APPLICATION OF NUMERICAL METHODS TO THE SIMULATION OF THE EARLIEST STAGES OF THE AIRBAG DEPLOYMENT.

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ABSTRACT

The application of numerical techniques to the study of the phenomena that occur during the first milliseconds after the activation of the airbag until recently has remained out of reach, due to the high complexity of the problem. On the one hand, the highly dynamic evolution of the gas produced by the inflator invalidates the hypothesis of uniform pressure within the volume. On the other hand, the simulation of the airbag opening involves problems such as the creation of extremely complex meshes representing the folded bag inside its housing, characterization of the behaviour of strain rate dependent materials, breaking of seam lines, etc.

During the last years several simulation packages have introduced modules to reproduce the gas flow inside the airbag, but experimental methods most commonly used to validate simulations involving airbags are not able to deal with the high speed and lack of accessibility that characterize this stage of the airbag deployment.

The objective of the present studies is the determination of the capability of these simulation tools to be used in the design of parts with attention to the loads produced during the opening of the airbag. This will help us not only to improve the development and integration of components, but, in later steps, also to provide airbag models able to be applied with guarantee in the simulation of OOP. In order to do this, a combined methodology using simulation and instrumentation has been defined, based on the development of numerical models using the FEM software PAM-CRASH and its module for simulation of fluids based on the algorithm FPM. These models have been validated with experimental tests specifically designed for this task. This paper intends to introduce the characteristics of the different stages of the airbag deployment and shows some of the results of the mentioned studies.

INTRODUCTION

As is well known, airbags are devices designed to provide protection to the users of vehicles during crash events. They are part of the so-called restraint system, which includes the different elements that help to reduce the damage to the occupants in case of accident, minimizing the loads necessary to adapt their movement to the movement of the car. Two of the main requirements of the airbags are in conflict. On the one hand, they should remain unseen until they are necessary, occupying as little space as possible. On the other hand, in case of accident they must fill the maximum available volume between the passenger and the parts of the interior of the vehicle that could harm him, in order to allow a progressive transmission of energy. In this case the airbag must reach its working position only a few milliseconds after the vehicle is impacted. To deal with these contradictory functions, the airbag is generally composed of a bag originally folded within a volume defined by mobile parts destined to open, allowing the way out (in order to generalize among the different types of airbag we will refer to them as “cover”), and a more or less rigid surface whose mission is to fasten the base of the bag and to orient its deployment in the desired way (it will be referred to here as “frame”). A very short time after the impact, the airbag receives a trigger signal, which causes an element commonly called generator or inflator to begin to inject gas into the bag. At a certain moment the pressure becomes high enough to open the cover, allowing the bag to unfold to its final position, where it is ready to receive the occupant. During these very rapid processes, the components of the bag, cover and frame can support pressures up to several bars, accelerations of several thousands of g’s and speeds over a hundred meters per second. Additionally, the violence of the deployment makes it potentially dangerous for occupants located in the deployment region. These situations are called “Out Of Position” or simply OOP.

The revision of the American standard FMVSS 208 [1] limiting the aggressiveness of the airbags in OOP situations has led the airbag manufacturers to look for “low risk deployment” properties in their products. This has introduced a higher complexity in the design of the airbag in regard to its opening and deployment functions, as it is expected not only to do it “quickly”, but also “softly”. The number of design parameters related to these functions makes it very desirable to count on numerical tools allowing the simulation of the process instead of testing expensive prototypes.

Finite Elements Method (FEM) based software have been widely employed in the design and development of restraint systems, focusing normally on the function of protecting the occupant once the airbag is deployed. For this task the airbag is simulated as a closed mesh of flat elements affected by a homogeneous field of pressure representing the gas. The hypothesis of uniform pressure within the whole volume of the airbag is quite accurate in this case, but it is very far from being applicable to the first moments of the deployment. To simulate correctly these phenomena we need to reproduce in some way the dynamics of the gas evolving within the folded bag.

Several software developers have accepted the challenge and have introduced modules of simulation of compressible fluids within their simulation packages. The most extended are LS-DYNA (introducing ALE), MADYMO (CFD) and PAM-CRASH (FPM) [2][3]. While the first two are based on the coupling of an eulerian mesh reproducing the fluids with a lagrangian mesh representing the solids, the third one is based on a meshless algorithm called Finite Pointset Method (FPM) [4]. This code fills the volume inside the bag with a cloud of points, as shown in Figure 1, and calculates a set of thermodynamic variables on them, including pressure, density, speed and temperature, relating them by interpolation to the neighbouring points. Finally, it calculates the transmission of momentum between the FPM points and the lagrangian mesh representing the bag.

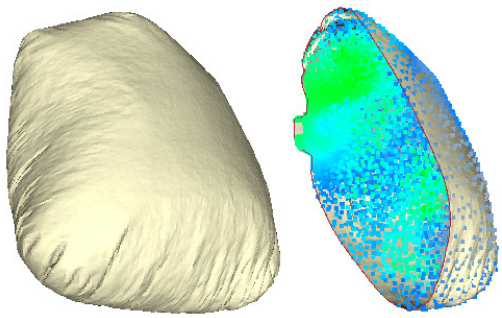


Figure 1. Simulation of airbag using FPM (external skin and section showing FPM points).

The studies presented in this paper were defined according to two main objectives:

1. To evaluate the capability of these numerical methods to be used as tools in the development of airbags, paying attention to three main scenarios: The interaction between the airbag and its surrounding parts during the process of opening, the kinematics during the deployment and, finally, the interaction of the airbag with an occupant in an OOP situation. PAM-CRASH and its module FPM were chosen to perform the simulations.

2. To develop a complete methodology of work, including numerical and experimental tools, designed according to the particularities and needs of each of the three designated scenarios.

METHODS

In order to achieve these objectives, it was necessary to find solutions to an important number of questions related to each one of the scenarios, so it was decided to face each one of them according to their logical order. First of all, we analyzed the problematic of the interactions during the opening of the cover. Once this part was properly solved we proceeded to the deployment analysis, and then we made the airbag interact with a mannequin in OOP. The numerical models used in each of the studies were related to the ones obtained as results in the previous steps and adapted to the needs of the new scenario.

The first step was to analyze the problematic of each of the scenarios using the available information in order to choose the most appropriate way to validate experimentally our numerical models. As a result of these previous analyses, three stages were defined in the deployment of the airbag.

Due to the complexity of the first scenario, which included problems involving the modelling of the folded bag and the inflator on the one hand, and on the other hand the modelling of their environment, including plastic materials and the breaking of seam lines, it was decided to incorporate a prior step in which the assembly bag-generator was validated separately within an environment easier to simulate. This gave us the chance to validate the capability of FPM to reproduce the loads of the deployment in a housing not only easier to simulate, but also easier to measure. These studies were denominated “in Controlled environment”.

The airbag chosen for the analysis was a passenger side frontal airbag, with the particularity of having and integrated cover, which made it unnecessary to use and model the rest of the dashboard. This simplified both the simulations and the tests. The housing was composed of a metallic base and a plastic component in Polypropylene with EPDM, as shown in Figure 2. This element played the roles of being the cover and a part of the frame simultaneously. The design of this element included a set of weakened points with the function of a breakable seam line.

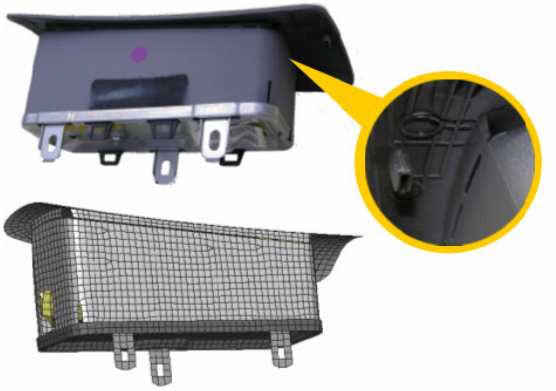


Figure 2. Airbag module with detail of the seam line and numerical model.

The gas generator had only one phase, so it was not possible to include the modification of the mass flow in our studies. It was composed of the inflator itself and a metallic diffuser with a hole allowing for the orientation of the gas towards the cover. The bag was made up of one single volume, with two circular ventings open during the entire deployment and without any strap to control or modify its external shape.

In order to evaluate the capacity of the numerical tools to deal with changes in the design, several modifications were introduced to the models. These modifications were designed taking into account that they should also be easy to perform in the physical components. This allowed us to count on a set of models with the following variables:

1. Folding pattern. Instead of using the original folding pattern of the airbag, Leporello (LE) and Rolling (RO) patterns were chosen because different behaviour was expected during the deployment (Figure 3).

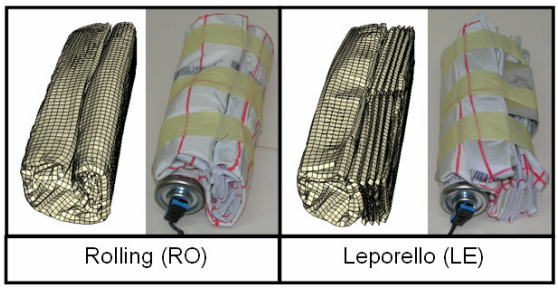


Figure 3. Folding patterns used in the studies.

2. Diffuser. Four diffuser geometries were introduced in order to produce different directions of the gas flow (Figure 4). The first one (Diffuser 1 or Dif 1) was the original one, with radial orientation of the gas flow towards the cover. In the second one (Dif 2) the diffuser was modified in order to get a more or less axial orientation of the gas flow, which should avoid the local concentration of pressure under the cover and produce a more homogeneous distribution of loads. The geometries of diffuser 3 and 4 (Dif 3 and Dif 4) were obtained rotating the original diffuser 54 and 32 degrees respectively with regard to the axis of the generator, in order to redirect the gas flow and originate different zones of concentration of pressure.

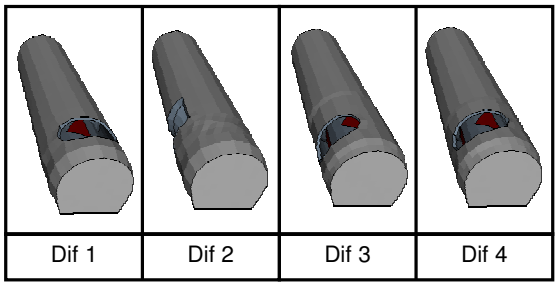


Figure 4. Generators and diffusers employed in the studies.

3. Resistance to the opening of the cover. In order to introduce this variable easily, approximately half of the points that composed the breakable seam line were removed from the model. The original part and the weakened one were named Cover 1 (C1) and Cover 2 (C2) respectively.

The resultant array included 16 cases, which enabled us to evaluate the influence of each variable and to choose the most interesting cases to be performed experimentally. Not all the cases were simulated or tested in each scenario. They were selected according to the particular requirements of the different studies.

The experimental methodologies employed were designed specifically, taking into account the particular needs of each study. Several series of tests were performed in parallel to the development of the numerical works. First of all, a test bench was designed for the tests in controlled environment. Secondly, highly instrumented airbag deployment tests were used simultaneously for the studies of the interaction against real environment and kinematics of deployment. Finally, out of position tests were carried out in several configurations.

On the numerical side, different models were defined according to each scenario. Most of the parameters that helped us to reach good results in the studies of controlled environment were kept in the rest of the models, in order to analyze the

predictability of the method. The smoothing length (associated to the number of FPM points) was modified in the different scenarios in order to keep a balance between accuracy and reasonable calculation times, which varied from an average of eight hours in the simulations of controlled and real environments, more detailed and with only 15 milliseconds of simulation, up to an average of 24 hours in the simulations of out of position tests, less detailed but arriving at 50 milliseconds of simulation. The calculations were performed on a two processors Linux based platform using PAM-CRASH v2005.

STAGES OF AIRBAG DEPLOYMENT

In the process of the deployment of an airbag different phases can be observed. A basic analysis of the processes that occur in each of them will help us to understand the phenomena associated to each of our scenarios.

Observing the evolution of the pressure and volume of the airbag we can define three main stages (see Figure 5):

1. First stage: The first stage begins when the generator starts to inject gas into the bag. At this stage the airbag is contained by its housing and cover, which prevent it from deploying freely. Due to this limitation of the available volume the pressure of the gas within the bag increases quickly, making the fabric push against its environment. At a certain moment the pressure grows enough so as to burst the seam that maintains the cover closed. The loads produced in this interaction depend not only on the gas generated, but also on the resistance opposed by the environment to the growing of the volume of the airbag.

2. Second stage: When the cover begins to open, the bag starts to protrude, being able at this point to increase its volume. Then the second stage begins, in which the bag leaves the case. Due to the difference between the atmospheric pressure and the pressure achieved in the airbag during the first stage, the bag tends to go out of the frame very quickly, producing an expansion of the available volume and, consequently, a drop in the pressure inside the bag. At the beginning of this stage the pressure is still high, and the bag is propelled violently. This situation, known as "Punch Out", is the most potentially dangerous for occupants placed too near the airbag (OOP situations). When the pressure inside the airbag has become closer to the atmospheric pressure, the bag keeps on developing until there is no more folded fabric in the case.

3. Third stage: Once all the fabric is outside the housing, the volume can still grow until the bag is completely filled. This is due to changes in the shape. Then the volume is limited again, this time by the bag, and the pressure grows again, due to the fact that the generation of gas still continues. This time the pressure grows much more slowly and the levels reached are generally lower than the ones reached during the first phase. At this point we can consider that the deployment has finished and that the airbag is ready to receive the occupant. From this stage we can generally accept the hypothesis of uniform pressure within the volume of the bag.

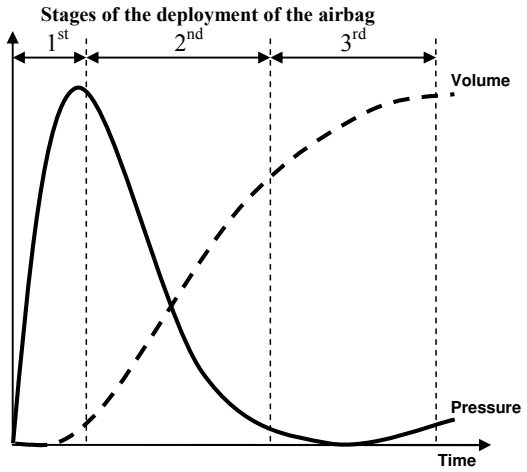


Figure 5. Typical evolution of the pressure and volume of an airbag during the different stages of its deployment.

Following this approach, our first scenario (the interaction of the airbag and its environment up to the opening) includes the entire first stage and the beginning of the second. The kinematics of the deployment (our second scenario) will be linked to the second and third stages, and the Out Of Position will be related mainly to the second stage.

CONTROLLED ENVIRONMENT

The simulation of the opening of a whole airbag includes several points that stretches the limits of the capabilities of the current state of the art techniques. On the one hand, we have the simulation of the folded bag, the generator and the gas itself, whose behaviour at this stage is highly dynamic and cannot be considered in any way as homogeneous. These elements compose what we could call "the active part" in the process of opening. On the other hand, we also need to simulate the housing and the cover, which include plastic components deformed at high strain rates, breakable parts, etc. These components constitute

the "reactive" part of the opening, restraining the deployment of the airbag until the cover is open.

In order to limit the uncertainties of the whole system, a controlled environment was designed, with the advantages of being easy to simulate and with a high degree of instrumentation in order to allow a complete validation of the numerical models. Only airbags with serial diffuser were tested and simulated, using both folding patterns (LE and RO).

The so-called "controlled environment" was composed of a rigid case equipped with transparent walls allowing the acquisition of high speed video images. It was fixed to a rigid support by a six-axis load cell, in order to measure reaction loads. Playing the role of the cover, a guided trolley was used. It was instrumented with an accelerometer and a set of eight small uniaxial load cells with the function of estimating the distribution of contact pressure produced by the airbag against the simulated cover. A pressure sensitive film was also used in order to register the map of maximum pressures achieved during the tests. Some details of the testing bench can be seen in Figure 6.

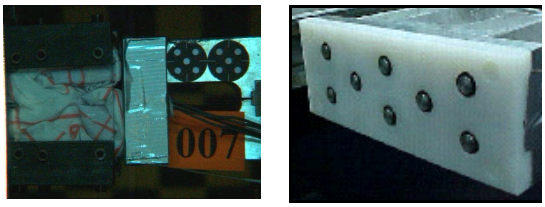


Figure 6. Constructive details of controlled environment tests.

The conclusions of these validations were published in [6]. Figure 7 shows some of the achieved results, comparing the curves obtained using simulation with FPM and experimental results (three tests were performed in each configuration in order to include repeatability factors)

These studies made possible the optimal validation of partial models of folded bags and generator independent of the housing, which allowed us to increase the predictability achieved in later steps. They also established a reference about the capability of FPM to deal with the phenomena associated to the earliest milliseconds of the airbag deployment.

REAL ENVIRONMENT

The interaction between the bag and its real housing during the first stage of the deployment presents some special characteristics that must be taken into account:

- As introduced above, the high dynamicity of the processes invalidates the assumption of uniform pressure of the gas and makes a careful modelization of the behaviour of the materials and breakable seams and their dependencies on the strain rate necessary.

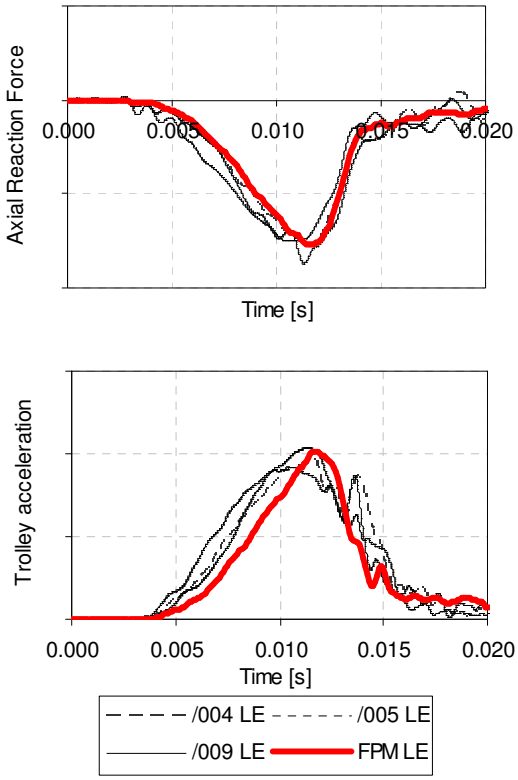


Figure 7. Results in controlled environment (Leporello Folding).

- Experimental tests are characterized by the lack of accessibility and, again, by the high dynamicity. Most of the volume inside the housing is already occupied by the folded bag, and there is no space for standard instrumentation. Besides, the high acceleration that the cover reaches can produce inertial effects that must be taken into account.

- The heterogeneous distribution of pressure within the volume of the airbag, the wide content of frequencies and the presence of phenomena of wave transmission invalidate the use of the pressure sensors commonly used in tests involving later stages of the airbag deployment.

The studies of opening in real environment were divided into two phases. The first of them was oriented to the validation of the numerical models. Six tests were performed using only two different configurations (Leporello and Rolling folding patterns, with serial diffuser and cover). The

instrumentation used in these tests was composed of up to six high speed video cameras at 1000 and 10.000 frames per second (depending on the function of each one), one six axis load cell in order to register the reaction loads at the base of the airbag and a set of eight small load cells in order to analyze the contact pressure between the bag and the cover. These load cells were specifically designed at CIDAUT with this function in mind. The set up of the tests can be seen at Figure 8, next to a diagram representing the position of the load cells under the cover.

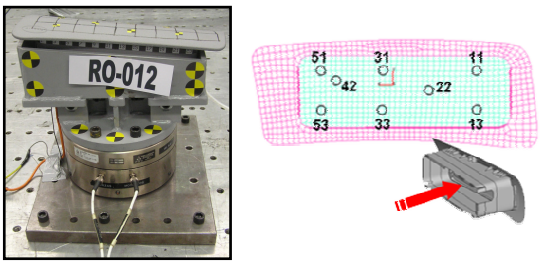


Figure 8. Set up of the deployment tests in real environment and positioning of load cells under the cover.

Numerical models were created from the models of bag and generator used in the previous phase, which were adapted to the new casing. In order to define the sub-model of the real environment, experimental characterisation of materials and seam line was performed, using both quasi-static and dynamic tests. The characterisation of the tearing of the seam line was made by testing the points that composed it separately. In order to do this, special tools were designed to fit to the geometry of the specimens, as shown in Figure 9. Tensile and shear test at several speeds were performed and reproduced in simulation using the different options available in PAM-CRASH, in order to chose the most realistic reproduction of the opening process.

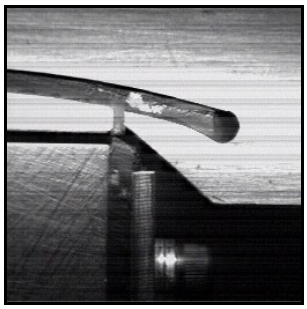


Figure 9. Detail of characterisation tests of seam line.

In addition to the numerical results equivalent to the respective experimental ones, several outputs were defined in the models in order to achieve a better understanding of the opening process. Among these outputs we can emphasize some interesting magnitudes difficult to be measured experimentally, such as the average force made by the bag against the cover or the force opposed by each point of the seam line, which gave us valuable information about the phenomena occurring during the first stage of the airbag deployment.

The results of these studies [7] showed a good numerical reproduction of the phenomena observed in the tests. Figure 10 shows the similarities of the kinematics in both cases.

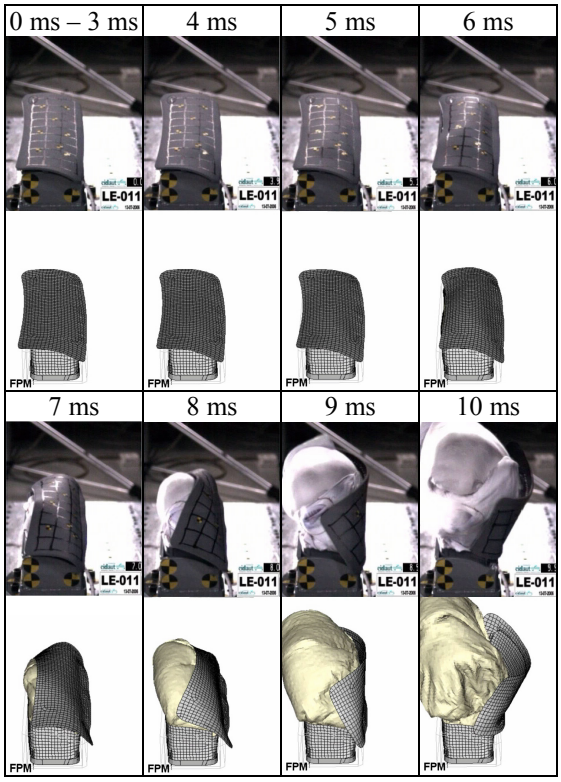


Figure 10. Comparison between experimental and simulated kinematics (Leporello folding).

With regards to the time of the opening, even though we are able to determine the exact time in which the seam line breaks in the simulated models, this was not measured in the experimental tests. The commonest way of estimating this is to consider the time of the frame in which the fabric of the bag is seen for the first time on the high speed video images of the deployment. This method, so called “white spot method” due to the colour of the textile, has also been used in simulation in order to get data comparable to the results obtained in the tests. Table 1 shows the registered values. In it we can see that opening in simulation occurs on average 0.6 milliseconds before. This can be related to the mathematical definition of the gas generated. The most interesting result is that the difference observed

when using both folding patterns has been well predicted numerically.

Table 1. Times of cover opening (white spot)

	Leporello	Rolling
Test 1	5.7 ms	5.6 ms
Test 2	5.7 ms	6.1 ms
Test 3	5.7 ms	6.4 ms
Average	**5.7 ms**	**6.0 ms**
Simulation (FPM)	**5.1 ms**	**5.4 ms**

One of the most promising applications of the use of simulation methods is related to the design of components paying attention to their function during the opening of the airbag. Figure 11 shows how zones with high plastic deformation were detected just in the places where cracks were produced during the tests (failure options were not included in the definition of the material used in the simulations)

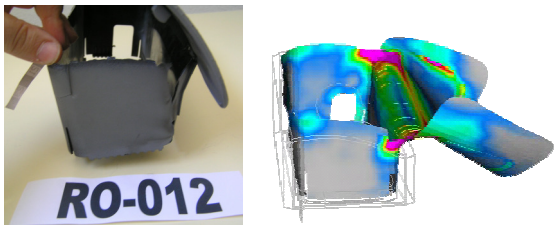


Figure 11. Identification of critical points by simulation (contours of plastic deformation displayed on the right).

With regards to the measurements taken by the load cells under the cover, Figure 12 shows the curves measured experimentally and the corresponding ones obtained by simulation. Numerical curves also reproduce inertial effects equivalent to those registered in the real sensors, in order to allow the comparison between both. The position of the different sensors is the same as displayed in Figure 8.

After the comparison of the local results we can observe that the distribution of pressure has been reasonably well reproduced up to the opening of the airbag (around 5ms in this folding pattern), whereas in later moments experimental deployment produces a sharp concentration of force in the sensor number 42, which is situated just over the outflow of the gas generator. This concentration of pressures is less marked in the numerical case, although still appreciable, as shown in Figure 13. On the other hand, the section displayed in the same figure shows that the pressure calculated in the FPM particles correlates well with the distribution observed experimentally. This fact seems to indicate that there is a loss of accuracy in the pressure distribution, probably associated to the contacts among the layers of folded fabric and with the cover. Still, as seen above, the global behaviour of the simulated cover is very similar to the one observed experimentally.

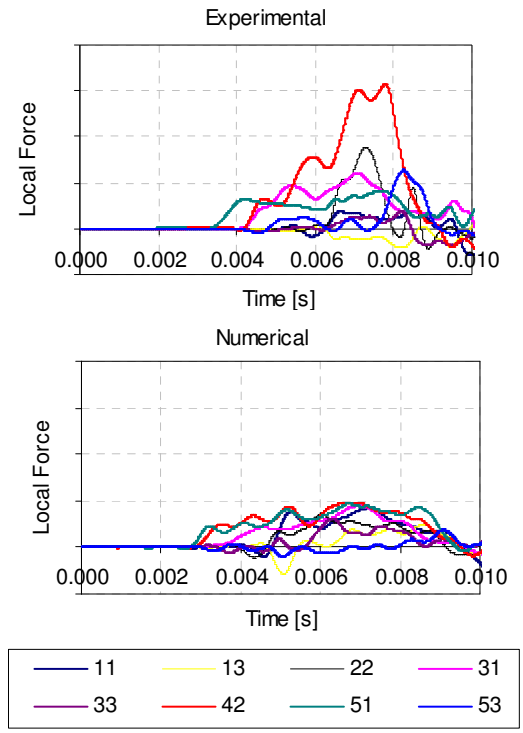


Figure 12. Forces measured under the cover (Leporello folding).

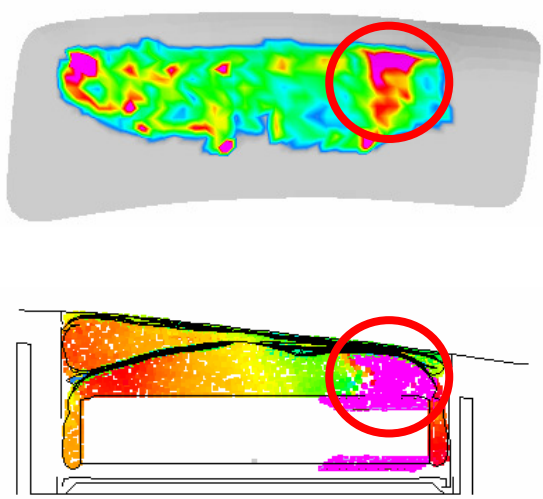


Figure 13. Distribution of contact pressure under the cover, and section with pressure in the fluid (Simulation of Leporello with Diffuser 1 at 5.5 milliseconds). Red circles indicate the position of the gas outflow.

After these studies, the numerical models were considered representative enough so as to proceed to their modification in order to analyze the

influences of the inclusion of different types of diffusers (Dif 1 to Dif 4) and cover configurations (C1 and C2). Two additional simulations were made using a third configuration (Without Cover or WOC), in which the door of the cover was removed in order to provide a reference in the evaluation of the influence of the modifications on the seam line.

Thanks to the specific outputs introduced in the models, it was possible to analyze values that are very difficult to obtain using experimental methods, such as the exact time when the points composing the seam line break, or the force the bag produces against the cover. Figure 14 displays the curves of average pressure inside the airbag and the corresponding forces against the cover in all the simulated cases (obviously, the force against the cover is not represented in the WOC configurations, which have no cover). Figure 15 shows the relation between the maximum values achieved in these curves. After both figures several observations can be made:

- Folding patterns and diffuser geometries are clearly conditioning the average pressure inside the airbag and the time of the opening (marked by the descending slope of the curves). In general, the rolling folding is producing higher pressures and later opening of the cover. It can also be appreciated that the scatter produced by Leporello folding is generally smaller than that produced by Rolling folding.

- Although the opening time is conditioning the shape of the force curves, the maximum values achieved are relatively similar in all the configurations. A certain reduction in the forces is observed when decreasing the resistance of the seam line (C2), although somewhat smaller than expected. We could conclude that this value is controlled mainly by the resistance of opening the door, due both to the seam line and to the energy needed to deform and accelerate the cover. This is easily understandable when thinking about Newton's law of action and reaction forces.

- One of the most interesting findings of the analysis was that, even when the variations of the opening times and average pressure inside the bag were of some importance, the maximum forces registered on the cover did not vary so much, even when the resistance of the seam line was reduced (Configurations C1 and C2). This effect has been related to the folding pattern, which modifies the stresses reached by the fabric and, therefore, the energy stored in it, and to the diffuser geometry, which is related to the concentration of pressure in determined zones of the bag and to the degree of homogeneity of the pressure field that is finally transmitted to the environment.

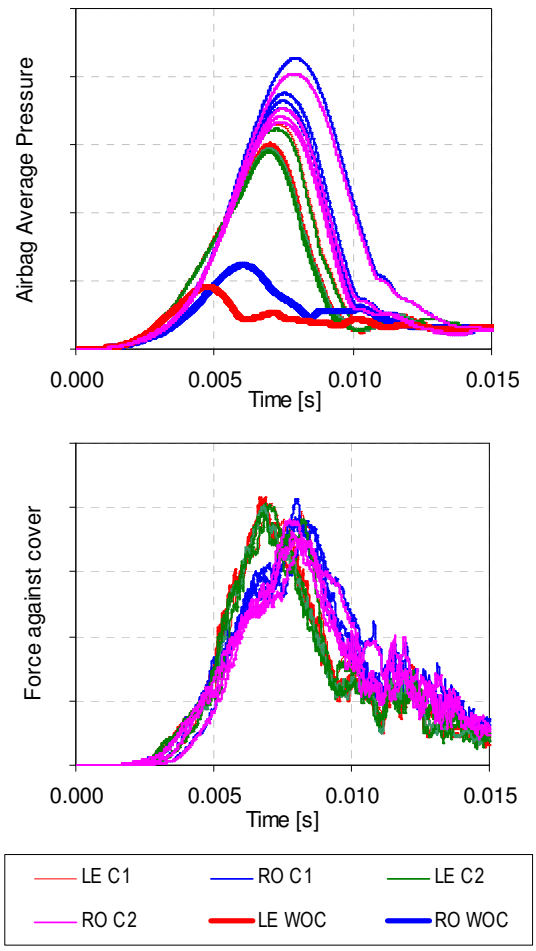


Figure 14. Curves of average pressure and force against cover.

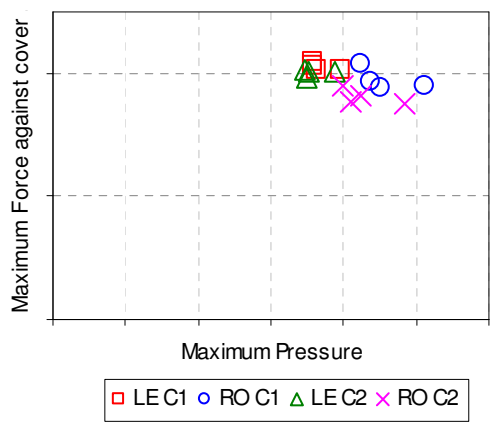


Figure 15. Relation between maximum average pressure in the airbag and maximum forces against cover.

Looking at the different results produced when

changing the diffuser geometry, as expected, the main variations were produced by diffuser 2. The design of this configuration was conceived to produce a more homogeneous pressure distribution, avoiding the concentration of loads on a determined zone of the cover.

Figure 16 shows some of the results achieved by the different geometries of the diffuser. It was observed how the variation of the gas flow direction allowed us to modify the distribution of pressure in the volume and, therefore, the load conditions on the cover. This was seen to affect the time of opening, as shown in Figure 17. The graphs in this figure represent the values of time when the last point of the seam line was broken (end of opening) and the duration from the rupture of the first point to the last. It can be seen how, because of the pressure being more homogeneous in configurations using diffuser 2, the duration of the opening is shorter, which means that the points are breaking almost at the same time, and occurring later than in other configurations.

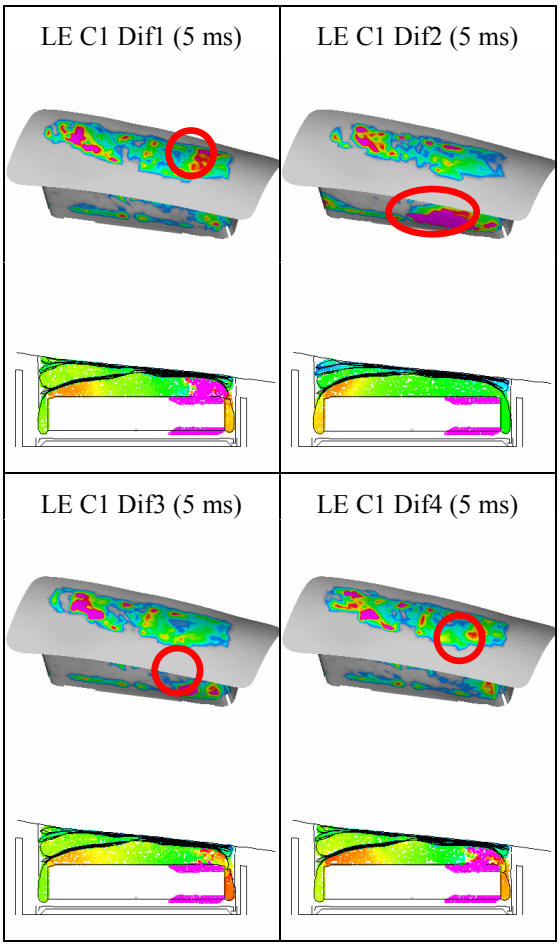


Figure 16. Dependency of contact pressure and gas pressure on the diffuser geometry. Red circles indicate the direction of the gas outflow.

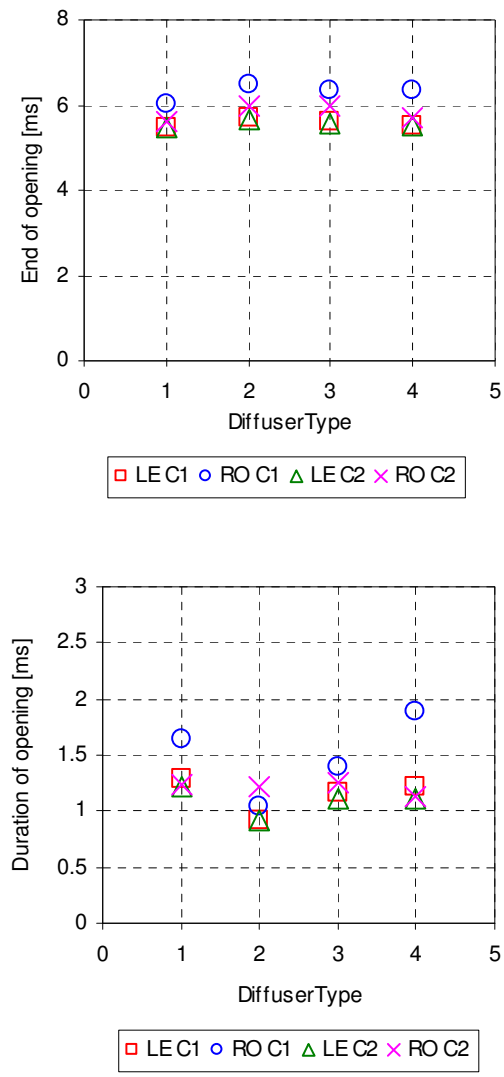


Figure 17. Influence of diffuser on opening time.

A second series of tests were performed in order to provide data for the validation of these results. It was decided to make modifications only in the diffuser, in order to avoid the influences of the folding pattern, which had been seen to be well reproduced before, and to evaluate the capability of FPM to work with different directions of flow. As the biggest differences in the models had been found between the diffusers 1 and 2 the configurations LE Dif1 C1 and LE Dif2 C1 were chosen to be tested. As the repeatability had proved to be good in the previous tests only one test was performed with each configuration. Although the first configuration had already been tested, it was decided to perform the test anyway in order to have exactly the same frame in the video images, which would be essential in the later analysis of the kinematics of deployment.

The main value taken into account for the validation of the models was the time of cover

opening. As experimentally it was difficult to know the exact time of rupture of the points of the seam line, the method of the white spot was employed again. Table 2 shows the obtained values. As had happened in the previous validations, there was a difference of around half a millisecond between experimental and numerical results, but, once more, the difference between the times of opening when using both configurations was well reproduced.

Table 2. Times of cover opening (white spot) with Leporello folding (LE C1)

	Diffuser 1	Diffuser 2
Experimental	5.7 ms	6.6 ms
Simulation (FPM)	5.1 ms	6.1 ms

KINEMATICS OF DEPLOYMENT

During the second and third stages of the deployment of the airbag, the bag is leaving the housing, unfolding and taking the shape required to receive the occupant. Whereas during the previous stage the variation of the pressure was very rapid, in this case, particularly during the second stage, there is a quick evolution of the volume and the pressure at the same time. As the cover is already open, the opposition to the increasing of volume, coming mainly from the resistance of the fabric deforming and the air displacing, is very weak. Consequently, slight variations in the folding or in the gas flow can produce important variations in the overall kinematics. Figure 18 shows how the modification in the gas flow produced by the different geometry of the diffuser is affecting the whole mechanism of deployment.

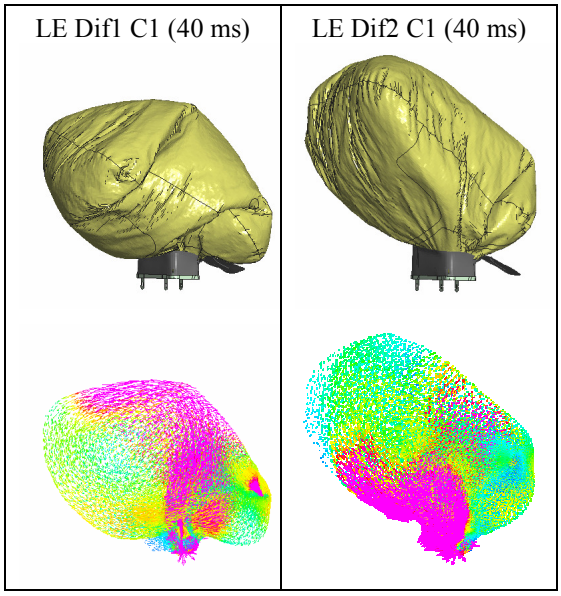


Figure 18. Influence of gas flow in kinematics of deployment (lower images represent the speed of the FPM gas particles).

Only the eight configurations with the serial seam line (C1) were used in the study of kinematics of deployment, showing clear differences in the deployment associated both to the folding pattern and to the geometry of the diffuser. Figure 19 represents the deployment in four of the cases, showing the geometry of the bag and the contour of pressure of the gas inside the bag. We can observe how not only the general kinematics, but also the distribution of pressure is quite different from one case to another. In particular, we can see how the configuration LE Dif2 deploys much less aggressively than, for instance, the configuration LE Dif 1, reducing the "whiplash" effect. On the other hand, we can appreciate also that the Rolling pattern presents less sensibility to variations in the geometry of the diffuser than the Leporello folding.

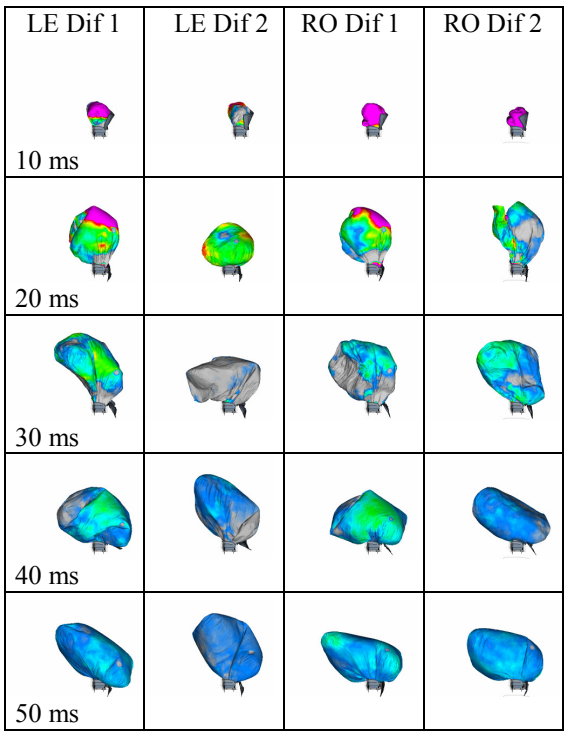


Figure 19. Kinematics of deployment and evolution of pressure distribution in several configurations.

In order to quantify the "whiplash" effect, and to provide data for a quantitative comparison among the different configurations, the values of maximum distance of a point of the bag to the base of the airbag and the time in which this distance was achieved were noted. Table 3 shows these values. In it we can see again how the scatter of the values for the Rolling cases is lower than for the configurations with Leporello folding, particularly looking at the time of maximum displacements. On the other hand, we can see how this time has been highly increased by the configuration LE Dif 2 C1, at the same time that the maximum displacement has been reduced. These values indicate that this

combination is unfolding in a less aggressive way to potential occupants, without the intervention of any tether or additional mechanism to control the geometry of the deployment. Among the other configurations, the one with Leporello folding and diffuser 3, which also directed the flow towards the lateral walls of the housing instead of to the cover, had the most similar results.

Table 3. Time and magnitude of maximum displacement of the bag measured from the base of the airbag

Configuration	**Time of maximum displacement [ms]**	**Maximum displacement from base [m]**
LE Dif 1 C1	26	0.63
LE Dif 2 C1	43	0.54
LE Dif 3 C1	33	0.54
LE Dif 4 C1	27	0.59
RO Dif 1 C1	25	0.63
RO Dif 2 C1	25	0.64
RO Dif 3 C1	25	0.59
RO Dif 4 C1	25	0.58

The tests used for the validation of the models of opening in real environment were also utilized for the validation of the models of kinematics of deployment (configurations LE Dif1 C1 and LE Dif2 C1). Although the frames extracted from the simulations were equivalent to the experimental ones, and therefore photogrammetric studies could have been performed in order to have a quantification of the results, the differences between both deployments were so obvious that a qualitative comparison of the geometries was decided to be indicative enough as to evaluate the capability of the software to simulate the real deployment. Figure 20 shows the comparison between experimental and numerical results. As predicted, the deployment after the modification of the diffuser was quite different to the original one, and followed well the tendencies marked by the simulations. This is particularly clear in the frames corresponding to the milliseconds 20 and 30, where the geometries of both configurations differ considerably.

On the other hand, the new direction of the outflow from the inflator increased the leakage of gas from some holes at the base of the bag, and produced important burns in the fabric next to the generator around the millisecond 40. These effects, which can be noticed in the video images, were not reproduced numerically. At any rate, the correct prediction of the tendencies of the deployment made them negligible to the conclusions of the study.

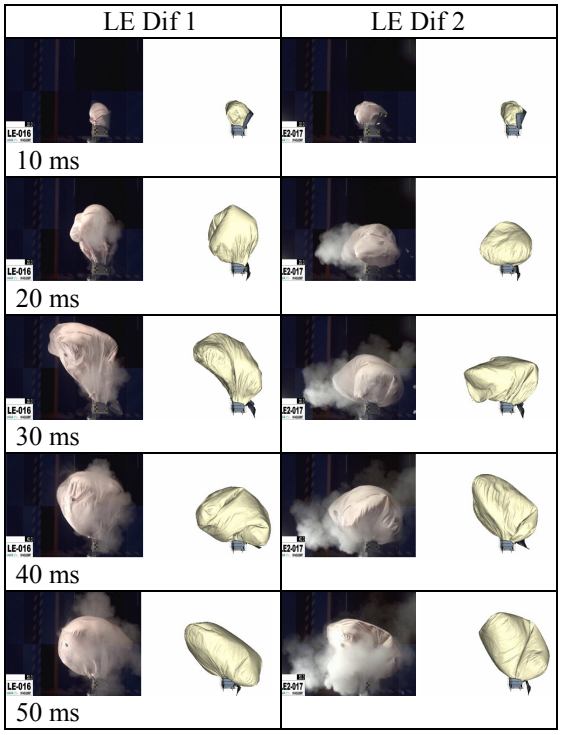


Figure 20. Comparison of experimental and simulated kinematics of deployment.

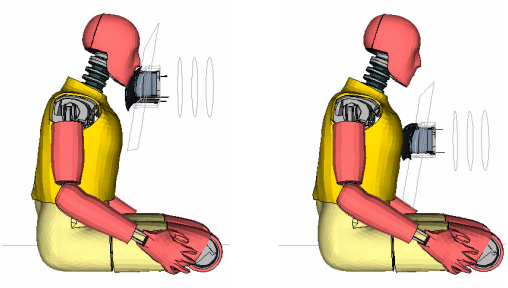
OUT OF POSITION

The last step of our studies was to check our models in deployments with an occupant placed in Out Of Position. Two configurations were initially selected to be analyzed, one of them looking for the maximum injury on the neck (Chin on module or "CHOM") and the other one trying to produce maximum damage on the thorax (Thorax on module or "THOM"). The dummy chosen for the occasion was the Hybrid III 50%, being the heaviest among those commonly used in OOP tests and, therefore, the one that should produce the maximum difference the static deployment. As no neck skin was present in the numerical models it was not used in testing either.

The standardized testing procedures for OOP testing require the use of elements of the vehicle interior, such as seat and dashboard. When necessary, foams and adhesive tapes are also used in order to maintain the dummy in the desired position. In our case, as our objective was not to simulate a specific type of test, it was decided to use a simplified rigid environment. This provided several advantages. First of all, it was not necessary to simulate these elements. This made it unnecessary to characterize them and eliminated the variability associated with them. On the other hand, the simplification of the environment of the dummy made its positioning much easier, in this way improving the reproducibility of the whole

test.

The tibias and feet of the dummy were removed in order to make the support of the airbag stiffer and easier to construct. The influence of these parts was considered negligible to the overall results of the test. Finally, a flat surface was built around the airbag support in order to avoid the airbag going forward during the deployment instead of pushing against the mannequin. This surface was fixed independently to the airbag, which was supported by the load cell used in the previous tests. The final make-up of the tests can be seen in Figure 21.



Chin on module (CHOM) | Thorax on module (THOM)

Figure 21. Configurations used in Out Of Position tests.

All the airbag configurations with serial cover (C1) were simulated in both set ups. Additionally, a third OOP scenario was included modifying slightly the distance of the dummy to the airbag in the THOM configuration (from 2 millimetres to 4 millimetres), in order to analyze the sensitivity to modifications in the positioning. Both situations were called "THOM d1" (2 mm) and "THOM d2" (4 mm) respectively.

Eight OOP tests were made for the validation of the models, all of them with serial diffuser (Dif 1) and cover (C1). The four first were "chin on module", performing three tests with airbags with Leporello folding, in order to analyze the repeatability, and a fourth one with Rolling folding, in order to study the sensitivity to the folding pattern. The second group of tests were "thorax on module". In this series there were two tests with Leporello folding placing the thorax at 2 mm (THOM d1), one more with Leporello folding and the thorax at 4 mm (THOM d2), and a last one with Rolling folding with the thorax at 2 mm.

Figure 22 represents the comparison of kinematics observed for the CHOM configuration in both folding patterns. In this image we can observe that the configurations with Leporello folding tended to unfold towards the right side of the dummy, influenced by the asymmetry of the airbag. This tendency, although also existing, was not so defined in the experimental results. On the other hand, in the Rolling configuration the deployment downward takes place some milliseconds earlier in simulation than in testing, while this movement is quite well reproduced by the Leporello folding. As a consequence, the loads in Rolling configuration descend before those observed experimentally (Figure 23). This seems to indicate that Rolling folding is less aggressive than Leporello folding, while experimental results point to the opposite.

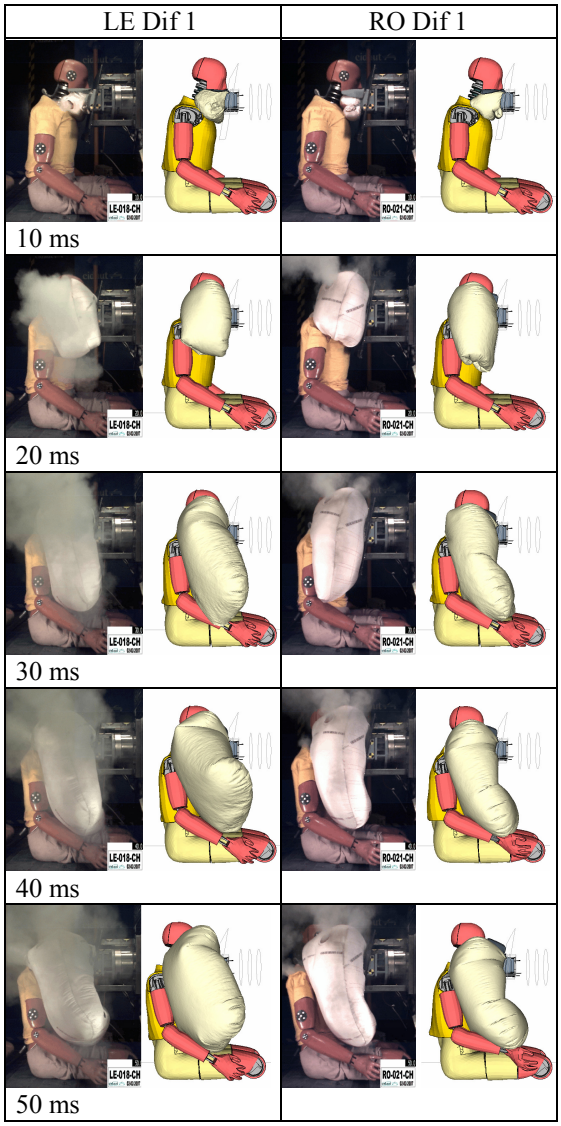


Figure 22. Comparison of experimental and simulated kinematics of deployment (CHOM).

Furthermore, the physical airbags employed in the test tended to break due to the high pressures and temperatures, creating new venting holes not reproduced numerically. This happened generally around the millisecond 20 in CHOM configurations and around the millisecond 30 in THOM configurations.

Some of the most interesting curves of the validation of the CHOM configuration can be seen in Figure 23. If we consider the different graphs separately, we can see that the main parts of the curves have been well reproduced numerically, and that the load levels have been more or less accurately achieved. However, as seen above, the tendencies observed experimentally when changing the folding pattern are not well reproduced by the simulations. Although some parameters were identified to be optimized in order to improve the results, the determination of their influence was left for further research.

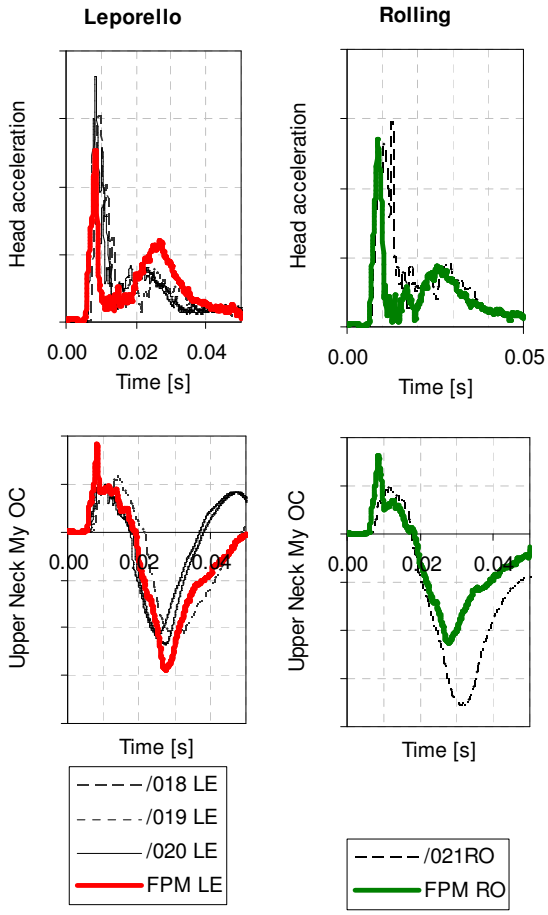


Figure 23. Comparison of experimental and simulated curves (CHOM).

In the case of THOM configuration the kinematics was in general well reproduced by all the numerical models. Observing the curves (Figure 24), we can see nevertheless that the results achieved by Rolling folding seem to be more accurate than the ones achieved when using Leporello folding. Looking at the separated curves, we see that the shape of the curves of thorax acceleration and axial reaction forces are being quite well predicted, particularly in the case of Rolling folding, while the curves of thorax deflection show a worse level of reproduction. This could be related to the numerical definition of the dummy.

With regards to the change of distance from the thorax to the airbag, we can say that the general tendencies have been well reproduced, although perhaps not as strongly as observed in tests.

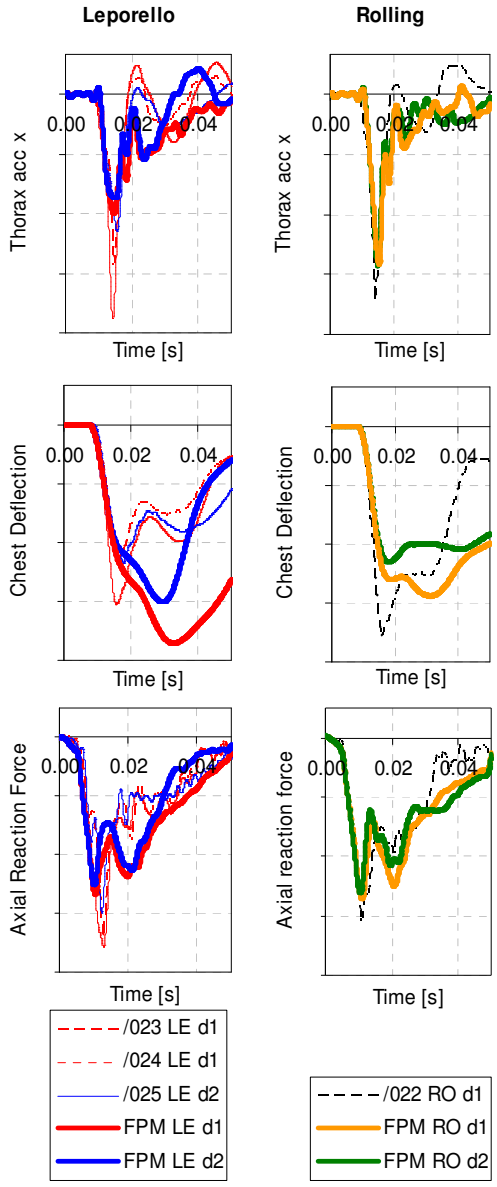


Figure 24. Comparison of experimental and simulated curves (THOM).

Looking at the totality of the simulations performed, different tendencies were observed depending on the airbag configuration. Figure 25 presents some sections of the models with the pressure distribution of the gas inside the airbag. We can observe how the modification in the gas flow due to the variation of the diffusers and folding patterns is producing different zones of concentration of pressure and, therefore, different

kinematics of deployment and different outputs in the dummy. As an example, diffuser 1, which was seen to produce a more aggressive deployment, is now causing lower loads on the neck of the dummy in the CHOM configuration. The explanation of this phenomenon has been related to the deflection of the gas flow produced by the cover, which is prevented by the dummy from opening normally, and that is directing the gas flow to the right side of the dummy when using diffuser 1, while diffusers 2, 3 and 4 are filling the airbag in a more homogeneous way and, at the same time, producing a higher pressure under the chin. This can be seen in Figure 26.

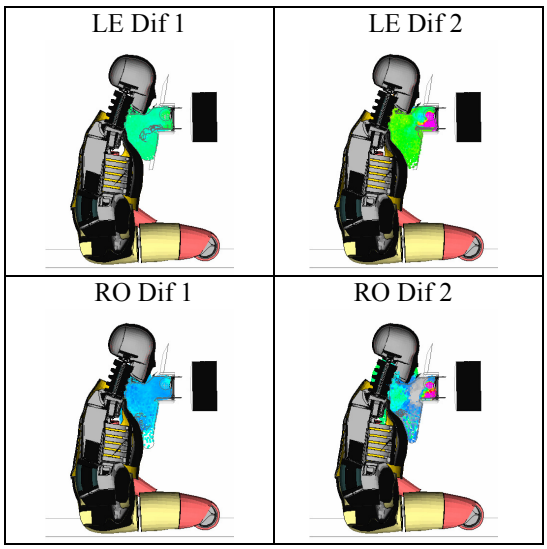


Figure 25. Sections with gas pressure contours (CHOM at 20 ms).

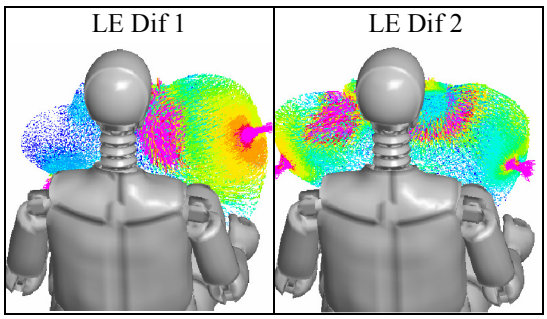


Figure 26. Velocity of the fluid for different diffuser options (CHOM at 20 ms).

One interesting study is the analysis of the relations between results achieved in different stages of the deployment, in order to establish design parameters to predict the behaviour in different situations. The graphs in Figure 27 show the relation between loads achieved in OOP simulations with the maximum average pressure reached in the simulations of opening in real environment. It can be seen that minimum moments of extension (negative values, according to [8]) at the upper neck during the OOP in CHOM configuration depend much less on the pressure during the opening than the thorax acceleration in the THOM configuration. These kinds of studies can help to identify and quantify the causes and effects related to the different factors associated to the airbag design.

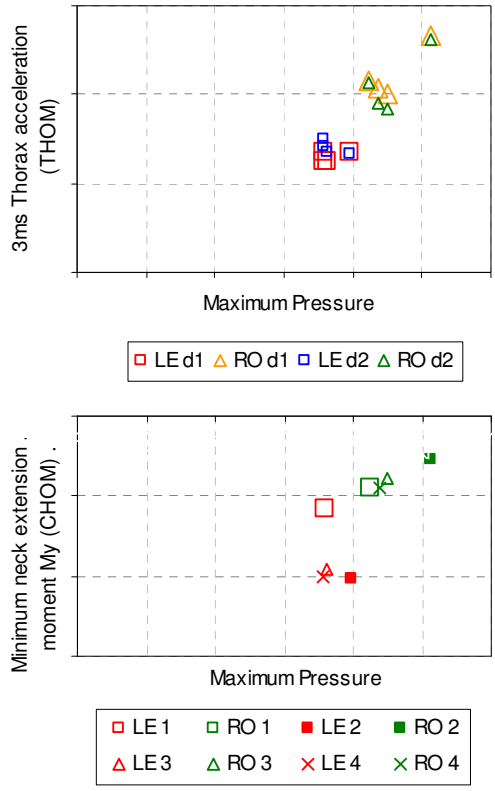


Figure 27. Relation between OOP results and maximum pressure achieved during opening.

DISCUSSION

Up to here we have described the characteristics of the different stages of the airbag deployment, as well as outlined the results obtained in their numerical simulation and experimental validation. The following points summarize the main findings of this group of studies:

- Three stages have been identified in the deployment of the airbag according to the evolution of the pressure and the volume.

- The interactions between the airbag and its environment (housing, cover, supports…) up to the opening of the cover are related to the first stage of the deployment. Numerical and experimental methods have been specifically developed for this phase in order to achieve simulation models as reliable as possible. Although some differences have been

identified in the local distribution of the contact pressure, overall results are very promising, reproducing accurately the general trends and timing observed experimentally.

- Tendencies of kinematics of deployment when using different folding patterns and diffusers have been well predicted numerically. Most aggressive deployments have been correctly identified.

- Good reproduction of load levels and timing has been achieved in the simulation of several OOP situations. In spite of this, some experimental tendencies have not been correctly predicted in simulation when changing the folding pattern. This has been related to the high instability inherent to this kind of events, which means that small variations in the inputs, either experimental or numerical, produce large variations in the results, reducing the reproducibility of the whole process. As a consequence, caution is suggested when using numerical tools to improve OOP results, the validation of the base models with testing still being recommended. Further research is required in order to improve both experimental and numerical methodologies.

CONCLUSIONS

This document outlines the current possibilities and limitations of the simulation of the first stages of the airbag deployment. Studies have been performed in three different scenarios: Interaction with the environment during the opening, kinematics of deployment and OOP. The degree of accuracy of the simulations in each one of them has been evaluated, as well as the sensitivity of the models to modifications of several parameters. Additionally, advantages provided by the use of numerical methods have been shown, such as the possibility of obtaining magnitudes difficult to measure experimentally (e.g. the force made by the bag against the cover during the opening or the distribution of pressure of the gas within the airbag), and the capacity to check different configurations with a high degree of control of the modified parameters. As a result of this, simulation has proved to be a valuable tool to be taken into account in tasks related to airbag deployment.

The studies presented have been performed using a commercial airbag. The numerical models have been developed systematically from the first validation of the generator and folded bag in a controlled environment to their final use in complex OOP scenarios with real cover and housing. At the same time, a complete set of validation tools and methods has been developed.

In conclusion, these technologies are able to be used not only as a tool to solve problems related to the airbag development, but also to help us arrive at a better understanding of the factors that influence the deployment of the airbag and its aggressiveness, and therefore get more efficient and safer designs.

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