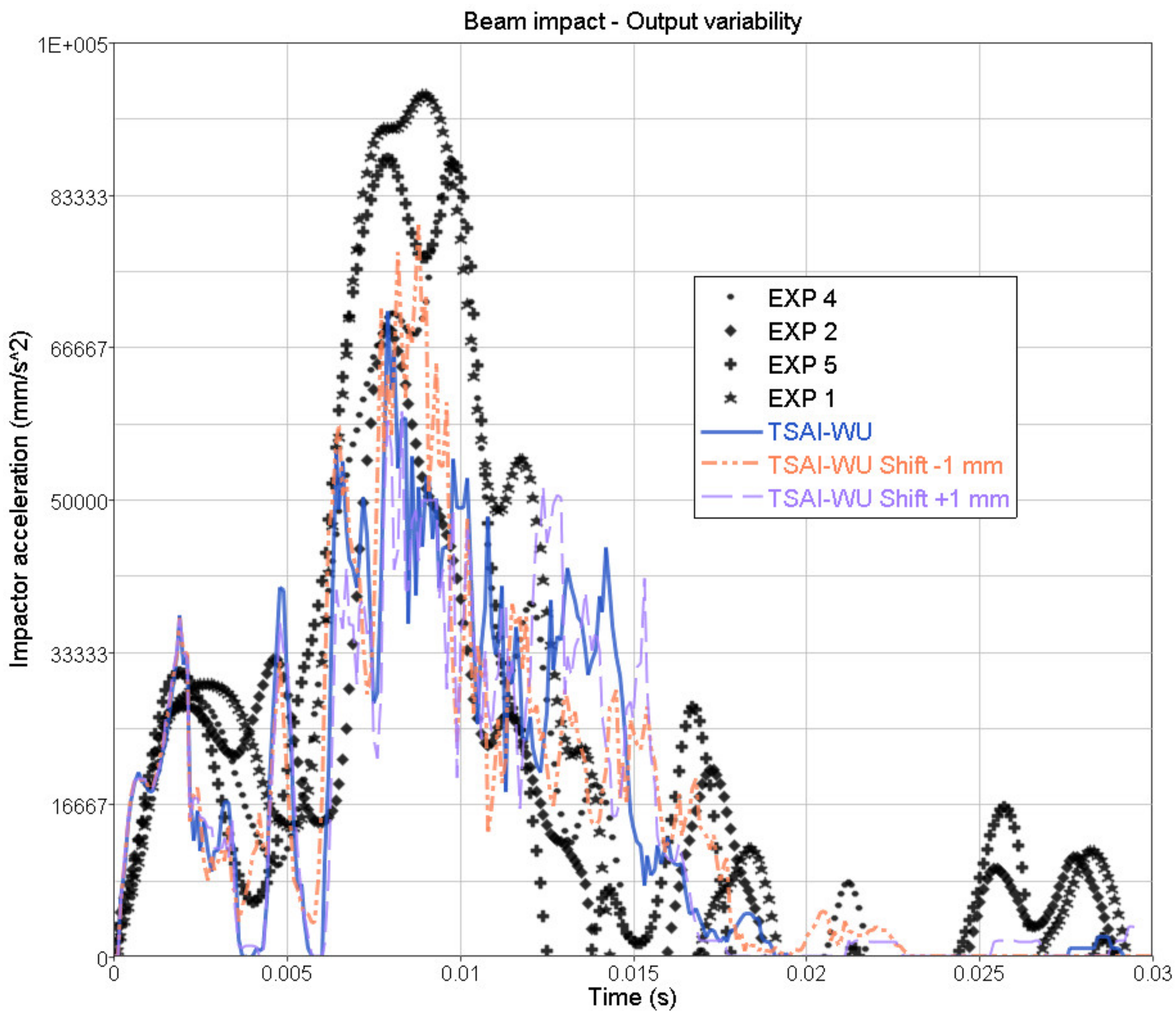
Ribbed Beam Impact Analysis: Force vs. Displacement

- In general an acceptable agreement with the measured curves is found, keeping into account the fluctuations in the experimental values
- Predictions with Tsai-Wu model seem better aligned with empirical evidence



Ribbed Beam Impact Analysis: Force vs. Displacement

- Slight shifts of the mutual position between the impactor and the beam can justify some variability in the experimental measurements

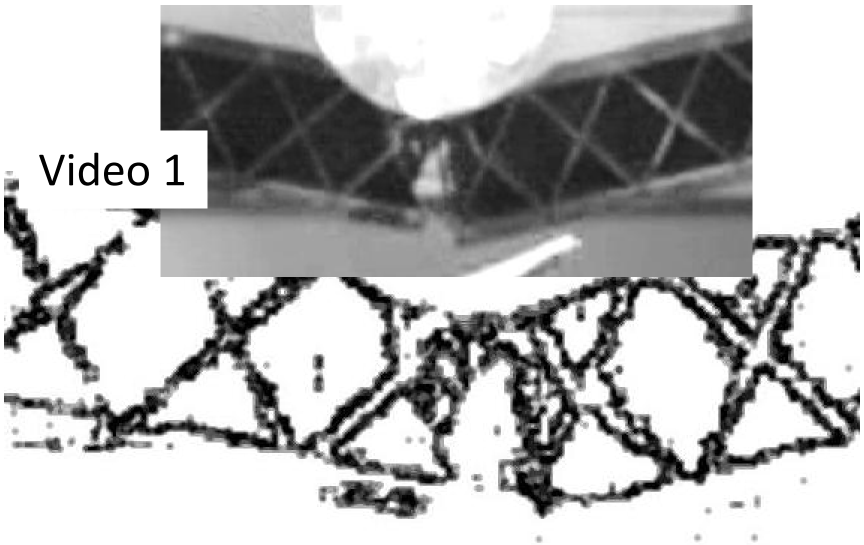


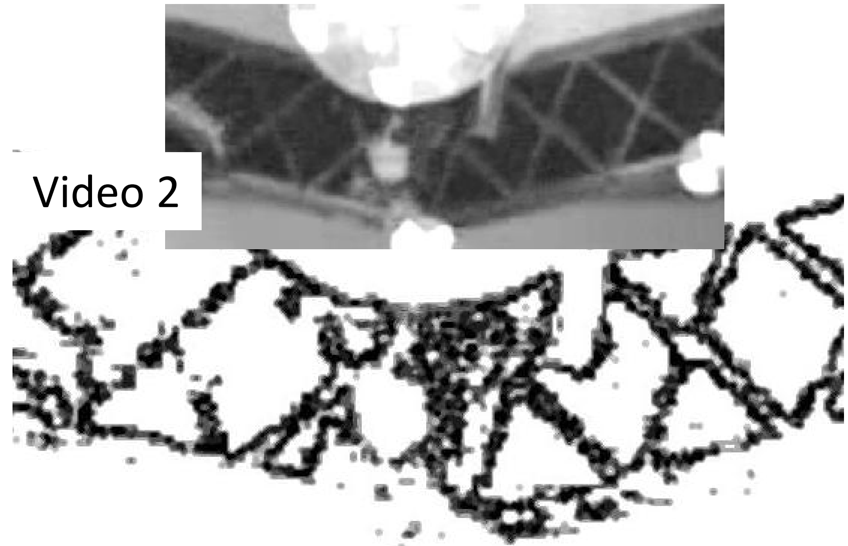
Ribbed Beam Impact Analysis: Transient Analysis

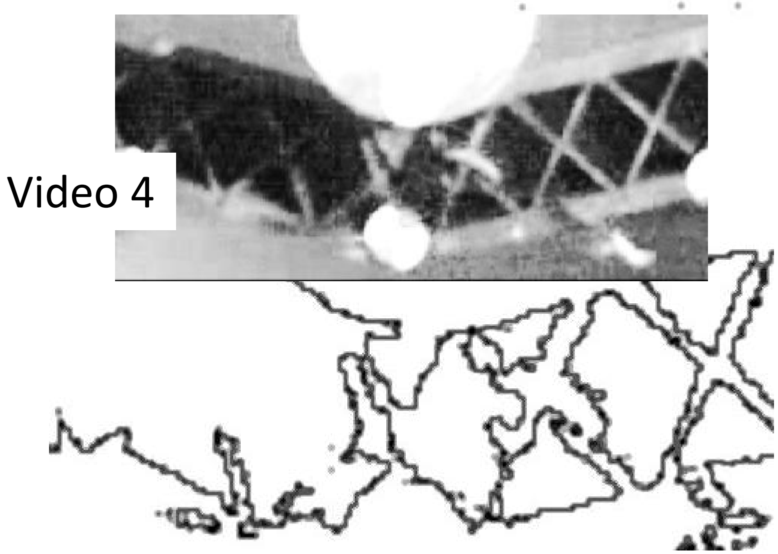
- A “backward-in-time“ analysis is here presented, focusing on:

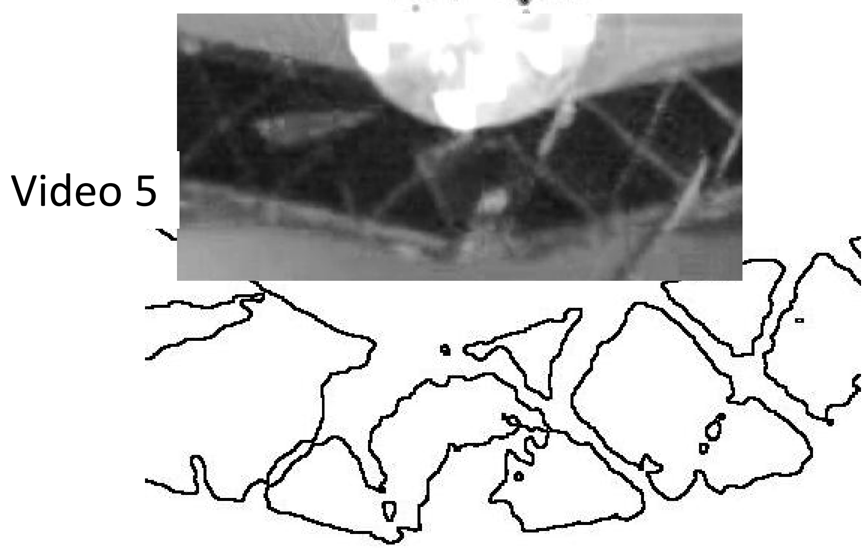
- Final rupture patterns
- Break onset (initial rupture)
- Initial transient details

Ribbed Beam Impact Analysis: Rupture Patterns (1 of 4)



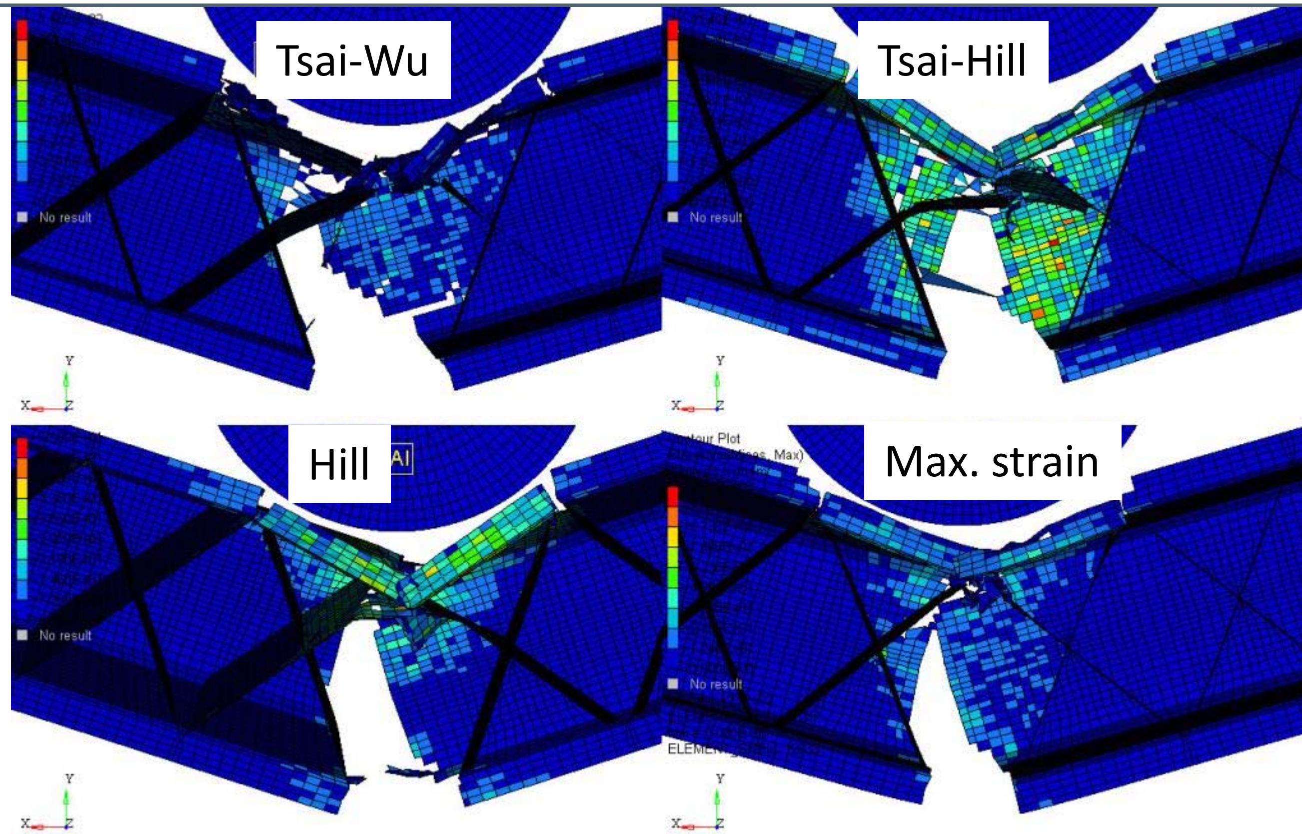






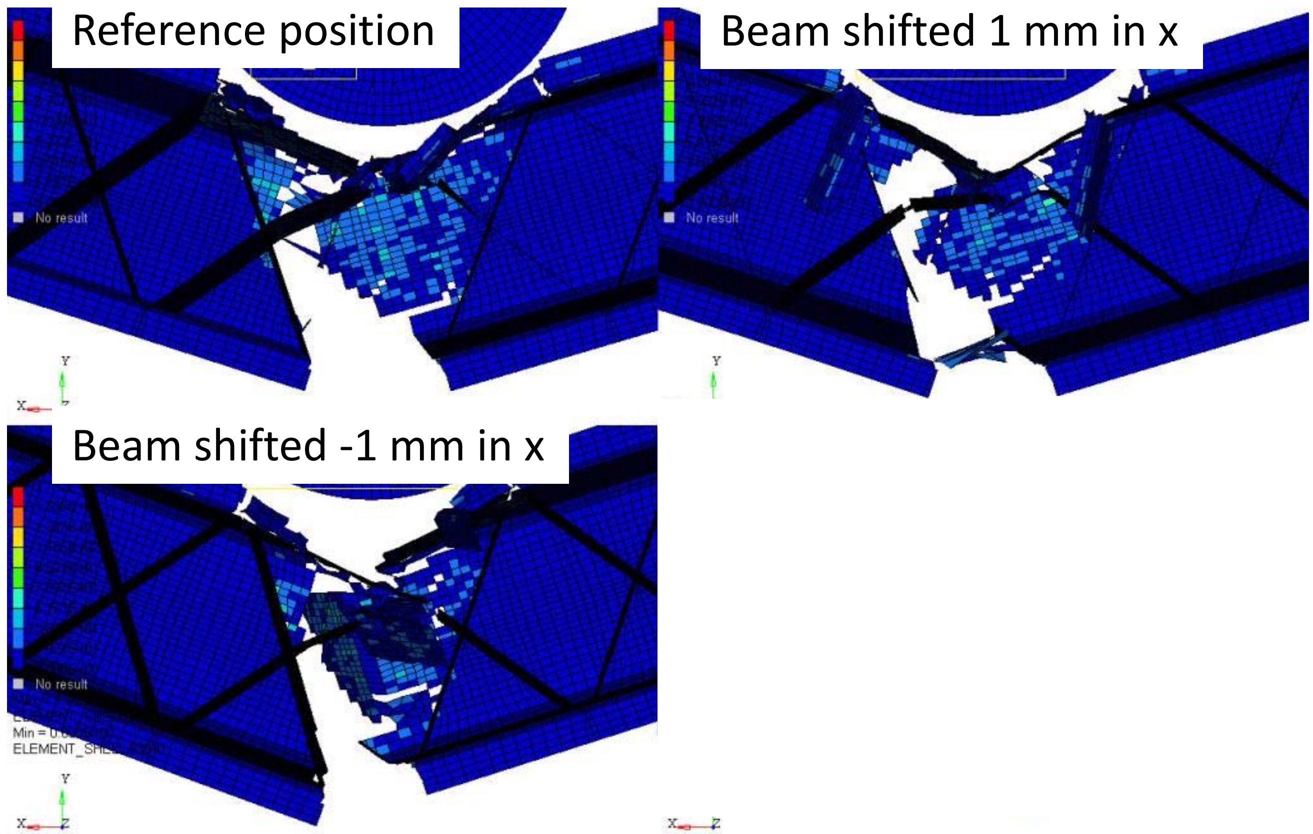
Ribbed Beam Impact Analysis: Rupture Patterns (2 of 4)

- The rupture patterns predicted using "interactive" approaches seem in better agreement with experimental data
- Among these, the Tsai-Wu / Tsai-Hill models offer predictions closest to the real ones
- The max-strain based models show too straight patterns



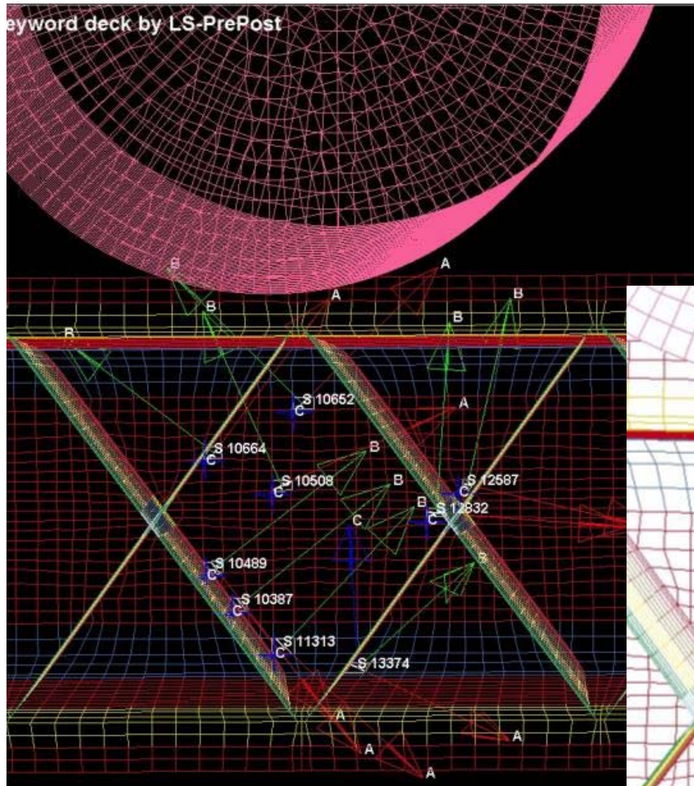
Ribbed Beam Impact Analysis: Rupture Patterns (3 of 4)

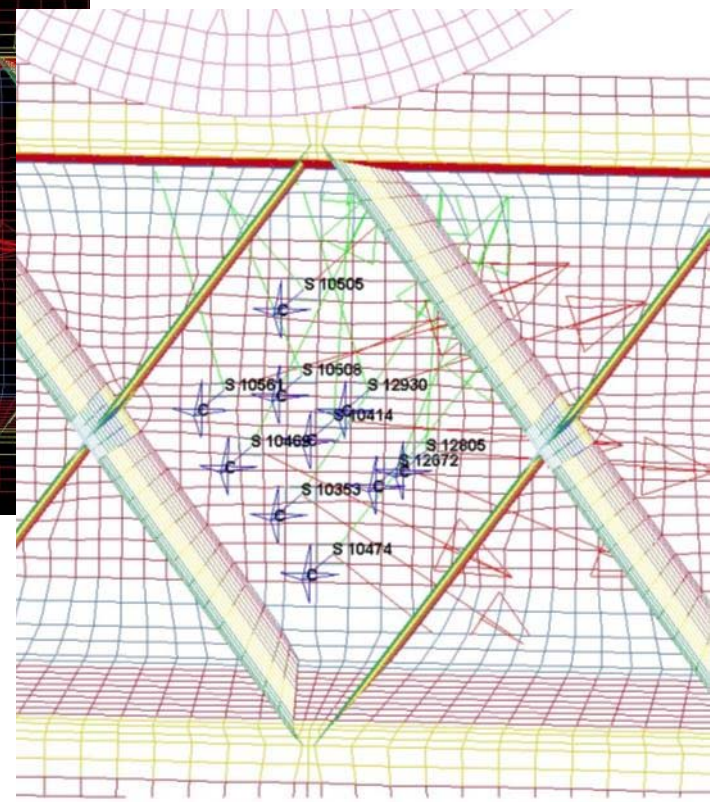
- A slight shift in the mutual position between the impactor and the target can justify minor changes in the rupture patterns, as visible in the different experimental realizations.



Ribbed Beam Impact Analysis: Rupture Patterns (4 of 4)

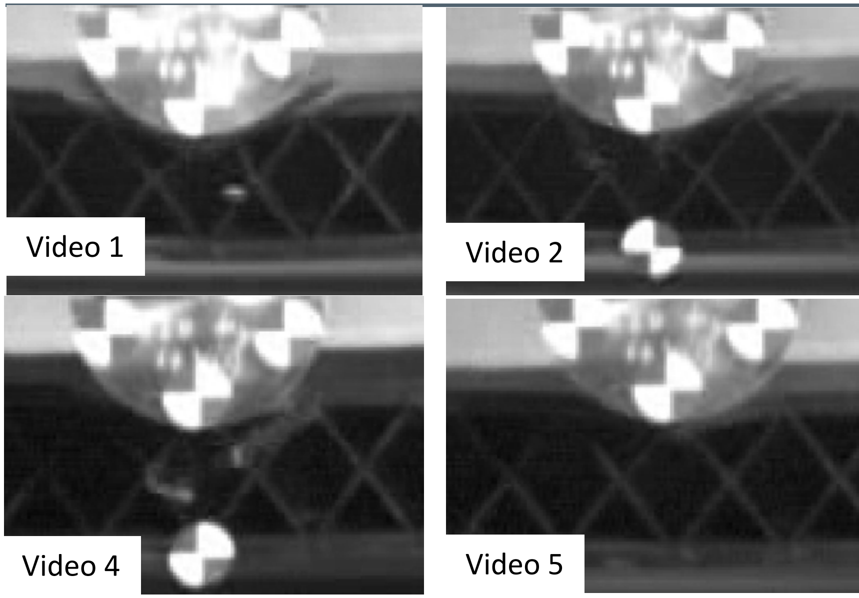
- The material orientation indicates preferential material orientation along the X axis in the break area.

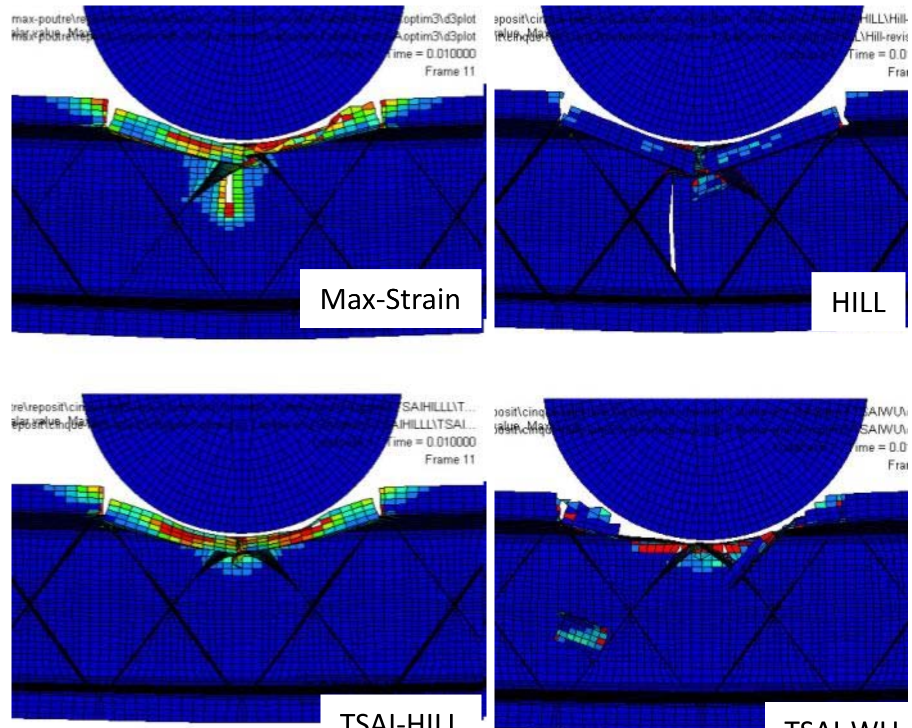




- To better explain rupture patterns, the initial onset of the break is then examined

Beam Impact Analysis: Initial Rupture, 1



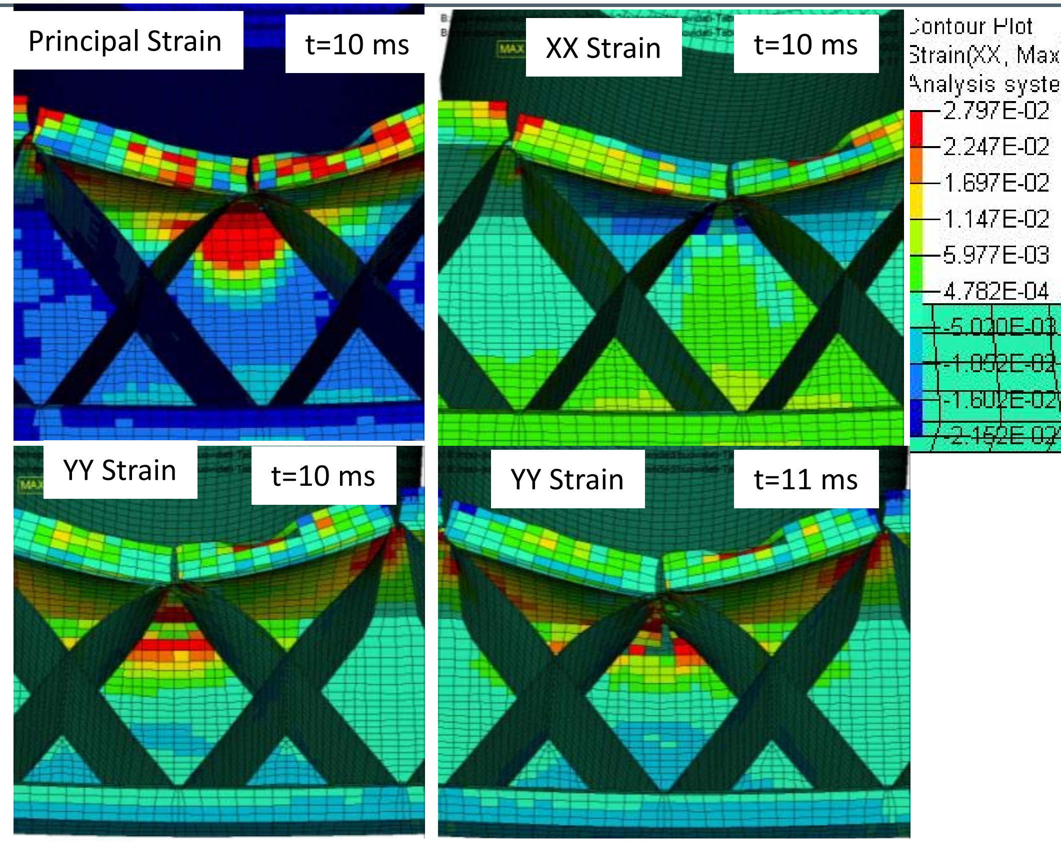


t=10 ms

- Rupture of the top part of the beam is evident in all the videos
- Its fragmentation (videos 1,2,4) seems better reproduced by Tsai-Wu approach
- Max-strain and Tsai criteria predict a longitudinal break in the beam (not visible in the videos)

Beam Impact Analysis: Initial Rupture, 2

- The beam area under the impactor shows principal strains close to the maximum admissible value
- The principal strains are positive in the Y direction (tension) and negative in the X direction
- The “interactive” criteria based on quadratic functionals do not see this condition as critical since compression values compensate for the high tension ones.
- The max-strain criterion does instead recognize this situation as a failure.

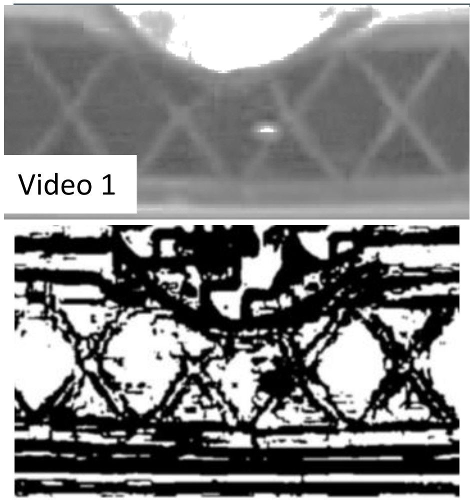


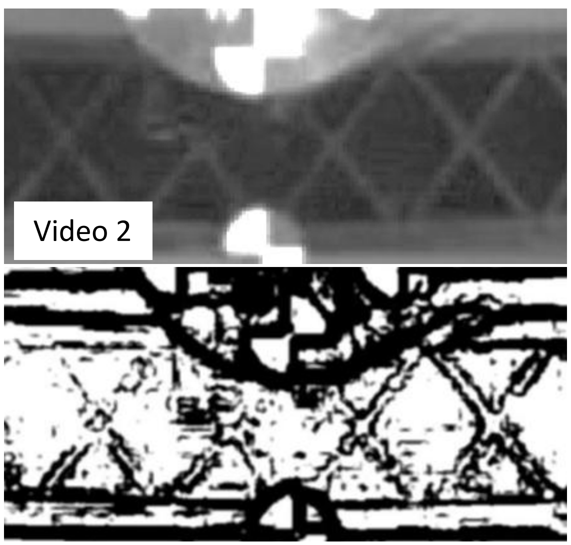
Plots from the simulations using max-strain based failure criteria

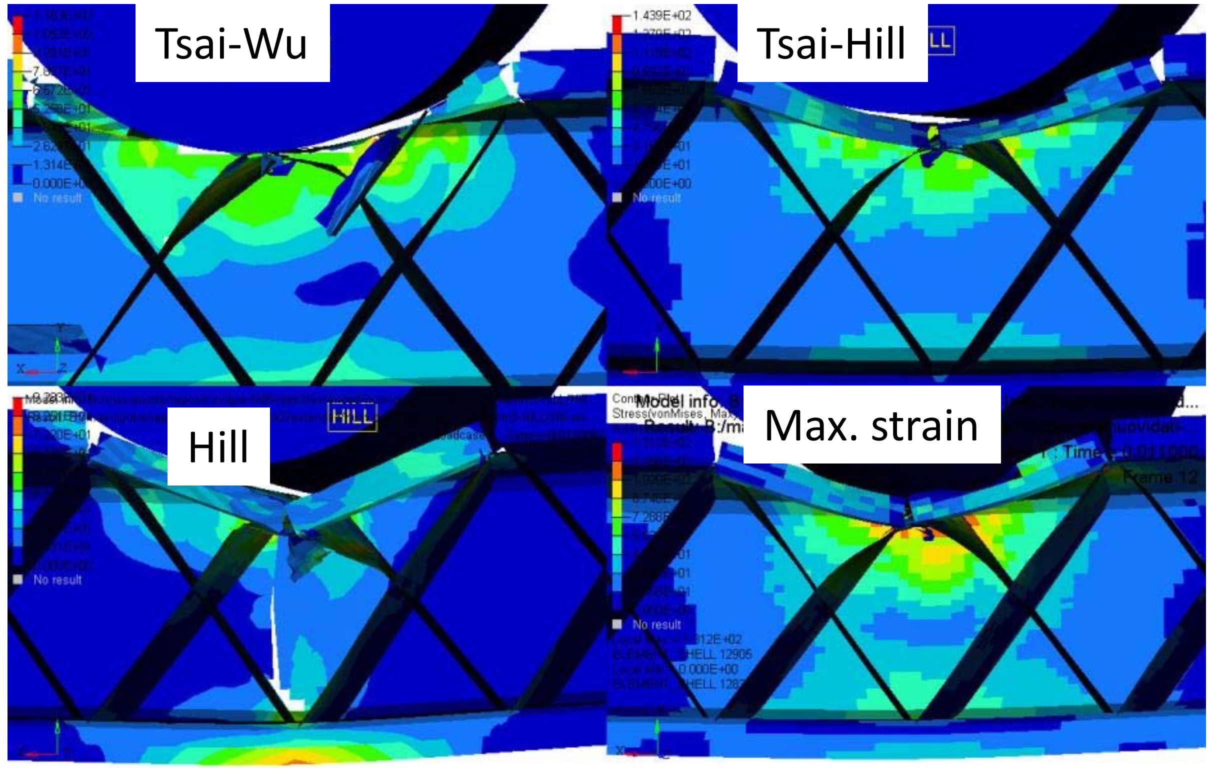
Ribbed Beam Impact Analysis: Rupture Patterns

- The rupture patterns are better predicted using “interactive” approaches
- Among those tested, the predictions obtained by using the Tsai-Wu approach seem closer to the ones from experiments
- Particularly, the relatively scarce accuracy of the predictions of the models simply based on max- admissible strains is believed to depend on:
  - Lack of differentiation on orientation in the input data
  - Lack of differentiation between tension-compression

Ribbed Beam Impact Analysis: Details



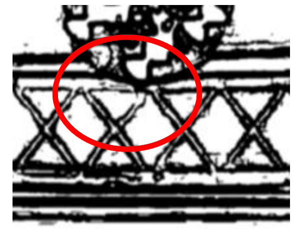


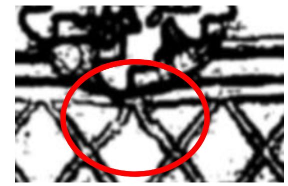


- Different deformations (e.g. in the central ribs) are obtained during the transient as a result of different rupture patterns

Ribbed Beam Impact Analysis: Initial Transient (1 of 3)

Time (ms)	Time abs. (ms)	Video 1	Video 2	Video 4	Video 5
0	-9	Contact onset	Contact onset	Contact onset	Contact onset
2	-7	Cusp shaped deformation at the top of the central rib	Nothing particular observed	(Slight) cusp shaped deformation at the top of the central rib	(Slight) cusp shaped deformation at the top of the central rib
3	-6	Well defined deformation as previous time observation	Cusp shaped deformation at the top of the central rib	Cusp shaped deformation at the top of the central rib	Break at the top beam near the side rib
4	-5	Instability in central ribs; break in the central ribs, top-right side	Break in the central ribs, top-right side	Break in the central rib, top part	Break in the beam top part under the impactor
5	-4	No more deformation visible in the central ribs, the impactor continues to the bottom. Manifeat failure of the top of the beam under the impactor	Manifest failure of the top beam under the impactor, whch centrally opens up	Break in the right side of the beam top part, fragments	As in 1
6	-3	Break in the side rib (right)	The top part of the beam detaches.	Manifest failure at the joint between right rib and top beam.	As in 4


t=2 ms

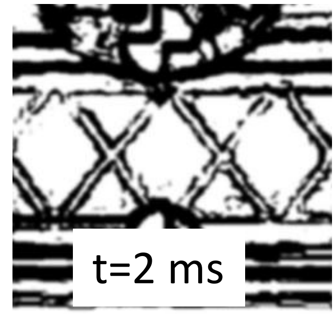

t=3 ms

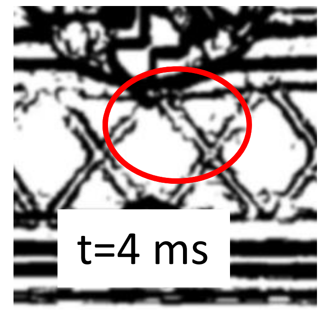

t=4 ms

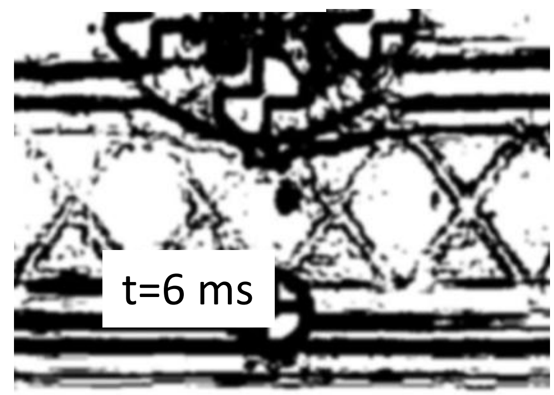

t=6 ms

Ribbed Beam Impact Analysis: Initial Transient (2 of 3)

Time (ms)	Time abs. (ms)	Video 1	Video 2	Video 4	Video 5
0	-9	Contact onset	Contact onset	Contact onset	Contact onset
2	-7	Cusp shaped deformation at the top of the central rib	Nothing particular observed	(Slight) cusp shaped deformation at the top of the central rib	(Slight) cusp shaped deformation at the top of the central rib
3	-6	Well defined deformation as previous time observation	Cusp shaped deformation at the top of the central rib	Cusp shaped deformation at the top of the central rib	Break at the top beam near the side rib
4	-5	Instability in central ribs; break in the central ribs, top-right side	Break in the central ribs, top-right side	Break in the central rib, top part	Break in the beam top part under the impactor
5	-4	No more deformation visible in the central ribs, the impactor continues to the bottom. Manifest failure of the top of the beam under the impactor	Manifest failure of the top beam under the impactor, whch centrally opens up	Break in the right side of the beam top part, fragments	As in 1
6	-3	Break in the side rib (right)	The top part of the beam detaches	Top part of the beam fragmented	As in 4

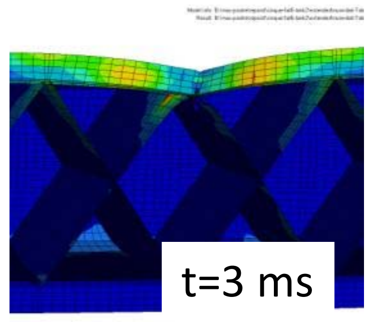


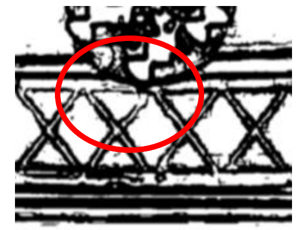




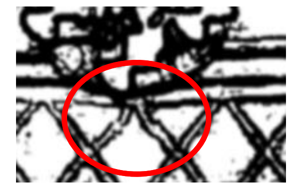
Ribbed Beam Impact Analysis: Initial Transient (3 of 3)

Time (ms)	Time abs. (ms)	Video 1	Video 2
0	-9	Contact onset	Contact onset
2	-7	Cusp shaped deformation at the top of the central rib	Nothing particular observed
3	-6	Well defined deformation as previous time observation	Cusp shaped deformation at the top of the central rib
4	-5	Instability in central ribs; break in the central ribs, top-right side	Break in the central ribs, top-right side
5	-4	No more deformation visible in the central ribs, the impactor continues to the bottom. Manifest failure of the top of the beam under the impactor	Manifest failure of the top beam under the impactor, whch centrally opens up
6	-3	Break in the side rib (right)	The top part of the beam detaches

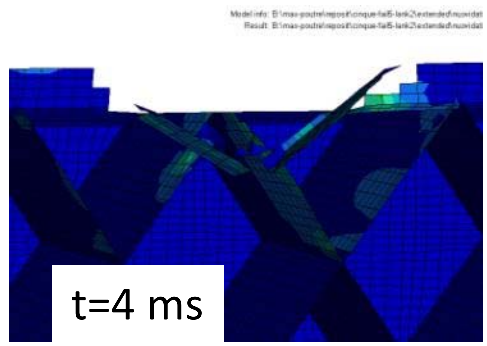




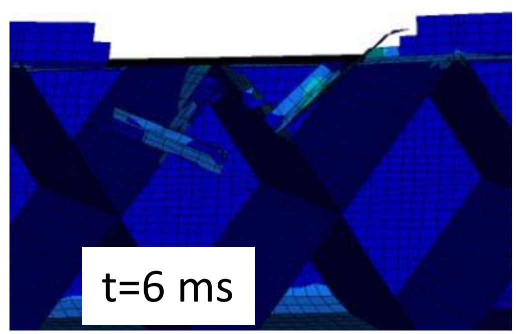
t=2 ms

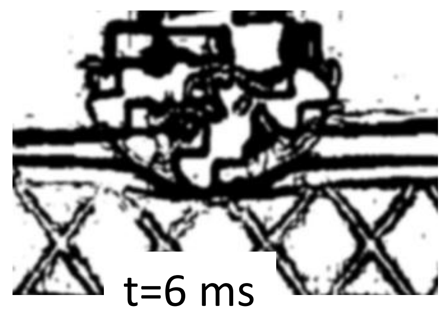


t=3 ms



t=4 ms





- LyondellBasell is…
- SGF-PP examples of applications
- SGF-PP modeling: overview
- Failure criteria, implementation
- Examples of validation (Ribbed beam)
- Conclusions

Conclusions

- Material orientation, strain rate dependence and unequal tension/compression behavior implemented within LyondellBasell simplified model for anisotropic materials.
- With respect to simple max-strain based models, these approaches allow a more accurate input of data from material characterization
- Preliminary validation carried on a ribbed beam model
- Results shows that the ruptures are better reproduced when more complex failure criteria are applied. In particular, the Tsai-Wu criterion allows a more accurate correlation with the real progressive fragmentation of the part.
- The introduction of more complex failure modeling, while increased the accuracy of the simulations, still maintains the whole approach to anisotropic material modeling easily and quickly
- Further benchmark cases need to be investigated to make these conclusions more general

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