Response of PBXs and Inert Substitutes in Launch and Impact Scenarios

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Abstract

The physical behaviour of a polymer bonded explosive (PBX) fill is important for the development of safe and reliable shells and penetrators. The strain rate environment during launch or impact is generally in the intermediate regime, below shock but above quasi-static. Confidence in the predictions of the constitutive response of PBXs is a necessary pre-requisite for accurate predictions of the likelihood of reactions. The level of deformation and the rate of that deformation can cause ignitions. A number of experiments have been completed with different levels of confinement of both PBXs and PB inerts to obtain data on their behaviour at these strain rates. Further experiments have been completed to obtain loading thresholds for ignitions in an idealised configuration. Instrumentation has included flash X-ray, Digital Speckle Radiography (DSR), VISAR, high speed video and pressure gauges. Experimental data is presented together with hydrocode modelling comparisons. Necessary features of the material models are discussed together with lessons learnt in its application across the strain rate regimes present during launch and impact.

Introduction

Within the UK, explosives in gun launched munitions and penetrators had until recently changed little since the Second World War. The explosive composition had generally remained with a TNT (Tri Nitro Toluene) basis to it, primarily RDX/TNT (cyclotrimethylene trinitramine). Given that the typical military use of these weapon classes had equally changed little in this time period, there had been little requirement to consider updating the warhead fill.

However three factors are now driving the requirement to review and update the explosive content in these weapon classes:

1. The insensitive munition (IM) requirement
2. The wish to exploit gun launch for different munition types
3. The requirement to improve the performance of penetrators.

It is UK Ministry of Defence (MOD) policy to reduce equipment safety risks. IMs contribute to this through fulfilling weapon system performance, readiness and operational requirements on demand, whilst minimising the probability of inadvertent initiation and severity of subsequent collateral damage to weapon platforms, logistic systems and personnel when subject to unplanned stimuli. NATO (North Atlantic Treaty Organisation) nations have agreed a policy for introduction, assessment and testing for IM. These are prescribed in STANAG (Standardisation Agreement) 4439 (Ref.19), which the UK has ratified.

IMs also offer compelling operational benefits including: the flexibility to concentrate assets and thus employ a smaller logistic 'footprint'; the retention of capability in face of hostile attack and accidents; reduced loss of assets and people following hostile

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attack and accidents; reduced site and stockpile defence demands; more efficient use of logistics equipment and manpower; and a contribution to the maintenance of morale.

In addition, when developing a new warhead, its safety and suitability for service also needs to be demonstrated. In the case of gun launched munitions a methodology is detailed in STANAG 4224 Ed. 3. It aims to demonstrate that the combination of propelling charge, projectile and cannon are bore and flight safe and can withstand firing stresses. The purpose of the tests in this standard and others such as ITOP (International Test Operating Procedure) 4-2-504 is to demonstrate that statistically less than one round in 1,000,000 could exceed the design conditions potentially leading to a catastrophic event or failure. ITOP 4-2-504 also demands that before the safety tests are undertaken there already exists some basis for expecting an acceptably low failure rate.

Energetic compositions based on a solid nitramine in a rubbery binder have been evolved as a replacement for TNT based explosives to achieve IM, since they offer considerable performance advantages, including: reduced sensitivity; and improved stability and physical ruggedness. Such compositions are called polymer bonded explosives (PBX).

It is therefore desirable to measure, understand and model the physical behaviour of PBX when subjected to pressures and accelerations/decelerations found during gun launch and penetrator impact. This is also known as set-back and set-forward. In order to understand the physical behaviour it is necessary to separate it from effects due to decomposition or reaction of the energetic component. Undertaking tests on representative PB inert (PBI) substitutes, such as replacing the solid nitramine by sugar, is one method to achieve this.

A methodology has been applied integrating a programme of laboratory, integrated and small scale tests with computer model development. The laboratory tests were quasi-static compression, plate impact and Hopkinson pressure bar. The integrated tests evolved over time into a form akin to a modified symmetrical Taylor test geometry. The small scale test employed a 40mm gun with an aluminium barrel [1]. The computer model development was initially based on a modified visco-elastic constitutive relationship calibrated with laboratory test data [2]. It was subsequently replaced with a model utilising the QinetiQ Quantitive Structural Property Modelling (QSPM) technique of Porter and Gould [3] to provide the equation of state (EOS) and their hierarchical approach to predict the constitutive approach. QSPM is a derivative of Molecular Dynamics Modelling (MDM).

Finally it was necessary to apply the understanding gained on the deformation behaviour to investigate the conditions that would lead to ignition. A small scale environmental test-rig (ETR) was developed where the loading and deformation conditions were modified to obtain thresholds for ignitions.

Deformation Environment

The environment that prevails inside a shell or penetrator during gun launch or impact is characterised by a period of high acceleration or deceleration and high stress followed by a gradual reduction in these levels as the projectile either reaches its terminal velocity or comes to rest, after which the explosive is expected to operate as designed.

The level of confinement and composition of the PBX dictates its response. Figure 1

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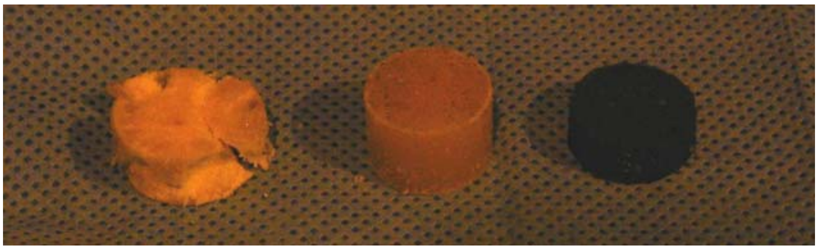
illustrates some examples of this behaviour following quasi-static compression. An unconfined sample of PBI (a) fails through cracking during the test and is obviously deformed post test with only a small elastic response. However a confined sample of PBI (b) initially appears to have returned to its original dimensions with purely an elastic response, the question is: Has it returned to its original state? In general the sample will have damaged, however assessment of the extent of the damage is only possible through internal inspection of the sample or repeating the loading and comparing the response. A sample of the binder material itself (c) returned to its original size and state following testing.



(a)	(b)	(c)
Unconfined PBI	Confined PBI	Binder only
Cracked and Damaged	No cracking but damaged	No cracking or damage

Figure 1: Examples of constitutive response – after quasi-static compression

Thus it can be concluded that the response of the PBX is a function of its confinement and its composition. Furthermore the computational constitutive model needed to replicate these effects and include a history term to record damage without implying a residual plastic strain.

The initial testing programme based on quasi-static and Hopkinson bar compression tests demonstrated significant behavioural trends inherent in PBX/PBI materials. These trends formed the fundamental underlying assumptions concerning the development of the initial constitutive model. Perhaps the most significant observation from these tests was that the material was visco-elastic in its deformation response. This implied that all the deformation was elastic and the material had a tendency to return to its original dimensions during unloading. However, for the PBXs under investigation, the viscous response was relatively small. The situation was complicated however, by the evolution of damage within the material during testing.

These tests allowed the construction of a relatively simple linear visco-elastic model. The original model was designed to predict polymer properties but did not include the effect of the particulate filler. The deformation behaviour was characterised by an initial high modulus followed by a reduction in this as damage occurred in the material. At high strains the damage ceased and was replaced by a strain-hardening response. A phenomenological model was thus constructed that replicated this behaviour. The model was a sum of two terms and is described by the following equation:

$$\sigma = A1 * \varepsilon * \exp(-A2 * \varepsilon) * [1 - \exp(-A2 * \varepsilon)] + \frac{A3 * \varepsilon}{(1+\varepsilon)[1 + A4 * (1 + A5 * \varepsilon^2)]^2}$$

$$A1 = A11 * \dot{\varepsilon}^{A12} * \exp(A13 * T)$$

$$A3 = A31 * \dot{\varepsilon}^{A32} * \exp(A33 * T)$$

Where, $\dot{\varepsilon}$ =strain rate, ε=strain and T= temperature (K) and A11, A12, A13, A2, A31, A32, A33, A4 and A5 are constants.

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In this model as shown A_1 and A_3 are functions of strain rate and temperature. The first term mimics the effect of the particulate filler: a high initial modulus that decays with strain due to damage, (the modulus in all cases refers to the absolute form σ/ε). The second term is a strain-hardening term; its form is taken from a physically-based elastomer model. The form of the model is seen to fit the experimental quasi-static compression data for a PBX, as shown in figure 2. The constants are empirical fits to the data.

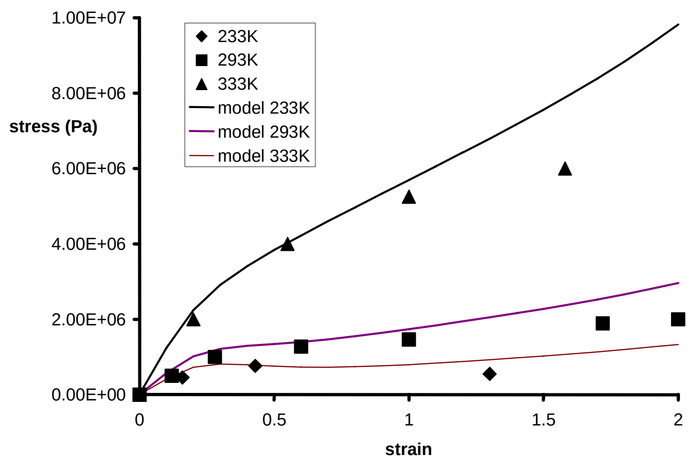

Figure 2 Comparison of constitutive model with quasi-static compression tests with temperature

The application of this constitutive model together with an associated EOS reflecting the variation of the bulk modulus with temperature provided considerable insight into the behaviour of PBX under both gun launch and impact scenarios and represented a significant improvement in understanding of the response of the PBX. Despite the model being based on the physics of PBX deformation it was essentially semi-empirical. It could be calibrated to fit most PBXs to a reasonable degree of accuracy up to strains of 2.

This model was initially applied to the results of a series of firings undertaken at smaller scale using a 40mm gun with an aluminium barrel [1]. A component of the gun system design was a mechanism to hold the projectile back in the breech, until the breech pressure had reached a threshold, to increase the acceleration levels. X-rays of the PBI were obtained at maximum acceleration and at exit to obtain measurements of the set-back induced in the PBI and its evolution, an example is shown in figure 3. The set-back was typically of the order of 1mm, however in some firings the set-back was uniform [1], in others, a graduated or dishing profile was observed, shown in figure 3.

The dishing shape suggested that friction between the PBI/PBX and the projectile case was an important feature of its response during launch. Simulations were undertaken to investigate the effect of friction coefficient on the set-back of the PBI/PBX [1]. These simulations failed to reproduce the extent of the dishing behaviour observed, primarily due to the assumptions present in the concept of friction, where the frictional force is a ratio of the surface reaction. At the top of the projectile where there is little lateral force exerted by the PBX/PBI the frictional force is also consequentially small. The motion of the PBX/PBI in relation to the side walls is actually a function of cohesion and friction which is more complex to replicate in a simulation. The importance of cohesion/friction in the gun launch scenario where spin is also a component is shown in figure 4; here it led to significant distortion of

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the energetic fill and high stresses. The typical level of the friction/cohesion was required from more detailed experiments.

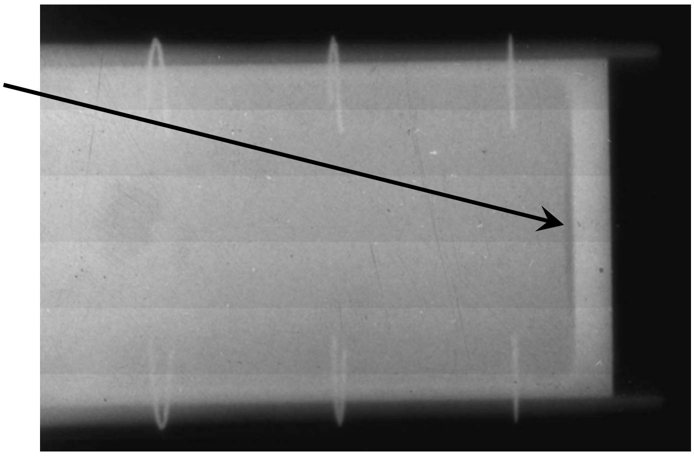

Figure 3: Flash X-ray of the projectile at exit of the 40mm gun showing set-back of the PBI

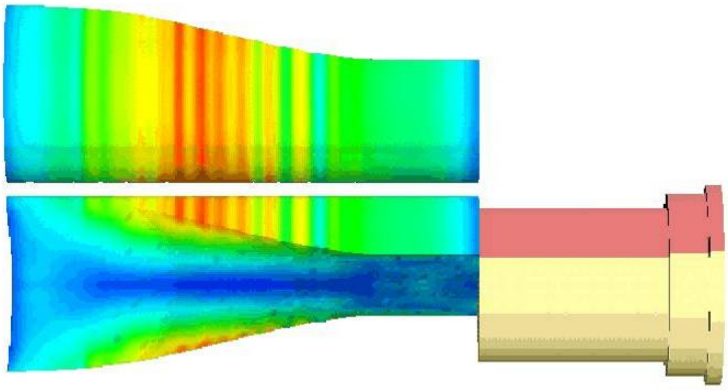

Figure 4: Stresses in the distorted energetic fill with a rifled barrel with a friction coefficient of 0.05

Simulations of the gun launch scenario applying the constitutive model also appeared to indicate that rather than the PBX/PBI setting-back under the initial high acceleration loads and remaining in that attitude until exit, the PBX/PBI actually set-back, followed by a fluctuation in displacement. The frequency and amplitude of the oscillations also changed with the addition of friction and alteration of the coefficient [1]. The experimental gun firings appeared to indicate that there was no discernable motion of the front face of the PBX, however, with only two X-ray snapshots during the launch it was difficult to disprove or validate the observation from the simulations.

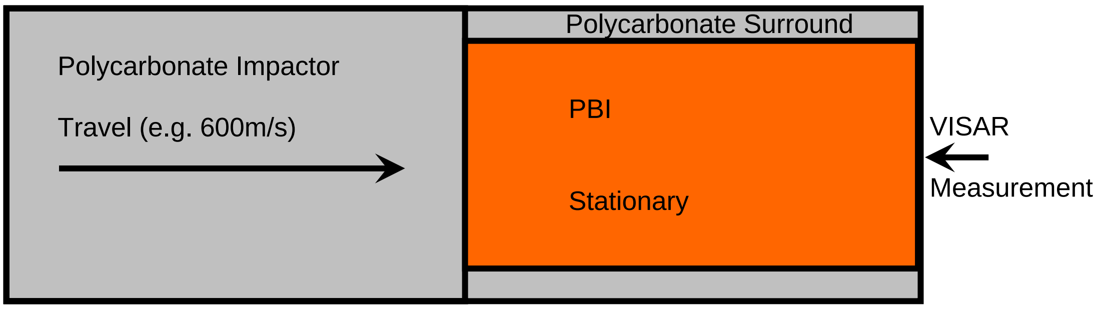

Figure 5: Experimental arrangement of the modifed Taylor test

A number of detailed laboratory experiments were therefore undertaken to explore the behaviour of PBX/PBI in a realistic environment but also in form where significant diagnostics could be included. Figure 5 shows the configuration of a modified

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symmetrical Taylor test that was developed to investigate the motion of the PBI including effects such as set-back, deformation and friction/cohesion.

The analysis of the experiment was primarily through flash X-ray DSR shortly after impact, which showed detailed deformation of the PBI and surround; and the velocity time history of the back face. However, the final deformation of the PBI and surround plus the final state of PBI (e.g. extent of damage) was also informative. Figure 6 shows a DSR image from one of the experiments and figure 7 the velocity time history. Figure 8 shows the stresses evolved in a simulation of this test, whilst the overall deformation appears correct, the comparison of the detailed internal deformation with the DSR image highlighted some important differences.

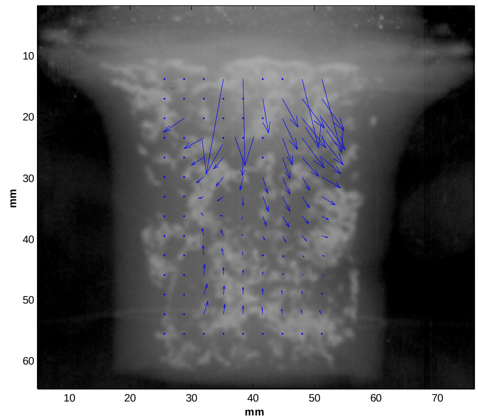

Figure 6: X-ray and DSR from an impact at 600m/s showing deformation and internal motion

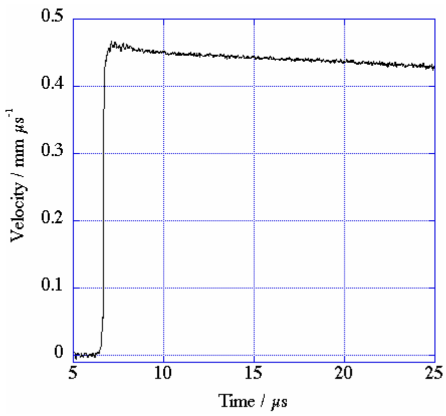

Figure 7: VISAR measurement from PBI impacted at 600m/s

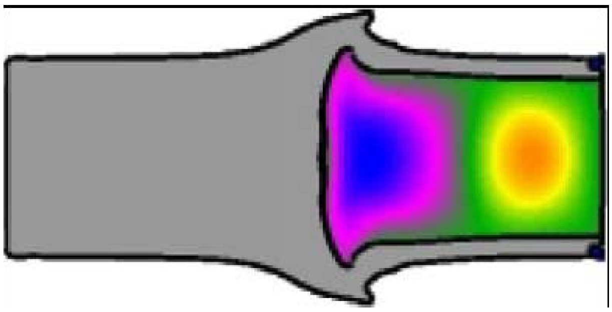

Figure 8: Simulation of the modified symmetrical Taylor test at 600m/s showing the stresses

The VISAR trace did not show any fluctuation in the motion of the rear face during the impact; this was contrary to the simulation predictions and indicated a limitation in the constitutive model. The limitation probably stemmed from the representation of damage in the model, primarily that it was not explicitly calculated and incremented but an implicit component of the constitutive response.

The experiences recorded above and those from the extension of the areas of application of this model to higher strain rates and to complex load-reload highlighted that an improved model was required. Higher strain rates occur for example with shocks and bullet impact scenarios, most real contexts also contain multiple loading pulses. This new model needed to incorporate theory from the physical behaviour of the polymer binder itself and its interaction with the particulate filler, rather than just empirical fits to experimental data. For example, in common with constitutive models for polymer fibre composites, damage should be a function of energy rather than stress or strain.

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The response of the PBX in the shock and high strain rate regime is dominated in the computer simulation by the EOS. A new EOS was provided by Porter & Gould [3] applying a QSPM methodology. This applied a well-validated potential function, to calculate the interactions between all the atoms in a periodic box that characterise the composition of the polymer and the PBX/PBI separately. Through the application of this data via a method of mixtures a prediction of the behaviour of the composite in terms of Pressure, Volume and Temperature was obtained.

Figure 9 shows a comparison between the simulation applying this EOS and the stress time response in a gauge embedded within a PBX in a plate impact test performed at the UK Defence Academy.

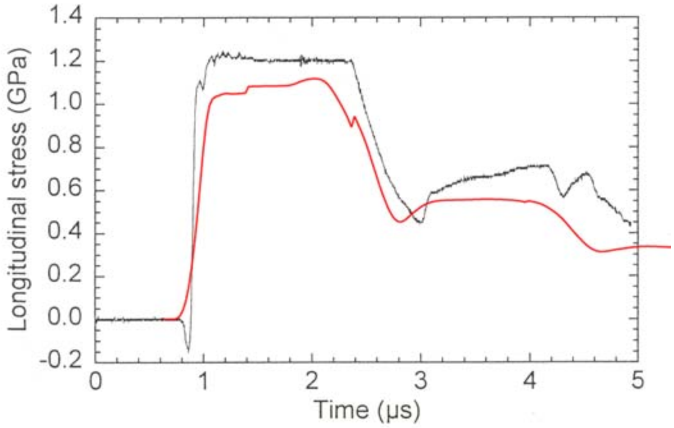

Figure 9: Comparison of Simulation (red) and experiment (black) for a plate impact test on a PBX

A more physically based constitutive relation was also required in particular to improve the representation of damage and the effect it had on the constitutive response. The modulus of the binder is several orders of magnitude lower than the particulate filler; this allowed the two components to be considered independently. The Porter & Gould approach again applied a QSPM methodology for the binder, here in conjunction with a hierarchical treatment of the filler particulates, accounting for the considerable variation in particulate dimensions [4]. The effect of damage will be to either modify interaction of the particulates and the binder on a particular length scale if a de-wetting form occurs or the binder itself if tearing occurs. The evolution of damage occurs independently based on an energy function. Figure 10 shows a comparison of the stress-strain prediction compared to data obtained from a Hopkinson pressure bar test. It predicted the correct stress level but not the precise shape of the curve, a more detailed consideration is provided in [5].

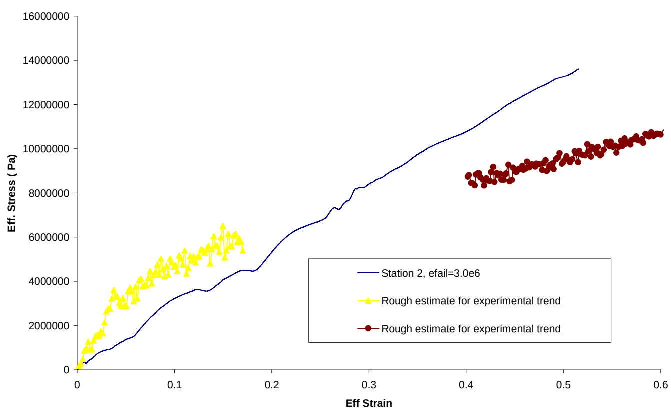

Figure 10: Comparison between constitutive model and Hopkinson bar results

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Thresholds for Ignition

The remaining component of information required to understand and predict the response of PBX in gun launch and impact scenarios is an understanding of the ignition threshold(s), i.e. the deformation or insult that is required to cause the PBX to ignite or decompose. An environmental test rig (ETR) was developed in collaboration [6]. The purpose of the ETR was to provide ignition thresholds in an environment representative of gun launch and impact, rather than violence of reaction. The ETR was designed with consideration of an investigation into two primary causes of ignition, shear and adiabatic compression.

An illustration of the laboratory scale ETR is shown in figure 11. The dimensions of the cavity can be varied to alter the amount of shearing; also it can be evacuated to remove adiabatic compression as a mechanism. The rate and magnitude of the loading can be adjusted to potentially identify thresholds due to different mechanisms. The two configurations illustrated in figure 11, represent a difference in self confinement since a reaction in the explosive can push back the piston and vent the ETR.

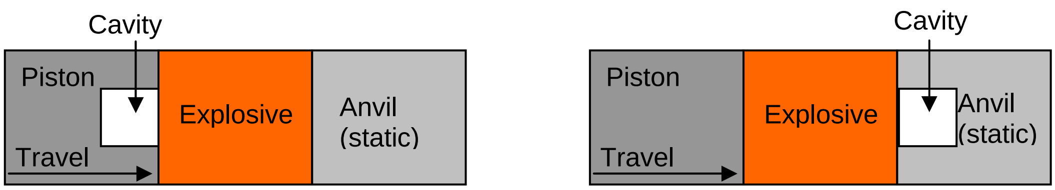

Figure 11: Illustration of the ETR for set-back (left) and set-forward (right)

The majority of the tests have been completed on the research PBX composition CPX301 and on PBXN109. After each test the explosive sample is recovered and weighed to determine the percentage mass lost when a reaction occurred. The ETR contains two pressure gauges which are used as the primary indicators of whether a reaction occurred or not.

The effect of self confinement was investigated by applying the two configurations illustrated in figure 11. The results from the ETR on CPX301 showed that the difference in confinement in either scenario had no discernable effect on the threshold of ignition. When ignition occurred, however, in the set-forward environment the confinement increased the mass lost due to burning of the PBX. Figure 12 shows the explosive sample post test from one of each set of experiments, the peak pressure applied was approximately 380MPa.

Figure 12: Sample post test with a change in confinement: set-back (L) set-forward (R)

The investigation of cavity diameter in the ETR was also completed on CPX301. Previous tests had shown that a very small reaction occurred with an applied peak pressure of approximately 68MPa. The cavity diameter was varied from 15mm down to 5mm. The results of the tests are listed in table 1, and show that the likelihood of reaction reduced as cavity diameter reduced. However except for the smallest diameter whenever a reaction occurred a similar amount of the sample remained.

It was not possible from these test results to determine whether the change in the level of reaction with the change in cavity size stemmed primarily from a reduction in the amount of shear applied to the sample or a reduced volume of air undergoing adiabatic compression. However analysis of the samples post test appeared to indicate that both processes were required for a reaction to occur. The ignition sites, at the top of the cavity, appeared to indicate it was the escaping compressed gas flowing into/over the shear damaged material that actually briefly ignited the sample, figure 13.

Cavity Diameter (mm)	Peak Applied Pressure (MPa)	Material Recovered (%)	Reaction Notes
15.0	81	88	Very Small 5 of 5
10.16	68	86	Very Small 5 of 5
7.5	65	89 (Reacting only)	Very Small 3 of 5 No Reaction 2 of 5
5.0	66	99 (Reacting only)	V Very Small 1 of 5 No Reaction 4 of 5

Table 1: Effect of cavity diameter on the reaction of CPX301 in the ETR

ETR tests on samples of both PBXN109 and CPX301 under vacuum conditions resulted in no reactions occurring under the standard loading conditions adopted in the ETR with an applied pressure of 380MPa. This indicated that adiabatic compression of gas was a necessary condition for a reaction to occur in a PBX, though as previously indicated it is probably not a sufficient condition. In the evacuated ETR the pressure rise rate was then increased to determine if there was an ignition threshold due to rate of deformation. These tests were completed on PBXN109. Table 2 lists the results obtained, and figure 14 shows a sample of PBXN109 post test at the highest loading rate

Figure 13: Reduced cavity sample post test

Figure 14: Higher rate sample post test

Rise Time (ms)	Peak Applied Pressure (MPa)	Material Recovered (%)	Reaction Notes
6.6	205	100	No reaction (5)
2.0	310	100	No reaction (3)
1.5	313	100	No reaction (3)
0.2	279	61	Small (3)
0.2	212	76	Small (3)
0.2	197	80	Very Small (3)

Table 2: Effect of loading rate on the reaction of PBXN109 in the ETR

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Simulations of a scenario either side of the loading rate ignition threshold for PBXN109 showed that the extent of the damage was significantly reduced below the threshold, figure 15. Above the threshold the simulation showed the sample quickly deformed into the cavity, causing high levels of damage throughout. Below the threshold the deformation into the cavity was considerably slower and the region of damage was more limited. Whilst, for the current damage evolution criteria, its extent was reduced below the threshold, the maximum was similar in both simulations. This indicated that damage was not a sufficient condition in order to predict whether a reaction will occur or not. It would suggest that a reaction kinetics model such as the QinetiQ CHARM model [7] is required.

Figure 15: Simulations of PBXN109 above (L) and below (R) rise rate threshold showing damage

Conclusions

A calibrated visco-elastic phenomenological model was able to represent the deformation of a PBX to reasonable degree of accuracy.

A constitutive model and EOS based on the physical properties of the individual components of the polymer composite overcame the shortcomings in the visco-elastic model, however further development is required to increase the model complexity to include other effects such as the differential between damage and failure.

It is necessary to be able to include effects such as cohesion and friction in the simulations to replicate PBX motion and deformation during gun launch and impact.

A number of different ignition thresholds have been identified, peak pressure, cavity dimension and pressure rise rate. These data can be used to exercise reaction kinetics models to predict ignitions.

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