Numerical simulation of the laser scoring line behavior in airbag deployment

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1 Abstract

The airbag door system is one of the most delicate aspects in the design phase of a car instrument panel: seamless systems are increasingly used, which combine styling criteria with good functional performances. These systems typically include a tear seam, which may be obtained through laser scoring, to pre-determine the location of the opening during airbag deployment.
The design of the scoring line is currently validated through experimental tests on real life exemplars, submitted to airbag deployment, resulting in high development times and relevant costs. This is the main reason which suggests proposing numerical simulation in the design phase, not to substitute actual part homologation by testing but in order to limit the scope and complexity of the experimental campaign, thus reducing the development costs and the time to market.
So far, modeling the scoring line has been difficult due to limitations in the testing methods and simulation codes available to the industry. The methodology proposed in this paper takes advantage from the availability of a material law as LS-Dyna SAMP-1, with polymer-dedicated plasticity, damage model and strain-rate dependent failure criteria, which is supported by local strain measurement used for material characterization.
The method, here described in detail, is validated on a benchmark test, consisting in the real and virtual testing on a variety of scoring profiles obtained on a polypropylene box submitted to high speed impact test.

2 Introduction

2.1 Purpose of the activity

Up today, the development of a component is made by a huge number of experimental tests, made to calibrate the designing parameters of the scoring. This generates a big amount of work made in conjunction by the car maker and the component supplier: this is why a methodology to virtually simulate this kind of phenomena is desirable: once the methodology will be ready to be used into the designing phase of the cover bag, this could reduce the amount of experimental test to calibrate the component and reduce the development cost of the component itself.

It is believed that CAE modeling will not replace the experimental test, but it may constitute a support of paramount importance to the design activity. On one side it will help reducing the scope of the experimental campaign; on the other side, it will provide a valuable insight into the part behavior, which is extremely useful for possible modifications and ameliorations in the design phase.

2.2 Prior art

Few studies are available in the literature. Several possibilities for scoring line behavior modeling were overviewed by G.Spingler [1]: four approaches were here identified, and in particular the article was focused on two of them. According to a first idea, the area affected by scoring was modeled using a modified material law, by which the properties locally assigned to the material in the laser scoring area were modified, with respect to the unscored material, by adding a damage function. The damage function here considered was a piecewise function, whose parameters needed to be found through experimental tests. An alternative approach was considered in this publication, where the elements in the mesh in which a scoring line is processed were modeled by properly reducing their thickness, while keeping the same material properties as for the unscored material. In this article

Spingler gave preference to the first approach, discarding the one based on thinning elements as this caused the computational times to be higher and not suitable for industrial application.
The first approach outlined in [1] was also followed in other works [2,3]. Within this framework, Olivero et al. [2] presented a solution with a material law taking into account not isochoric deformation and pressure sensitive yielding. For the shell elements in the scoring area the material characteristics were scaled from those of the base material, according to geometric parameters in a comparison with a 3D simulation, based on the simulation of bending tests. The model was validated in a reproduction of an experimental case, consisting in an impact of a pneumatic cylinder onto an airbag cover; the results were promising, although the authors recognized the possibility of further improvements to take into account different behavior in compression and shear and the influence of the molding process as well.
In Rodenburg et al. [3] a finite element approach was proposed, where several material mathematical formulations were investigated, corresponding to material laws available in the commercial code LS-Dyna. The final choice was for a strain rate dependent law based on Von Mises plasticity. In order to provide the input data for this law, the author highlighted the needs for strain rate dependent data, which should cover high strain and high strain rate ranges. The results there presented were only preliminary as strain rate dependent data were not available.
Muñoz et al.[4] presented a different computational strategy, where half of the points that composed the breakable seam line were removed from the finite element model to easier simulate the local weakening due to scoring.
An approach according to the alternative solution presented in [1] was used by Wieczorek at al.[5]. Here a miniature 3-D solid model was built and used to determine an equivalent thickness of a similar shell model, then developing a transfer function which took into account other laser scoring parameters as hole diameter, hole pitch and remaining wall thickness. However, this was coupled with a Von Mises based material law as MAT_024 of Ls-dyna. Furthermore, a validation of the model was not presented.

2.3 Present work

The approach based on thinning elements is reprised in the present work, taking advantage of the evolution of the material laws in the computational codes that occurred since Spingler's article, and also of the evolution in the hardware that makes CPU times shorter and thus affordable for industrial application. A further key point in the present work is the evolution of material characterization which proved to be suitable for providing data for Finite Element simulation, as Nutini and Vitali showed [6].

3 Materials and methods

3.1 Material data and material law

In the airbag deployment, the portion of the instrument panel affected by laser scoring is subjected to high strains and high strain rates, due to the localization of the deformation. As such, material laws suitable for taking these aspects into account are needed. In particular, material laws based on Von Mises plasticity cannot well reproduce the behavior of polymeric materials at high strains [6,7]. It is thus better to use material laws based on a different mathematical implementation of plasticity. Furthermore, due to the occurrence of high strains in a very fast transient, local high strain rates develop which need to be properly modeled. Since typical Polypropylene-based materials used for instrument panel have strain rate dependent mechanical characteristics [7], a material law which enables inputting strain rate dependent properties is recommended [3,4].

The material law commonly referred to as "SAMP-1" available in LS-dyna [8] satisfies both the requirements above. SAMP-1 models non Von-Mises yield behavior, and attempts to account for deviatoric and volumetric flow. Additionally, strain rate dependent behavior is implemented.

Considering the SAMP-1 law, previous works showed that material characterization based on tensile tests conducted at different speeds can generate input data which lead to virtual predictions closer to reality when the stress – strain input curves are measured using optical tools, as DIC (Digital Image Correlation) [9] or videoextensometry [6,10,11]. The tests used for generating the material data for the present work were carried out accordingly.

In the present study case the material used for the instrument panel was a new product developed by LyondellBasell for Fiat specification, consisting in a mineral filled Polypropylene for injection molding

The study was conducted at a temperature T=-29°C, which is recognized as being particularly critical. The material characterization was accordingly carried out at these temperature. The extension of this study to other temperature of interest, namely T=23°C and T=85°C will be reported in future publications.

The true stress, i.e. the stress measured dividing the measured force by the actual cross sectional area of the specimen, is plotted on the left side of Fig. 1 with respect to the local strain measured locally on the specimen. For details about the measurement methodology the reader is referred to the reported bibliography [6,10].
As it is clear from Fig. 1, although the numerical values are not shown, there is a manifest influence of the strain rate on the stress levels; furthermore, material failure, as visible from the values of the elongation at break, is definitely affected by the strain rate.
The curves reported on Fig. 1 suggest that also strain rate dependent material failure must be modeled. This is one more feature which is also easily input in the material law SAMP-1.

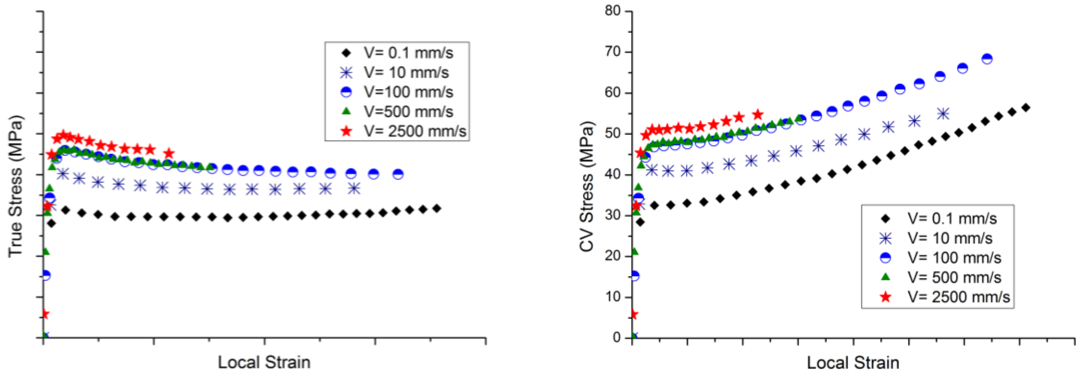

Fig.1: True Stress - Local-strain curves from high speed tensile test on the material used for this study (left); same curves but with stress values corrected under the assumption of isochoric deformation (right)

Being the stress computed with respect to the actual specimen cross section, the curves in Fig. 1 give the most accurate representation of the material behavior [9]: however, in order to model ductile materials using SAMP-1 an alternative choice of input data is suitable and can also provide accurate results with improved numerical stability and additional information, consisting in activating the damage model which is available in the SAMP-1 formulation [6,11,17]. The damage parameter is properly derived from the volume strain occurring during the tensile test, for which the above mentioned local strain measurement technique based on optical means is recommended [6,11,18,19]. An example of a curve for the input damage parameter plotted vs. the local strain is on left side of Fig. 1. Following this approach, the stress-strain input curves for the material law are those computed in the assumption of isochoric deformation [6], which are shown on the right side of Fig. 1 for the material of the present study. Considerations on damage modeling will also be reprised in the following section, but with specific reference on modeling the scoring pattern.
The same measuring technique can be also used to obtain the post-yield Poisson ratio measurement, which is derived from the ratio between the strain respectively along and perpendicular with respect to the tensile direction. An example of a related curve is in fig. 2, right side. Here, both the curves refer to a test at 100 mm/s.

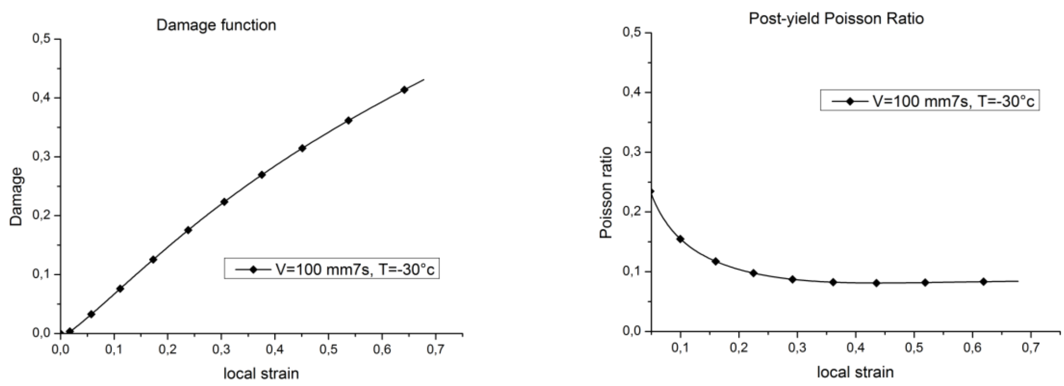

Fig.2: Example of damage function (left) and post-yield Poisson ratio (right) measured at V=100 mm/s and T=-29°C

Additionally, the plasticity description in SAMP-1 requires stress-strain data to characterize the material behavior in shear and compression. Compressive tests were executed according to ASTM D 695-2010 standard, while shear tests were carried out according to a non-standard method at the external laboratories of Datapointlabs, under their protocol M-219 [15]. All the tests were on specimens cut from an injection molded plaque.

3.2 Scoring Line Modeling

The purpose of this study is to tune a methodology which can be practically used in an industrial environment. Accordingly, the computational methodology here presented was developed for shell-based finite element modeling, as solid modeling is assessed as too complex and time consuming for the current state of the art of the technology, with reference both to the computational times needed and also to the complexity of the all operations needed when even only minor change in the part design and geometry are requested.

The basic idea reprised from previous works [1] is that the scoring line behavior can be input in the model through elements thinning, although, as previously noted, said previous work rejected this approach.

The fundamental idea behind the criteria used in our work for thinning the elements in the scoring line is the observation that the scoring pattern can be regarded as a local damage into the material, and, as such, can be treated as in continuum damage modeling according to the Chaboche-Lemaitre approach [10]. The concept of effective stress is introduced, as the stress calculated over the section A_{EFF} which effectively resists an applied force f. The effective stress is defined as:

$$\sigma_{eff} = \frac{f}{A_{EFF}} = \frac{f}{A(1-d)} = \frac{\sigma}{1-d} \qquad (1)$$

In the Chaboche-Lemaitre formulation, the parameter *d* in Eq. (1) is the local damage parameter, which - in its simplest approach of isotropic damage - is a scalar representing the relative area of cracks or cavities.

This concept is here extended to the scored line. It is useful to consider the sketch on Fig.3, where an idealized cross section of a material is represented along the tear seam, showing a plurality of exemplary laser cuts. Each laser cut is here visible as a hole or recess. On the contrary, the portion of original material which has not been eroded by the laser is here visible as a continuum.

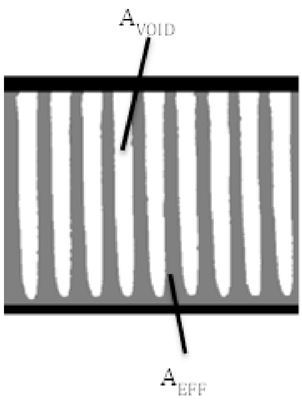

Fig.3: Scored material cross section

Considering the overall cross sectional area as represented, an effective area can be identified as the area not occupied by the laser cuts, thus defining a damage parameter d = 1- ω, ω being the ratio between effective area A_{EFF} s and the overall cross sectional area, as:

$$\omega = \frac{A_{EFF}}{A_{EFF} + A_{VOID}} \qquad (2)$$

where with A_{VOID} we named the part of the cross section area which was eroded by the action of the laser.
We adopt the assumption that the scoring process does not affect the characteristics of the remaining material; this allows to combine the Eqs. (1) and (2), thus considering that scoring can be locally modeled by scaling the local cross sectional area, and hence the local element thickness, of a factor ω defined as above.

3.3 Method Validation

The method here proposed was validated on a benchmark test, consisting in the real and virtual testing on a variety of scoring profiles obtained on a Polypropylene box submitted to high speed impact test.
A validation test must in fact respond to some specific criteria, as:
- The test must be indicative of the behavior of the real part
- The test must be easily simulated through FEM without adding further complications than those arising from seam line modeling
- The test must offer clearly measurable parameters to be compared with simulation
- The test must be "sensitive" to different laser scoring patterns

The validation tool chosen, consisting in a simple polypropylene box of 300 x 200 x 120 mm with an average thickness of 2.4 mm, for which molding conditions are known, was previously used in a variety of testing cases, proving to be an useful tool for validating material laws and simulation approaches [6,14]. For the present work, several boxes were molded; onto the top surface of each box a scoring line was applied with laser technology following a rectangular pattern of dimensions of 140 x 100 mm; these dimensions were such to be comparable to the ones occurring in reality. The vertexes of the rectangular shape were rounded, the injection gate was kept outside of the scored profile. In order to check the sensitivity of the methodology to variations in the scoring profile, five types of scoring patterns were practiced An image of the box with a sketch of the scoring pattern is on Fig. 4.
The scoring profiles considered were obtained by varying the dimensional parameters of the laser cuts, so that for each laser scoring type a different parameter ω was obtained. The tested exemplars were characterized by values of ω ranging from 0.4 to 0.75, classified according to the scoring types in Table 1.

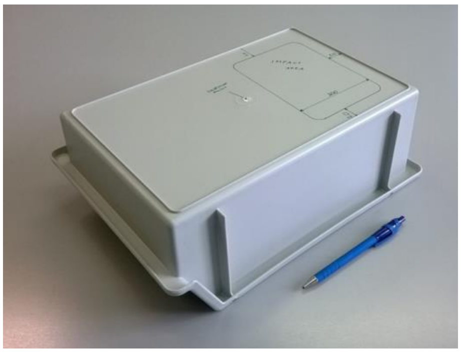

Fig.4: Tested box

Scoring Type	Scaling parameter ω
1	0.4
2	0.7
3	0.43
4	0.53
5	0.75

Table 1: Scaling parameter measured on the scoring types used in this study

The impactor was a 80 mm diameter cylinder, where its axis was aligned with the impact velocity; its top surface, impacting the box, was rounded and machined in the shape of a sphere of 150 mm radius. The impactor was launched at constant speed using a servo hydraulic testing machine, so that it collided the box onto its upper surface at the center of the scored profile; tests were conducted at impact speeds of 1 m/s, 5 m/s and 9 m/s, with temperatures at T=-29°C, to detect critical behavior at temperatures possibly occurring in the reality. In order to carry out the tests the boxes were conditioned for at least eight hours in a climatic chamber, and extracted therefrom just immediately before the test execution. The time interval elapsing from the extraction out of the chamber till the impact was not long enough for the box to significantly change its temperature.

Experimental tests were executed under a combination of such experimental conditions, with at least two replications for each test.. The tests were executed at the Fundacion Cidaut in Valladolid (E).

4 Results and Discussion

This section shows the results of the application of the method here presented to the virtual reproduction of the impact tests on the box under a variety of experimental conditions, conducted on several scoring profiles.
Fig. 5 shows the comparison between the experimental and predicted values of the force on the impactor, plotted vs. its displacement, for five different test conditions, all referred to an impact speed of 9 m/s.. The five set of curves plotted there refer to four different scoring pattern and to an additional impact on an unscored box. Each set of data in the plot comprises two curves; the curve plotted with markers refer to experimental data, the curve without markers is instead a simulation result.

There are several aspects about the experimental curves that need to be here highlighted. In fact, due to the test setup, with the force transducer mounted on the moving part, the force signal was affected by inertia effects. In order to keep it into account, trial tests without box were performed, collecting force and displacement data. After filtering and signal elaboration, the inertial mass was derived and used for the rest of the tests. Once the inertial mass was known, the displacement signal was derived twice and then multiplied times the inertial mass for the force correction, to be subtracted from the original force values. The corrected force values are those plotted on Fig. 5, there passed through a CFC180 filter.

Filtering the experimental values is believed to be at the root of the smooth rising up and decreasing of the experimental curves, especially if compared with the steeper ramping up and dropping which characterize the simulation results. Even before discussing the model predictions and how they are close to the experimental evidence, some considerations are worth based on the examination of the experimental curves only. In fact the experimental curves in Fig. 5 are related to tests carried out on boxes with different scoring patterns; earlier fractures observed for deeper scoring lines show that the experiment can be used to discriminate between the different scoring profiles and thus can be used for the purpose of testing the model sensitivity thereon. This will be clearer from the images of tested exemplars, which are reported in the remaining part of this section, where it is manifest that in presence of invasive scoring the box breaks right in correspondence of the scoring patterns; however, when the material erosion due to scoring is less pronounced, the box may break not necessarily in correspondence of the scoring line. This is in fact a situation occurring in the real parts, and that a computational model is requested to predict in order to facilitate the part design. Accordingly, this is an important feature in the chosen experiment that makes it useful for evaluating the model performances from the point of view of its applicability to real cases.

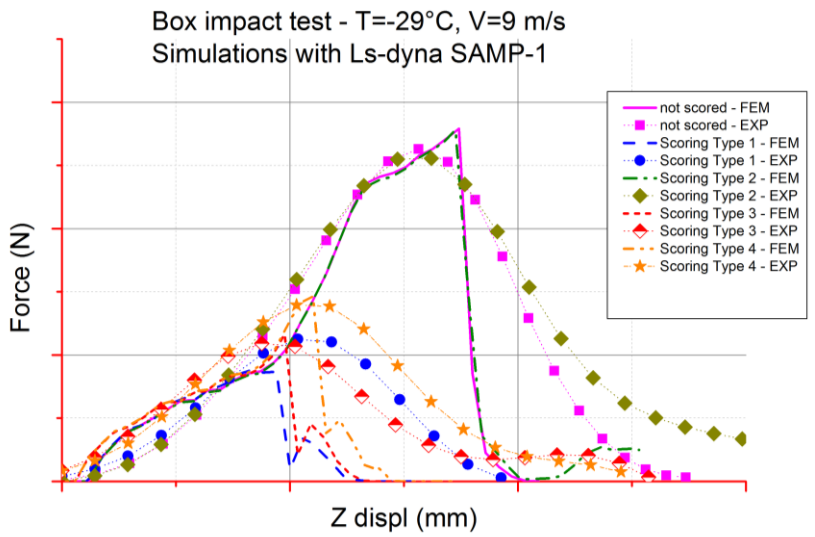

Fig.5: Force vs. displacement measured from impact tests on the laser scored box (dotted lines) compared to the values predicted from numerical simulation (Continuous lines)

Coming then to the simulation results, some consideration about the mesh are worth. The results presented in this section are obtained using a mesh which is locally refined at the scoring interface area. The mesh refinement is here accomplished using a bias parameter, in order to have a gradual reduction of the elements dimension when reaching the scoring line. A detail of the mesh used for this simulation is in Fig. 6.

As far as the failure mods are concerned, the behavior of the model is better discussed with the aid of Fig. 7 to 9, which show the comparison between the real and virtual deformations under tests on boxes with quite different scoring patterns, but under the same conditions as those of fig. 5.

The first result presented on Fig. 7 refers to an unscored box. Purpose of this study was to verify the validity of the material law and of the failure criteria chosen. In fact, the initiation of the fracture on the box corner is well predicted; the evolution of the transient is also well predicted, with good correspondence between the localization of the fracture between the virtual and the experimental test.

The results displayed on Fig. 8 are related to an impact on a box characterized by a parameter ω =0.4. i.e. the scoring eroded the 60 % of the original cross section. Under this conditions, the structure is definitely weakened at the scoring line, and the impact causes a failure which is essentially located at the border of the scored area. The simulation replicates well this behavior, although there is a time difference of some milliseconds between simulation and reality. A possible reason for this discrepancy in the occurrence of failure during the impact transient may be related to several causes, mainly it is believed that it could be due to mesh sensitivity of the failure criteria or to errors in determining the parameter ω from image analysis.

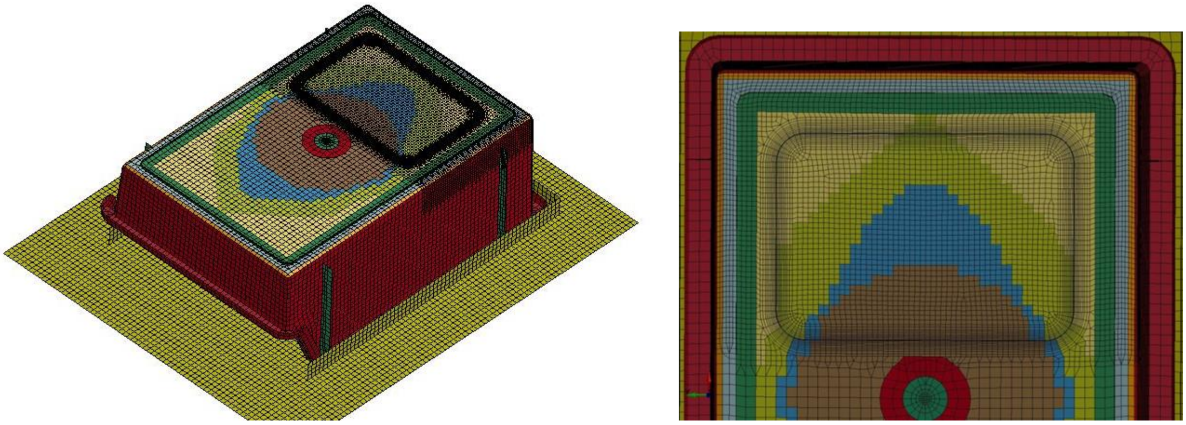

Fig.6: Mesh used for the simulation of the impact on the box. The local refinement at the scoring interface area is visible. Different colors refer to different thickness values.

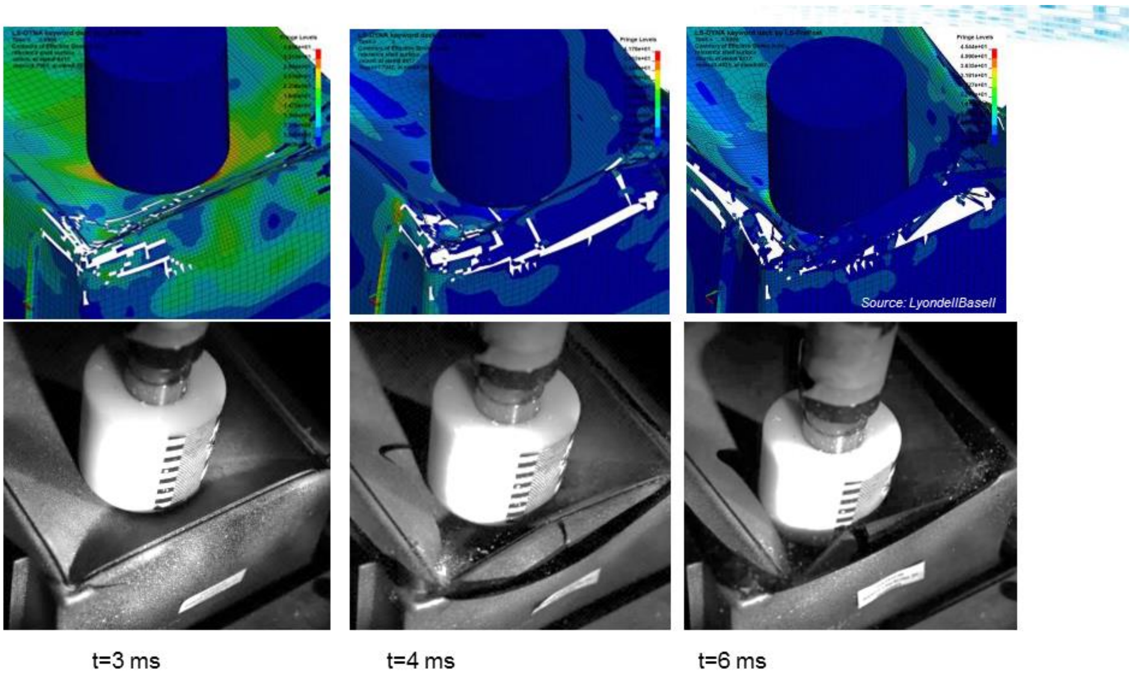

Fig.7: Test and simulation for the a box without any scoring

The results displayed on Fig. 9 show instead what happens in a case where the scoring profile is less invasive. In fact, in this case the impacted box is characterized by a parameter ω =0.7, thus only the 30% of the original cross sectional area was eroded by the action of the laser. As shown from the pictures taken from the physical test, an initial failure is caused to occur in correspondence of the vertexes, and then progressively propagates causing a wide opening at the border of the box top surface in proximity of the side vertical surface on the box short side. Only thereafter the failure propagates and localizes in proximity of the scored profile. The plots from the simulation show that the model is capable of capturing the progressive evolution of the failure starting from the box vertexes and then along the top surface border, up to its final localization onto the scored line.

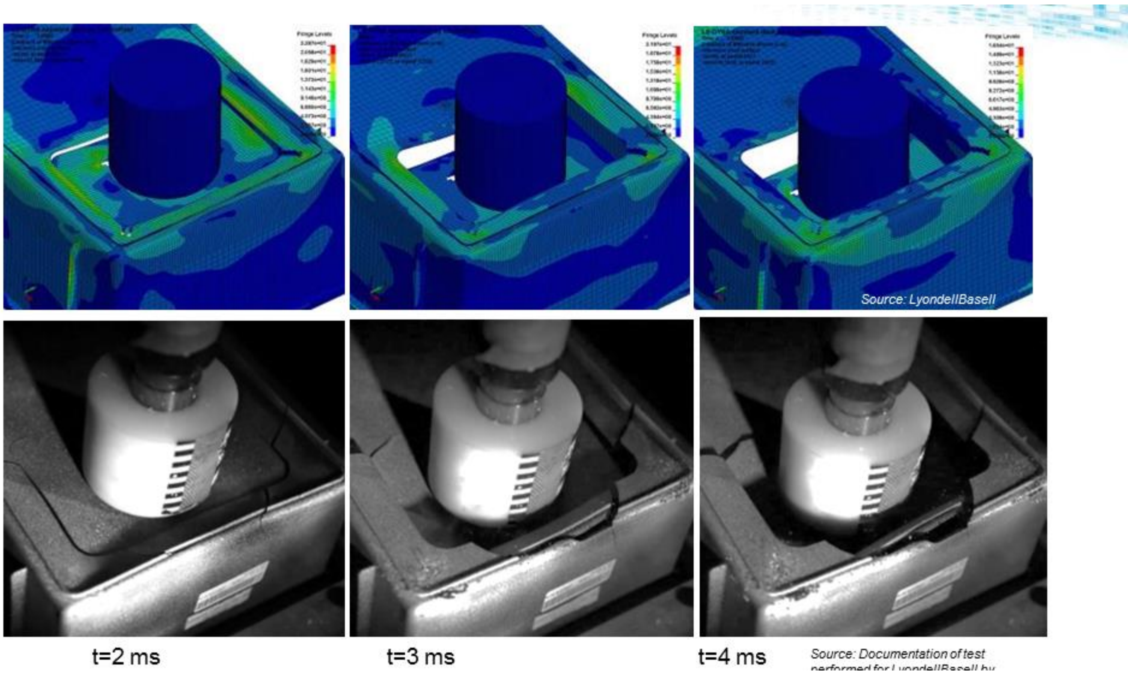

Fig.8: Test and simulation for the scoring type 1 (w=0.4) at T=-29°C V=9 m/s

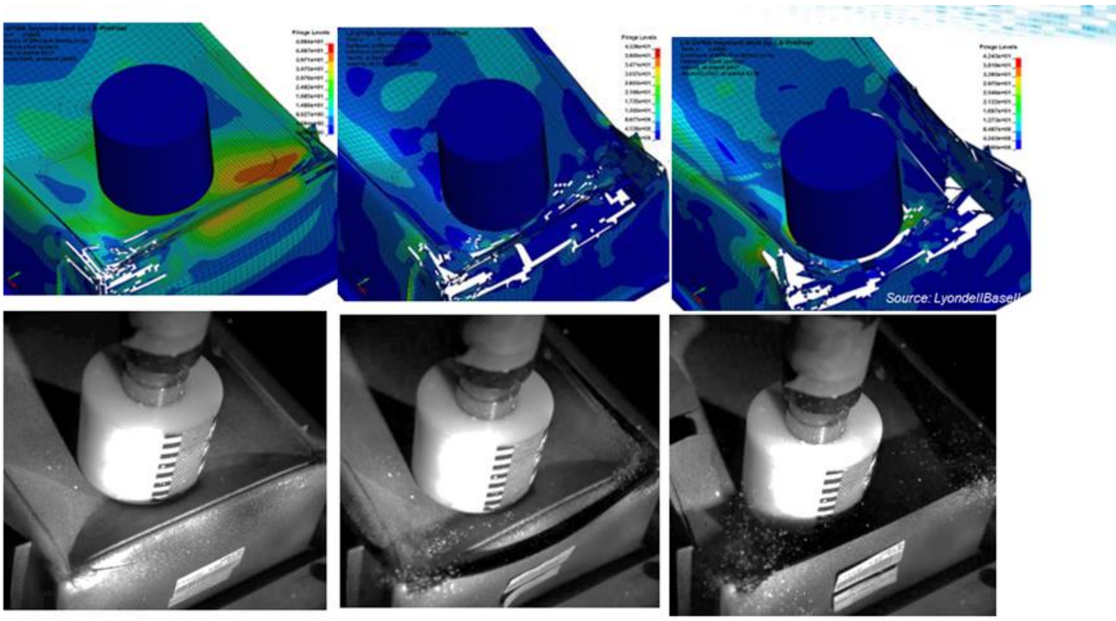

Fig.9: Test and simulation for the scoring type 2 (w=0.7) at T=-29°C V=9 m/s

5 Summary

A simulation strategy has been developed in order to simulate the laser scoring line behavior in airbag deployment. This is a critical step in the design of an instrument panel and setting up appropriate tools for numerical simulation may reduce the high testing costs and long development times that a car manufacturer has today to sustain before introducing a car model into the market. The modeling tool here proposed can help reducing the complexity of the design phase, although an experimental validation and verification of model predictions will be anyway unavoidable. The solution here adopted uses a non-von Mises yield based material law, with strain dependent failure criteria, fed with input stress-strain curves, Poisson ratio and damage parameters obtained through local strain measurement. The methodology proposed has been validated on a simplified test case, submitting to impact test several polypropylene-based boxes, onto which a scoring pattern was practiced. The validity of the prediction was confirmed under several testing conditions and scoring profiles. However, a validation on a real instrument panel and under a real airbag deployment has not been carried out yet and, when done, will provide the final assessment of the validity of the approach here presented.

6 Acknowledgments

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