

Numerical and Experimental Study on the High Strain Rate Deformation of Tubes for Perforating Gun Applications

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Abstract: *The perforating guns are systems subjected to intense, impulsive pressure loading resulting from the detonation of shaped charges loaded in the inner pipe. Upon detonation, the charges are responsible for different significant damaging loading mechanisms such as during jet perforation, case fragment impact and explosive blast. It is usually desired that a gun carrier tube survives the perforation event without excessive swelling, cracking, or catastrophic rupturing (i.e. splitting) or fragmentation, its survivability being a major consideration in perforating system design and manufacture.*

In this work, a numerical-experimental study aimed to better understand the loading rate and damage mechanisms involved on the carried tube, as well as the local deformation response of the full scale component when loaded under real loads are presented.

The numerical model is based on a multiple (three) shaped charges analysis fed by real tube and shape charges geometries as well as carrier tube material curve at high strain rate similar to the real event. An explicit multi-material Coupled Eulerian-Lagrangian (CEL) model that simulates the sequential shaped charges detonation has been developed, the results in terms of local deformation of carrier tube has been then compared with experimental data obtained from instrumented full scale tests.

Keywords: *CEL analysis, dynamic loads, high strain rate, perforating gun, explosion, detonation.*

1. Introduction

Large strain and high strain rate phenomena may be defined as events that occur in a short time, in the order of fractions of seconds, and that involve large strains and therefore high strain rates. Plastic strains, damage and fracture are usually present in this kind of processes.

Generally when a dynamic phenomenon is studied, the first challenge to deal with is the material properties evaluation at high and very high strain rate. Material behavior study under dynamic loading involves the analysis of stress waves propagation in solid and fluid materials, for both elastic and plastic cases. Stress propagates through continuous media as waves with finite velocity. Therefore, a certain time is required in order to allow these waves to spread in the matter. Elastic waves, plastic waves and shock waves are phenomena of utter importance for the study of dynamic behavior of materials (Meyers, 1994, Wang, 2007, Graff, 1965, Achenbach, 1973, Asay and Shahinpoor, 1993, Graham, 1993, Horie et al., 2003, Ben-Dor, 2007 and Davison, 2008). A second key aspect in the dynamic material behavior evaluation consists in the study of experimental procedures capable to expose the material response under dynamic conditions. Throughout the years, some particular experimental procedures have emerged over others, thanks to their better feasibility and effectiveness. Drop-weight machines, Hopkinson bars, Taylor tests and plate impact tests have become fairly popular. Nowadays, their use is common in many situations, both academic and industrial. Procedures to carry out these tests and efficiently measure material responses keep on being elaborated and improved as well (Meyers, 1994, Field et al., 2004, Taylor, 1948, Whiffin, 1948, Jiang and Vecchio, 2009, Rajendran and Bless, 1985, Rajendran, 1992).

Another challenge in dynamic field is represented by the evaluation, differentiation and measurement of all the phenomena which can take place when a very high speed/strain rate complex event is studied. Such events can be ballistic impact, explosion, etc., in which several different phenomena such as damage, spalling, failure and local large deformation are involved.

Finite element (FE) technique can be an useful, and sometime essential, tool which can help not only to study material at very high strain rate but also to study dynamic complex phenomena.

In this work a finite element model of a perforating gun (PG) has been prepared to better understand the loading evolution and damage mechanisms involved in the carried tube (a PG part) as well as the local deformation response of the full scale component when loaded under real loads, that is multiple internal blasts.

Laboratory tests have been performed in order to evaluate the material response to very high strain rate. In particular a split Hopkinson tension test has been used to obtain the material flow stress curve at different strain rate.

Furthermore, full scale tests on real PG have been carried out. PG component has been instrumented with high deformation strain gauges for high acquisition frequency in order to evaluate strain evolution against time in specific PG zone.

2. Component description

Gun carrier is a part of a more complex system called perforating gun (Figure 1a). It is a sealed hollow steel tube, used to convey multiple small shaped explosive charges (Figure 1b) down a wellbore to the vicinity of a hydrocarbon reservoir, isolating the charges from the wellbore fluid and pressure. At a prescribed time and location the charges are detonated, producing perforating jets which in turn create tunnels into the reservoir and allowing subsequent hydrocarbon flow into the wellbore and uphole to surface facilities.

Upon detonation, the charges present three significant and damaging loading mechanisms within the carrier tube: jet perforation, case fragment impact and explosive blast.

Carrier tube after detonation shows several holes and bulges which do not compromise the PG extraction from wellbore. Our customers accept the possibility to have local bulges or localized deformations along the tube but do not accept an excessive PG swelling or even a catastrophic rupturing (splitting). Swelling is the maximum tube diameter of deformed gun carrier.

For this reason gun survivability is a major consideration in perforating system design and manufacturing. Achieving reliable survivability requires an understanding of the loading regime and damage mechanisms involved, and the requisite material properties and geometric characteristics. The event bridges hypervelocity impact, blast loading, shock physics and material science disciplines, as well as rigorous manufacturing process control (Grove et al., 2006).

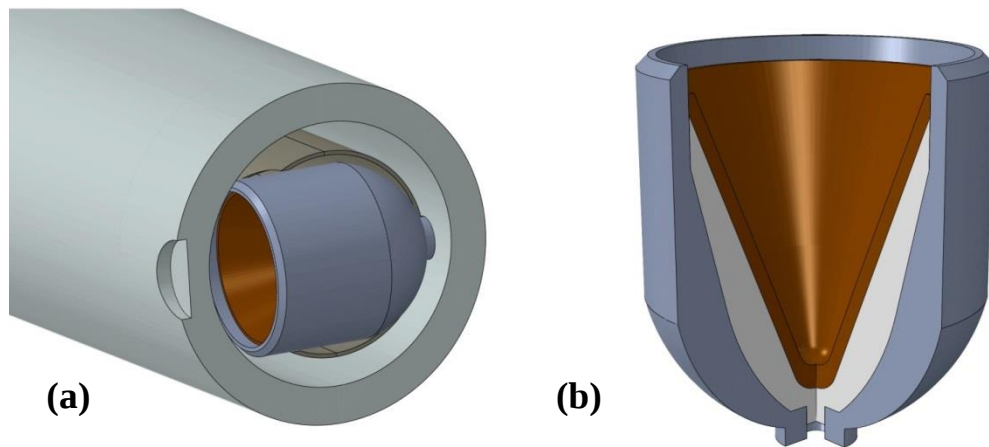


Figure 1. Perforating gun (a) and shaped charge section (b).

The main issue considered in this work regards the local and global PG deformations to meet the demands of our clients.

Perforating charge detonation provides a combination of dynamic internal loading, namely fragment impact and explosive blast, combined with the jet-formed exit holes which can become stress concentration sites. The fragments which impact the carrier internal diameter generally come from the thin steel tube used to package the charges within the carrier (loading tube), which is driven by the expanding metallic charge confining cases. In some cases the case fragments directly impact the carrier internal diameter.

The interaction of these various internal loadings and the carrier tube, whose response is a function of geometry, material composition, manufacturing process, and pre-shooting environmental exposure, determine the extent to which the carrier will survive (Grove et al., 2006).

3. Experimental test

In order to obtain a material characterization as close as possible to the real dynamic phenomena, and then to be used as input for the numerical simulations, two types of experimental tests were performed. For the tensile characterization of the carrier tube steel grade, an experimental tests matrix at different strain rates levels were carried out by means of split Hopkinson tension device.

Moreover, with the aim of calibrate and validate the results in terms of local and global deformations of the perforating gun FE model, full scale tests of a strain gages instrumented perforating gun with different shape charges configurations were carried out.

3.1 Material characterization

Generally we distinguish the "dynamics" materials properties from the "static" one. Difference between this two categories is essentially in the speed of the effects of deformation. Very often, however, in addition to high strain rate there are even large deformations and high temperatures. Therefore, it is important to take into account also the last two factors.

Including the strain rate effect in the constitutive law is essential for a correct structures impact behavior characterization. In particular metallic materials subject to high strain rate are affected by a phenomenon also known as dynamic strain hardening.

To characterize the dynamic behavior of materials have been developed appropriate constitutive laws and specific experimental procedures. The greater the complexity of the constitutive laws and the greater will be the number of tests and measurements to perform.

Make a test that allows to determine the dependence between material mechanical properties and strain rate is not a trivial problem; the dynamic event is in fact complicated by the presence of other factors, such as large deformations and temperature variations. Only one type of test, in general, is not sufficient to fully characterize the behavior of a material.

As regards material strength models, several are suitable for the modeling of materials subjected to large strains and high strain rates (Zener and Hollomon, 1944, Johnson and Cook, 1983, Zerilli and Armstrong, 1987, Steinberg et al., 1980, Steinberg and Lund, 1988). These models are considered to represent some of the most suitable options for the description of high to very high strain rate material behavior, in particular for metals. Moreover, these models are potentially suitable to describe materials subjected to the strain rate ranges involved in the considered industrial application.

To characterize the PG carrier material, Hopkinson tension bar test that allows to achieve higher strain rate (from 10^3 to 10^4 s⁻¹) is used, and to take into account strain rate effect and material temperature. Johnson-Cook plasticity model is chosen for FE implementation.

In the Figure 2 different strain rate flow stress curves of the gun carrier material, obtained from experimental test reported.

It can be noted the differences between the material behavior under static and dynamic conditions and consequently the different local and global behavior of the carrier tube when subjected to impulsive loads. Again, the importance to feed the numerical simulation with material models calibrated at the same strain rates with the one expected during the real phenomena it becomes a key factor for the reliable result of the FEM model.

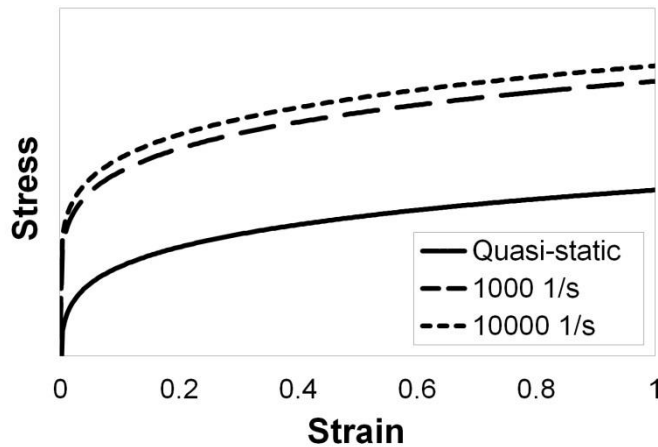


Figure 2. Dimensionless material flow stress curve at different strain rate.

3.2 Full scale test

Full scale test of a simplified PG system has been performed to collect data for FE model calibration and validation. In particular, a perforating gun with a single shaped charge is used to calibrate the model and one with three shaped charges for FE model validation. The aim of the experiments is to validate the model globally by comparing the swelling and locally by comparing the local strain.

The measure of the swelling is a trivial procedure. It is done post-mortem by measuring the diameter with a digital caliper with a resolution of 0.01 mm.

The measure of the local strain is more challenging. In fact, it involves the measures of a small local deformation, in an area involved in the explosion. To do so, a measure of the relative distance of a set of points present in the interesting area has been done before and after the trial. Figure 3 shows a PG where 4 points have been stamped with a puncheon. The top couple is around 70° (represented by the shallow engraved line), the bottom one around 55°. The relative distances have been measured with a digital caliper with a resolution of 0.01 mm.



Figure 3. Local surface displacement by distance between stamps.

For the strain local validation, the results from the measurement of the grid deformation have been used and reported in Table 1.

Table 1. Local strain measurement.

Measurement Position	Experimental
70°	10.3 %
55°	5.1 %

4. Finite element model

The impulsive nature of stresses which characterized the PG behavior, forces to consider large deformations and high strain rate, and it involves phenomena such as mechanical impacts, fracture mechanics in solids and material thermal softening.

To be able to take into account all these variables a coupled Eulerian-Lagrangian FE model has been developed. In particular two different kinds of PG have been prepared with Abaqus/CAE and then run with Abaqus/Explicit:

- Single shaped charge configuration (Figure 4a);
- Multiple shaped charges (up to 3) configuration (Figure 4b).

Both the configurations are characterized by a Lagrangian tube, the carrier, in which shaped charges modelled as Eulerian part are placed. It has been chosen to adopt a Lagrangian technique for the carrier model because of it is important to have good accuracy of the strain field and to have the possibility to implement as accurate as possible damage criterion. Differently, shaped charges have been modeled as Eulerian part because of the very high deformation they experience during the detonation. All the shaped charge parts are obtained from the Eulerian domain by means of volume fraction tool implemented in Abaqus/CAE.

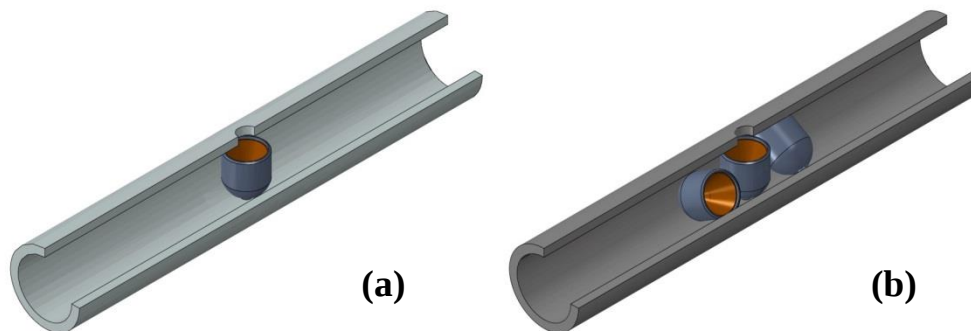


Figure 4. Single shaped charge (a) and multiple shaped charge configuration (b).

FE model is made up of a tube, the gun carrier, in which one or three explosive shaped charges are placed in a helicoidal arrangement of 60° . In the multiple shaped charge model the explosive capsules detonate sequentially with a delay of $5 \mu\text{s}$ from one shaped charge to the following one.

In the real gun carrier component a so called “scallop” is usually present at the shaped charge location. The scallop is a recess profile in the perforating gun body adjacent to the shaped charge which reduces the external burrs created as the perforating jet exits the gun body. The PG zone of interest is not near the scallop but on the opposite side and then, to avoid contact problem between high speed perforating jet and gun carrier, a passing hole is created instead of scallop. Moreover, perforating jet is the first part of shaped charge which impact on the gun carrier creating a hole; later the shaped charge case expands and hits the gun carrier. For this reason, the artificial creation of a passing hole does not affect the carrier deformation during explosion.

Gun carrier tube has been discretized using more than 350000 full integration linear brick elements (C3D8) and Johnson-Cook plasticity model, obtained from experimental tests, has been used for the carrier material description. To take into account possible local failure into the component, Johnson-Cook damage initiation model has been used.

Shaped charge is made of three different parts: the metal liner, the explosive (cyclotetramethylene-tetranitramine, commercially called HMX) and the case. The case is a metallic capsule in which is placed the explosive which, on turn, are covered by a thin copper layer, namely the liner. During detonation, the explosive pushes the liner, which acts as a bullet and the case has the task of controlling the explosion.

For the case and liner, Johnson-Cook material model and Johnson-Cook damage model have been used.

For what it concerns the volumetric behavior of the carrier and the shaped charge, linear U_s - U_p Hugoniot form of the Mie-Grüneisen equation of state is used. In the case in which the materials reach or get over the melting temperature, the Johnson-Cook model prescribes a null yield stress and it provides no deviatoric resistance. Its behavior is then volumetric only and it is regulated by the considered Mie-Grüneisen equation of state.

For both the Eulerian metallic parts and Lagrangian one, possible spalling failure (two waves of compression are reflected on the free-surfaces of the component and then interact to generate a

region of high tensile stress) has been taken into account by means of the ***Tensile Failure** keyword.

Explosive has been characterized by Jones-Wilkins-Lee (JWL) equation of state capable of modeling the volumetric behavior of detonation products of explosives. Eulerian volume which is not occupied by the shaped charge has been modeled as air using ideal gas equation of state.

At the moment all the material properties, except the carrier Johnson-Cook plasticity model obtained from experimental tests, have been taken from literature.

During the simulations several issues about mesh dimension have been encountered. One of the most recurring issue was about the contact at high speed between Eulerian and Lagrangian parts. Moreover, due to the very different density of the materials considered in the simulation, the material deformation speed exceeded the wave propagation speed in certain elements. Several analyses have been run in order to find the best elements dimension to work around these issues without too much compromising time increment.

More than 1.2 million of reduced integration linear Eulerian brick elements (EC3D8R) have been used. Eulerian mesh motion domain has been also used to help reducing the computational expense.

Eulerian to Lagrangian contact interactions between the Eulerian parts and the Lagrangian carrier are modeled in Abaqus/Explicit using a penalty-based general contact approach.

All the dynamic explosion simulation, performed with Abaqus/Explicit have been followed by elastic springback simulation with Abaqus/Standard. The gun carrier deformed instance has been transferred from Abaqus/Explicit to Abaqus/Standard to simulate the springback to obtain the carrier configuration after dynamic event.

The single shaped charge configuration has been used to calibrate the FE model. The variable used for this purpose is the explosive detonation energy which depends on the explosive chemistry. Once the single shaped charge configuration has been calibrated, the multiple shaped charge model has been run to validate the FE model and then understand the effect of shaped charges interaction on the carrier behavior.

Figure 5 shows the explosion simulation at different time instants. To better understand the shaped charge explosion evolution, model has been cut in half and Eulerian explosive material has not been shown (Figure 6).

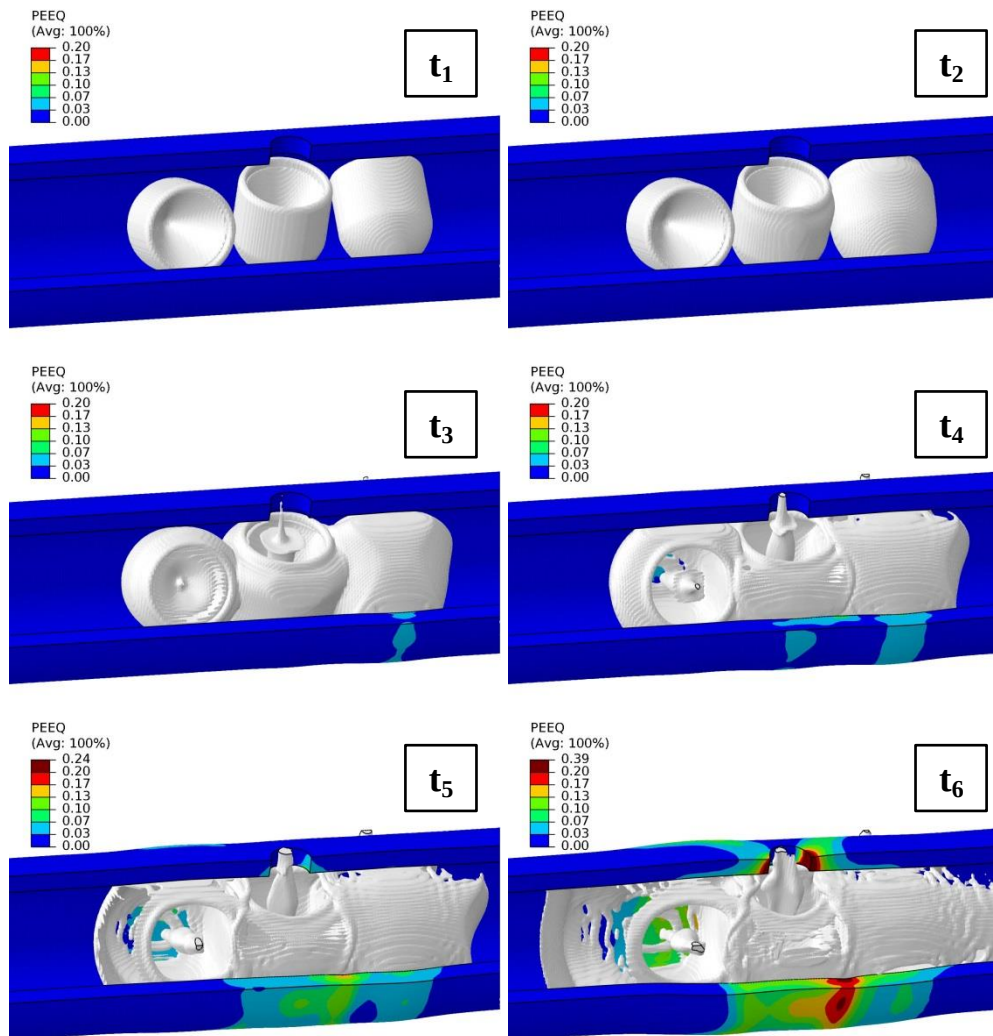


Figure 5. Three shaped charge explosion evolution.

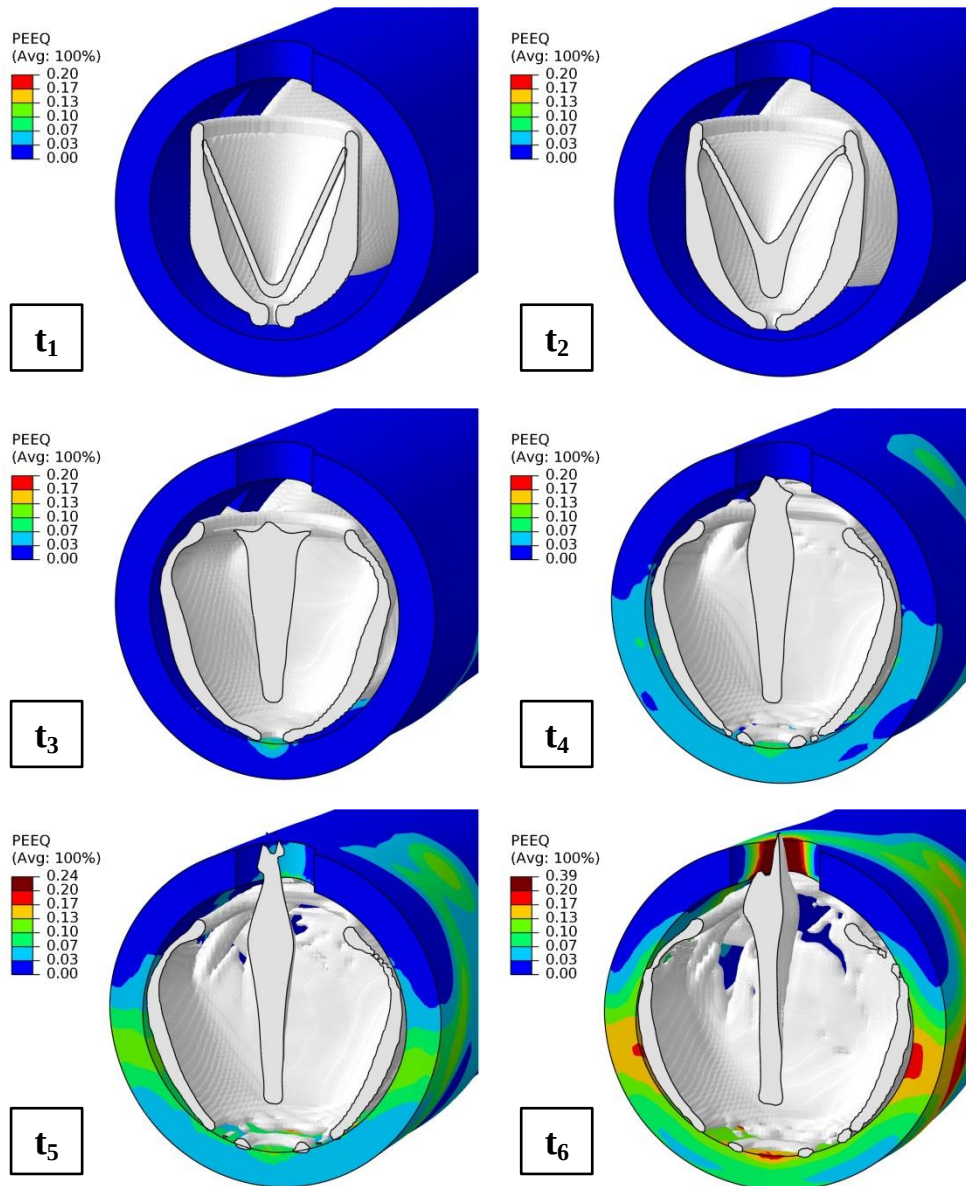


Figure 6. Detail of shaped charge evolution against time.

5. Numerical and experimental correlation

The carrier deformed configuration after springback analysis has been compared with the real post-mortem carrier configuration. Furthermore, also the local deformation in specific carrier location has been compared with carrier real deformation measured on its surface. Figure 7 shows the comparison between FE maximum carrier swelling and real one. Post-mortem tube swelling prediction is very good as regards both the maximum values and the global tube section shape.

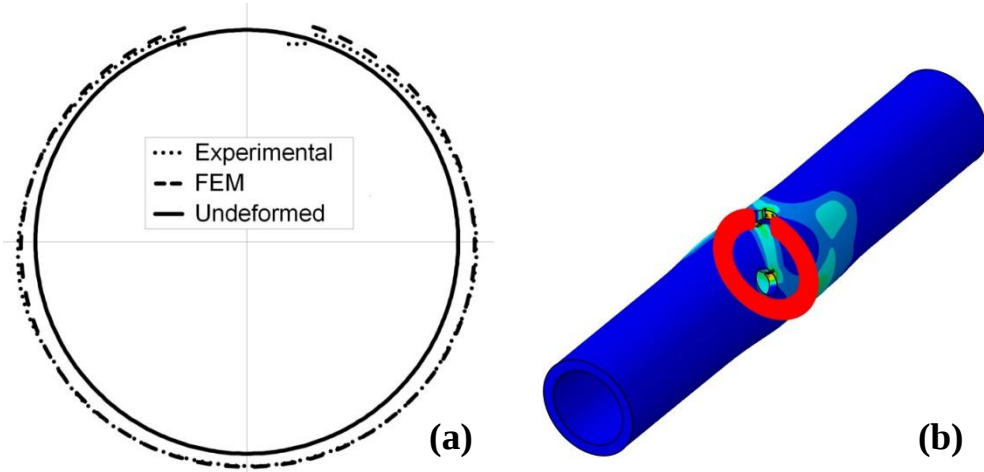


Figure 7. FE vs. real max. carrier swelling (a), in red the considered section (b).

For the strain local validation, the results from the measurement of the grid deformation have been used. Also with regards to the local strain, comparison between FE result and experimental one confirms the good results prediction (Table 2).

Table 2. Global and local strain comparison.

Case	Measurement Position	Experimental	FEM
Global	Location with max value	8.3 %	8.0 %
Local	70°	10.3 %	10.2 %
	55°	5.1 %	6.5 %

6. Conclusion

FE model shows a good correlation with results obtained from field tests as regard both the local strain and post-mortem carrier swelling.

Furthermore, FE simulation has shown the absolute need of having strain rate dependent flow stress curve when so fast phenomena are studied. Material curve related to static behavior are not able to correctly reproduce the phenomenon.

Additional simulations have shown that this model are suitable to separately study the variables which characterize the gun carrier, such as explosive quantity, shaped charge geometry, carrier wall thickness and diameter, wall thickness variation along carrier length, wall thickness eccentricity, etc.

Another challenge we are dealing with is the measure of the local strain against time, during the explosion, by strain gauges installed in the area of interest to validate FE model also during phenomenon evolution and not only at the end of it. This issue offers significant challenges from the point of view of the experimental setup because the explosion causes a high strain at a high strain rate on the material (it is worth remembering that this phenomenon takes place in around 100 microseconds). The most critical issues to overcome during this type of test are the signal acquisition (which comprises conditioning and sampling) and the protection of the electrical sensors and equipment. In fact, the strain gauges and their cables can suffer premature damage or debonding. Some trials have already been done; the results are under interpretation.

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