Failure criteria for polypropylene-based compounds: current development with MAT_157

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Infoday Composites at Dynamore
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Some PP compounds in automotive

Material type / Inclusion	**Matrix**	**Application in automotive**	**Anisotropy**	**Elongation at rupture at 23°C**	**CAE Modeling**
“Rigid” SGF-PP (short glass Fiber)	PP-Homopolymer, copolymer	Structural parts 	YES	Low	Anisotropic laws (MAT_157, MAT_103) . Failure: interactive failure criteria
Softell SGF-PP (short glass Fiber)	PP- Soft matrix	Interiors 	Less than “rigid” SGF-PP	Medium	Anisotropic laws (MAT_157, MAT_103) . Failure: interactive failure criteria
Mineral filled PP	PP-Homopolymer, copolymer	Interiors and exteriors	Minor	Low-medium-high	Isotropic (MAT_024) or anisotropic laws; max. strain-based Criteria
Mineral filled – impact modified PP; Unfilled PP copolymers	PP-Homopolymer, copolymer	Instrument panels, bumpers 	Minor	Medium-high	Isotropic (MAT_024, MAT_187) or anisotropic laws; max. strain-based criteria

Ls-dyna Material laws used at LYB for PP-Compounds

MAT_024

- Most used law in Automotive industry
- Elasto - viscoplastic
- Isotropic
- Constant volume in plastic phase
- Possible external failure crierion routine

MAT_187

- Viscoelastic - viscoplastic
- Isotropic
- Non-constant volume in plastic phase
- Tensile-compression-shear differentiation
- Damage criterion embedded

MAT_103/ MAT_157

- Elasto – viscoplastic/ Viscoelastic-viscoplastic
- Orthotropic
- Constant volume in plastic phase
- Possible external failure criterion routine/

Damage-rupture criterion embedded

Failure criteria : coupling and relevance

Material type / Inclusion	Matrix	Strain rate dependent	Orientation sensitive	Compression/ tension	CAE Modeling ☺
"Rigid" SGF-PP (short glass Fiber)	PP-Homopolymer, copolymer	☺✓	☺✓	☺✓	MAT_103: Interactive Criteria (Ls-dyna German Forum 2016)
Softell SGF-PP (short glass Fiber)	PP- Soft matrix	✓	✓	✓	MAT_157
Mineral filled PP	PP-Homopolymer, copolymer	☺✓	✓	✓	MAT_024: Max strain
Mineral filled – impact modified PP – Unfilled PP copolymers	PP-Homopolymer, copolymer	☺✓	✓	✓	MAT_024: Max strain

Purpose of this study

Failure criteria : coupling and relevance

To extend to *Softell* materials and MAT_157 the application of interactive failure criteria as previously done with “rigid” GF-PP and MAT_103

Purpose of this study

Interactive failure criteria for SGF-PP

Background:

Activity Presented at

Ls-dyna German Forum 2012

Ls-dyna German Forum 2016 (colllaboration LyondellBasell-Opel)

Interactive failure criteria for SGF-PP:

- Tsai-Hill and Tsai-Wu criteria implemented in a user subroutine for MAT_103 (isotropic elastic-orthotropic visco plastic law)
- Application to benchmark tests (ribbed beams) on industrial parts made of 30% SGF-PP
- Both the criteria predicted the component fracture better than the simple “max-strain” criterion

Interactive failure criteria for SGF-PP: Tsai-Wu criterion

- Interactive criteria take into account the interaction between the stress components

General formulation:

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

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

Tsai-Wu Criterion in Ls-dyna:

Transversally isotropic material (anisotropy direction: fiber direction)

$$\left(\frac{1}{\mathrm{XT}}-\frac{1}{\mathrm{XC}}\right)\sigma_{aa}+\left(\frac{1}{\mathrm{YT}}-\frac{1}{\mathrm{YC}}\right)\sigma_{bb}+\left(\frac{1}{\mathrm{ZT}}-\frac{1}{\mathrm{ZC}}\right)\sigma_{cc}$$

$$+\frac{1}{\mathrm{XT}\cdot\mathrm{XC}}\sigma_{aa}^2+\frac{1}{\mathrm{YT}\cdot\mathrm{YC}}\sigma_{bb}^2+\frac{1}{\mathrm{ZT}\cdot\mathrm{ZC}}\sigma_{cc}^2+\frac{1}{\mathrm{SXY}^2}\sigma_{ab}^2+\frac{1}{\mathrm{SYZ}^2}\sigma_{bc}^2+\frac{1}{\mathrm{SZX}^2}\sigma_{ca}^2$$

$$+2\cdot F_{12}\cdot\sigma_{aa}\sigma_{bb}+2\cdot F_{23}\cdot\sigma_{bb}\sigma_{cc}+2\cdot F_{31}\cdot\sigma_{cc}\sigma_{aa}<1$$

Anisotropy – strain rate dependency – tension/compression asymmetry

Tsai-Wu and Tsai-Hill criteria implementation in MAT_157

- After the good performance with MAT_103, Tsai-Hill and Tsai-Wu criteria have been implemented by Dynamore for MAT_157 in a Ls-dyna 8.1 developmental version
- A first comparison (internal LyondellBasell Study) showed a reasonably similar behavior with the results achieved with LYB implementation on MAT_103.

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www.lstc.com

LS-DYNA, A Program for Nonlinear Dynamic
Analysis of Structures in Three Dimensions
Version : smp d Dev          Date: 10/06/2016
Revision: 111321             Time: 15:36:34

Features enabled in this version:
  Shared Memory Parallel
  CESE CHEMISTRY EM ICFD STOCHASTIC_PARTICLES
  FFTW (multi-dimensional FFTW Library)
  ARPACK (nonsymmetric eigensolver library)
  ANSYS Database format
  NSYS License (ANSYS145)

Licensed to: Basell Poliolefine Italia srl
Issued by  : dynamore_03302016

Platform   : WINDOWS X64
OS Level   : Windows Vista/7/8 Server 2008/2012
Compiler   : Intel Fortran Compiler XE 13.1
Hostname   : Stratocaster
Precision  : Double precision (I8R8)
SVN Version: 111321

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•In this paper:

Preliminary validation of Tsai-Wu criterion coupled with MAT_157

Variety of behavior

Material card for *Softell* grade TKG300N


Source: LyondellBasell

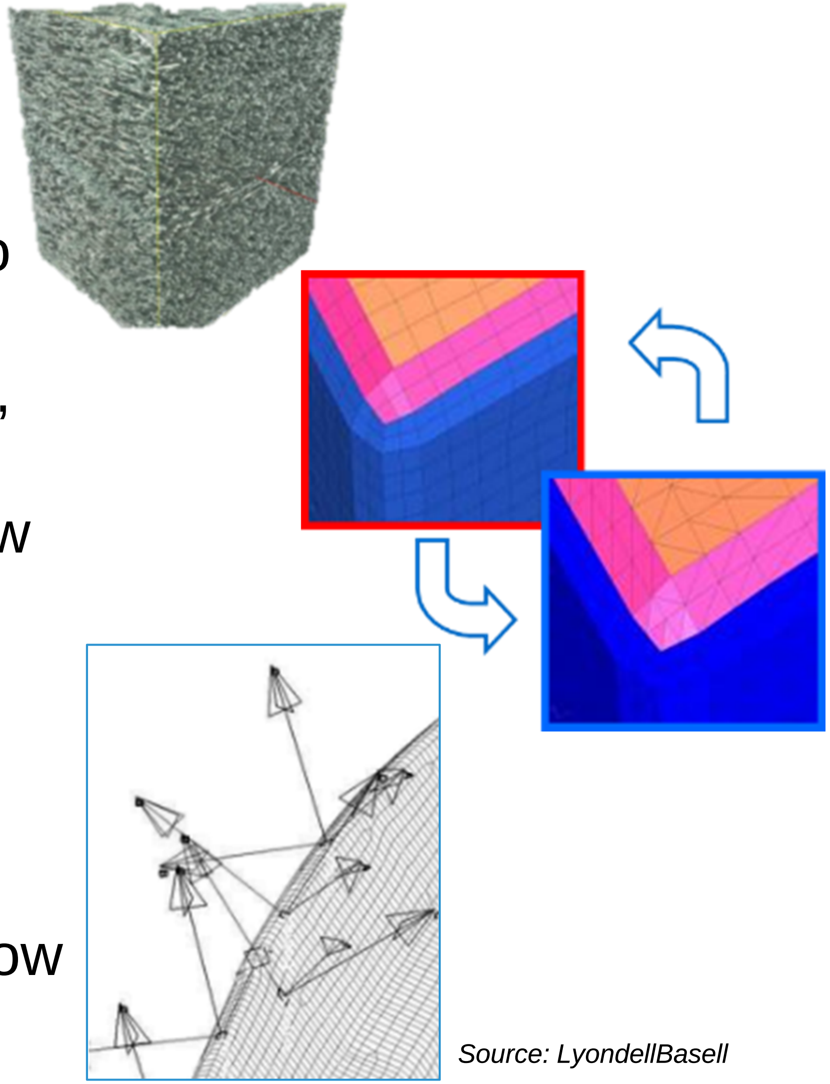
- Elastic behavior parameters
- Anisotropy coefficients
- Failure parameters:
  - Under Tension, through tensile test reverse engineering
  - Under Compression, through validation tools

Anisotropy computations

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: orthotropic symmetry, material principal directions determined by flow direction in the mold.



Source: LyondellBasell

lyondellbasell

Determination of elastic parameters

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	SIGY	LCSS	QR1	CR1	QR2	CR2
Type	A8	F	F	F	F	F	F	F

Card 2	1	2	3	4	5	6	7	8
Variable	C11	C12	C13	C14	C15	C16	C22	C23
Type	F	F	F	F	F	F	F	F

Card 3	1	2	3	4	5	6	7	8
Variable	C24	C25	C26	C33	C34	C35	C36	C44
Type	F	F	F	F	F	F	F	F

Card 4	1	2	3	4	5	6	7	8
Variable	C45	C46	C55	C56	C66	R00 or F	R45 or G	R90 or H
Type	F	F	F	F	F	F	F	F

Determination of elastic parameters

$$\begin{pmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{12}\\ \sigma_{23}\\ \sigma_{31}\end{pmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0\\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix} \begin{pmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \varepsilon_{12}\\ \varepsilon_{23}\\ \varepsilon_{31}\end{pmatrix}$$

$$\begin{pmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{12}\\ \sigma_{23}\\ \sigma_{31}\end{pmatrix} = \begin{bmatrix} \frac{1-\upsilon_{23}\upsilon_{32}}{E_{22}E_{33}\Delta} & \frac{\upsilon_{21}+\upsilon_{31}\upsilon_{23}}{E_{22}E_{33}\Delta} & \frac{\upsilon_{31}+\upsilon_{21}\upsilon_{32}}{E_{22}E_{33}\Delta} & 0 & 0 & 0\\ \frac{\upsilon_{12}+\upsilon_{13}\upsilon_{32}}{E_{11}E_{33}\Delta} & \frac{1-\upsilon_{13}\upsilon_{31}}{E_{11}E_{33}\Delta} & \frac{\upsilon_{32}+\upsilon_{12}\upsilon_{31}}{E_{11}E_{33}\Delta} & 0 & 0 & 0\\ \frac{\upsilon_{13}+\upsilon_{12}\upsilon_{23}}{E_{11}E_{22}\Delta} & \frac{\upsilon_{23}+\upsilon_{13}\upsilon_{21}}{E_{11}E_{22}\Delta} & \frac{1-\upsilon_{12}\upsilon_{21}}{E_{11}E_{22}\Delta} & 0 & 0 & 0\\ 0 & 0 & 0 & 2G_{12} & 0 & 0\\ 0 & 0 & 0 & 0 & 2G_{23} & 0\\ 0 & 0 & 0 & 0 & 0 & 2G_{31}\end{bmatrix} \begin{pmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \varepsilon_{12}\\ \varepsilon_{23}\\ \varepsilon_{31}\end{pmatrix}$$

$$\Delta = \frac{1-\upsilon_{12}\upsilon_{21}-\upsilon_{23}\upsilon_{32}-\upsilon_{31}\upsilon_{13}-2\upsilon_{12}\upsilon_{23}\upsilon_{31}}{E_{11}E_{22}E_{33}}$$

$$-\frac{\upsilon_{21}}{E_{22}} = -\frac{\upsilon_{12}}{E_{11}}\ ;\ -\frac{\upsilon_{31}}{E_{33}} = -\frac{\upsilon_{13}}{E_{11}}\ ;\ -\frac{\upsilon_{32}}{E_{33}} = -\frac{\upsilon_{23}}{E_{22}}$$

Ea (MPa)	2620
Eb (MPa)	1500
Ec (MPa)	1500
nu_a_b	0,35
nu_a_c	0,35
nu_b_a	0,200381679
nu_c_a	0,200381679
nu_c_b	0,35
nu_b_c	0,35

C11	3341
C12	1030
C13	1030
C22	2027
c23	916
c33	2027
c44	1941
c55	1111
c66	1250

A.Hatt, “Anisotropic modeling of short fibers reinforced thermoplastics materials with LS-DYNA”, 13.LS-DYNA Forum, Bamberg, 2014

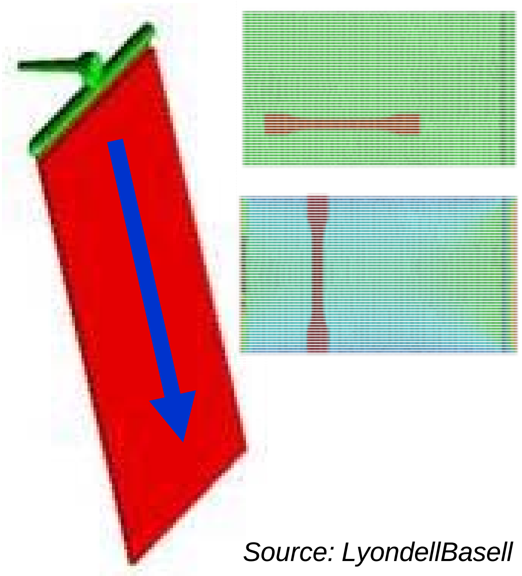
Determination of anisotropy coefficients

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	SIGY	LCSS	QR1	CR1	QR2	CR2
Type	A8	F	F	F	F	F	F	F

Card 2	1	2	3	4	5	6	7	8
Variable	C11	C12	C13	C14	C15	C16	C22	C23
Type	F	F	F	F	F	F	F	F

Card 3	1	2	3	4	5	6	7	8
Variable	C24	C25	C26	C33	C34	C35	C36	C44
Type	F	F	F	F	F	F	F	F

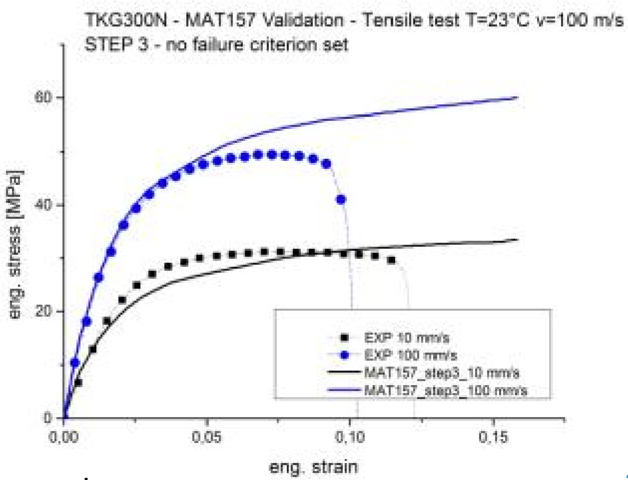
Card 4	1	2	3	4	5	6	7	8
Variable	C45	C46	C55	C56	C66	R00 or F	R45 or G	R90 or H
Type	F	F	F	F	F	F	F	F



Source: LyondellBasell

Tool: tensile test reverse engineering on two specimen orientations

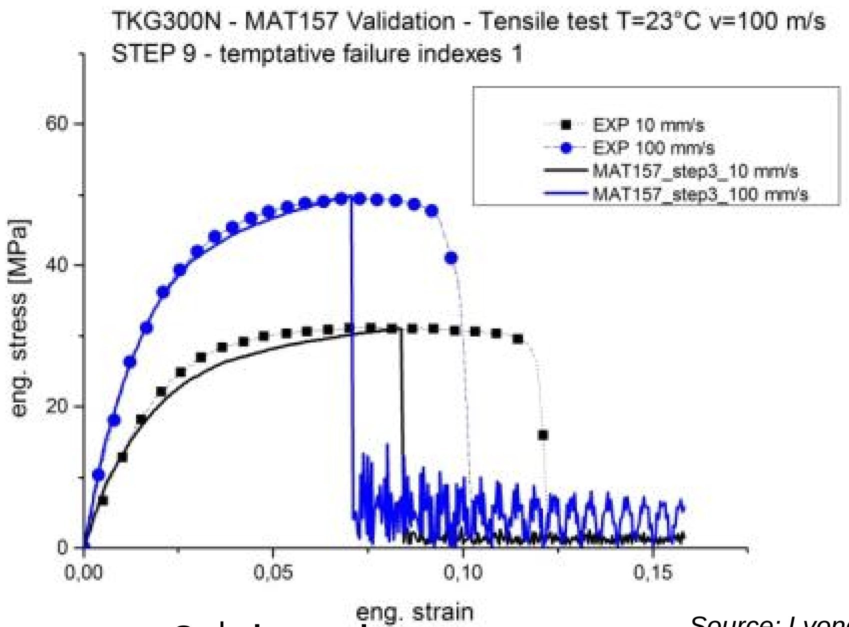
Card creation – Validation. 1° step: tensile test



0th iteration: initial guess, from elastic parameters and isotropic longitudinal parameters

Here: element formulation: "2" (underintegrated element)

"manual" identification of MAT_157 card parameters



3rd iteration: adjusted Lankford parameters

Source: LyondellBasell

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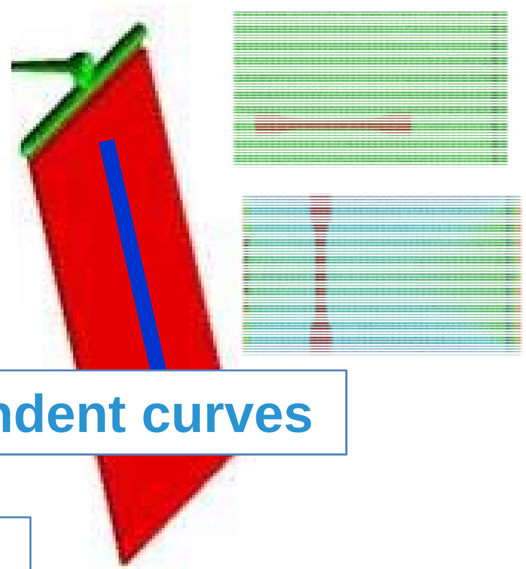
Determination of failure index parameters

Card 6	1	2	3	4	5	6	7	8
Variable	XP	YP	ZP	A1	A2	A3		EXTRA
Type	F	F	F	F	F	F		F

EXTRA=1.0: Tsai-Wu



Card 7	1	2	3	4	5	6	7	8
Variable	V1	V2	V3	D1	D2	D3	BETA	IHIS
Type	F	F	F	F	F	F	F	F

Two addition

Strengths: logarithmic strain rate dependent curves

Card 8	1	2	3	4	5	6	7	8
Variable	XT	XC	YT	YC	SXY	FF12		
Type	F	F	F	F	F	F		

Tsai WU:
FF12=-0.5

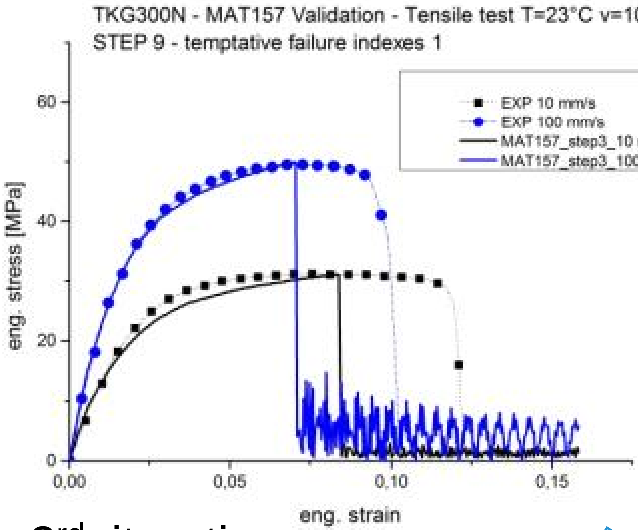
```
*DEFINE_CURVE
$#     tbidXTLong
       1080              0  1.000000  1.070000       0.000
$#                  value      lcid
                   -10.12      29.0
                     -7.8      45.7
                    -5.52      51.3
                   -2.300     60.04
```

FF12

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

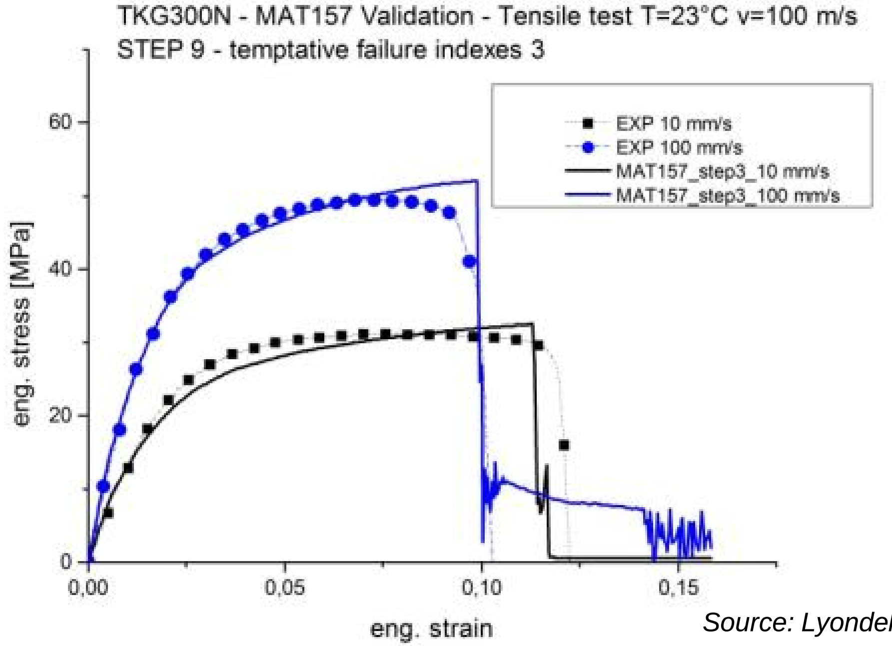
lyondellbasell

Card creation – Validation. 1° step: tensile test



3rd iteration: adjusted Lankford parameters

"manual" identification of MAT_157 card parameters

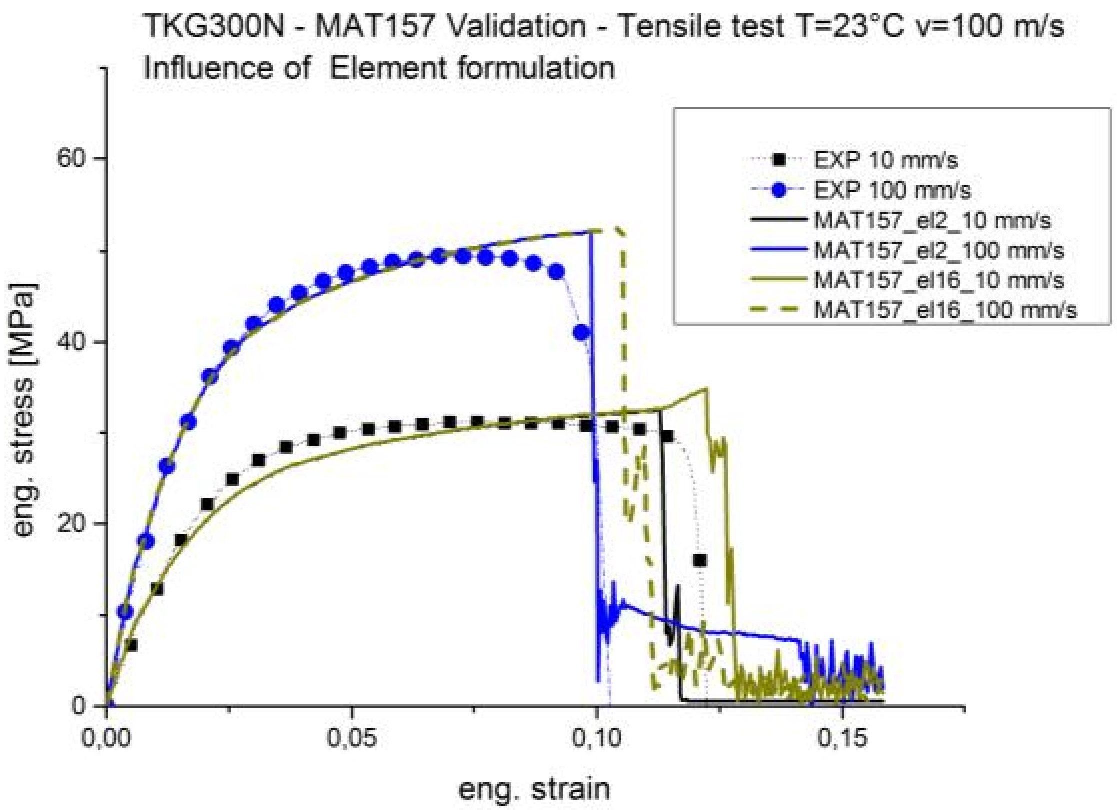


Source: LyondellBasell

9th iteration: adjusted tensional stress at failure (strain-rate dependent)

Here: element formulation: "2" (underintegrated element)

Card creation – Validation. 1° step: tensile test. Element formulation



Source: LyondellBasell

- An influence of element formulation is visible
- A minor variation in the elongation at break suggested to keep the parameters found with under-integrated element formulation

Determination of failure index parameters. Compression strengths

Card 6	1	2	3	4	5	6	7	8
Variable	XP	YP	ZP	A1	A2	A3		EXTRA
Type	F	F	F	F	F	F		F

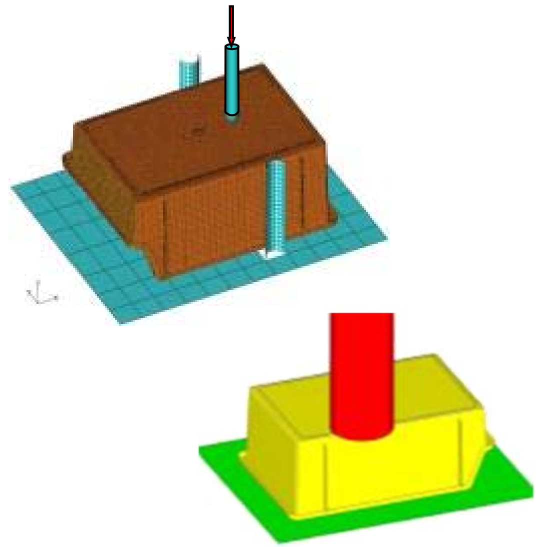
Card 7	1	2	3	4	5	6	7	8
Variable	V1	V2	V3	D1	D2	D3	BETA	IHIS
Type	F	F	F	F	F	F	F	F

Two addition

Strengths: strain rate dependent curves

Card 8	1	2	3	4	5	6	7	8
Variable	XT	XC	YT	YC	SXY	FF12		NCFAIL
Type	F	F	F	F	F	F		F

Card 9	1	2	3	4	5	6	7	8
Variable	ZT	ZC	SYZ	SZX	FF23	FF31		
Type	F	F	F	F	F	F		



Source: LyondellBasell

Tool: compression-strengths from additional validation tools

Determination of failure index parameters. Compression strengths

- In the absence of experimental data, compression data are simulated scaling by a proper coefficient the tensile curves, as in

  M.Nutini and M.Vitali, *Validation of a SAMP1 Material Card for Polypropylene/based components*, 12th Ls-dyna German Forum, Filderstadt, 2013.

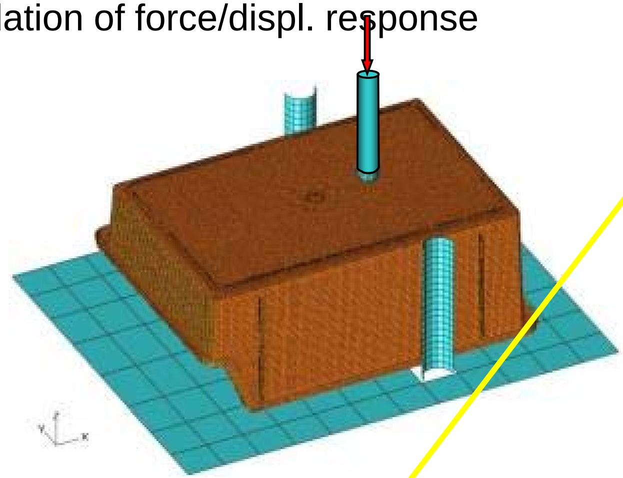
- A scaling coefficient from 1.3 to 1.5 for compression can be also derived from literature

  A.M. Hartl, M.Jerabek, R.W.Lang, *Anisotropy and compression/tension asymmetry of PP containing soft and hard particles and short glass fibers*, eXPRESS Polymers Letters Vol. 9, No. 7, 2015, pp. 658-670

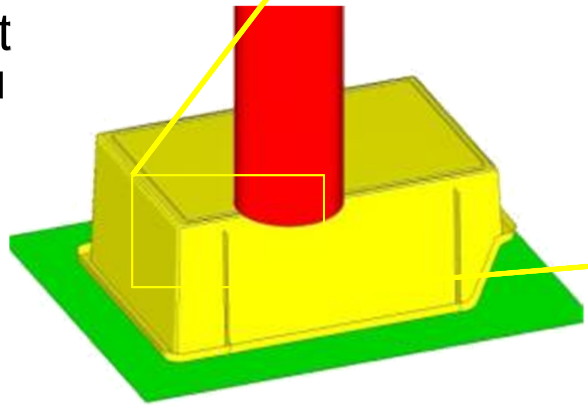
- Tuning the scaling coefficient can be done based on further tests available

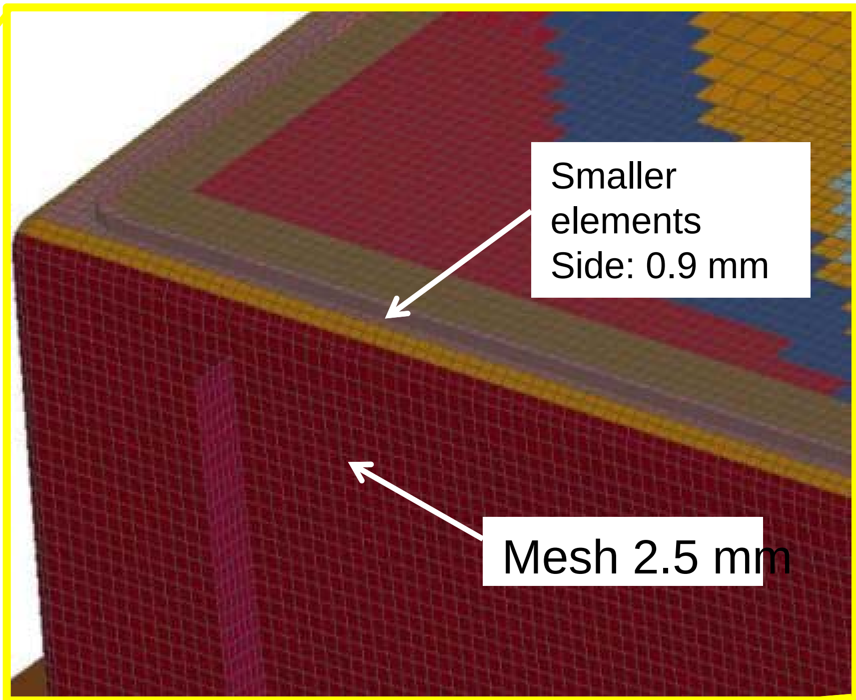
Other validation tools

Box «dart» test
• localized impact
• validation of force/displ. response



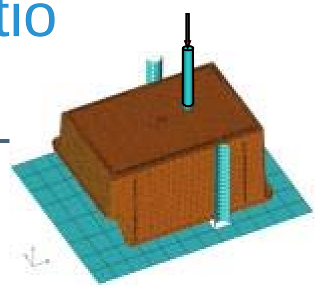
Box drop test
• wall buckling and crushing
• validation of rupture behaviour

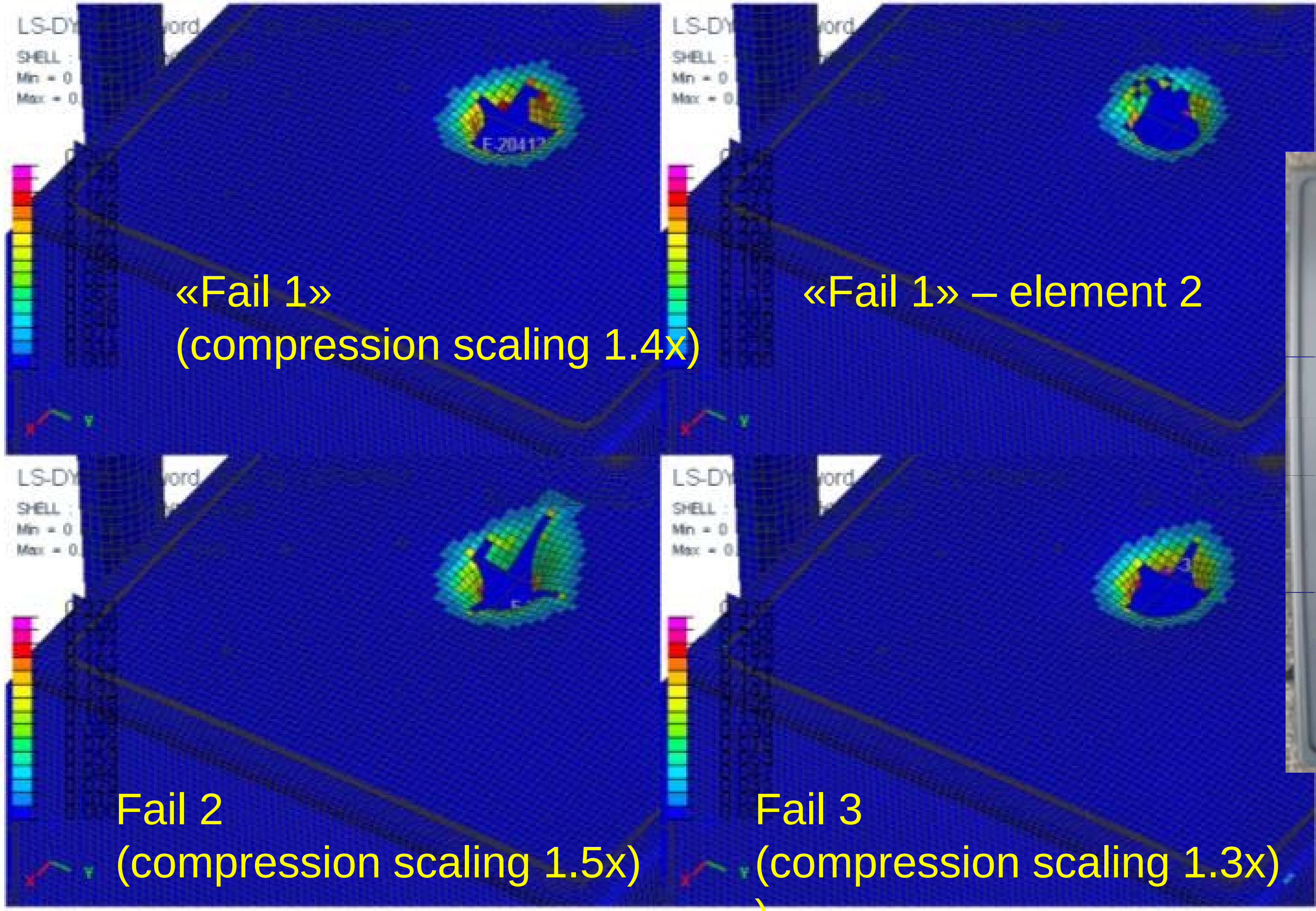




Source: LyondellBasell

Box «dart» test. Exploring Compression-to-tension ratio





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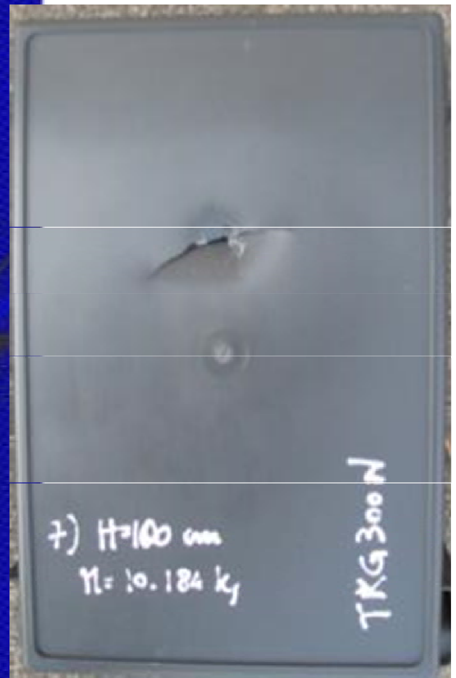
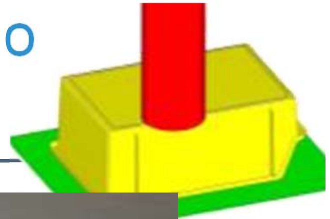
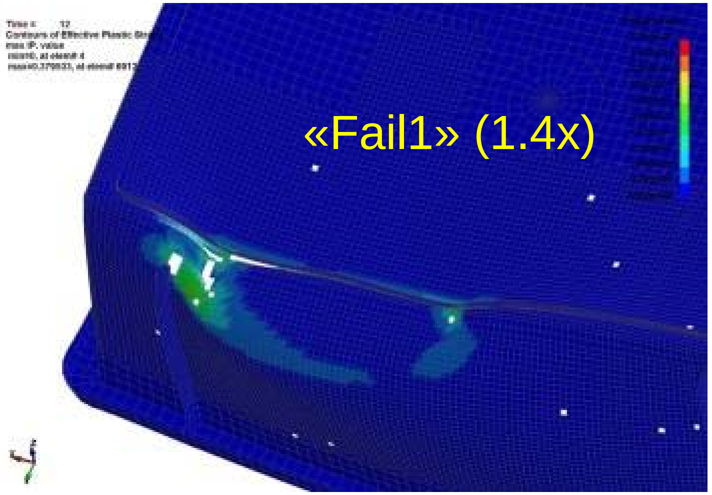
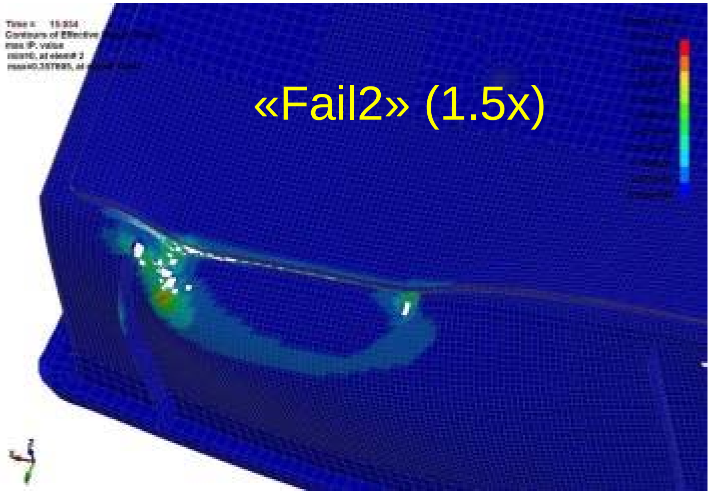


Source: LyondellBasell

Box «drop» test. Exploring Compression-to-tension ratio

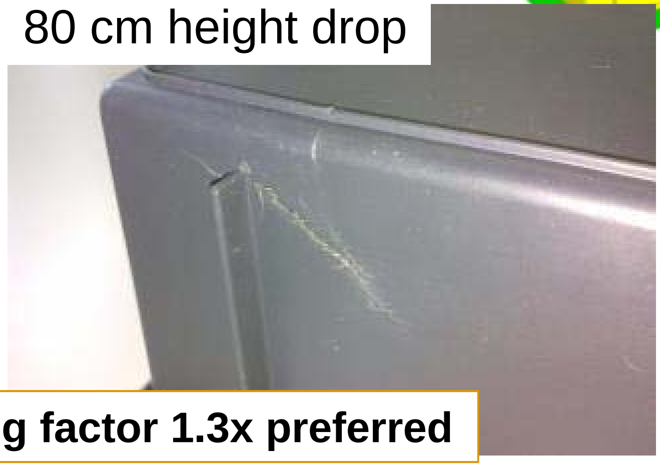




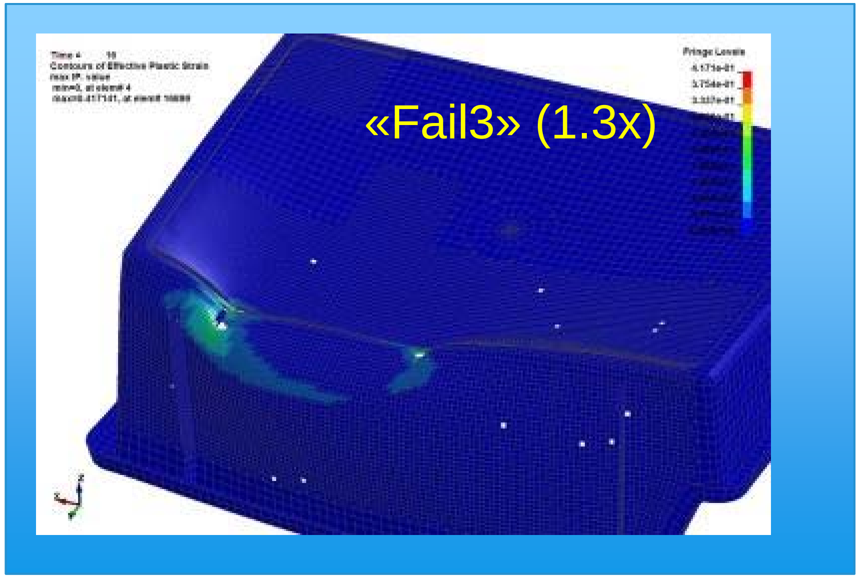


Full integrated element (elem. 16)

80 cm height drop

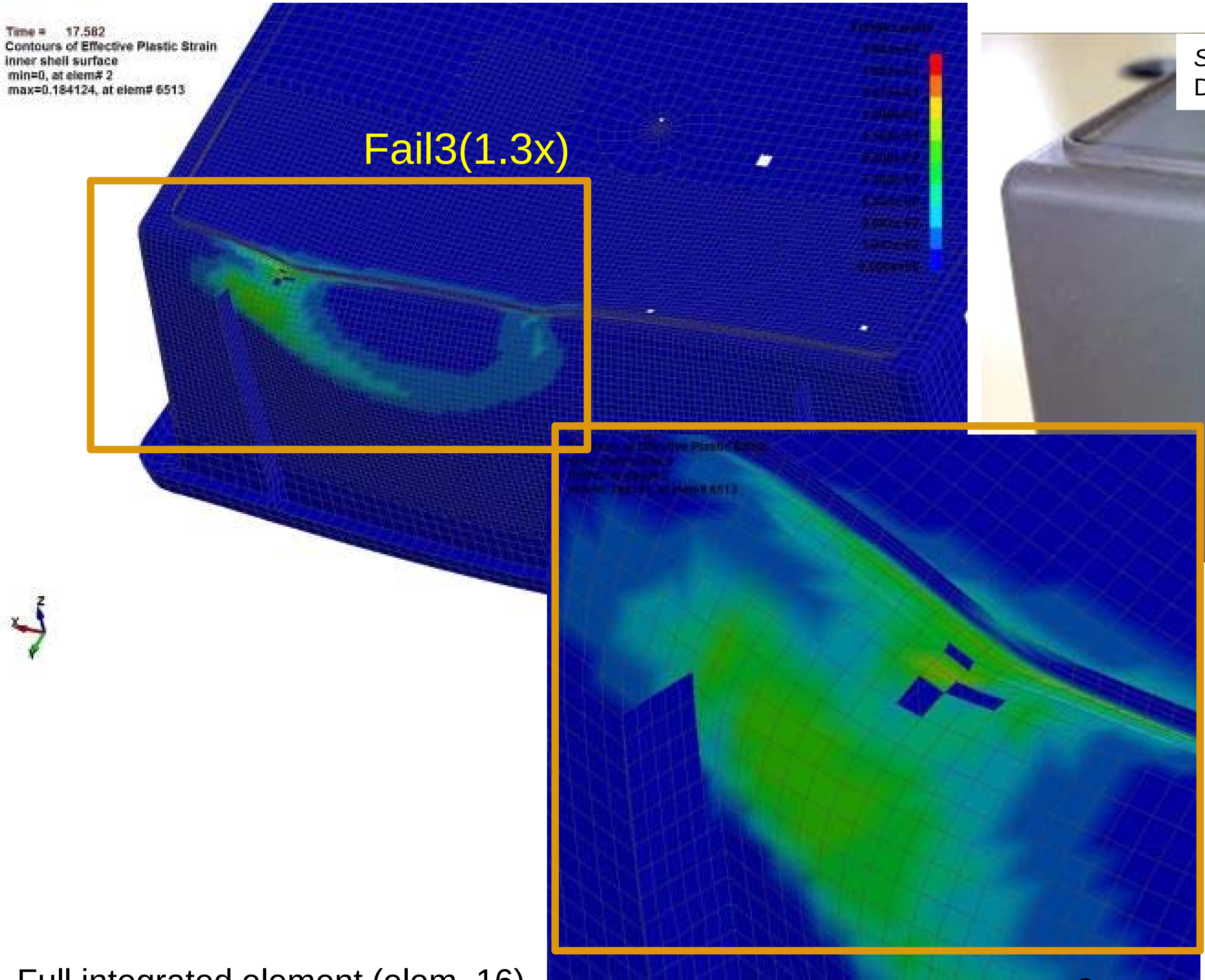


Scaling factor 1.3x preferred



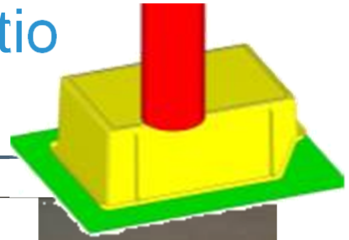
Source: LyondellBasell

Box «drop» test. Exploring Compression-to-tension ratio



Full integrated element (elem. 16)

Source: LyondellBasell

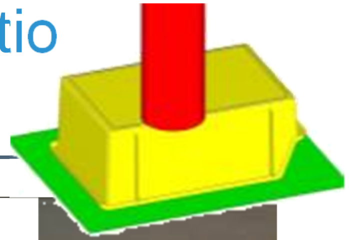


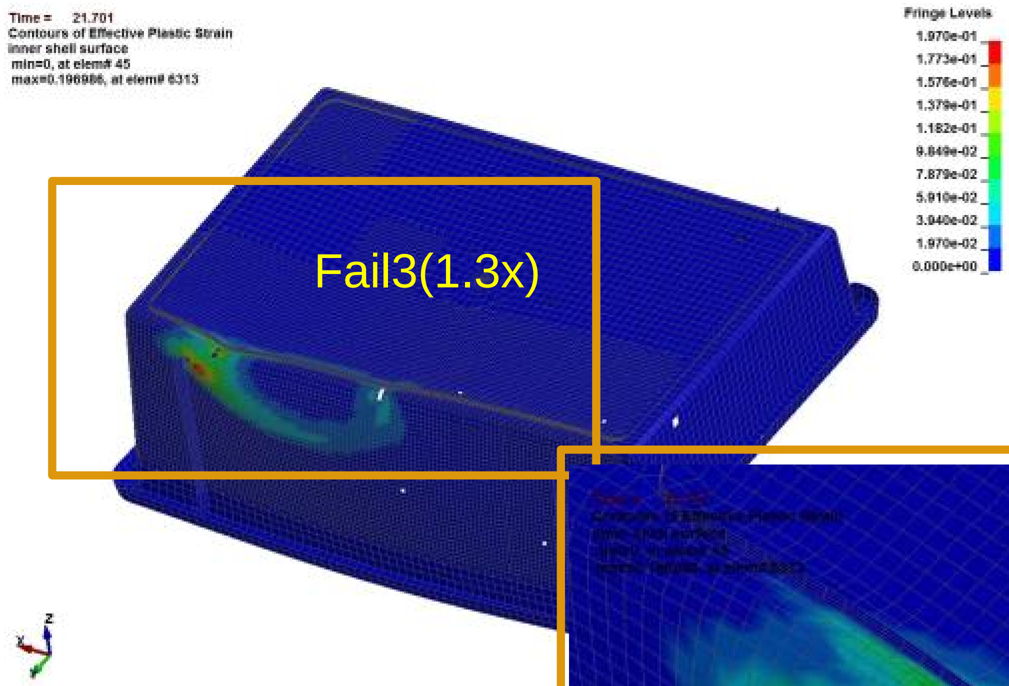
Softell TKG300N
Drop height 50 cm

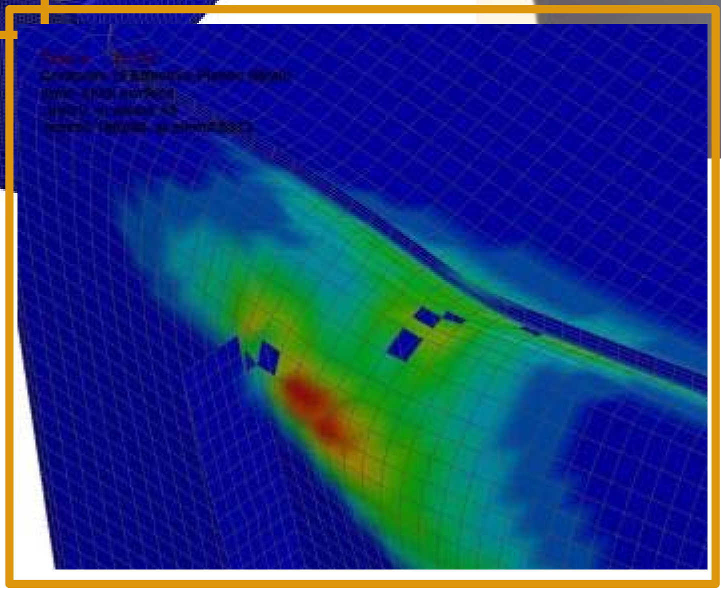
50 cm height drop

Source: LyondellBasell

Box «drop» test. Exploring Compression-to-tension ratio







50 cm height drop

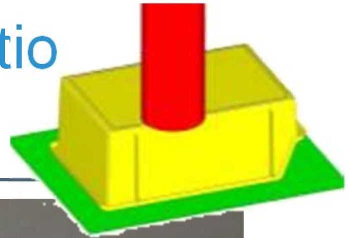
Source: LyondellBasell

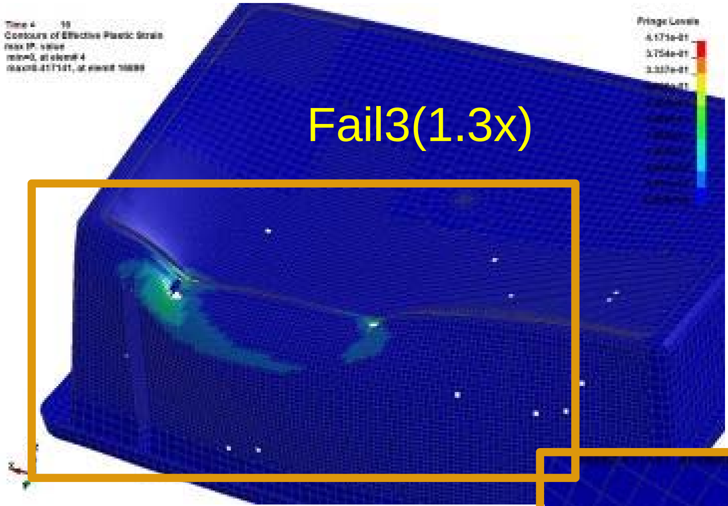
*MAT_NONLOCAL

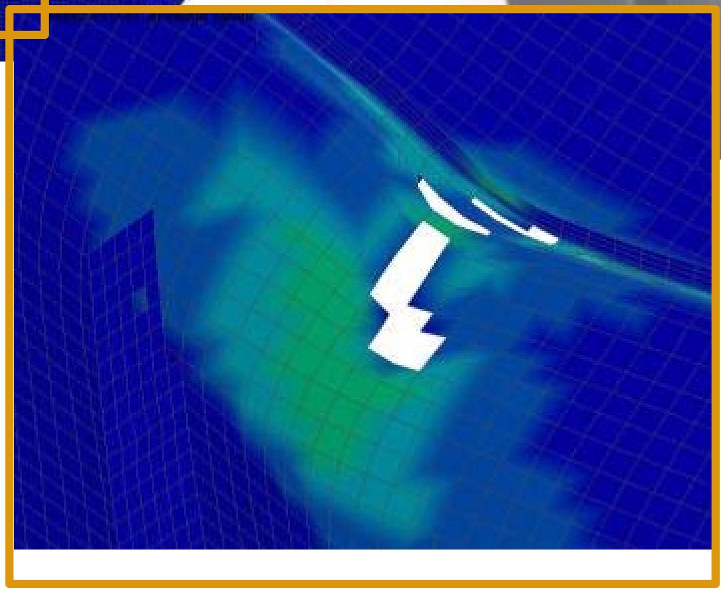
Full integrated element (elem. 16)

Source: LyondellBasell

Box «drop» test. Exploring Compression-to-tension ratio (detail)







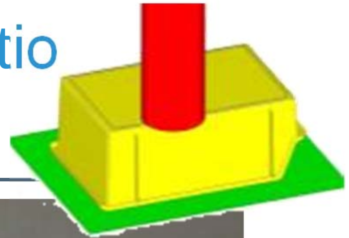
80 cm height drop

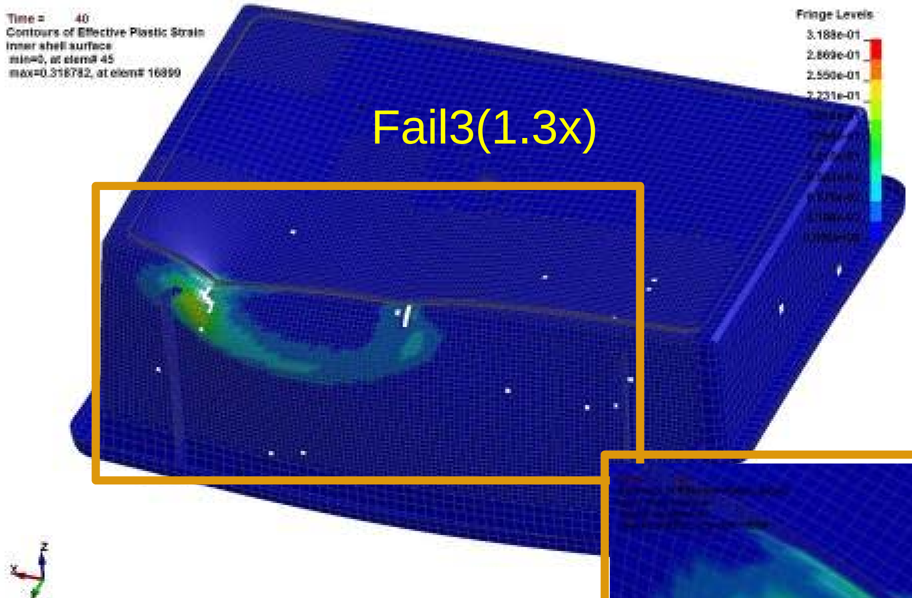
Source: LyondellBasell

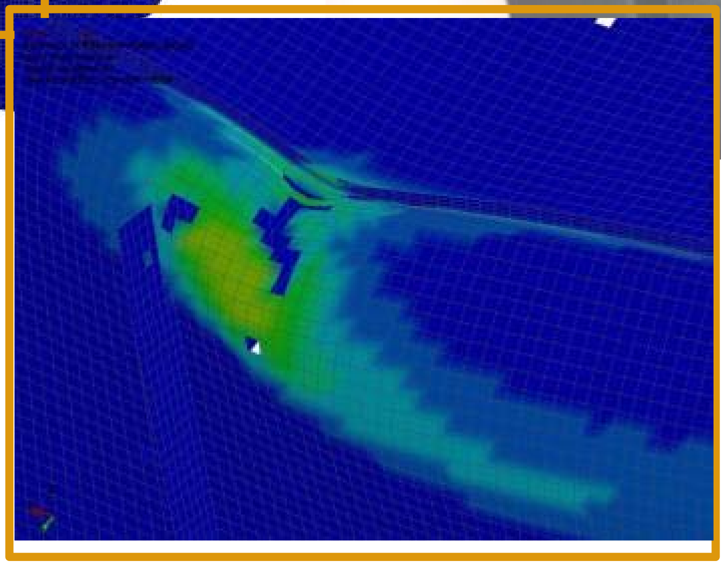
Full integrated element (elem. 16)

Source: LyondellBasell

Box «drop» test. Exploring Compression-to-tension ratio (detail)







80 cm height drop

Source: LyondellBasell

*MAT_NONLOCAL

Source: LyondellBasell

Full integrated element (elem. 16)

Comment

- MAT_157 can be used to simulate *Softell* TKG300N in impact problems. In this study the orthotropic MAT_157 law was applied in a model which neglects the fiber stratification, i.e. the variation of fiber orientation within the material thickness. The information from the process simulation which originated the material orientation was simply the flow direction in the mold.
- The combination of Tsai-Wu failure criterion with MAT_157 resulted in sufficiently accurate prediction of fracture occurrence and localization in the test cases. Better results achieved with *MAT_NONLOCAL
- More accurate results are expected when material stratification will be considered, i.e. when fiber orientation will be imported layer by layer within the part thickness

Open questions and possibilities: GF-PP materials

- Tsai-Wu failure criterion provided sufficiently accurate results in its application to Glass Fiber reinforced polymers using MAT-103.
- No significant variations in failure criterion response are then expected when combined with MAT_157 law. Work is in progress

Open questions and possibilities: *Softell* materials

- The application of interactive failure criteria coupled with MAT_157 will be validated on other test cases and industrial parts
- The results presented so far included a validation of guesses related to compressional behavior, which may be available from testing. However the proper scaling value here found is in agreement with literature and previous tests, although it can be further tuned. Accordingly, reasonable results can be obtained even without dedicated compression data.

Open questions and possibilities: mineral filled materials

- For parts made of mineral filled PP, anisotropic material behavior is not so relevant and is usually modeled using average values.
- However the approach here presented, based on flow direction in the mold, could be in principle applied with minor additional computational effort, due to the stability of MAT_157 which was proved.
- In this case proper failure criteria are to be envisaged

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