Characterization of Polyolefins for Design Under Impact: from True Stress/ Local Strain Measurements to the F.E. Simulation with LS-Dyna Mat. SAMP-1

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Summary:

Optical strain measurement for the mechanical characterization of polymers, and in particular of polyolefins, is becoming a common practice to determine the parameters to be used in a finite element analysis of crash problems.
This experimental technique allows measuring the strain locally on the specimen, so that it is particularly suitable when the deformation is localized, as in the case of polymers: therefore a more accurate description of the behaviour of the material is obtained.
By so doing, it is possible to describe the material constitutive law in terms of the true, local strain and of the true stress. As these data are those needed by the most complete material models developed for impact calculation, it is clear that this technique is particularly suitable for coupling with the most advanced material models currently available in the F.E. codes, as for instance with Mat 187 (SAMP-1) of LS-Dyna.
The local measurement of the strain can also be used for evaluating the volume strain, whose evolution with the increasing strain shows that for PP-based material the deformation is not isochoric in most the cases. The observed increase in the material volume reflects the fact that voids generate and coalesce within the material, possibly resulting in fracture.
The measure of the volume strain, computed as the trace of the strain tensor, is here used for determining the damage function utilized by the damage model implemented in SAMP-1. The effective stress is here estimated as the stress which would be measured if the deformation was isochoric, and it can be assessed on the basis of the measurement of the longitudinal local strain only. Corresponding to each value of longitudinal strain, the volume strain is then used to calculate the ratio between the effective and the true stress.
Adopting this procedure, the damage function is thus determined without the needs of repeated loading-unloading tests used to derive the damage parameter from the unloading slope, which is furthermore difficult to be measured.
As an application, the results of the numerical reproduction of a benchmark test, consisting in a drop test on a polypropylene box, are presented and discussed

Keywords:

Crash Simulation, polymers, mechanical testing, material modelling, damage models

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1. Introduction

The fundamental idea behind the construction presented in this note is the observation that the increasing complexity of the material laws specifically developed for the simulation of thermoplastics is to be assisted by adequate experimental support, which should sustain the numerical analyst with an appropriate and *coherent* set of data.

In the recent years, constitutive models for the description of polymers, including important phenomena like necking, crazing, strain rate dependency, unloading behaviour and damage, different yield surfaces in compression and tension and strain rate dependent failure have been presented and introduced in commercial codes. The material model SAMP-1 available in LS-Dyna is a typical example of the new generation of material models for the description of polymers, in order to allow a reliable prediction of structures made of such materials.

On the other side, new experimental techniques have been developed in the recent years to support the F.E. models with more reliable and more precise input data sets. In particular, the introduction of optical methods for strain measurement has opened a real opportunity for polymers characterization. In previous papers [1,2] the authors have shown how these measurements can be useful for increasing the quality of F.E. prediction in impact analysis. An experimental benchmark test was then presented [2,3], and its reproduction with numerical simulation was introduced to validate the whole approach.

The present paper extends the validation to a wider set of materials and experimental conditions.
Moreover, purpose of this memory is also to address a possible way to use optical strain measurement to derive the input data for a damage model. The validation of this further approach to a set of benchmark tests is also within the scope of this paper.

2. Optical strain measurement: method description

The local behaviour of a polymeric material can be easily and efficiently investigated through optical strain measurement [1,2,8]. Here we will briefly overview the fundamentals of this approach, concerning in particular its application to tensile testing.
In a basic embodiment of the method, some markers are disposed onto the surface of the specimen subjected to tensile test; a video sequence of the test is recorded at high speed, and by means of a dedicated motion tracking software the displacement of the markers is followed and their position recorded corresponding to each frame. From the relative displacement of two selected markers the local value of the strain is derived; by appropriately choosing the measuring points on the sample, one can determine the strain both in the directions longitudinal and transverse with respect to the direction of the force applied, thus allowing also to measure the actual specimen cross section.
At the same time the synchronization with the force signal, simultaneously measured and associated to each frame, allows to couple the value of the strain to the value of the force, and finally, through the actual cross section, to the true stress. By so doing, the local strain – true stress curve is build.

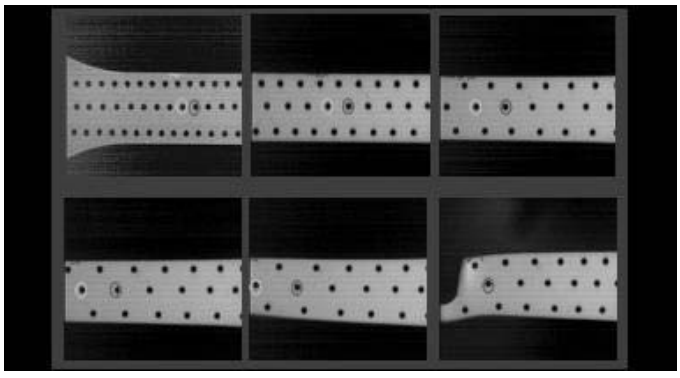

Fig. 1: Example of images for motion tracking

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3. Optical strain measurement: output data

Based on the measurements of the displacements of the markers, as described in the previous paragraph, some definitions of strain are here introduced and will be used in the following. The nomenclature used for the stress is also here below indicated. The definition of “engineering” and “true” values here reported is in agreement to previous literature [12].

First, the engineering strain ε_{eng} and engineering stress σ_{eng} are evaluated starting from the crosshead displacement ΔL and the force F, respectively divided by an appropriate initial length L_0 and the initial cross section A_0 as:

$$\varepsilon_{eng} = \frac{\Delta L}{L_0} \tag{1}$$

$$\sigma_{eng} = \frac{F}{A_0} \tag{2}$$

The “true” local strain values ε_{true} are defined by taking the logarithm of the current distance between two selected markers and their distance before the application of the load; the “true” stress σ_{true} is instead defined as the ratio between the force signal F and the current value of the cross section A; thus, indicating with d*l* the local variation of distance between two markers evaluated along the direction *i*:

$$\varepsilon_{TRUE,i} = \ln\left(\frac{l_0 + d\,l}{l_0}\right)_i \tag{3}$$

$$\sigma_{TRUE} = \frac{F}{A} \tag{4}$$

Based on this definition, one will obtain the longitudinal or the transverse deformation by taking the distance between the selected markers along the appropriate direction. With the assumption that the deformation along the thickness direction is the same as along transverse direction, the current section area *A* can be easily determined.

Additionally, one can determine the values of stress which would occur in the hypothesis of isochoric deformation, as requested by most of the codes. In this case the transverse strain is not measured, but is derived from the measured longitudinal strain applying the hypothesis of volume conservation. This leads to the stress value which in the following will be labeled as “Constant Volume stress” $\sigma_{cv.}$ as:

$$\sigma_{CV} = \sigma_{ENG}\left(\frac{l_0 + d\,l}{l_0}\right) \tag{5}$$

4. Input to SAMP-1

One of the more interesting features of SAMP-1 is that the all material data can be introduced in tabular form: the user can directly input measurement results from uniaxial tension, uniaxial compression and simple shear tests in terms of load curves giving the yield stress as a function of the

corresponding plastic strain. Any time-demanding or complex intermediate manipulation of experimental data to derive material parameters is not requested, no fitting of coefficients is demanded to the users. This is extremely user-friendly; accordingly, the curves measured from tensile tests – obtained as described in paragraph 2 - can be directly provided as an input to Ls-Dyna, although, as a common practice, smoothing the curves and selecting a reduced number of points is suggested.
If no damage model is used, the code allow the introduction of "true" stress values as defined by the (4); otherwise, as it will be explained in the following, "effective" stresses will be introduced.
The strain rate dependence is described through the introduction of multiple load curves corresponding to different values of the plastic strain rate. Accordingly, for the results presented in this paper four tensile tests at nominal strain rates of 0.04, 0.4, 4 and 100 s^{-1} have been used for the description of the materials.
An average Plastic Poisson coefficient has been used for the simulation, 0.15 for the copolymer, 0.13 for the glass charged material, 0.12 for the mineral filled PP used in the present work.
As far as the introduction of compression data is concerned: as compression data were not available, reference has been made to a work by Berstad et al. [11], were a compression curve for a PP-based material was presented. This curve has now been used to scale the available quasi static curve, to obtain a working curve for compression.

5. Damage modelling and traditional measurements

In this paragraph we will briefly review the approach commonly used in damage modelling, with the purpose of showing how the local strain measurement from optical methods can assist the CAE engineer in setting the model and the data for the F.E. analysis. In particular the approach will then be focused on the preparation followed for the Ls-Dyna material model SAMP.1.

Several damage models can be found in the literature. In the simplest formulation of ductile damage, a variable d_n is introduce to represent the relative area of cracks or cavities, evaluated locally with respect to a direction n. d_n =0 corresponds to the undamaged or virgin state, d_n =1 corresponds instead to the breaking of the volume element; $0 \le d_n \le 1$ characterizes the damaged state. In the general case of anisotropic damage consisting of cracks and cavities with preferred orientations the value of the scalar variable d_n depends on the orientation of the normal; the corresponding intrinsic variable can be represented by a tensor [4,6]. In the case of an isotropic damage, with cracks and cavities with an orientation distributed normally in all directions, the variable d_n does not depend on the orientation n and the damaged state is completely represented by the scalar *d.*
The concept of effective stress σ_{eff} is then consequently introduced, as the stress calculated over the section which effectively resists the forces. The effective stress is defined as:

$$\sigma_{eff} = \frac{F}{A_{eff}} = \frac{F}{A(1-d)} = \frac{\sigma_T}{1-d} \tag{6}$$

In the f.e. analysis, failure is usually approximated by the deletion of the element; in most damage models the damage variable serves as a failure variable simultaneously and a critical value for the damage parameter is assigned as the one at which the onset of element deletion occurs. The actual deletion of the element is then postponed by a rupture value d_{FAIL}.

When this approach is followed, the user must usually provide a load curve giving the parameter *d* as a function of the plastic strain under uniaxial tension.

A problem then may arise, as damage is not directly accessible to measurement. In the traditional approaches [6] reference is made to the Principle of Strain Equivalence, assuming that all the different behaviors (elasticity, plasticity, visco-plasticity) are affected in the same way by the damage. Accordingly, the damage parameter is recognized as to effectively reduce the elastic modulus: the elastic modulus of the damaged material E_d is related to the elasticity modulus of the undamaged

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material *E* as $E_d = E\left(1-d\right)$; thus, if the modulus *E* of the undamaged material is known, one can determine d as a function of the plastic strain ε_p as:

$$d\left(\varepsilon_p\right) = 1 - \frac{E_d\left(\varepsilon_p\right)}{E} \tag{7}$$

The usual practice is then to perform unloading at different strain values during the uniaxial tensile test, then using the unloading slopes to estimate the damage parameter for a given plastic strain.
This general approach can be transferred to the damage model(s) in SAMP [5]: here, the damage curve is to be introduced as a function of the equivalent plastic strain, to fit experimentally determined unloading moduli at different values of plastic deformation; the damage curve is then combined with a hardening curve giving effective yield stress in function of effective equivalent plastic strain; then the user can either chose whether providing effective or true stress values.

This approach appears very simple and user-friendly; however, some difficulties are evident in the testing and data manipulation required. First of all, by so doing, building up a damage curve implies the repetition of a certain number of tests, as each single point on the curve requires a dedicated tensile test. Moreover, the measurement of the modulus is always critical, due to the nonlinearities in the material: a best straight line in the graph representing the unloading is not easily defined.
All this considered, it seems that for an easier and quicker utilization of a damage model, there is a need for a more immediate and practical derivation of the material parameters: purpose of this paper is to show that the local strain measurement with optical methods can practically and efficiently assist the CAE engineer in determining the damage parameter for the analysis.

6. Damage modelling and optical measurements

According to a traditional approach, the mechanical behaviour of polymers was often studied using experimental protocols set and tuned for the investigation of metallic materials; consequently, some simplistic assumptions were generally used without any experimental verifications, as, for instance, the assumption of isochoric deformation.
On the contrary, in the recent years the development of advanced experimental techniques has allowed to analyse the stress-strain response of polymeric materials without any restrictive hypothesis during data processing over a large range of strain rates. The new methodologies have shown that plastic deformation in these materials does not obey incompressibility assumption, and that damage processes like voiding or crazing result in fact in volume expansion of the deformed specimens.
Several works have been published on experimental analysis on polymeric materials. In particular, in [7] SEM observations on an unfilled and filled-polypropylene samples showed that in both the cases voiding damage results in volume change and significant decrease in Young modulus; here the authors also note that for the unfilled polypropylene voids are nucleated in a very early stage of deformation (strain 0.2), and as the strain increases the number and size of voids increase significantly.
According to the experience of authors, the onset of damage may occur at even lower strains; in particular in [9] a measurement of the volume change applied to different PP-based compounds is reported. Moreover here, as in [7], measurements show that the volume change mechanism are not strain rate sensitive.

We now show a practical method to derive the damage parameter from a tensile test.
Let us isolate an element of volume V_0 within the undamaged solid, before any deformation, i.e. before the application of the tensile load. Be X_0, Y_0 and Z_0 its dimensions in the directions of a Cartesian reference frame; let us consider a tensile test, where the element is stretched in the direction Z, being d*x*, d*y* and d*z* the infinitesimal variations of its dimensions along the three axis. Accordingly, the initial volume defined as V0=X0 Y0 Z0 becomes V = (X_0+d*x*)(Y_0+d*y*)(Z_0+d*z*); the basic assumption is that the volume has varied due to the creation of voids within the material.
Thus, be δV *the* volume variation, hence corresponding to the volume of the voids; then introducing the definition of true strain ε_i in the three directions i=X,Y,Z, the volume strain, indicated with *m*, is:

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$$m := \varepsilon_X + \varepsilon_Y + \varepsilon_Z = \ln\left(1 + \frac{\delta V}{V_0}\right) \tag{8}$$

Note that from optical strain measurement all the local true strains can be measured and consequently the quantity *m* is available.
Experimentally, the "true" stress σ_T is calculated as the ratio between the force F and the actual cross sectional area *A* of the specimen, being $A = (X_0+dx)(Y_0+dy)$. With simple passages one obtains:

$$\sigma_T = \frac{F}{X_0\, Y_0}\left(1 + \frac{\mathrm{dz}}{\mathrm{Z}_0}\right)\mathrm{e}^{-m} = \sigma_{eng}\ \left(1 + \frac{\mathrm{dz}}{\mathrm{Z}_0}\right)\mathrm{e}^{-m} \tag{9}$$

Where the quantity σ_{eng} is the engineering stress previously defined. Now, referring to the definition of constant volume stress, from the (9):

$$\sigma_T = \sigma_{CV}\ \ \mathrm{e}^{-m} \tag{10}$$

Here, assuming as a working hypothesis that the volume of the undamaged material remains constant during the test, the effective stress is thus identified with the constant volume stress, i.e. $\sigma_{eff} = \sigma_{CV}$;
Then from the (6) the damage parameter can be derived as:

$$d = 1 - e^{-m} \tag{11}$$

An example of the damage parameter d as a function of the strain, measured on a copolymer (the same will be used in the test presented thereafter) is on fig. 2.

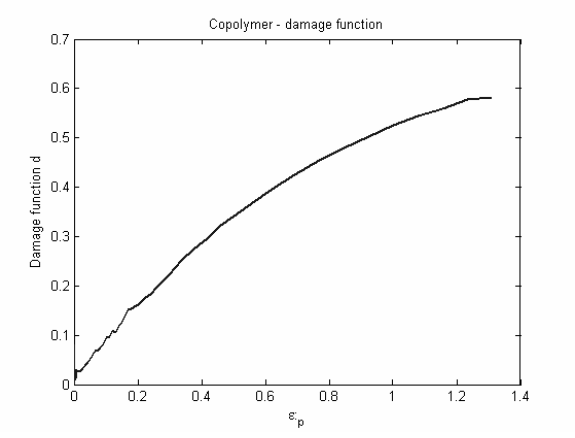

Fig. 2: Damage function measured for the copolymer, as a function of the plastic strain

7. Experimental test for validation

The following test has been designed and used at Basell – Ferrara Labs - to validate material and finite element models [2,3]. An image of the test assembly is in fig. 2 A Polypropylene box (dimensions

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300 x 200 x 120 mm, average thickness 2.4 mm) is impacted in a drop test, using a spherical impactor with a diameter of 20 mm; the overall impacting mass *M* was either 5.184 Kg or 10.184 Kg; the impactor falling height *h* was in the range from 0.2 to 1.0 m. Several tests, varying the experimental conditions, have been executed.
The impact point on the box was chosen to be sufficiently (about 40 mm) far from the injection point; lubricant grease was used at the interfaces box/impactor and box/floor to reduce the friction.
A load cell was mounted on the impactor, and its signal was used to obtain the impactor acceleration. Its velocity at the onset of the collision with the box was calculated as $v = \sqrt{2gh}$; this value was verified by recording a high speed movie, then tracking a marker located onto the impactor itself. The impact velocity was then used to double integrate the acceleration signal to determine the impactor displacement.
The curves force vs. displacement were then stored and used as experimental benchmark.
Three materials have been used for this test, exploring a variety of products, covering a wide range of applications in the automotive panorama. A first material, labelled in the following as “GF”, is a short-fiber glass reinforced material, whose application is for automotive interiors; a second material, labelled in the following as “COPO”, is a copolymer, designed for interior trims. Finally, a test is presented for a 20% mineral filled copolymer, typically used for bumpers. This material will be labelled in the following as “TC”.

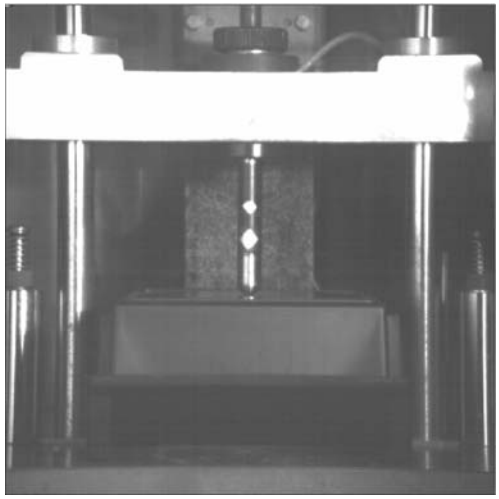

Fig. 3: Testing assembly

Test Label	Material	Mass (Kg)	Height (m)	Energy (J)	Break? (Y/N)
GF1	Glass Fiber 10%	5.184	0.6	31	YES
COPO 1	Copolymer	5.184	0.6	31	NO
COPO 4	Copolymer	5.184	0.98	50	NO
COPO 7	Copolymer	5.184	0.8	41	NO
COPO 10	Copolymer	10.184	0.49	49	YES
TC4	Mineral filled 20%	5.184	0.98	50	NO

Fig. 4: Table. Overview of the tests

The tests carried out are briefly summarized in the table on fig. 4. Together with the Test label and the material specification, for each experiment presented the mass, the falling height and the corresponding impact energy are reported. The last column in the table indicates whether the sample broke at the end of the experiment.

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8. Results

All the results here presented have been obtained with Ls-Dyna ls971s, Revision 7600.129.
The simulation of the impact on the box made of short-fiber glass reinforced material has been carried out using Mat. 187 coupled with the damage model, as described, on a mesh of average 5 mm side, locally refined to about 2 mm in proximity of the impact point and of the box vertexes. The results are in Fig. 5. The obtained curve force-displacement is well overlapped with the experimental data, although the computed onset of the break is delayed to higher strains. As also visible from the pictures in Fig. 5, the location of the break onto the box is correctly assessed.

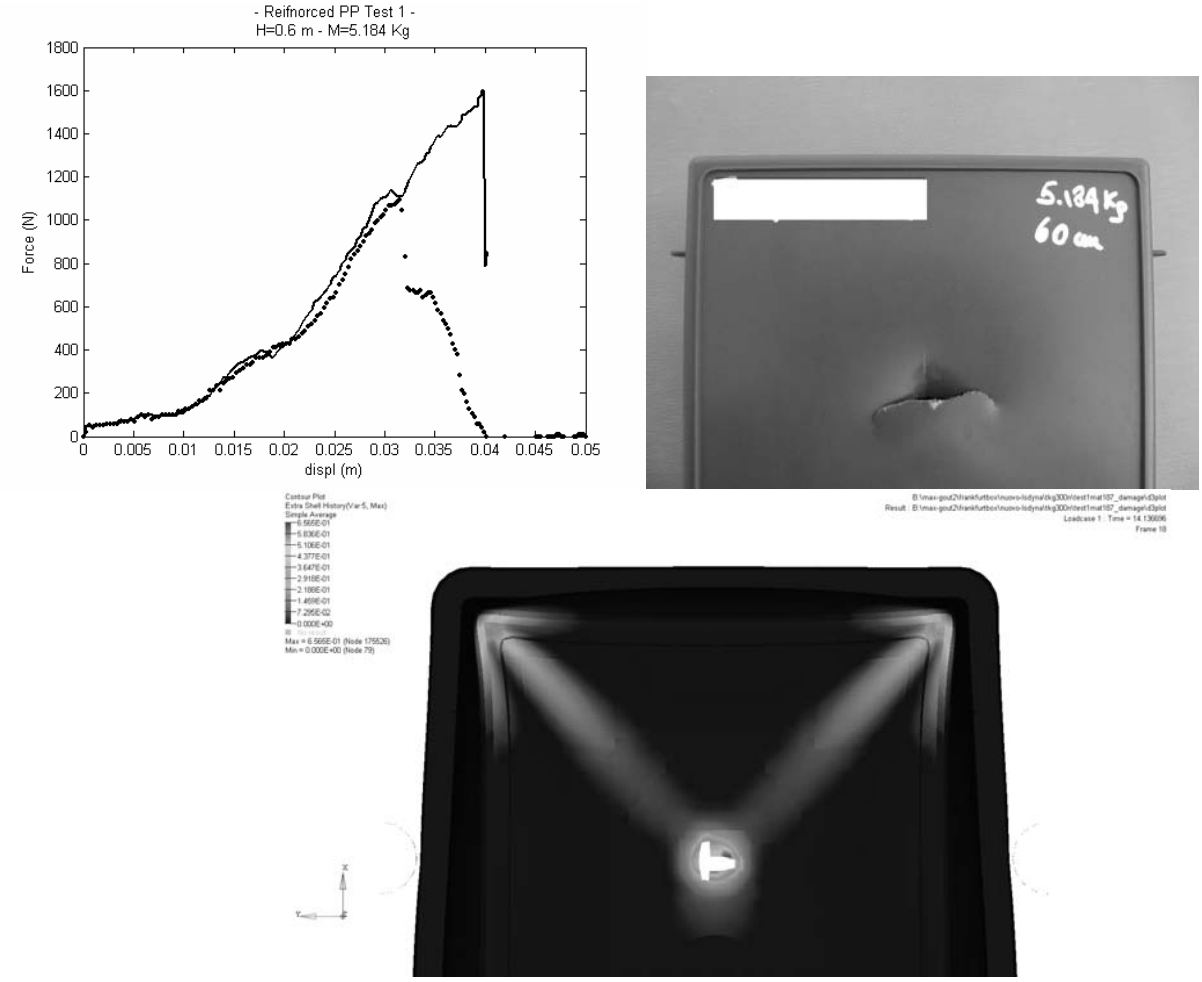

Fig. 5. Results for material "GF" – Top left: Curve force-displacement: simulated (continuous) vs. experimental (dots); Top right: specimen after test; Bottom: damage function – Extra Shell History 5 - after test simulation

Four experimental conditions have been tested for the box made of a copolymer (label "COPO"), referring to various combinations of falling mass and impact height. In all the cases, a 5 mm mesh was used. The curves force vs. displacement are reported in fig. 6, where together with the approach using a damage function, the results from a simpler approach based on the introduction of "true" stress curves are presented. A very accurate prediction is observed in general. These results are quite acceptable for the designer, considering also that further improvements can derive from using advanced options available from mat. 187, as the dependence of the failure criteria on the strain rate, or from a fine tuning of the triaxiality factor, and/or from the possibility of taking into account the element dimension in the failure criteria: all these options were not within the scope of the present work.

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As visible, the utilization of a damage model allows highlighting critical areas in the component. As visible from fig. 8, which refers to the test COPO1, the damage distribution obtained from simulation is in good agreement to what experienced in the real test.
One note about the case COPO10, which is characterized by a physical rupture following the impact. In this case a less accurate prediction is obtained using the damage function; this is believed to be related to the occurrence of the fracture and to the needs for a refined mesh (as per case GF) when a damage model is used. The prediction remains well accurate instead when using the "true" stress formulation.
Finally, the case TC4 relative to the mineral filled material offers also a good prediction, although in this case the material orientation – not kept into account in the model, for which only material data measured in the direction transverse with respect to the flow lines have been used – is believed to affect the result.

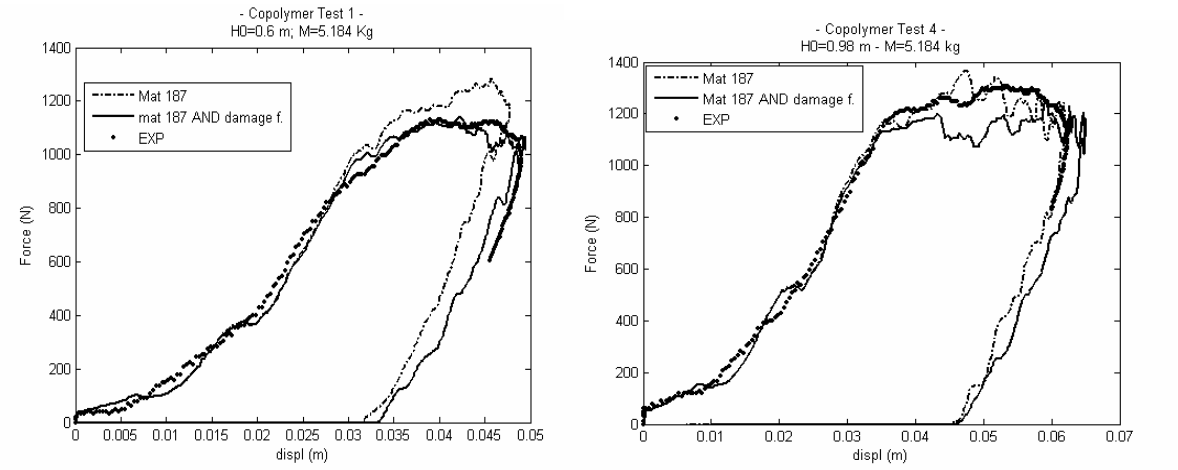

Fig. 6: Results (Force vs. displacement) for tests COPO1 (left) and COPO4 (right)

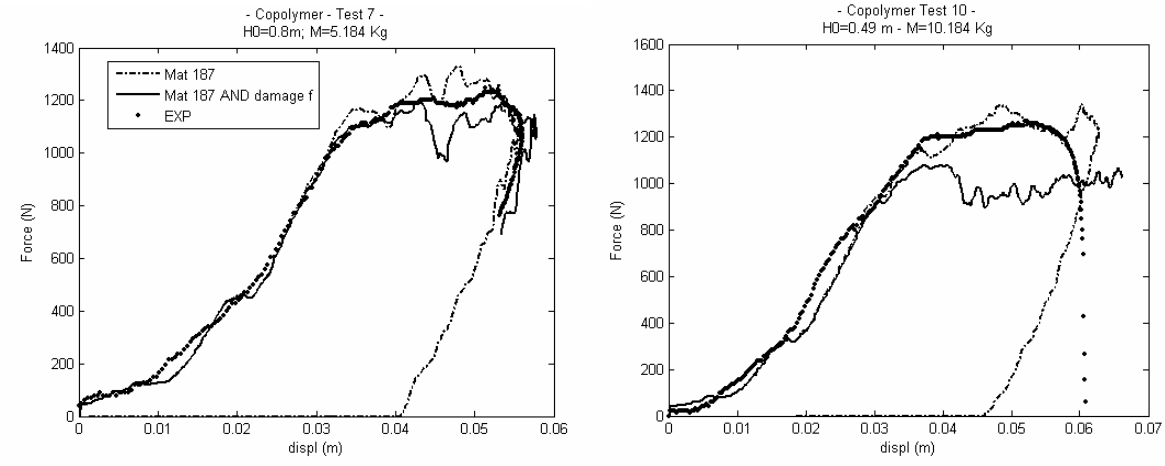

Fig. 7: Results (Force vs. displacement) for tests COPO7 8 (left) and COPO10 (right)

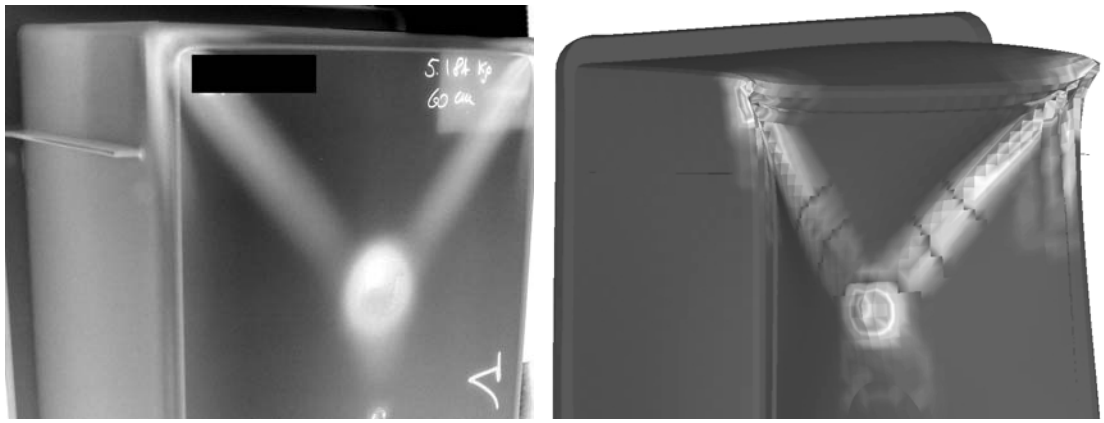

Fig. 8: Damage on the tested exemplar (left) and damage function distribution from simulation (right). Test COPO1

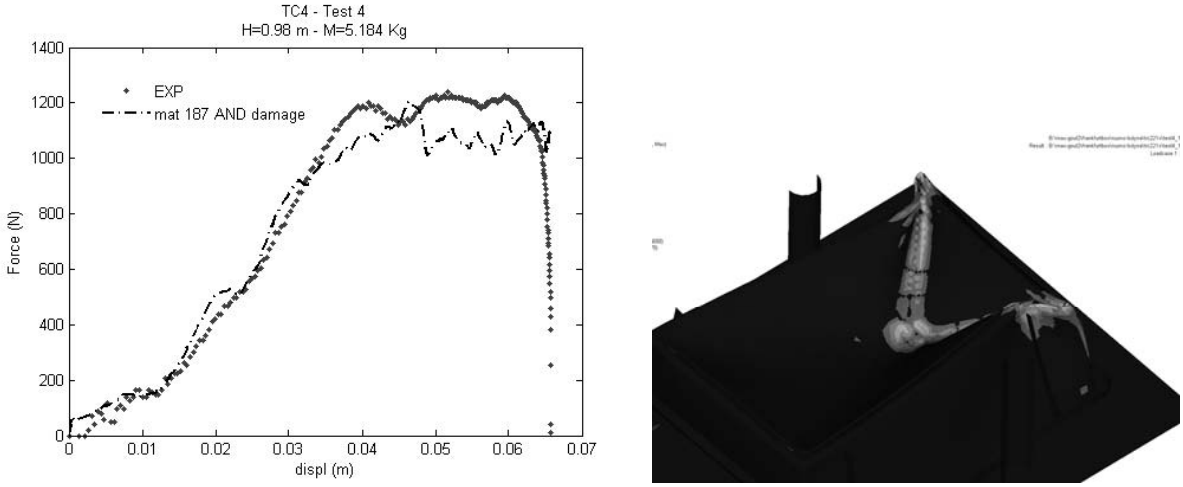

Fig. 9: Result (Force vs. displacement and damage distribution) for test TC4

9. Conclusions

The optical strain measurement applied to tensile testing of polymers, and in particular of polyolefins, provides a detailed description of the material behaviour, which can well be suitable to be coupled with advanced material models, as Ls-Dyna Mat. 187 (SAMP-1), specifically dedicated to polymers.
In fact, experimental data coming out from the measurement equipment can be easily introduced into a Mat.187 card, without the needs for significant manipulation, other than normal filtering to reduce fluctuations. Following this simple approach, the authors have compared the results from simulation to a wide set of experimental data, in an application previously developed by Basell, and consisting to a drop test on a polypropylene box.

In this paper, the experimental test has been extended to various experimental conditions, exploring also different materials, which together cover a wide range of applications in the automotive industry.
In all the tested cases, coupling the material model SAMP-1 with data from optical strain measurement has provided a very accurate reproduction of the experimental test.
Moreover, the authors have suggested a way to derive the data for a damage model, always on the basis of optical strain measurement, applied to tensile tests. Compared to Prior Art methods, the suggested procedure tremendously simplifies the operations needed to derive the damage parameters.
When this approach has been applied to the numerical reproduction of the impact test, the results have been definitely accurate, also allowing indicating critical regions in the tested component.
A fine tuning of the parameters available in Mat.187, together with the introduction of its advanced options, is expected to further increase the accuracy of the analysis.

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10. Aknowledgments

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11. Literature

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