Modelling of Ductile Polymer Model for Crash Application

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1 Introduction

Due to their lightweight and mechanical properties, ductile polymers are widely used in automotive industry, especially for parts involved in pedestrian impact performance as they are designed to absorb some of the energy induced by the collision.
Having reliable and physically accurate CAE model of those polymers is important during vehicle development as it allows its efficient implementation in the design loop. However, CAE studies show some discrepancies between simulation and experimental tests. Root cause analysis showed us that current CAE model doesn't correctly capture all behaviours exhibited by our polymer under impact.
In order to improve our CAE accuracy for ductile polymer we worked with Valenciennes University to develop a model which considers behaviours exhibited by those materials under impact (Visco-elasticity, hydrostatic pressure dependency yield surface, triaxiality dependent damage, strain rate effect)[1] [2].

2 Polymer material behaviour under impact, current material model and limitation

Polymer materials are generally used for pedestrian protection purpose on bumper and lower absorber. Under pedestrian impact, those parts undergo elastic, followed by plastic deformation and finally an elastic rebound due to the loss of transmitted force in those polymeric parts. During the plastic deformation other phenomena can be noticed as well, those are a reduction of load bearing capabilities and failure. Experimental studies on the material we currently used showed that their plastic and elastic responses are affected by the strain rate effect (Fig.1:) and it exhibits different yield criteria under tension and compression loading (Fig.2:).

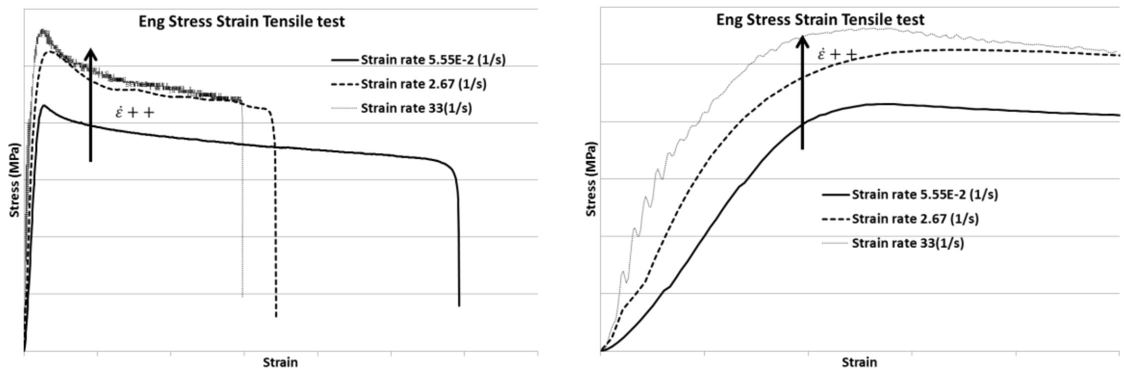


Fig.1: Influence of strain rate effect on polymer force response

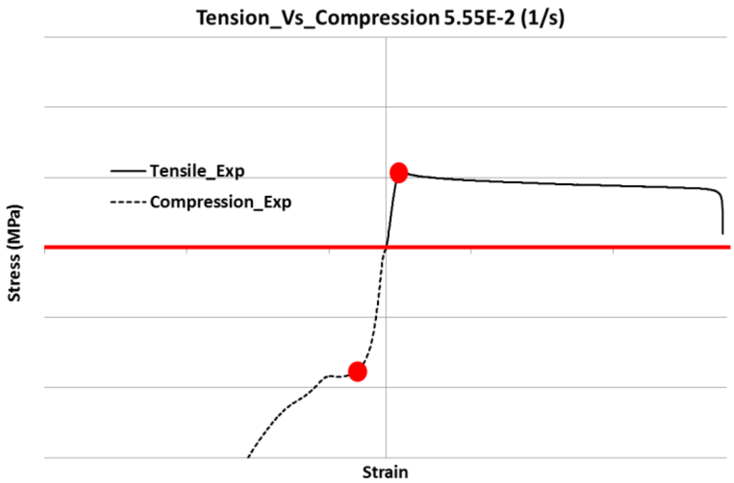


Fig.2: Difference in yield value between tension and compression

The most commonly used models available within LS-DYNA for polymer modelling from the least to the most appropriate for our materials are the following:
***MAT_PIECEWISE_LINEAR_PLASTICITY**
***MAT_PLASTICITY_WITH_DAMAGE**
***MAT_SAMP-1**

2.1 MAT_PIECEWIESE_LINEAR_PLASTICITY: MAT 24

This material law is an elastic plastic model developed for the description of metallic materials based on crystal plasticity and using Von Mises criteria as yield function [3]. This criterion cannot represent the difference in yielding under tensile and compression loading. Another drawback of this model is the lack of damage evolution which is exhibited by our materials as it expects only increasing plastic stress value before failure. This model can therefore not be used to accurately predict our pedestrian impact performance.

2.2 MAT_PLASTICITY_WITH_DAMAGE: MAT 81

This material law is an elasto-visco-plastic. It uses as well Von Mises criteria as yield function. The main difference in regards with polymer modelling versus MAT_PIECEWISE_LINEAR_PLASTICITY is the implementation of a damage evolution curve [3]. This allows the consideration of the softening behaviour of polymer under plastic loading. However this model is still not able to represent the difference in yielding in tension and compression, therefore a more suitable material model is needed.

2.3 MAT_SAMP-1

SAMP_1 material has been mainly developed to model polymer under impact. To consider the behavioural difference in compression, tension and shear, the SAMP-1 uses an isotropic C-1 smooth yield surface. Depending on the input data, the yield surface can be similar to Von Mises yield surface (if only tensile curve is given) or a Drucker-Prager cone (if a compressive, shear or biaxial curve is given on top of the tensile one) [3] [4]. To consider damage evolution in the material SAMP-1 implements a simple continuous damage model. The user should provide a curve representing the damage evolution in function of the true plastic strain. Another good point of SAMP-1 model is the fact that no calibration is necessary as only curve data obtained from test should be provided. This seems like a good fit for polymer calibration.
When using this model to calibrate our model a small problem arose. SAMP-1 expects as input curve a monotonic increasing true stress strain curves however our material model exhibits a softening even for the true stress strain curve (Fig.3:).

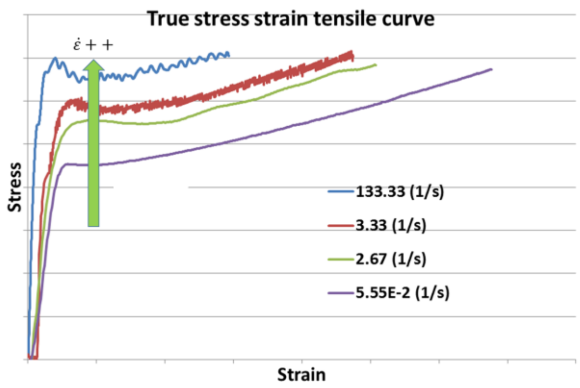


Fig.3: True stress strain curve of polymer under tensile loading

Also another phenomenon not taken into consideration by SAMP-1 model is the visco elasticity. We have noticed during our experimental testing that the elastic region of polymer material can also be affected by strain rate (Fig.1:). Therefore using a purely elastic model is not suitable. Thus SAMP-1 is somehow limited for our used case.

3 Development of a new material model for polymer modelling: USPM

To be able to properly model our polymer material under impact, we develop in collaboration with Valenciennes University a model which should consider phenomena exhibited by our polymer under pedestrian impact.

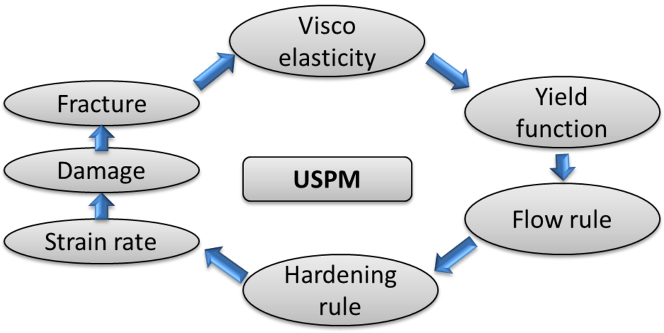


Fig.4: Phenomena considered in the USPM material model

This model is a visco-elastic-visco-plastic material model, which uses Maxwell elements to represent viscoelasticity.

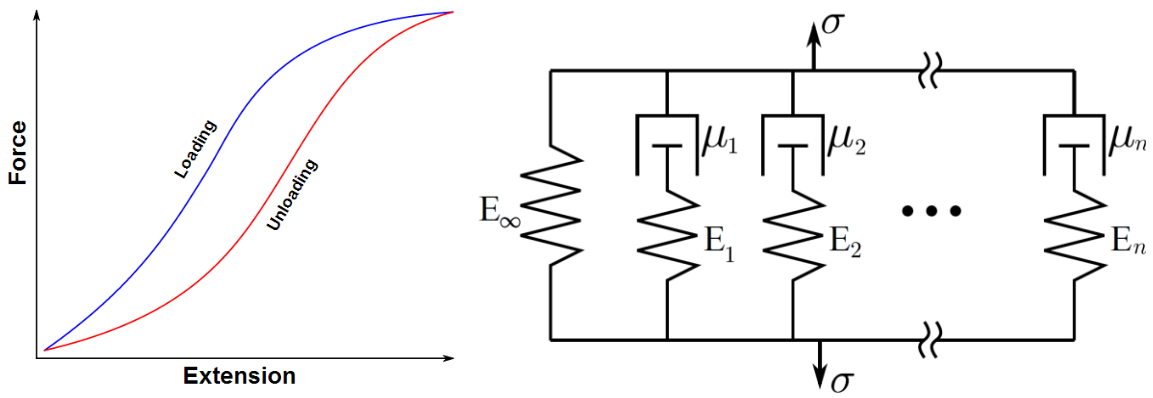


Fig.5: (Left) loading and unloading exhibited by polymer (Right) visco elastic rheological model of Valenciennes material model

The yield function is based on Rhagava formulation while the hardening curve is based on an exponential function. It considers as well softening in the material under the undamaged configuration. The damage evolution is based on a simple continuous damage model. By assuming that damage evolution is linked to the growth of cracks and voids within the specimen, an isotropic variable D has been defined.

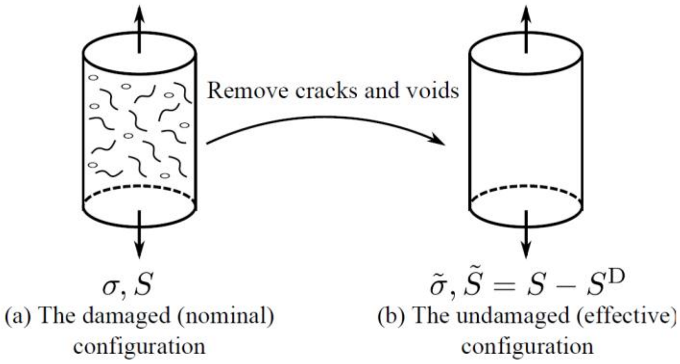


Fig.6: Relation between damage and undamaged configuration

A study of our material under biaxial loading showed us that our material exhibits a low biaxial strength while undergoing a permanent increase of volume. In order to consider this phenomenon, the damage evolution function has been made dependent of triaxiality ratio.

$$\mathrm{D} = 1 - \exp\left(-\frac{\varepsilon_p}{k}\right) \tag{1}$$

$$\mathrm{k} = \mathrm{k_c} \exp\left(C_a\left(1 - 3 * abs\left(\frac{\varepsilon_p}{\sqrt{3J_2}}\right)\right)\right) \tag{2}$$

Where ε_p is the true plastic strain, k_c and C_a are materials parameters.

The newly developed material has been tuned to correctly capture all the behaviour exhibited by our polymer under impact (Table 1:)

Model	**Visco elasticity**	**Hydrostatic pressure dependent yield**	**Hardening rule**	**Strain rate**	**Damage**
MAT_024	X	X	Δ	O	X
MAT_081	X	X	Δ	O	Δ
MAT_187	X	O	Δ	O	O
USPM	O	O	O	O	O

Table 1: Summary functionality implemented in existing material model (X: not available, Δ: available but missing some features, O: available)

4 Calibration test

Accurate, repeatable, and reliable experimental test results are needed for the good calibration of constitutive model. In order to calibrate this model several test are needed (Table 2:)

Phenomena	**Experimental tests**
Visco elasticity	DMA
Yield function	Tensile, Compression
Flow rule	Tensile, Compression
Hardening rule	Tensile
Strain rate	Tensile
Damage	Tensile, Biaxial
Fracture	Tensile, Biaxial

Table 2: List of tests for USPM calibration

4.1 DMA

4.1.1 Methodology

The DMA performed for this calibration is based on small amplitude tensile test. A sinusoidal displacement is applied to the specimen and a sinusoidal force is checked as output. The input strain is of the following form (3):

$$\varepsilon(\mathrm{t}) = \varepsilon_0 \cos(\omega t) \tag{3}$$

Expected output is supposed to be sinusoidal and out of phase with the input curve

$$\sigma(t) = \sigma_0 \cos(\omega t + \delta) \tag{4}$$

Thus the ratio of the stress and strain gives a complex modulus E^*, storage modulus E‘ and loss modulus E‘‘.

$$E^*(i\omega) = \frac{\sigma_0}{\varepsilon_0} \exp(i\delta) = E' + iE'' \tag{5}$$

$$E' = \frac{\sigma_0}{\varepsilon_0} \cos(\delta), E'' = \frac{\sigma_0}{\varepsilon_0} \sin(\delta) \tag{6}$$

In uniaxial loading the Maxwell element (Fig.5:) approximation gives the following relaxation modulus (7)

$$E(t) = E_\infty + \sum_{i=1}^{N} E_i \exp\left(-\frac{t}{\tau_i}\right) \tag{7}$$

Where $E_\infty$is the long term modulus of the material, E_i is the rigidity of each spring, and τ_i is defined as μ_i/E_i. Relation between storage, loss and the prony parameters are the following (8, 9)

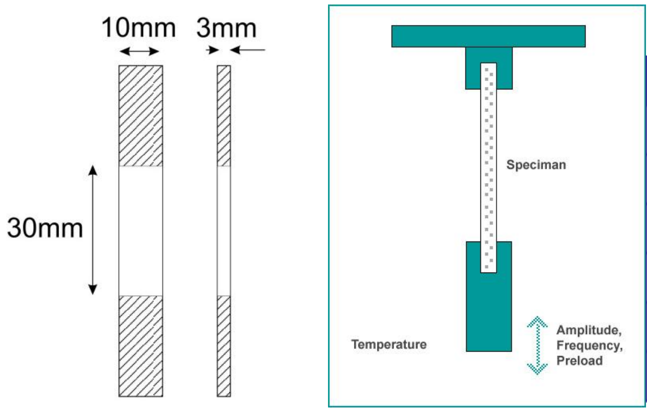
$$E'(\omega) = E_\infty + \sum_{i=1}^{N} E_i \frac{(\omega\tau_i)^2}{1+(\omega\tau_i)^2} \tag{8}$$

$$E''(\omega) = \sum_{i=1}^{N} E_i \frac{\omega\tau_i}{1+(\omega\tau_i)^2} \tag{9}$$

Here τ_i, E_∞ and E_i are material parameters. The loss, and storage modulus being obtained from experimental test, an optimization loop is performed to obtain the above-mentioned material parameters.

4.1.2 Specimen geometry and test setup

Specimens used for this test is a rectangular parallelepiped with a width of 10mm, thickness of 3mm and a working length of 30mm (Fig.7:)



Frequencies	
0.01Hz	0.03Hz
0.075Hz	0.1Hz
0.4Hz	1Hz
3Hz	5Hz
10Hz	30Hz
40Hz	

Fig.7: DMA test setup

4.1.3 Correlation test

DMA simulations were performed to confirm whether or not the viscoelasticity model is correctly implemented.

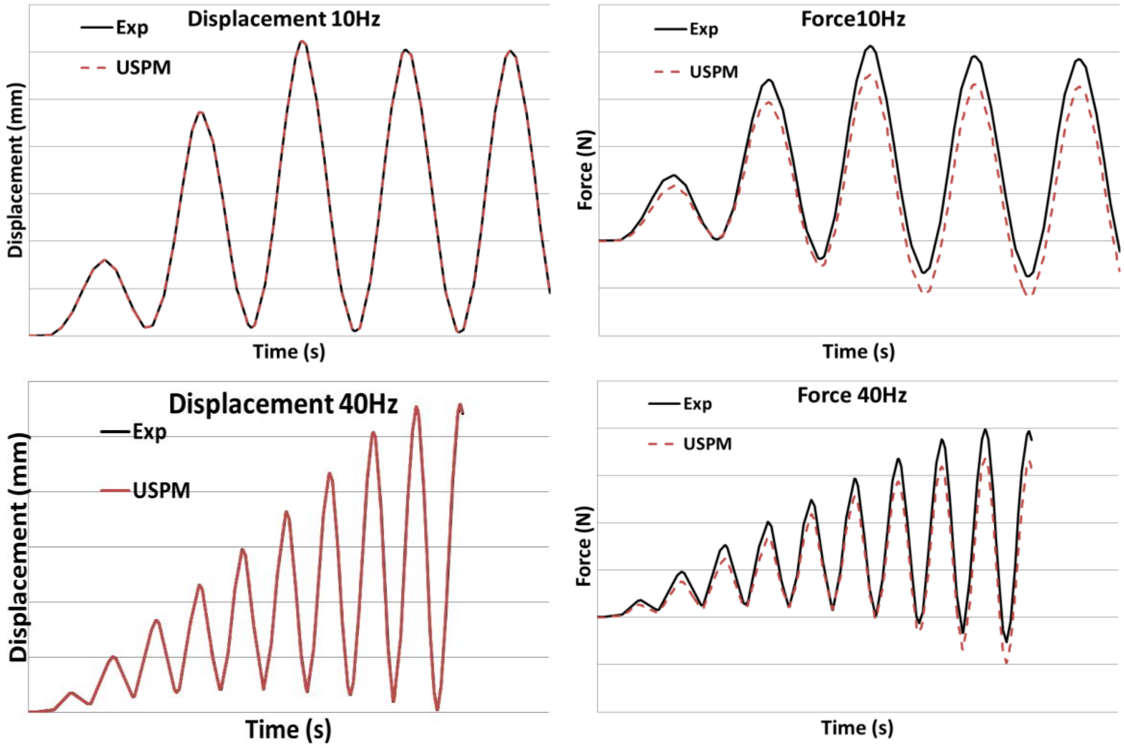


Fig.8: DMA correlation results

The new model gives good correlation versus test data, meaning the implementation of the visco elasticity model is correctly done.

4.2 Tensile test

Tensile test were performed to obtain parameters for hardening, strain rate effect, and partially those for the yield function, flow rule, and damage evolution. Tests were performed with a dog bone specimen cut from a moulded plate (Fig.9:).

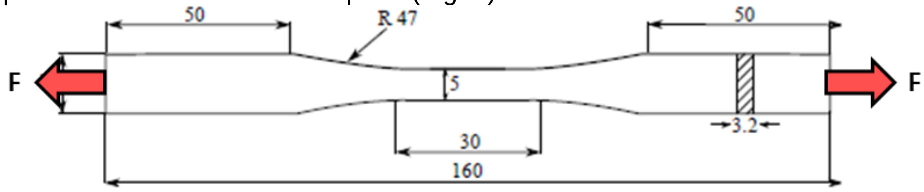


Fig.9: Dog bone specimen used for tensile test

Simulations were then performed to find out how the model is working for simple uniaxial tensile test. Here strain rate of interest are 33 and 2.67 s^{-1} (Fig.10:)

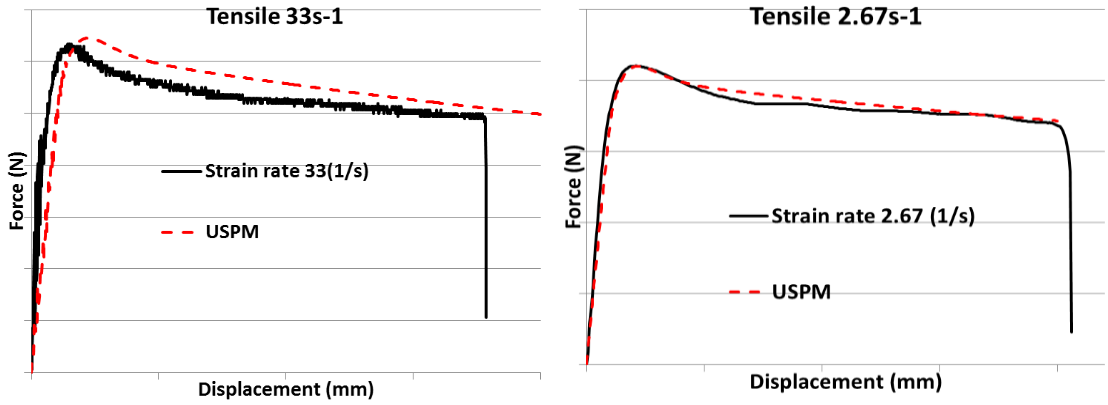


Fig.10: Correlation tensile test CAE vs. test

The material model gives an acceptable correlation level with the experimental test, even considering the change in damage evolution due to the strain rate. A small discrepancy between the test and CAE at strain rate of 33s^{-1} can be noticed. This is due to the calibration technique which tries to approximate as much as possible the response of the material by an exponential function, hence not always having a spot on matching.

4.3 Compression test

As mentioned in chapter 3, the yield function is based on Rhagava yield surface. This surface takes into consideration the hydrostatic pressure dependency, hence can represent the difference in stress response between the uniaxial tension and compression test. As the material is strain rate dependent, compression test has to be done at the same strain rate as tensile test to allow proper yield function calibration.
The specimen used for compression test is of cylindrical shape. Lubricants were used in order to reduce the friction between specimen and, and therefore reduced the barrelling effect.

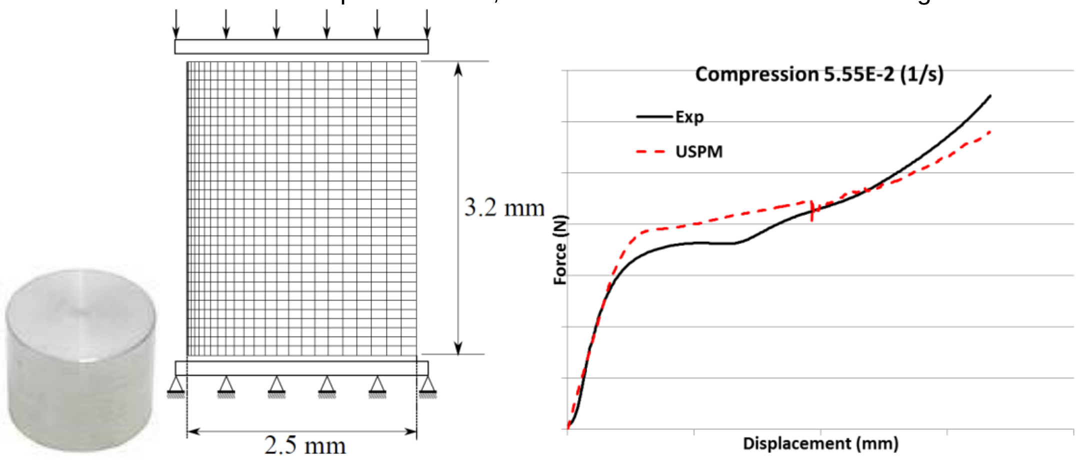


Fig.11: (Left) Compression test specimen, (Right) correlation test vs. CAE

Comparison test versus CAE show that the material model gives a good correlation for a simple compression test. The small discrepancy which exists between test and CAE can be explained by the friction between the device and the specimen, as the friction coefficient between the testing device and the specimen is not well known.

4.4 Bulge test

In order to calibrate the model for biaxial damage, a bulge test was performed. A cylindrical specimen is clamped above a semi spherical punch which pierces through it at a constant velocity. The calibration for biaxial damage is done by reverse engineering. The k damage value is obtained by simulation then knowing the k_c damage parameters from uniaxial tensile test, and the triaxiality ratio, C_a parameters can be found (equation 2).

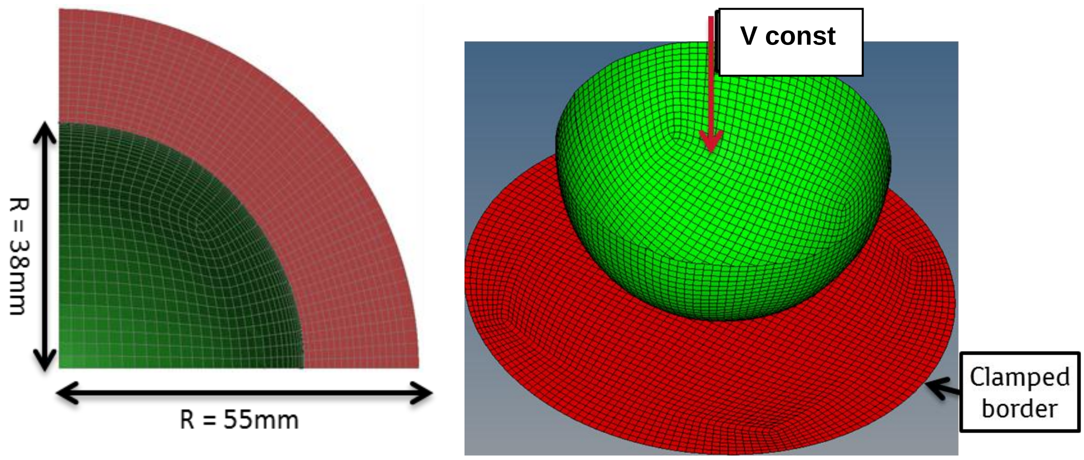


Fig.12: Bulge simulation setup

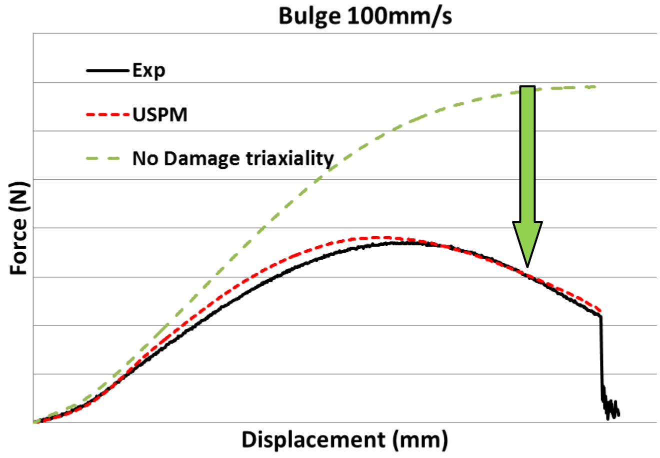


Fig.13: Bulge test correlation result

The extended version of the damage evolution implemented in the model allows the consideration of the rapid damage evolution which can be noticed in our polymer under biaxial loading.

5 Validations

The material calibration done, a validation was necessary to confirm whether or not it was suitable for our intended used case. In order to do so, 2 sets of test were performed: a drop test on a polypropylene box and a lower leg impact test on vehicle.

5.1 Polypropylene box drop test

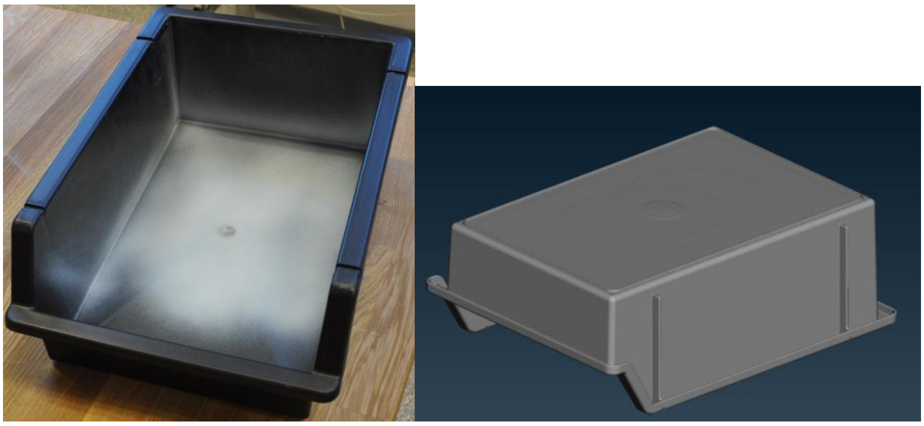


Fig.14: Polypropylene box used for test

The polypropylene box was used as specimen due to its relatively simple shape and the complexity of the loading condition depending on the impact location. This allows us to have complex loading condition while reducing as much as possible geometric effect.
In order to have some high level of complexity and a "non-standard" triaxiality ratio, it was decided to perform a drop tower test on the corner of the box. The test input conditions are the following: target velocity 10m/s, target kinematic energy 290J.

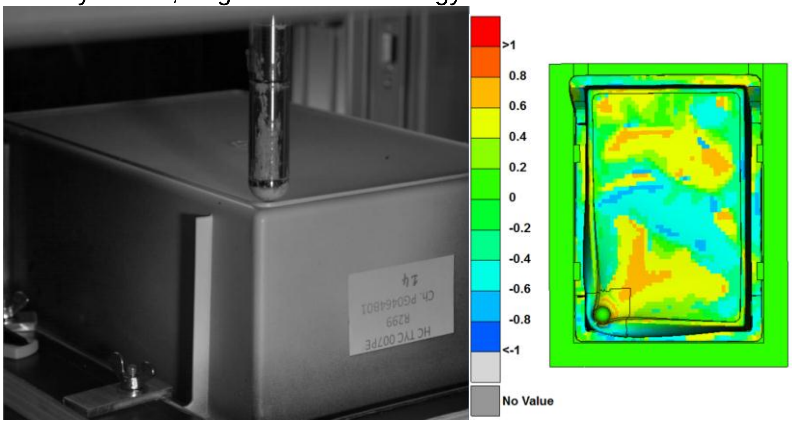


Fig.15: (Left) Drop tower test on polypropylene box, (Right) Stress state (triaxiality ratio) for corner impact.

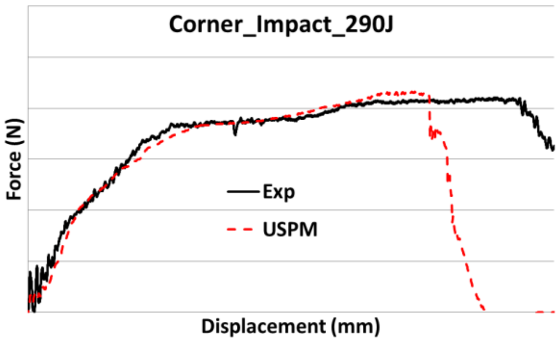


Fig.16: Correlation drop tower test on polypropylene box

The material model captures correctly the main events exhibited by the box up to a certain point where it fails prematurely. This early failure has 2 possible root causes:

1. Our material model suffers from strain localization thus accelerating the damage evolution (Fig.17:)
2. Mesh discretization. Even though the box has a simple shape, it has some side ribs. During the impact a failure occurred at this rib location which is difficult to predict without the use of small shell mesh size or solid elements (Fig.18:)

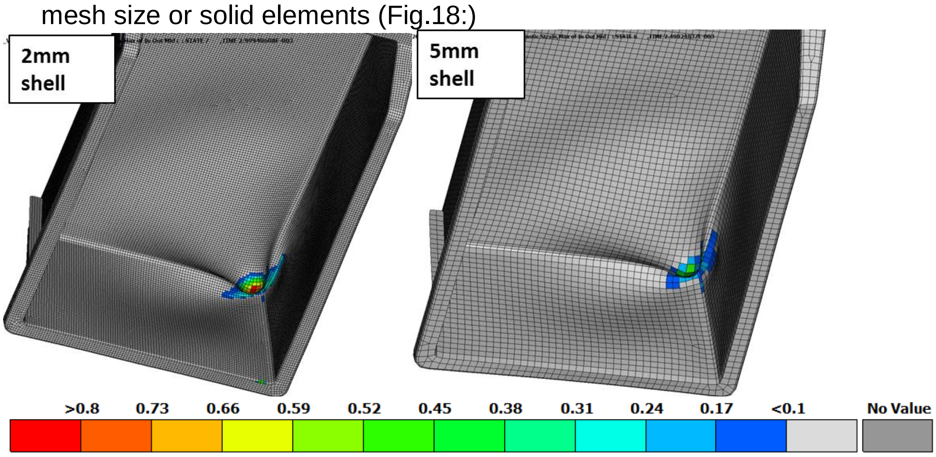


Fig.17: Equivalent plastic strain difference between 2 meshes size at a certain time.

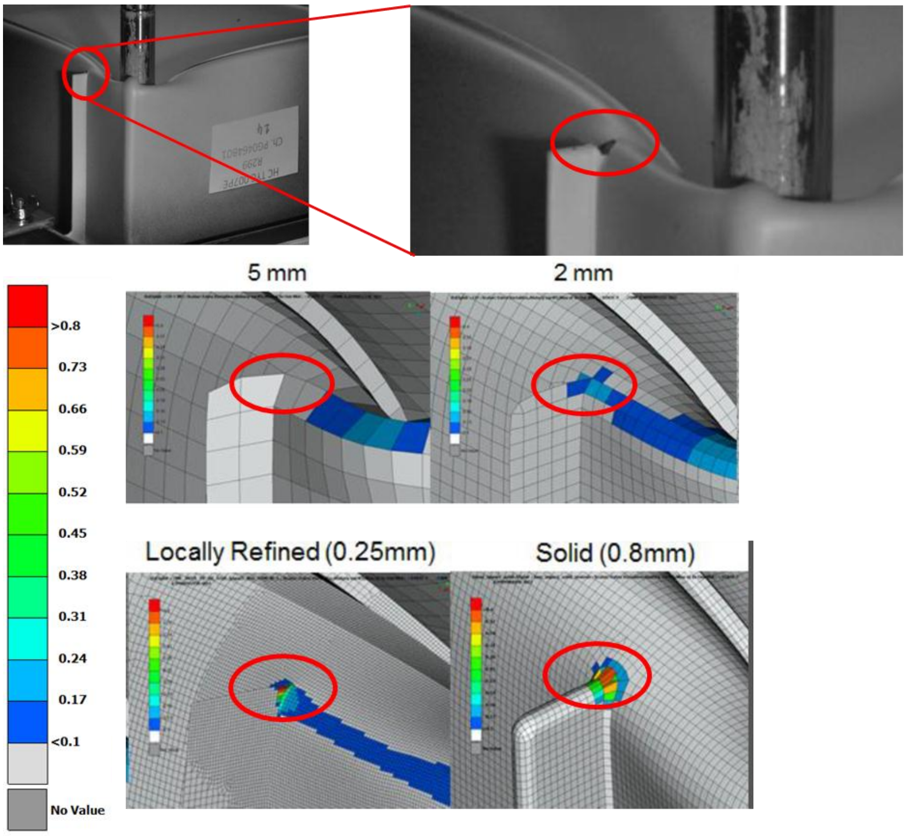


Fig.18: Ribs failure highly dependent on mesh discretization

5.2 EEVC17 test

Once the material model was validated with the paper box and its limitation found, it was decided to investigate how the model behaves for actual vehicle development purpose. For this purpose, a lower leg impact following the EEVC17 has been performed as polymer deformation is not as big as to lead to the strain localisation.

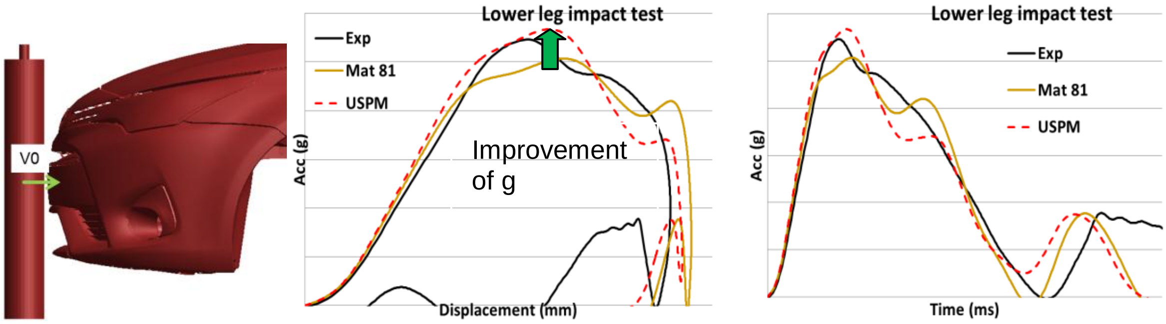


Fig.19: Lower leg impact test: New model able to better capture peak acceleration

The new material model developed is able to give good correlation to a certain degree of test vs. CAE, and to match the peak acceleration felt by the lower leg. Also, all the main events are correctly captured by the model. There is still a discrepancy between test and CAE; however there are still some CAE oversimplifications which cause this discrepancy:

- Mesh discretization imperfection
- Connection and contact between vehicle parts
- Moulding effect (weld line, skin core effect)
- Tests variability

6 Conclusion and perspectives

The deformation and behaviour of ductile polymer were investigated under impact loading. From this analysis a material model suitable for its simulation has been developped. A visco elastic model based on maxwell elements was implemented to describe the strain rate effect on the elastic response. The rhagava yield surface has been implemented as our polymers exhibit a difference in yield value in function of triaxiality. On top of it, a semi-empirical damage evolution dependent on stress triaxiality and plastic strain has been implemented as it has been noticed under biaxial loading our material show a crazing behaviour.
It has to be noted thought that some assumptions were taken into consideration when working on this model which currently limit its usage to a certain type of ductile polymers. Those assumptions are the following:

- Isotropic material and isotropic damage
- Elastic modulus and hardening curve similar in tension and compression

Also during the validation of this model, it has been found out that our model is sort of suffering of strain localization. This issue is currently under investigation in order to remove the dependency to mesh size and hence make it more accurate.

7 Literature

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