

A COMBINED EXPERIMENTAL/NUMERICAL METHODOLOGY TO ASSESS THE SENSITIVITY OF PBX's (*)

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The development of PBX's filled warheads of low vulnerability, intended to work behind large thickness of ever harder concrete wall, has led to the statement of a procedure aimed at insuring the integrity of PBXs submitted to such extreme mechanical loading. An experimental/numerical-based procedure has been defined to parameterize in strain, strain rate, and pressure levels, mechanical loading on PBXs samples. Reactivity threshold, and safety margins are investigated. A typical LS-DYNA code finite element modeling of a warhead is given. The usual way to model the viscoelastic behavior law of the PBX is shown and the experimental setup leading to the chosen loading levels is described including its latest developments : a light gas gun launches a projectile acting on a piston which loads a PBX's sample within a hollow cylinder. Results concerning a few PBXs are given. Fit quality between different signals records illustrates the accuracy of our FEM model, and shows the ability of the procedure at reproducing the PBX's dynamical loading taking place inside the warhead through our reduced scale experimental facility.

INTRODUCTION

An original methodology^{1,2}, based on an experimental / numerical procedure was developed to investigate the sensitivity of high explosives in penetrator applications

The input data are the geometry of the warhead's case and the deceleration which is applied to it. For an internal design of the payload, the dynamical behavior of the explosive (pressure, stress, and strain field histories), is assessed through a series of finite element numerical simulations of the functional impact.

These stress/strain levels are then applied at reduced scale to PBX's samples through various laboratory tests. The occurrence of any pyrotechnical event is stated after macroscopic observations. Specific analyses at microscopic scale may be done to investigate the level of integrity of the explosive³. In case of a no reaction statement, a final stage consists in the full scale testing of the warhead.

This paper gives some insight into our methodology, mainly at the functional impact finite element modeling and at the so called

Shear and Compression Test. This experimental set-up is intended to reproduce on PBX samples, at the laboratory scale, the stress and strain history loads derived from the finite element modeling of the impact process.

The first part of this article focuses at the finite element impact modeling and to the derived stress and strain displayed within the explosive's grain, the second part is concerned with the laboratory scale study of the reactive response of the explosive subjected to the previously computed dynamical loading. Then some results examples obtained with this test on a Plastic Bonded explosive are given in the last part.

FUNCTIONAL IMPACT FINITE ELEMENT MODELING

1. Configuration

The LS-DYNA finite element code is used to model the warhead. A 3000 elements mesh is shown in figure 1.

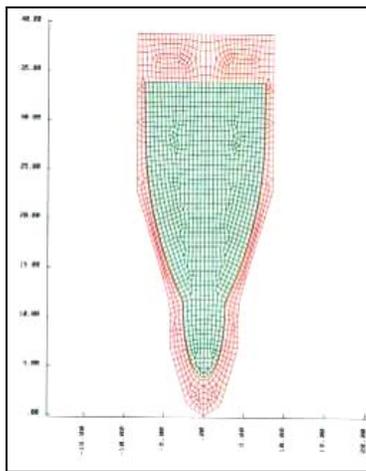


FIGURE 1. WARHEAD DESIGN

Main modeling assumptions are given in the following. The rear end of the PBX's grain shows a flat surface Thermal shrinkage of the grain corresponding to the cooling from the +60°C cast PBX to the +20°C impact temperature is taken into account ; the shell being completely filled at +60°C. That thermal shrinkage implies there is some gap all around the grain. There is no bonding between the grain and the shell, and the contact between them is modeled as a sliding interface without friction. The acceleration signal applied to the warhead is modeled through a velocity boundary condition imposed to the steel case as a whole. A 450 m/s impact velocity is illustrated in the following with a deceleration magnitude up to 50000 g.

Figure 2 shows both velocities histories of the grain and the shell, at the centers of mass, for the schematic warhead given in figure 1.

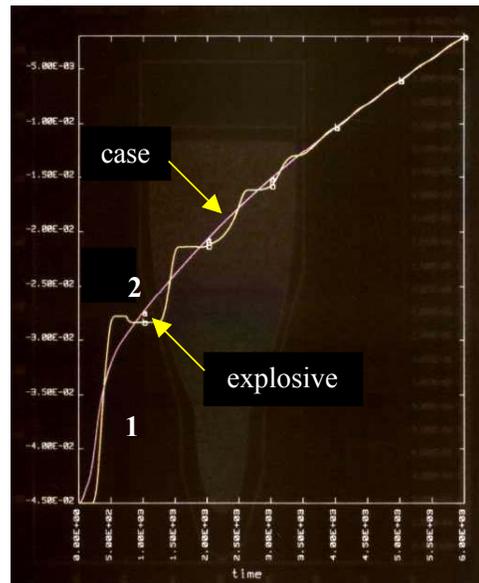


FIGURE 2. AXIAL BODY VELOCITY – SHELL AND PBX GRAIN – $V_i = 450$ m/s
MAXIMUM DECELERATION : 50000G

Figure 2 shows a periodic two stage deceleration, corresponding to the travel time of the compressive wave throughout the grain. It is noticeable that this way, the explosive is subjected to a deceleration level twice as high as the one applied to the shell. First, at the beginning of the penetrating process, the explosive's displacement closes the thermal gap at the front end of the ammunition. This corresponds to a free flight of the grain within the case.

Then stage 1 of the deceleration process occurs that shows an amplitude within the grain twice as high as the one applied to the shell. The duration of this steep slope corresponds to the travel time of the compressive wave sweeping back and forth all through the height of the grain. Stage 2 exhibits a constant velocity value, corresponding to a free flight of the grain within the shell, awaiting for a new bounce against the front end of the case. This two stage decelerating process keeps recurring until the warhead stops.

For the sake of simplicity, the tridimensional aspect of the impact is discarded. The finite element modeling is thus restricted to a bidimensional approach. That is, two geometrical modeling of the impact configuration are usually performed under 2D axisymmetric and 2D plane assumptions. That latter allows the impact incidence to be considered in some way.

This 2D simplification is highly valuable for performing exhaustive parameterization or design optimization.

This option of 2D (plane) calculations for conditions of impact, covers the three-dimensional real situation associated for

conventional targets or the level of deceleration transverse rest around 15 000 g. The values of the stress/strain parameters (P, σ and ε) are the same, only the spatial area differs.

2. Dynamical properties of the materials

The mechanical behavior of the steel case is modeled with a classical elastoplastic law coupled to a Mie Gruneisen equation of state⁴, while the behavior of the cast PBX is modeled with a linear viscoelastic Maxwell law where the Young modulus is developed on a 5 terms⁵ Prony series, and a constant bulk modulus :

$$\sigma(t) = \int_0^t E(t-\tau) d\varepsilon(\tau) \quad (1)$$

where

$$E(t) = E_\infty + \sum_{i=1}^5 E_i e^{-\frac{t}{\tau_i}} \quad (2)$$

$$E_0 = E_\infty + \sum_{i=1}^5 E_i \quad (3)$$

Table 1 gives the set of coefficients corresponding to a PBX composition (20 % RDX, 43 % AP, 25 %Al) :

TABLE 1. PRONY SERIES OF THE PBX'S MAXWELL MODEL

τ_i (μ s)	∞	0.01	1	10	100	1000	10,000
E_i (Mpa)	0	4.533	11.96	74	24.76	-	9.3

This set of coefficients is obtained from Split Hopkinson Bar experiments. The fit between the Maxwell model and the experimental data is given on figure 3. Figure 4

shows the tensile relaxation modulus (2), versus temperature. The time validity range of this set of coefficients is restricted to a [1 ; 1000] microseconds interval. This range is derived from the slope extent of the moduli curves on figure 4. In order to handle realistic moduli beyond 1000 μ s, a static tensile modulus is set equal to E_{∞} .

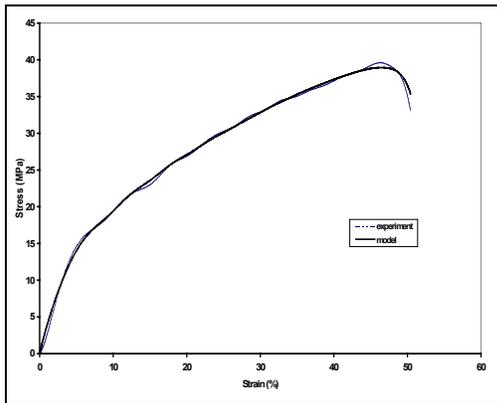


FIGURE 3. STRESS/STRAIN RELATION DERIVED FROM THE SHB EXPERIMENT

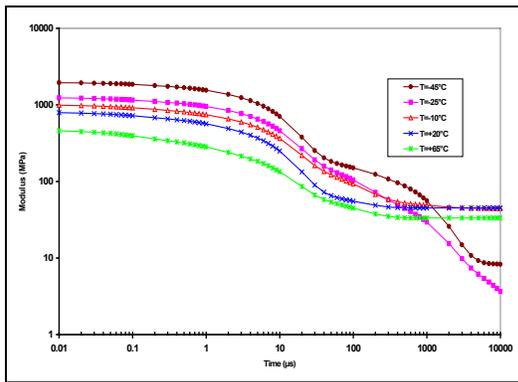


FIGURE 4. TENSILE RELAXATION MODULUS VERSUS TEMPERATURE DERIVED FROM THE SHB EXPERIMENT

The bulk modulus is measured from a dynamic compression test, or derived from Hugoniot data :

$$K = \rho C_0^2 \quad (4)$$

with C_0 : ambient pressure bulk sound velocity read on the Hugoniot.

The value of this coefficient obtained by the two ways is given in the table 2.

TABLE 2. PBX BULK MODULUS K

Dynamic compression test (MPa)	Hugoniot data (MPa)
5250	6000

2. Dynamical loading

Warhead impact safety margins may be inferred from modeling hardened impact loading. One way to do so is to shorten the deceleration profile applied to the warhead, by halving the time scale of the velocity profile for instance.

Figure 5 shows the pressure field within the warhead in the case of a such hardened loading (up to 90000s-1 deceleration). Pressure, effective strain, strain rate and Von Mises effective stress are given in figure 6.

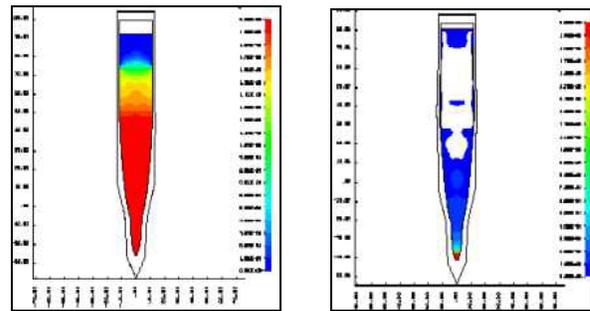


FIGURE 5. WARHEAD PRESSURE FIELD UNDER HARDENED DECELERATION FOR TWO DIFFERENT TIMES

Figure 6 allows warhead maximum field variables under hardened conditions to be derived. The pyrotechnical behavior of the PBX under such levels is to be assessed through the small scale Shear & Compression Test device. This set-up is then designed in order to reproduce these field variables.

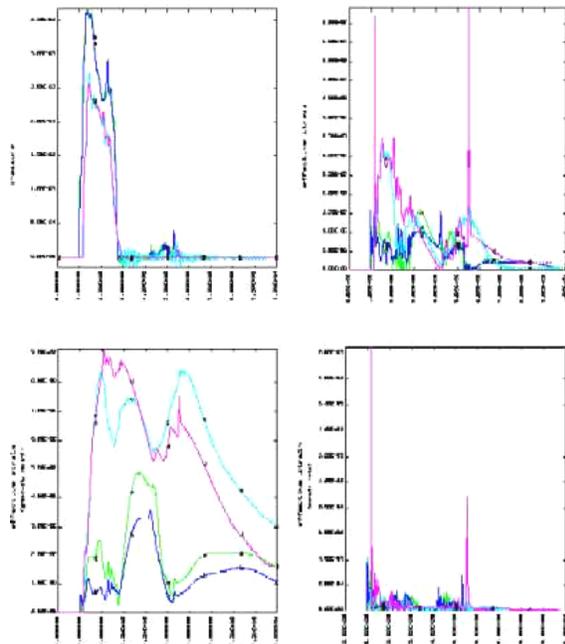


FIGURE 6. PRESSURE, STRAIN, VON MISES STRESS, AND STRAIN RATE HISTORIES, AT DIFFERENT LOCATIONS WITHIN A WARHEAD

SMALL SCALE DEVICE : SHEAR AND COMPRESSION TEST

1. Experimental set-up

A dynamic *Shear and Compression Test* is designed to reproduce the stress/strain field variables histories computed in the simulation of the hardened functional impact. This small scale set-up generates a two steps loading of the sample : at first is occurring a

deformation process under a weak pressure field, then a compression loading is applied to the sample. This two steps loading of the PBX is representative of observed loading within the warhead, the first step corresponding to the functional and thermal gaps closure at impact, and the second step being representative of the PBX compression under the warhead following deceleration.

Figures 7 and 8 show a diagram and pictures of the experimental setup.

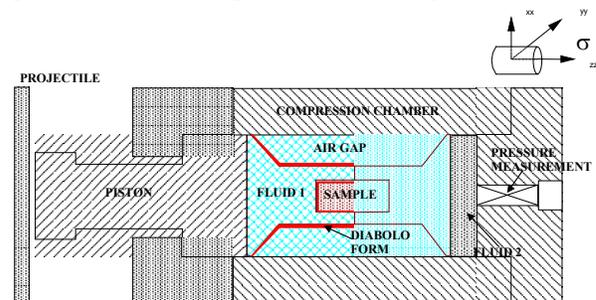


FIGURE 7. EXPERIMENTAL S&C TEST SETUP

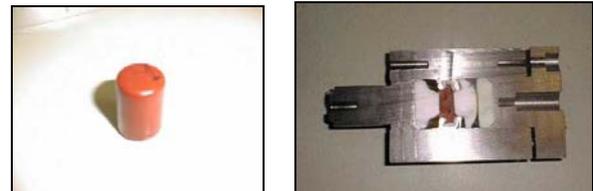


FIGURE 8. S&C TEST PHOTOGRAPHS : SAMPLE, SETUP SECTION AND FULL VIEW.

The sample has a cylindrical shape (ϕ 18 / h 30 mm), and is coated with some PBHT binder. It is inserted within a diabolo shaped shell which acts as a "compression fluid". The diabolo shape settles a void gap around the sample up to the casing, and is made of PTFE in order to prevent any friction phenomenon. The gap amplitude rules the strain level applied to the sample. The vacuum is created in this gap. The second "compression fluid" at the rear end of the device, drives the pressure rate (dp/dt) applied to the material.

Except for the gap which allows a strain parameterization, the S&C Test is similar to the Piston Test settled by the AFRL⁶.

The piston is put into motion by the impact of a light gas gun propelled heavy projectile. The piston displacement generates a small pressure increase within the sample during the void filling stage, related to the rigidity of the PTFE diabolo, but mainly activates the radial deformation process of the sample, monitoring the stress and strain loading of the material, figure 9.

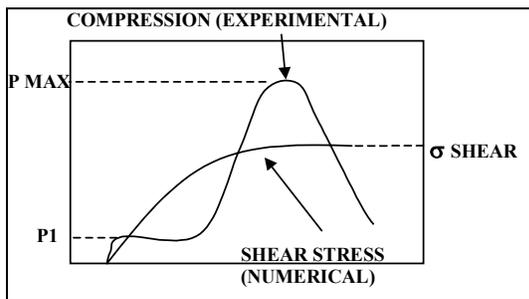


FIGURE 9. PRESSURE AND EFFECTIVE SHEAR STRESS HISTORIES

Once the void is filled, the second stage of the loading is a pressure build up applied to the sample, up to several thousands bars,

depending on the casing rigidity. The build up ends at the stop of the piston, driven back by the stopping devices or if not, by the sample.

The pressure amplitude and loading duration are related to both the piston stroke and the casing rigidity. Illustration of short and long duration signals are given on figure 10, along with the pressure signal from the functional impact simulation (figure 6). It can be seen the ability of the S&C Test to reproduce the impact loading.

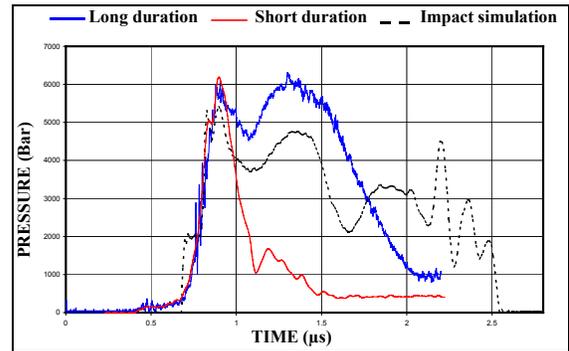


FIGURE 10. PRESSURE SIGNALS MEASURED AND MODELED

The pressure signal is recorded through a piezoelectric sensor, and the piston displacement with numeric video or electronic streak cameras. The S&C device allows the investigation of the PBX behavior under pressure range up to a few kbars, and strain range up to 100 % and above.

The projectile may be accelerated from 10 to 150 m/s. Performing the test at various temperatures is accomplished through the use of nitrogen vapor for conditioning the assembly at low temperatures, or through heating rings around the casing high temperatures (figure 8).

Maximum strain, effective strain and stress, or strain rate, are not measured but modeled with the finite element LS-DYNA code. Confidence in the modeling results is closely related to the ability of the code to fit the pressure signal and the sample residual deformation.

2. *Shear and Compression Test finite element modeling*

2.1. Configuration

Great care was devoted to the finite element modeling of the S&C Test. The parameterization of the test, that is the pressure, strain, strain-rate and stress histories, applied to the PBX's sample, is achieved through the following boundary conditions : mass and velocity of the light gas gun launched projectile, stroke of both projectile and piston, and through the vacuum gap amplitude.

A fair modeling of the S&C Test depends primarily on the accuracy of the behavior laws of the different materials involved in the test. The mechanical data (table 1) associated to the explosive sample are the same as the ones used in the functional impact simulations (Maxwell Visco-elastic model eq. 1,2 and 3). Metals (projectile, piston, case) and the first compression fluid (Teflon), obey a classic elastic-plastic behavior law with hardening modulus, coupled to a Mie Gruneisen equation of state⁴.

The mechanical behavior of the second compression fluid (Silicone) is modeled through a hydrodynamic behavior governed by the same equation of state. The finite

element mesh for the S&C Test is given in figure 11.



FIGURE 11. FINITE ELEMENT MESH OF THE S&C TEST

2.2. Pressure, stress and strain calculations

Finite element modeling of the S&C test shows that the material's sample is subjected to very high stress levels. The Cauchy stress tensor σ_{ij} is decomposed into its deviatoric part σ^d_{ij} and spherical part σ^S_{ij} ; the Von Mises effective stress and the pressure respectively :

$$\sigma_{ij} = \sigma^d_{ij} + \sigma^S_{ij} \quad (5)$$

The spherical part expresses the material response to a pure volumic loading :

$$\sigma^S_{ij} = \frac{1}{3} tr(\sigma) \delta_{ij} = -p \delta_{ij} \quad (6)$$

The deviatoric part represents the material response to the so called distorsion ; that is the response to some deformation without volume variation :

$$\sigma^d_{ij} = \sigma_{ij} - \sigma^S_{ij} = \sigma_{ij} - \frac{1}{3} tr(\sigma) \delta_{ij} \quad (7)$$

In the S&C Test case, the stress tensor is written :

$$\sigma = \begin{pmatrix} \sigma^u + \sigma^h & 0 & 0 \\ 0 & \sigma^h & 0 \\ 0 & 0 & \sigma^h \end{pmatrix} \quad (8)$$

Where σ^h represent the hydrostatic pressure (Recorded within the second compression fluid), and σ^u represents some added uniaxial compression load. The decomposition of this stress tensor σ into its deviatoric and spherical parts may be given :

$$\begin{aligned} \sigma &= \sigma^S + \sigma^d \\ &= \begin{pmatrix} \frac{2}{3}\sigma^u & 0 & 0 \\ 0 & -\frac{1}{3}\sigma^u & 0 \\ 0 & 0 & -\frac{1}{3}\sigma^u \end{pmatrix} \\ &+ \begin{pmatrix} \frac{1}{3}\sigma^u + \sigma^h & 0 & 0 \\ 0 & \frac{1}{3}\sigma^u + \sigma^h & 0 \\ 0 & 0 & \frac{1}{3}\sigma^u + \sigma^h \end{pmatrix} \quad (9) \end{aligned}$$

This is the stress field of an uniaxial compressive test under some independent pressure control. So the total pressure is obtained from :

$$p = -\frac{1}{3}tr(\sigma) = -\frac{1}{3}\sigma^u - \sigma^h \quad (10)$$

And the Von Mises effective stress is given by :

$$\sigma_{VM} = \sigma^u \quad (11)$$

Through its numerous parameters, the S&C Test gives ways to modulate both σ^u and σ^h , that is the pressure and stress histories applied to the PBX's sample. Moreover, in order to analyze the strain amplitude applied to the PBX, we define the effective strain $\bar{\varepsilon}$ as :

$$\bar{\varepsilon} = \left(\frac{2}{3} \varepsilon_{ij}^d \varepsilon_{ij}^d \right)^{\frac{1}{2}} \text{ with } \varepsilon_{ij}^d = \varepsilon_{ij} - \frac{1}{3} \varepsilon_{kk} \delta_{ij} \quad (12)$$

Where the strain tensor ε is defined from the deformation gradient tensor F :

$$\varepsilon = \frac{1}{2}(F + F^T) - I \quad (13)$$

2.3. Validations and results

Figure 12 shows a comparison between the deformed shape of the sample recovered after testing and the calculated shape. This is the case of a S&C Test displaying a 7 mm vacuum gap, and launch parameters leading to a 2 ms compression duration. Usually there is quite a good agreement between the experimental deformation obtained after shot and the simulated one, for vacuum gaps up to a 7 mm value. Beyond that level, due to both the large deformation of the Lagrangian mesh and to the restricted validity range of the materials' behavior laws, the agreement quality declines.

Measured and calculated pressure are compared in the figure 13. We observe a good fit between these signals.

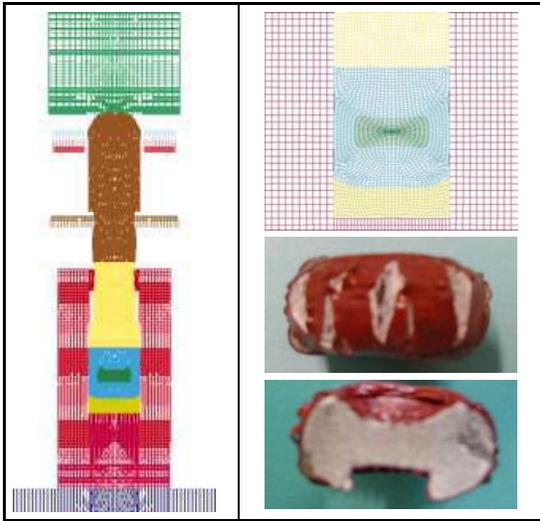


FIGURE 12. RECOVERED SAMPLE AND CALCULATED DEFORMED SHAPE.

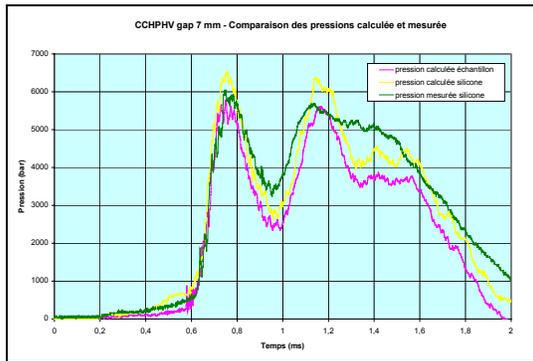


FIGURE 13. MEASURED AND CALCULATED PRESSURE IN THE S&C TEST

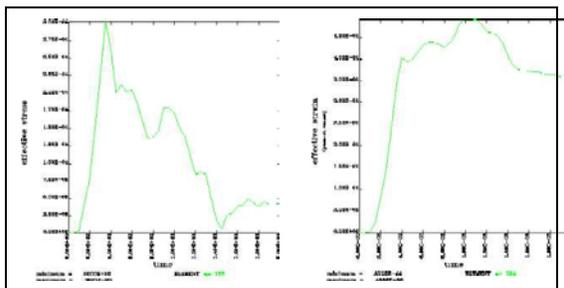


FIGURE 14. CALCULATED VON MISES STRESS AND STRAIN

The ability of the finite element simulations to reproduce the deformed shape of the PBX sample and the pressure experimental record, gives us some confidence in their ability to fit the stress and strain histories.

The stress and strain time histories shown in figure 14 come from a 5 mm gap configuration shot. As it may be seen, the stress and strain magnitudes obtained for this configuration (30 MPa and 40 % respectively) are close to the ones that were computed for the functional impact (Figure 6).

The table 3 illustrates the ability of the S&C Test to parameterize the strain level applied to the sample, with the maximum stress and strain magnitudes deduced from the finite element modeling.

TABLE 3

Air gap 2 mm	Air gap 5 mm	Air gap 7 mm	Air gap 10 mm
$\epsilon^* = 15/24\%$	$\epsilon^* = 30/45\%$	$\epsilon^* = 66/65\%$	$\epsilon^* = >100\%$
$\sigma_{VM} = 16 \text{ MPa}$	$\sigma_{VM} = 30 \text{ MPa}$	$\sigma_{VM} = 62 \text{ MPa}$	$\sigma_{VM} = 114 \text{ MPa}$

* : Height / diameter

The last figure in table 3 shows that for S&C Test configuration with vacuum gap above 7 mm, the PBX sample is subjected to a far non homogeneous loading, that prevents mechanical fields simple analysis. Conversely, up to the 5 mm vacuum gap, the test may be analyzed as a homogeneous one ; i.e. a 0D experimental setup. Moreover, the 7 mm configuration put an end to the validity range of the viscoelastic model of the undamaged material.

In order to avoid this loss of homogeneity in the mechanical loading of our explosive's sample, and restore the full OD character of the S&C Test, we are working on a new design for the compression fluid (figure 15). Furthermore, some radial stress measurement is implemented in this new S&C Test design.

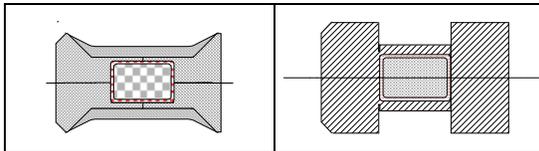


FIGURE 15. S&C TEST NEW SETUP

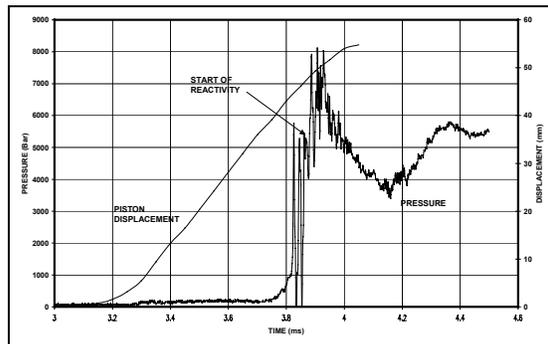


FIGURE 16. PRESSURE SIGNAL AND S&C ASSEMBLY AFTER EVENT

The 10 mm vacuum gap may lead to pyrotechnical events with some cast PBX. Figure 16 gives a typical pressure signal record, with ignition read on the pressure build up. A safety margin may be derived from the gap amplitude threshold between ignition or not, and from the various field variables given by the S&C finite element modeling compared to the levels given by the hardened impact modeling.

CONCLUSIONS

This paper has given some insight into parts of the methodology developed at SNPE to qualify plastic bonded explosives dedicated to penetrator applications. In particular it gives a closer look to the laboratory scale Shear and Compression Test, intended to assess the pyrotechnic sensitivity of an explosive composition subjected to a dynamical loading that compares to the one occurring within the warhead grain at impact against hard targets.

The dynamical loading of the PBX is derived from a 2D finite element numerical simulation of the impact based on a viscoelastic description of the mechanical behavior of the explosive fitted on Split Hopkinson Bar experimental results. We show the Shear & Compression Test ability to parameterize the different loading variables through various combinations of pressure, strain, strain-rate and subsequently applied stress. The recovery of the sample allows further examination of the PBX's sample in order to search for some reactivity evidence.

Typical 2-300% safety margins may be derived from this device over the impact values given by finite element modeling on the different mechanical variables : pressure, strain, strain-rate, or stress. Design improvement of the S&C Test is still in progress with the addition of radial pressure recording device or with the modification of the compression fluid location.

The goal we are aiming at is to make this test as much homogeneous (0D) as possible. That way it is possible to assess the pyrotechnic behavior of PBXs under large strain dynamical loading applied homogeneously to the sample.

ACKNOWLEDGEMENTS

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REFERENCES

1. Lécume S., Brunet P., Chabin P., Briquet B., Minguet L., Sallé P., "Survival of high explosives during penetration", August 1999, presented at the ASME pressure vessels and piping conference, Boston.
2. Lécume S., Chabin P., Minguet L., "The SNPE survivability protocol", October 2001, presented at the 2001 IMENT Symposium, Bordeaux.
3. Lécume S., Chabin P., Lefrançois A., "Structural and chemical changes in PBX induced by rapid shear followed by compression", August 2002, 12th detonation symposium, San Diego.
4. M.J.Murphy, "Material database for DYNA2D" applied mechanics group, LLNL.
5. Quidot M., Racimor P., Chabin P., "Constitutive models for PBX at high strain rate", 1999, Shock compression matter meeting of APS, Snowbird.
6. Glenn J.G., Gunger M.E., " Explosive survivability protocol overview", MWD DES-AF-71-F/G-7304, physics of explosives, 26th technical exchange meetings, 1999, Eglin.