

3D scanning applied in the evaluation of large plastic deformation

Digitalização 3D aplicada na avaliação de grandes deformações plásticas

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Abstract

Crash test are experimental studies demanded by specialized agencies in order to evaluate the performance of a component (or entire vehicle) when subjected to an impact. The results, often highly destructive, produce large deformations in the product. The use of numerical simulation in initial stages of a project is essential to reduce costs. One difficulty in validating numerical results involves the correlation between the level and the deformation mode of the component, since it is a highly nonlinear simulation in which various parameters can affect the results. The main objective of this study was to propose a methodology to correlate the result of crash tests of a fuel tank with the numerical simulations, using an optical 3D scanner. The results are promising, and the methodology implemented would be used for any products that involve large deformations.

Key words: 3D scanning. Crash test. Numerical simulation.

Resumo

Os *crash test* são ensaios experimentais solicitados por agências especializadas com o objetivo de avaliar o desempenho de um componente (ou o veículo inteiro) quando submetidos a um impacto. Os resultados, em geral, altamente destrutivos, produzem grandes deformações no produto. O uso de simulação numérica em estágios iniciais de um projeto é fundamental para a redução de custos. Uma das dificuldades na validação dos resultados numéricos envolve a correlação entre o nível e o modo de deformação do componente, uma vez que se trata de uma simulação altamente não linear em que vários parâmetros podem afetar os resultados. O objetivo principal deste estudo foi propor uma metodologia para correlacionar os resultados de um *crash test* de um tanque de combustível com os obtidos por simulação numérica, utilizando um digitalizador ótico 3D. Os resultados são promissores e a metodologia implementada poderia ser utilizada em qualquer produto que envolve grandes deformações.

1 Introduction

Crash tests are fundamental to evaluate the safety and functionality of automotive components. The aim is to simulate car performance in case of accidents, evaluating the results and determining if certain safety standards are met.

In order to regulate car safety standards, regulatory agencies were created to qualify and certify vehicles according to their performance in crash tests. Today, the most widely known ones are the European New Car Assessment Programme – EuroNCAP (Europe) and the National Highway Traffic Safety Administration – NHTSA (USA). These programs are responsible for improving occupant safety through the development and implementation of information that encourages manufacturers to improve the safety of their vehicles. In 2014, under the management of the New Car Assessment Programme for Latin America and the Caribbean – LatinNCAP, the vehicles produced in Brazil will also have to meet crash test standards, such as ABNT NBR 15300 (2005), for frontal impact, and ABNT NBR 15240 (2005), for rear impact.

Usually, crash tests are performed with standard speeds: between 13.9 m/s and 17.8 m/s for frontal impacts, 8.06 m/s for side impacts and 11.1 m/s for impacts against pedestrians. These values may vary according to the regulatory agency of the country.

A steel fuel tank also needs to meet certain performance and security requirements. Concerned with the advance of plastic tanks in the automotive market, the major producers of metallic tanks created the Strategic Alliance for Steel Fuel Tanks (SASFT). SASFT was organized by American Iron and Steel Institute (AISI) in 2000 to bring together various commercial departments involved in the design, manufacture and supply of metallic tanks for the automotive market. Today, SASFT counts among its ranks of members companies from all

major markets of the world, such as Aethra (Brazil), Donghee (Korea), Elsa (USA), Metal Horie (Japan), Martinrea (Canada), Metals (Mexico), Unipart Eberspächer (UK), etc. Among the main advantages of metal tanks, one can cite (SASFT, 2011):

- Low evaporative emissions – the inherent impermeability of steel is ideal to restrict evaporative emissions, allowing the certification of metal tanks with a Partial Zero Emission Vehicle (PZEV) label.
- Recyclability – steel tanks are very recyclable.
- Durability – steel tanks produced by Sasft meet stringent requirements for corrosion and structural durability.
- Safety – in the event of frontal, side or rear impact, it is necessary to maintain the integrity of the fuel system without leakage or explosion. Steel, due to its high strength and great capability to absorb impacts, has shown satisfactory performance in all safety tests.

In regard to safety, fuel tank location in the vehicle is a decisive factor. Fuel tanks located on the rear, depending on the impact level, may cause fire in case of rear collision. In pickup trucks and sport utility vehicles, the fuel tank is usually located on the side of the vehicle and oriented lengthwise. In this case, the main risk of explosion is in side collisions.

Besides its location, the design and manufacture of a fuel system in a car has a key role in its security. The tank and the filler pipe must meet certain security requirements in case of possible collisions of the vehicle. Usually, automakers create their own safety standards for specific components, such as the fuel tank. In early stages of design (and in the validation of a component of a new supplier), it is useful to perform the crash test for the fuel tank and then, at a later stage, for the entire vehicle. For the tank, many manufacturers

use a sled test (SILVEIRA et al., 2008). This procedure consists of a sled guided by rails, raised to a certain height and then released to crash the tank (partially filled with water) with a pre-established kinetic energy. In this test, deformation and tightness of the tank are evaluated after the impact.

These impact tests are classified as highly destructive tests and generally need to be carried out more than once to completely validate the product. This can make the procedure onerous and increase the validation time considerably. With the rise of high-performance computers, the use of numerical simulations in crash tests increased significantly, making the process of validating products faster, reducing costs and increasing their reliability. The main tools of numerical analysis available in the market for this purpose are based on the Finite Element Method, using an incremental Lagrangian formulation in time based on explicit and implicit integration techniques. In these formulations, nonlinear behavior of material (plasticity), geometric nonlinearity (large displacements and large deformations) and boundary nonlinearity (contact and friction between the components) must be considered.

One of the difficulties in the process of validating the numerical results is in the correlation of the level and deformation mode of the component, since the correlation of other parameters (such as impact energy and internal pressure) can be obtained by specific sensors.

The increasing need for stamping products with high quality has generated a demand for non-destructive methods for controlling shape and size of the final product. Digital image methods have emerged to fill this need, because they are able to create a digital model of a physical product in a very short time, besides making it possible to obtain excellent parameters for correlations and calibration in constitutive models (TARIGOPULA et al., 2008), (VASSOLER; FANCELLO, 2011).

Non-contact 3D optical scanning has some advantages over other measurement techniques. Coordinate measuring machines (CMM) are extremely accurate, but they have limited speed due to the inertia of mechanical components. The same limitation applies to tactile 3D digitizers. Optical 3D scanners can collect millions of points per second, without any contact of the device with the product (LEMES, 2010).

The aim of this study was to propose a numerical/experimental evaluation methodology of a metal fuel tank that endures significant deformation in crash tests, using a 3D laser scanner.

2 Experimental test

Figure 1 show the equipment for performing the sled crash test of a fuel tank that meets all the requirements and standards of automakers.



Figure 1: Picture of the sled crash test equipment

The kinetic energy E_c can be determined using the classic equation:

$$E_c = \frac{mv^2}{2} \quad (1)$$

where m is the mass of the sled and v its speed. At first, ignoring the losses by friction, it can be said that the potential energy (E_p) of the sled at the maximum height is equal to the kinetic energy (E_c) of the sled at the time of impact. Thus, one can determine the height at which the sled should be released to reach the speed equivalent to the specified energy as follows:

$$E_p = E_c; \Rightarrow mgh = E_c; \Rightarrow h = \frac{E_c}{mg}; \quad (2)$$

where g is the acceleration of gravity and h is the height.

However, in a real test, there will be considerable losses by friction between moving and fixed parts of the equipment – e.g., between pulleys and rails – which need to be taken into account to calculate the real height h . A device to measure the velocity just before the impact was used to accurately calculate the total loss by friction. After five measurements, an average loss of 10% was found.

The experimental test data are given in Table 1. All the open parts of the tank were sealed to prevent leakage of air or water, creating considerable internal pressure during the test.

Table 1: Experimental data

Sled Mass (kg)	Energy (J)	Volume of water inside the tank (m ³)
439.5	3200	0.015

3 3D Laser scanning

In addition to being extremely slow, conventional measuring machines, tactile digitizers and CMMs involve a contact force between touch-probe and measured object. The advantages of optical measurement techniques are evident.

A large number of different techniques for optical measurements are currently available such as: shape from shading, shape from texture, time of flight and light-in-flight, laser scanning, laser tracking, Moiré interferometry, photogrammetry, structured light, etc. (LEMES, 2010).

In this study, a 3D laser scanner was used, that is, a device used to capture in a short time physical objects in a digital format without contact with the object. It works by projecting a laser light onto surfaces while cameras triangulate the profile of the laser as it sweeps, enabling the object to be digitized in 3D. The device used in this work is an arm-mounted scanner, produced by FARO, Figure 2. This type of scanner establishes the location of the object in relation to the arm's base. Because of this, the base of the arm and the object to be scanned must be mounted on a stable surface with minimal environmental interference.



Figure 2: Crashed tank and arm-mounted laser scanner

Thus, the crashed tank was fixed on a rigid surface as shown in the Figure 2 above. After scanning, the Geomagic software was used to process and generate a digital file (IGES extension), Figure 3.

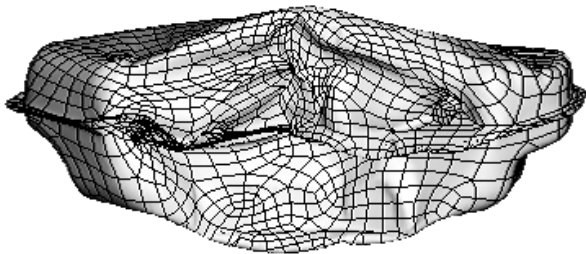


Figure 3: (a) Picture of crashed tank; (b) scanned tank by 3D laser scanner; (c) IGES surface of scanned tank generated by Geomagic software

4 Numerical simulation

Finite element methods began to be introduced in the fifties as an analytical tool to aid engineering projects. In the sixties, with advances in the aerospace field, the demand for more efficient and reliable methods increased dramatically at

universities and in industry. Nonlinear analysis using finite element methods also started in this period. Among the first articles about nonlinear analysis, one can cite Argyries (1965) and Marcal et al. (1967), cited in Belytschko et al. (2000). Pedro Marcal, who was a professor at Brown University, created in 1969 a company that released MARC, the first software on the market with nonlinear finite element analysis, whose implicit formulation is still used nowadays. A milestone of the progress in explicit finite element formulation was the work of John Hallquist at Lawrence Livermore Laboratory. John began his work in 1975, and the first version of Dyna explicit code was released in 1976. Dyna code evolved over time and formed the basis for several commercial programs such as LS-Dyna, PamCrash, Dytran and Radioss (software used for simulations of crash tests in this study).

The equilibrium equation of a dynamic analysis discretized in finite elements can be given as follows:

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{F(t)\} \quad (3)$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix and $\{F(t)\}$ is the vector of external forces. The vectors of acceleration, velocity and displacement are given by $\{\ddot{U}\}$, $\{\dot{U}\}$ and $\{U\}$ for $t = t_0$. Radioss uses in its explicit formulation the finite difference method which uses equation (3) evaluated at a time t , where the vectors of acceleration and velocity are given as (BATHE, 1996):

$$\begin{aligned} {}^t\{\ddot{U}\} &= \frac{1}{\Delta t^2} \left({}^{t-\Delta t}\{U\} - 2 {}^t\{U\} + {}^{t+\Delta t}\{U\} \right) \\ {}^t\{\dot{U}\} &= \frac{1}{2\Delta t} \left(- {}^{t-\Delta t}\{U\} + {}^{t+\Delta t}\{U\} \right) \end{aligned} \quad (4)$$

The solution for ${}^{t+\Delta t}\{U\}$ can be written as:

$$\begin{aligned} \left(\frac{1}{\Delta t^2}[M] + \frac{1}{2\Delta t}[C] \right) {}^{t+\Delta t}\{U\} = \\ {}^t\{F\} - \left([K] - \frac{2}{\Delta t^2}[M] \right) {}^t\{U\} - \\ \left(\frac{1}{\Delta t^2}[M] - \frac{1}{2\Delta t}[C] \right) {}^{t-\Delta t}\{U\} \end{aligned} \quad (5)$$

It can be observed that it is not necessary to factorize the matrices on each time-step, since $[C]$ and $[M]$ are approximate to diagonal matrices (lumped mass). This is the main factor in the robustness and low computational cost of explicit methods. The stability of the problem depends on the size of the time-step, which is determined by the Courant criterion that is directly related to the element size and the speed of sound in the environment (OWEN et al, 1986).

In this study, the Updated Lagrangian method was used and the tank modeled with plate elements, bi-linear interpolation and six degrees of freedom per node. In this case, the Mindlin model was adopted, where the cross-section remains plane after deformation but not necessarily orthogonal. This element has only one point of integration in the plane, which is convenient to avoid locking problems, but can generate questionable results due to the hour-glass phenomenon (spurious zero energy modes). To minimize this problem, it was necessary to add “anti-hourglass” forces and moments, using a plate formulation with physical stability. Along the thickness, five points of integration were used. The material was modeled as elastic-plastic with isotropic hardening and the von Mises yield criterion. The update of the stresses is done through an incremental iterative process proposed by Mendelson (1968) that is more accurate (but with greater computational cost) than the traditional radial return.

To model the effects of the fluid inside the tank, a Lagrangian formulation was used based on hydrodynamics particles (IDELSOHN et al., 2004). And to simulate pressure effects due to volume reduction of the tank during the impact, volume control technique (or Monitored Volume Technique) was used, where the numerical model is subjected to an adiabatic relationship between pressure and volume. With this technique, it is possible to define the percentages of compressible and incompressible volumes of the model inside the tank.

An initial velocity of 3.8 m/s was imposed on the sled. Displacement constraints were imposed on the normal directions of the sled’s motion, in order to simulate the rails. Contact models based on the penalty method (BABUSKA, 1973) were established between the sled, tank and supports. Besides the initial velocity of the sled, the vertical acceleration (gravity) was considered on all the system. The simulation time of the event was 0.15s.

5 Material and geometrical data

Figure 4 shows the finite element model of the tank, with the thickness of each component. The sled and the supports were considered rigid (undeformable).

In crash simulations it is very important to have a constitutive model that represents well the behavior of the material for a wide range of strain rates, which can vary from a quasi-static behavior to values of about $300s^{-1}$ (BENASSI, 2005). Currently, there are some well-known constitutive models in the scientific community to describe this dynamic behavior of metallic materials, such as those of Cowper-Symonds (ALVES, 2000), Johnson-Cook and Zerilli-Armstrong (HUH et al., 2003). The Johnson-Cook model, used in this study, was developed empirically in 1983, and is currently the

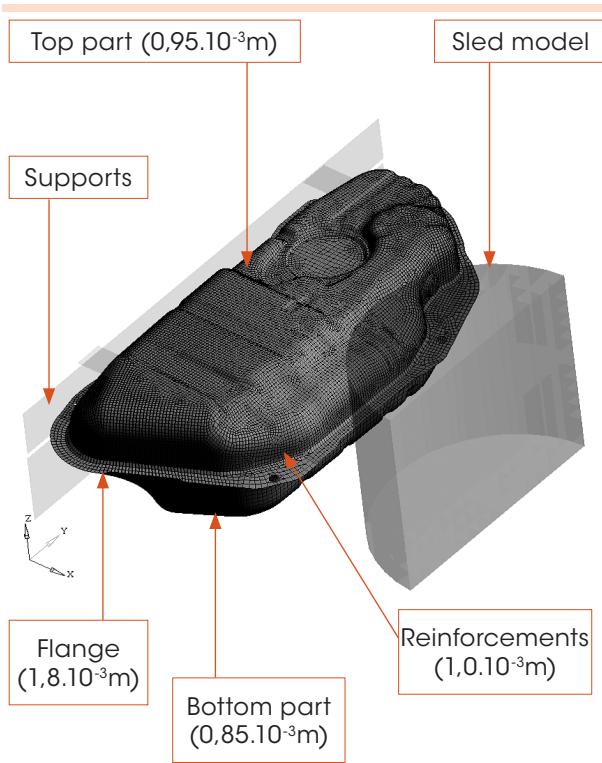


Figure 4: Specification of the main components of the sled crash test

most used model due to its simplicity for obtaining the parameters, as shown in Equation (6):

$$\sigma = \left(a + b\varepsilon^n \right) \left(1 + c \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) (1 - T^m) \tag{6}$$

where a , b and n are the parameters referring to hardening, c and $\dot{\varepsilon}_0$ to the dynamic effects and m to the temperature. The values of these parameters for DDQ steel are shown in Table 2 (THOMPSON, 2006):

Table 2: Material properties				
a (10^6 Pa)	b (10^6 Pa)	n	C	$\dot{\varepsilon}_0$
240	640	0,55	0,0346	1

The data related to temperature were ignored, since the temperature variation during the impact is insignificant. In previous studies, it was

observed that the effect of strain rate is negligible in this sled crash test. In simulations considering the strain rate of the material, the difference in deformation modes was very small.

Figure 5 show that the fuel tank was largely deformed after the crash, despite the relatively low impact energy (3200 J).

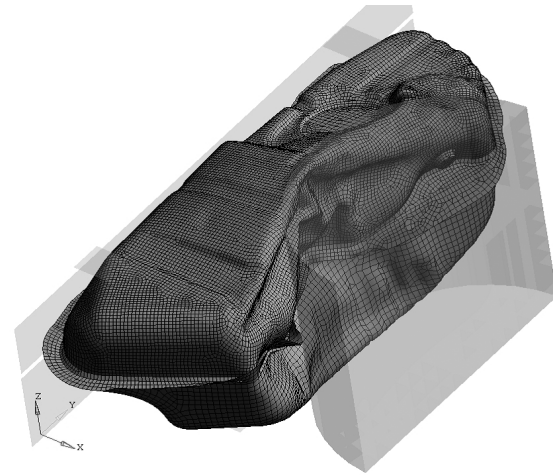


Figure 5: Result of numerical simulation of the sled crash test

Figure 6 show the graphics of the energy variation (internal, kinetic and hourglass) over time, showing that the hourglass energy was very low, which proves that the “anti-hourglass” formulation inhibited the spurious modes.

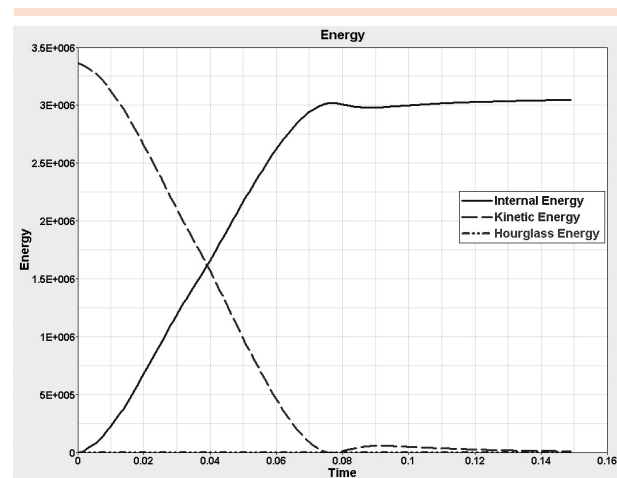


Figure 6: Variation of the energies (joules) over time

Figure 7 shows the change in volume and pressure inside the tank during the impact simulation. It can be seen that the internal pressure increases by approximately 50% due to the reduction of the volume in the tank. The ratio between water (incompressible) and air (compressible) inside the tank is a key factor in the amount of deformation.

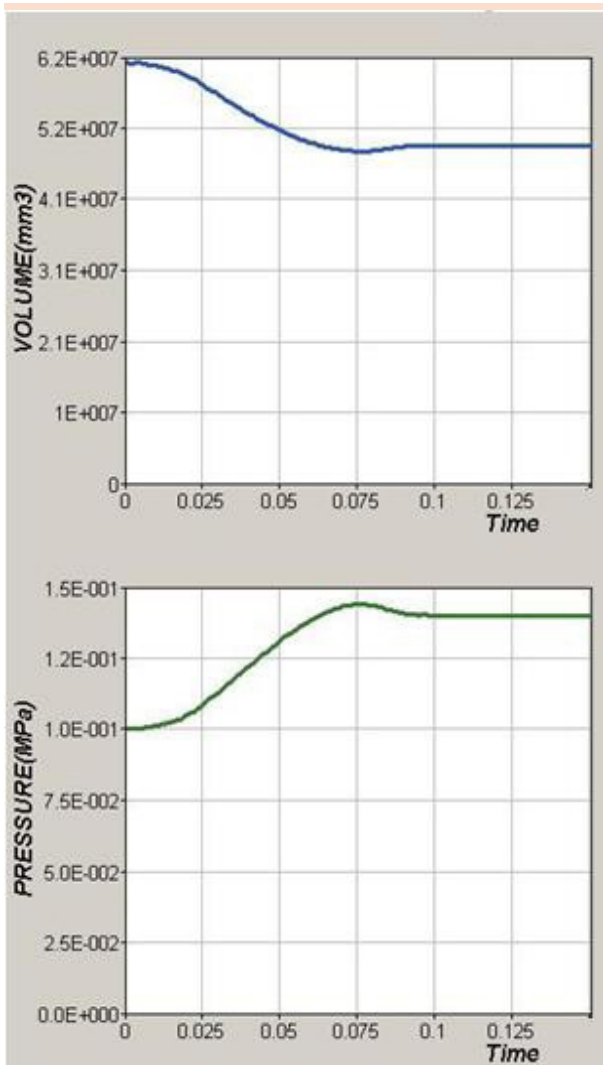


Figure 7: Variation of volume and pressure inside the tank over time

6 Evaluation of results

Figure 8a show the result of the numerical simulation and the Figure8b show the scanned tank from the experimental test. A preliminary

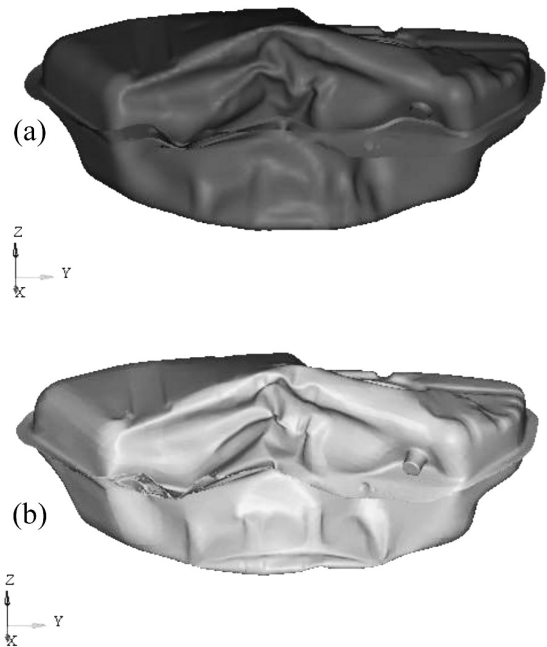


Figure 8: Result of the numerical simulation (a) and the scanned tank from experimental test (b)

visual analysis suggests the results are relatively close. But it is not possible, just visually, to perform a more accurate analysis of the numerical/experimental correlation. In this study, the fact that the experimental crashed tank was able to be scanned into a digital file made it possible to superimpose the geometries of both results, numerical and experimental, as shown in Figure 9.

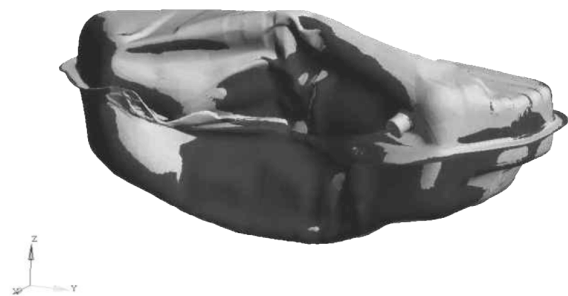


Figure 9: Scanned crashed tank and numerical simulation result superimposed

With the geometries superimposed, it was possible to make cross-sections on the tank and

evaluate how close the result of the numerical simulation was in relation to the experimental result. Figures 10, 11 and 12 shows some examples of cross-sections made on the Y-axis, at distances of 0.3 m, 0.5 m and 0.7 m, respectively.

It can be observed in Figure 12 that there was a small discrepancy between numerical and experimental results in the lower part of the tank. Since both are digital images, with appropriate software to measure positions in digital files, it would be possible to measure the difference between the results.

Figure 13 shows the deformation by numerical simulation of the fuel tank over time, together with experimental results. In these images, it is possible to follow the deformation of the simulated tank until the superimposition with the experimental result.

Figure 14 shows an overview of the cross-sections cuts along the Y-axis at intervals of 0.1 m between each one. It can be observed that the

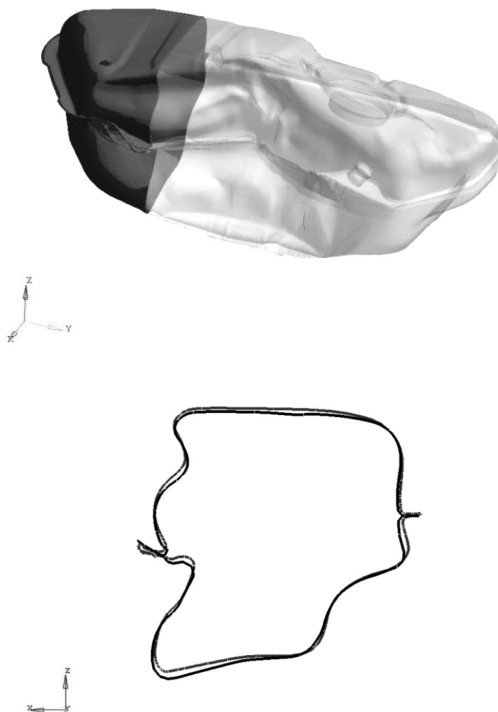


Figure 10: Superimposed results and cross-section cut on the Y-axis at 0.3 m

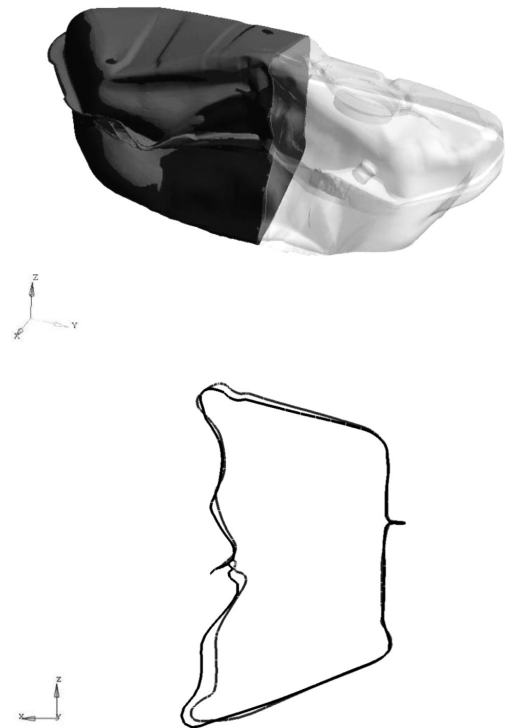


Figure 11: Superimposed results and cross-section cut on the Y-axis at 0.5 m

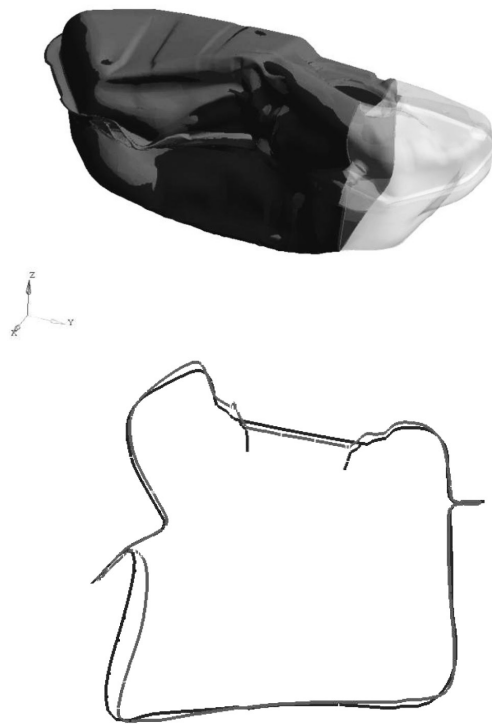


Figure 12: Superimposed results and cross-section cut on the Y-axis at 0.3 m

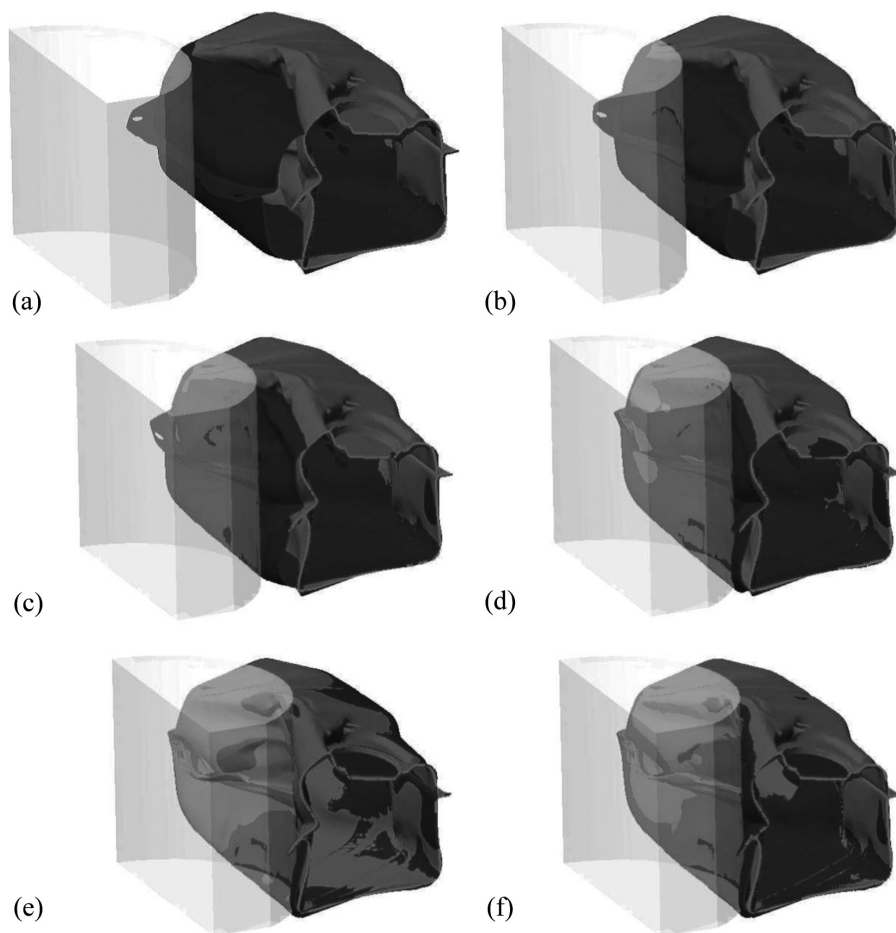


Figure 13: Superimposed results and the cross-section cut on the Y-axis at 0.7 m, over the time: (a) 0.00 s; (b) 0.02 s; (c) 0.04 s; (d) 0.06 s; (e) 0.10 s; (f) 0.12 s

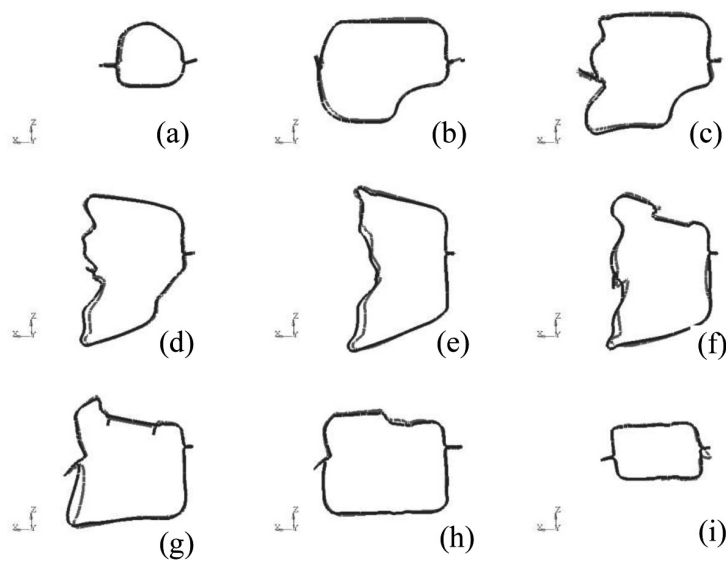


Figure 14: Overview of cross-sections cut on the Y-axis at: (a) 0.1 m; (b) 0.2 m; (c) 0.3 m; (d) 0.4 m; (e) 0.5 m; (f) 0.6m; (g) 0.7 m; (h) 0.8 m and (i) 0.9 m from left side of the superimposed models

overall results are very close, showing that the numerical model is well-correlated

The same type of analysis can be applied for cross-sections made in other directions, as suggested by Figure 15. This methodology allows evaluating any section of the component and making a comparison with the scanned experimental result on a 2D plan. As the surface of the tank does not follow a linear path during the impact, the evaluation of a point's displacement on the surface may lead to wrong conclusions. Visual evaluation and interpretation by the professional is an important factor for determining the correct correlation.

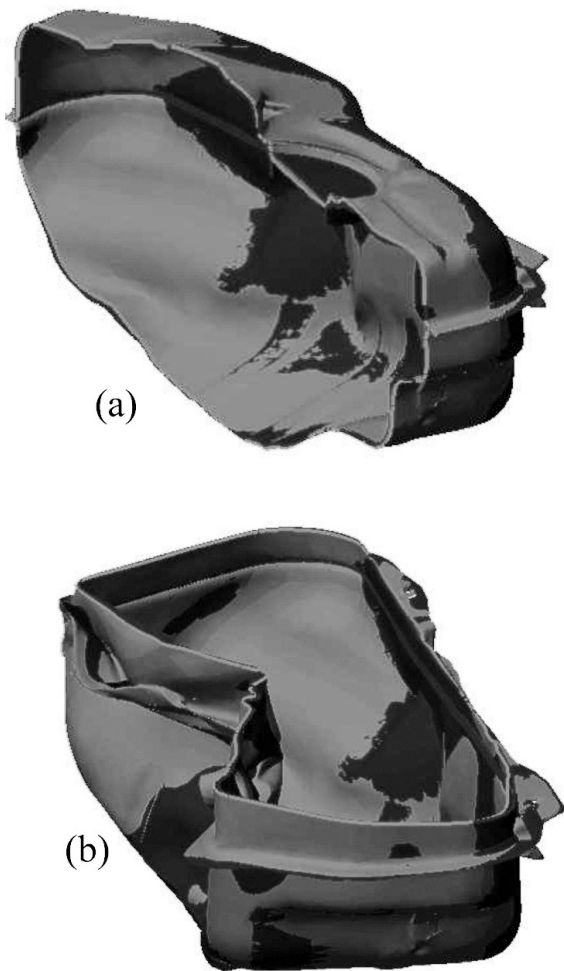


Figure 15: (a) Cross-section on the X-axis; (b) Cross-section on the Z-axis

7 Conclusion

In this study using optical 3D laser scanning, a methodology was implemented to evaluate numerical/experimental results of components subjected to large deformations. The digitalization of the experimental results allowed evaluating the modes and levels of deformation along the component.

From the results, it will be possible to adjust the parameters of numerical simulation, changing the mesh refinement, types of elements, constitutive models, hardening laws, yield criteria, etc., in a way that will make the crash simulation strongly reliable. This methodology can be applied to other automotive components such as bumpers, doors and safety side bars.

To improve the accuracy of numerical simulation results, data of the stress/strain curves for different strain rates are being studied. The data obtained from the simulation result of the stamping process, such as residual plastic strain and final thickness, will be imported into the numerical model to make the input parameters closer to reality.

For a future studies, using appropriate CAD software, a more accurate correlation will be carried out through a qualitative and quantitative analysis of the measurements of the differences between the numerical and experimental results.

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