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The Numerical Simulation of High Explosives using AUTODYN-2D & 3D

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This paper describes how 2 and 3-dimensional numerical analysis tools can be applied to the simulation of high explosives. The capabilities of the AUTODYN-2D & AUTODYN-3D hydrocodes are described, with emphasis on the modelling of blast and explosive events. The results of a number of example analyses are presented, to illustrate the application of various modelling techniques to high explosives events. These examples describe the analysis of channelling of air blast down a street, structural response due to an explosion in a munitions store, an explosively formed penetrator, a shaped charge and a fragmenting warhead.

1. Introduction

1.1. Overview Of Analysis Techniques

The objective of this paper is to show examples where 2-dimensional (2D) and 3-dimensional (3D) numerical analysis software tools have been used the simulation of high explosives. The paper will concentrate on five particular case studies associated with explosion and blast problems, including the analysis of loading, response and fluid-structure interaction effects.

High explosive loading and response problems involve highly non-linear transient phenomena. A great range of physical processes must be taken into account to enable accurate characterisation of such events. It is the responsibility of the engineer/scientist/designer/assessor to consider these complex interacting phenomena using a range of appropriate techniques. There are four basic techniques that can be applied, together with more general skills such as experience and judgement, and these are outlined below. Firstly **hand calculations** can be applied; however, only the simplest highly idealised problems are practically solvable. For example, the well known Gurney equations can be used to calculate the acceleration of materials in contact with high explosives, [1]. More complex **analytical techniques** which are usually computer based or involve the use of look-up graphs and charts, are very useful in enabling consideration of many different cases relatively quickly. By their very nature analytical techniques are only applicable to a narrow range of problems; this is because they are based on a limited set of experimental data or particular gross simplifying assumptions. Examples include the SPLIT-X [2] program for the calculation of warhead fragmentation effects, and the ‘CONWEP’ [3] program which includes options for air blast calculations. Difficulties in modelling these highly non-linear phenomena mean that **physical experiments** play a vital role in the characterisation of such problems. However, these experiments can be very costly, are often difficult to instrument and interpretation of results is rarely straightforward.

Numerical software tools offer an alternative approach to high explosive blast and explosion phenomena. Their advantage is that they attempt to model the full physics of the phenomena. In other words, they are designed to solve from first principles the governing conservation equations that describe the behaviour of the system. By their nature numerical techniques are suitable for solving a wider range of problems than any particular analytical technique. They enable great savings to be made in the costs of investigative physical experiments and allow the analyst to look at "perfectly instrumented numerical experiments". Thus parameters that are virtually impossible to measure in physical experiments can be examined in detail.

In reality, numerical techniques for these highly non-linear phenomena are not able to model the complete physics and often the sub-models, which exist in all state-of-the art tools, are empirically based or require data which must be obtained through experimental validation. For example, equation of state parameters for HE are often determined using data from so called cylinder tests where the motion of the wall of a copper cylinder filled with explosive is measured [4]. There are two major general problems to be faced in the numerical analysis of the types of events described in this paper. Firstly, for problems of solid dynamics (e.g. structural response) the chief problem is material characterisation in terms of the models that are used and the data required for them. For fluid dynamics (e.g. the expansion of high explosive products and blast) the chief problem is the lack of numerical resolution available for solving such problems. Much of the current research and development work related to numerical codes is concerned with better overcoming these two major issues.

Despite the computational requirements of numerical analysis, the increased power and availability of computers has led to the widespread use of numerical software tools for solving highly non-linear dynamic events. The barriers between experimentalists, analysts and designers are gradually breaking down as such tools become more widely used. Indeed, problems are most efficiently and effectively solved when a combined approach involving physical experimentation, analytical and numerical techniques is taken.

A more general problem faced by all techniques, but which becomes particularly apparent when developing numerical techniques, is that many areas of non-linear response are poorly understood; two notable examples are the details of dynamic material fracture and turbulent fluid flow. This poor understanding does not mean that modelling techniques are rendered useless, indeed numerical modelling is a major vehicle in developing our understanding of these complex phenomena.

The paper will start by reviewing the current status of the AUTODYN numerical software used in the analyses illustrated here. Following this each of the applications will be described together with sample results from the analyses

1.2. AUTODYN-2D & 3D

The specific features and capabilities of AUTODYN-2D & 3D are described below. Importantly, they both include all the required functions for model generation, analysis and display of results in a single graphical menu-driven package. The codes can be run, with the same functionality albeit at varying speeds, on personal computers and engineering workstations through to mainframes and supercomputers. The codes are written in ANSI standard FORTRAN and C for portability. These codes are under constant and active development through industrial and academic research and development. Such developments are to a great extent driven by the feedback obtained from users of the codes.

AUTODYN-2D & 3D are fully integrated engineering analysis codes specifically designed for non-linear dynamic problems. They are particularly suited to the modelling of impact, penetration, blast and explosion events [5], [6]. AUTODYN-2D & 3D are explicit numerical analysis codes, sometimes referred to as **"hydrocodes"** where the equations of mass, momentum and energy conservation coupled with materials descriptions are solved. **Finite difference, finite volume, finite element and meshless** methods are used depending on the solution technique (or "processor") being used. Reviews of the theoretical methods used in hydrocodes can be found in [7] and [8].

Alternative numerical processors are available and can be selectively used to model different regions of a problem. The currently available processors include **Lagrange**, typically used for modelling solid continua and structures, and Euler for modelling gases, fluids and the large distortion of solids. The **Euler** capability allows for multi-material flow and material strength to be included. A fast single material high resolution Euler FCT processor in both 2D and 3D has also been developed, to more efficiently address blast problems. In addition, the software includes an **ALE (Arbitrary Lagrange Euler)** processor which can be used to provide automatic rezoning of distorted grids; ALE rezoning algorithms can range from Lagrangian (i.e. grid moves with material) to Eulerian (i.e. grid fixed in space). A **Shell** processor is available for modelling thin structures and both codes include an **erosion** algorithm that enhances the ability of the Lagrange and shell processors to simulate impact problems where large deformations occur. Coupling between the processor types is available so that the best processor type for each region of a problem can be used. Various techniques, such as remapping which uses an initial explosion calculation to set up the initial conditions for a subsequent calculation stage, can be used to improve computational efficiency and solution accuracy.

The Lagrange processor, in which the grid distorts with the material, has the advantage of being computationally fast and gives good definition of material interfaces. The Euler processor, which uses a fixed grid through which material flows, is computationally more expensive but is often better suited to modelling larger deformations and fluid flow.

An **SPH (Smooth Particle Hydrodynamics)** processor is also available in the codes. SPH is a Lagrangian method that is gridless/meshless, so the usual grid tangling processes that occur in Lagrange calculations are avoided, and the lack of a grid removes the necessity for unphysical erosion algorithms. At present, the SPH capability is best suited to the modelling of impact / penetration problems, although the rapid evolution of the SPH technique is likely to lead to a much wider range of applications for which SPH is a good choice. A description of the SPH technique and examples of impact and penetration simulations are given in [9] and [10].

A large range of material equations of state (EOS) and constitutive models are available and the user can incorporate further options through the provided user-subroutine facilities. High explosives are usually modelled using the Jones Wilkins and Lee [4] EOS common to most hydrocodes. This is an empirical material model with parameters typically derived from cylinder test data. The explosive is initiated at points or planes, and a detonation wave propagates away from the initiation locations into the material at the detonation velocity. This process converts the explosive to high pressure detonation products. Alternatively, the Lee Tarver ignition and growth model can be used for more detailed explosive initiation studies [11].

2. Application Examples

Numerical analysis methods can be used to simulate a wide range of explosive applications:

- Explosions in air, underground, underwater and in other materials
- Shaped charges for the military, demolition and oil well perforation
- Materials forming, welding, cutting and powder compaction
- Other types of warhead such as explosively formed projectiles or fragmentation

Numerical analyses of five example applications are described in this section.

2.1. Street Channelled Air Blast

In recent years high explosive bomb attacks have been increasingly directed against civil structures by various terrorist organisations. This has encouraged structural designers to look for new and improved methods of protecting civil structures without resorting to military style massive reinforced concrete construction [12]. Such improved designs must be based on design blast loads with an appropriate degree of accuracy. For conceptual design studies it is possible to use simple analysis methods such as analytical or 1 or 2 dimensional numerical methods. For detailed design of a protection system, better accuracy design loads are required, and for the typical complex geometries found in congested urban environments this means that a three dimensional analysis tool must be used. However, if such a tool is to be used, it must first be validated to show that it can reproduce the complex effects associated with blast waves propagating and interacting with multiple obstacles. Whatever method is used to generate the blast loading predictions it must be capable of predicting load time histories on entire building facades and on structural components such as individual panels in a building facade.

In order to validate 3D blast calculations conducted using the Euler-FCT processor, and the remapping facilities in AUTODYN-2D & 3D, results from a series of numerical calculations were compared with results from a small scale experiment. The plan of the experimental rig is shown in Figure 1. The test is 1/50th scale and therefore represents a 1000kg TNT charge detonating at the centre of a typical street geometry. As shown, a pressure gauge was placed on one of the building faces opposite the end of the street. The experiments were conducted by the Royal Military College of Science, and further details can be found in [13].

Figure 2 shows the numerical mesh used to model the experiment. This model used two symmetry planes to reduce the size of the numerical mesh and hence the calculation time, and with a cell size of 10mm within the street it contained approximately 360,000 cells. Further details of the experiments and the numerical calculations can be found in [14].

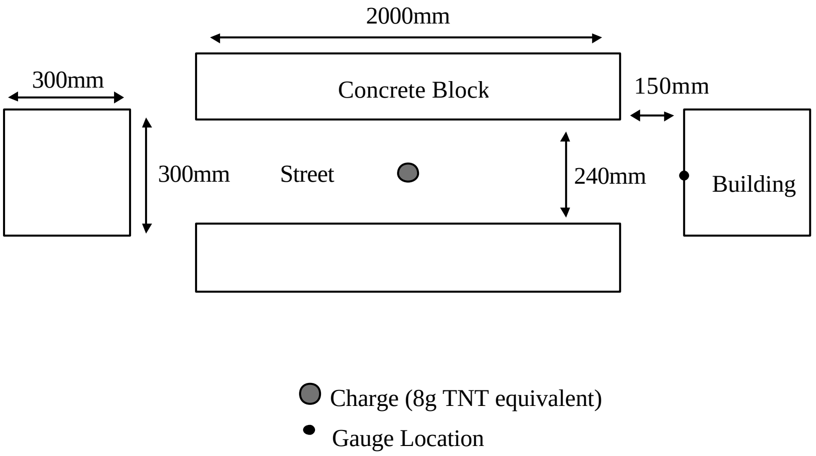

Figure 1 Plan of Experiment Geometry

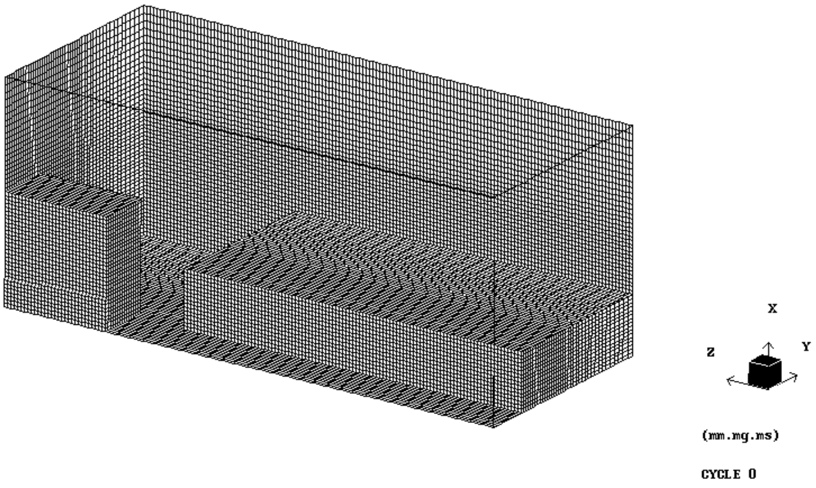

Figure 2 3D Street Channelled Blast Model

Pressure time histories on the front face of the building opposite the end of the street are shown in Figure 3. A 2 dimensional approximation of the street geometry results in a significant over-prediction of the peak pressure, while the full 3D calculation agrees well with the experimental results. The 'Conwep' time history shows the effects of using a simple analytical calculation that neglects the channelling of the blast wave down the street.

These calculations show that for a complex geometry with the blast wave channelled down a street only a 3D numerical analysis that incorporated all of the 3 dimensional geometry of the problem gave good agreement with experimental results. Comparison of blast wave predictions made using the Conwep program with the experimental results showed that neglecting the effects of channelling the blast wave along the street caused severe under prediction of the blast wave peak pressure and impulse. A protection system based on these blast loads would be very unsafe.

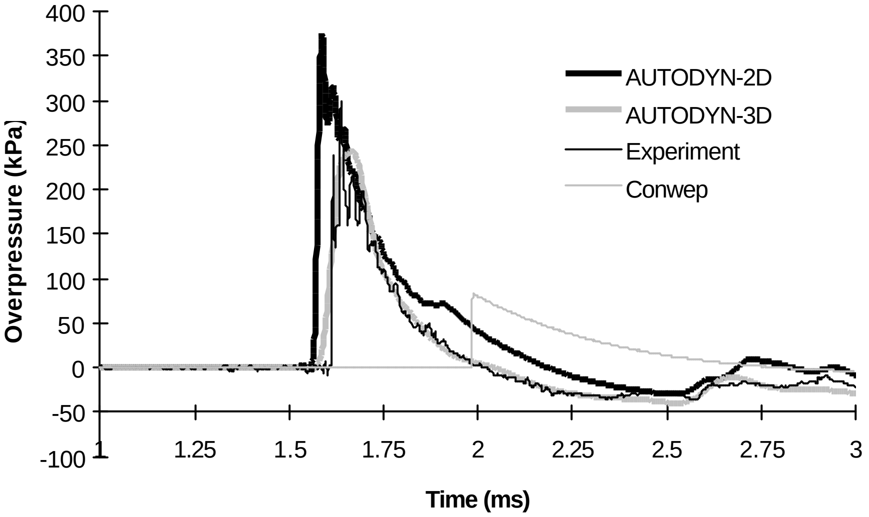

Figure 3 Street Channelled Blast Pressure Time Histories on Front Face of Building

2.2. Structure/Blast Interaction In An Explosive Store

The investigation of a number of possible configurations for ordnance storage facilities was carried out for the USA Naval Facilities Engineering and Service Center. The blast loading and structural response for a particular explosive storage facility due a high explosive blast were analysed numerically using AUTODYN-3D [15]. The analyses considered the fluid structure interaction in a single model using the ALE processor to couple Lagrange regions to ALE or Euler regions of the problem. Some details of one particular analysis are described here.

The explosive store consists of storage areas with a roof, a fixed wall and a relocatable sliding wall. The relocatable wall can slide along the fixed wall in order to allow modification of the room sizes in the explosive storage areas. The explosives are stored in the room shown at the front and base of Figure 4, detonations being assumed to take place simultaneously at multiple sites inside this room.

The physical dimensions of the region modelled are approximately 14m by 12m by 12m. A symmetry plane was used to reduce the size of the numerical model, which consisted of 27,000 rectangular cells. This resolution was too coarse to obtain accurate peak blast pressures but sufficient to obtain impulses on and the response of the structure. Note that halving the cell size would increased computation time by a factor of 16. As is usual in 3D simulations, practical considerations determine the resolution of the model that can be considered. Nevertheless by using a combination of 1D and 3D modelling as follows, better resolution can be achieved without incurring much additional computation cost. Further details of the calculation methodology and results can be found in reference [15].

The detonation sources were first modelled in 1D numerical models, to a radius at which the blast expansion from the explosives becomes non-spherical. The results from this 1D model were then remapped into the full 3D model of the store, using automated procedures in the software.

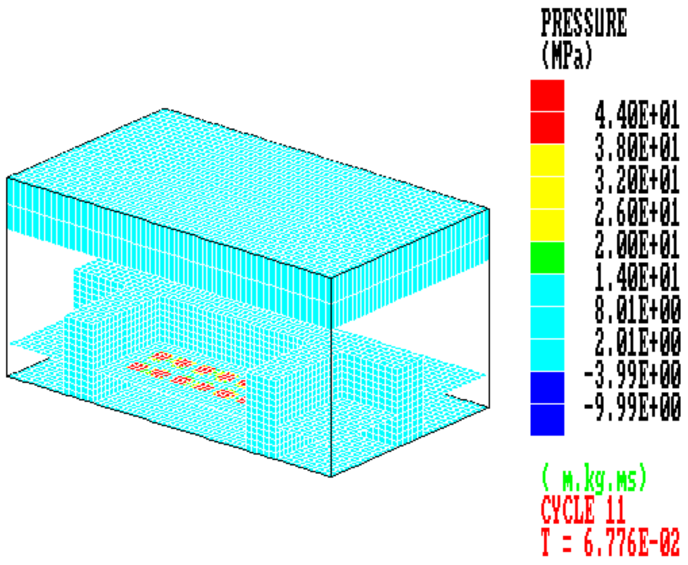

Figure 4 Slices through AUTODYN-3D Model of an Explosive Store (Lagrange Grid for Walls & Roof, ALE Grid for Gases)

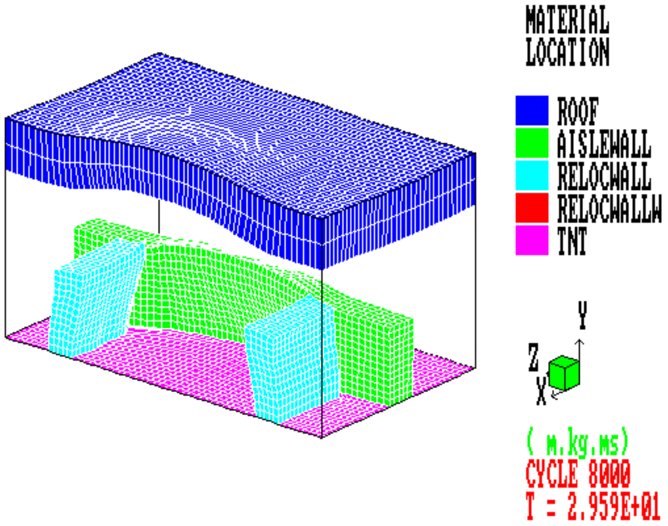

Figure 5 Structural Deformations in the Explosive Store (gases not plotted)

The 3D analyses were run to 30 milliseconds when the peak impulses on the walls had been reached. Each 3D analysis took about 50 hours on a 90 MHz Pentium PC (equivalent to about 46 hours on a 133 MHz Dec Alpha). A plot of the resultant structural deformation at the end of the analysis is shown in Figure 5.

2.3. Explosively Formed Projectile

An EFP problem is generally characterised by the detonation of a confined explosive and the subsequent loading on the confinement and the liner with the formation of a high-speed projectile.

The dynamic interactions between the explosive, explosive products, base plate, confinement and liner present a challenging numerical problem. Designing an optimal EFP warhead is a complex task, since the liner has to undergo severe, yet controlled, plastic deformation without breaking. Extensive experimental and theoretical studies are required to find the required liner, explosive and confinement shapes, as well as initiation procedure. The design process becomes even more complex if one desires to form fins on the EFP [16].

It is well known that the EFP deformation path is very sensitive to the explosively driven loading pressures. The total impulse that is imparted to the liner only determines the total liner momentum. However, the final shape of the deformed liner is controlled by the complex interaction of loading and unloading waves in the explosive products, and the velocity gradients that these produce in the liner. A powerful hydrocode such as AUTODYN enables the researcher to analyse the influence of small changes in the design on the final liner shape and velocity.

For the EFP problem, the large material motions and venting of explosive gases are best modelled using the Euler processor where the numerical mesh is fixed and the "fluid" flows through the mesh. The "structural" elements of the problem (casing, liner, and base plate) are best suited for a Lagrangian framework wherein the numerical mesh moves and distorts with the material motion. AUTODYN-2D allows both of these approaches to be combined in the same analysis. Note that this Euler-Lagrange coupling allows AUTODYN to readily model such phenomenon as the venting of the explosive gases between the structural elements.

An AUTODYN model of a generic EFP problem is shown in Figure 6. The liner is spherical and manufactured from ARMCO iron, the confinement consists of a cylindrical steel outer case and back plate and the explosive filling is Composition B. The charge is detonated on axis at the back plate. This simulation is axisymmetric and therefore can be simulated with AUTODYN-2D. For problems involving non-axisymmetric phenomena (non-symmetric initiation, non-cylindrical confinement or liner geometry), AUTODYN-3D can be used [17]. The liner and confinement are modelled using Lagrange while the explosive is Eulerian. The empty quadrilateral regions in Figure 6 indicate initial void regions where the explosive gases may escape after the case, base plate, and liner separate.

The AUTODYN-2D simulation was carried out on a PC and the results compared with experiment. Computational time was approximately 4 hours on a PC with a 486/66 processor. Excellent agreement is shown in the liner profiles at various times, as well as with measured parameters given in Table 1. These results were obtained without further calibration of the standard library material data included in AUTODYN.

EFP at 50µs	Tip diameter (mm)	Tail diameter (mm)	Tip length (mm)	Total length (mm)	Max. velocity (m/s)
AUTODYN-2D	9.6	16	7.0	30	2868
Experiment	8.4	15	7.0	30	2700

Table 1: Comparison of AUTODYN-2D and experimental results

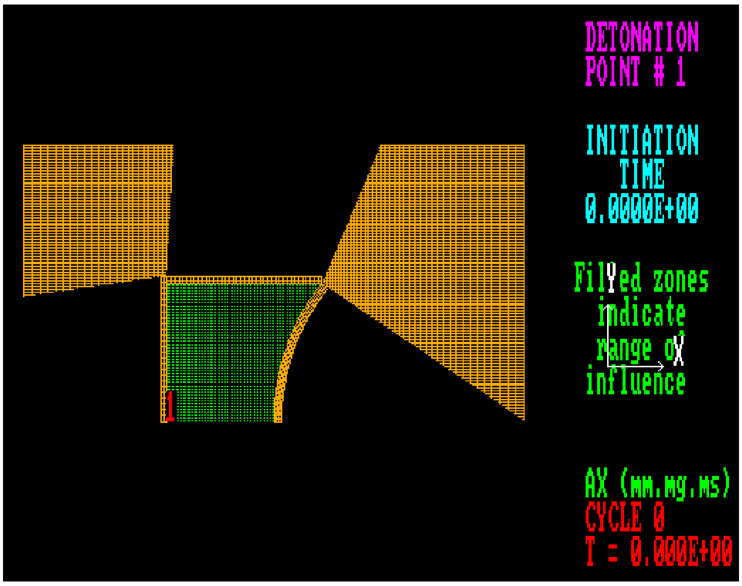

Figure 6 EFP Warhead Analysis

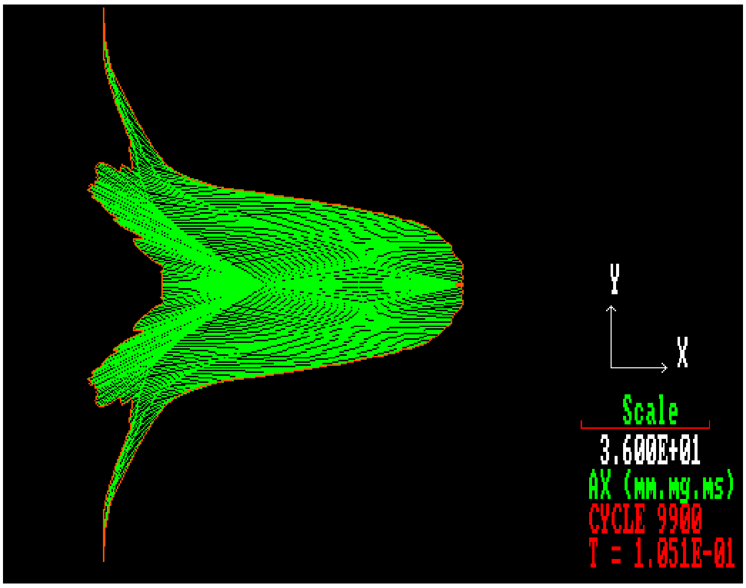

Figure 7 Grid plot of EFP after 105 microseconds

The final shape at 105 microseconds is shown in Figure 7. At any point we can introduce a target depending on the stand-off desired and impact the EFP onto it. The target can be modelled as Lagrange or Euler. If Lagrange is chosen, the erosion feature may be desirable to erode highly distorted zones.

2.4. Shaped Charge Jet Formation

Shaped charge warheads are used in many weapons systems, in addition to civil applications such as oil well perforation and demolition. Over the past four decades, enormous amounts of effort have been invested in attempting to maximise the performance of shaped charges and to understanding the effects of material properties and manufacturing tolerances.

Extensive experimental programmes have helped to identify the crucial factors in charge design, allowing geometries and dimensions to be optimised. Sophisticated measurement techniques have similarly given an understanding of the processes involved in the jet formation. This development has been well supported by the availability of 2D and 3D numerical models capable of accepting readily available design data and generating simulations of shaped charge operation which allow visualisation of the jetting and penetration process. The information produced can be validated experimentally.

The jet formation process within a shaped charge involves extremely high pressures, deformations and strain rates in the liner material at the jetting point and in the early stages of jet formation. For this reason, the numerical modelling of the jetting process is commonly carried out using the Euler processor. An alternative approach available in AUTODYN-2D is a combined numerical / analytical method where the liner is modelled using a Shell subgrid coupled to an Euler grid containing the explosive charge. The acceleration and deformation of the liner are calculated numerically until the liner reaches the symmetry axis. An analytical calculation is then used to predict the resulting jet and slug behaviour.

The following example illustrates the application of the AUTODYN-2D Euler processor to analysis of a 90mm diameter precision shaped charge. The charge configuration is shown below, consisting of an Octol explosive fill and an OFHC copper liner. A single Euler grid of about 100,000 cells (equivalent to a grid size of approximately 0.5mm) is used. The warhead configuration and resultant jet at 50 microseconds are shown in Figure 8 and Figure 9.

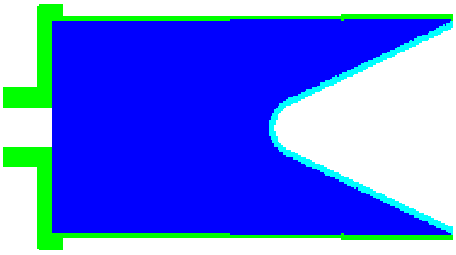

Figure 8 Shaped Charge Warhead

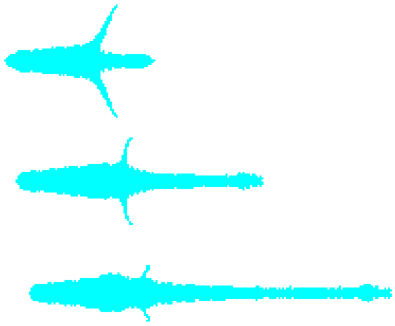

Figure 9 Jet Formation

2.5. 3D Fragmenting Warhead

Recent advances in numerical techniques, and increasingly powerful desktop computers, mean that it is now possible to analyse full size fragmenting warheads containing many hundreds of discrete fragments on a personal computer. The analysis reported here used Lagrange grids to represent the charge and the fragments; with each discrete fragment represented in the mesh so that all of the fragments could interact realistically. Relatively simple geometries such as cylindrical or conical charges can be set up using the pre-processor built into AUTODYN. More complex novel warhead geometries can be created using the True*Grid* [18] grid generation package based on CAD design data. Importantly, True*Grid* incorporates powerful geometry manipulation capabilities for easy design modifications or parametric studies. Essential features of the numerical solution within AUTODYN are an efficient and robust contact algorithm which can track the many contacting surfaces between adjacent fragments and between the fragments and the explosive, and an erosion algorithm that allows highly distorted numerical cells to be automatically removed from the explosive or the fragments.

An example 3D warhead geometry, which consists of two truncated conic sections, is shown in Figure 10. The maximum diameter of the charge is 120mm, tapering to a minimum diameter of 90mm with a total length of 150mm. The charge is Composition B with a mass of 2.3kg. The curved surfaces of the charge are covered with 3.5g steel cubes with sides of 7.6mm. Moving away from the mid length of the warhead, the first three rows contain 36 fragments. The complete warhead contains 816 fragments with a total mass of fragments of 2.9kg. The model did not include a case. The charge was simultaneously initiated at the centre of both end faces. This meant that three symmetry planes could be used to reduce the size of the numerical model to 1/8 of the complete geometry, and the model took approximately 24 hours to run on a 300MHz Pentium II PC. The geometry of the warhead, and the location of the ignition points, mean that the majority of the fragments converge towards the mid plane of the system. They then interact, and some fragments undergo significant distortion before travelling in a radial direction in a plane normal to the warhead's axis. Figure 11 shows absolute fragment velocity at 100μs. The two rings of fragments closest to the mid-plane have been compressed by their neighbours and ejected with a significantly enhanced velocity of about 2200m/s. The velocity of the remainder of the fragments drops from 2000 to 1100m/s with increasing distance from the warhead's mid-plane.

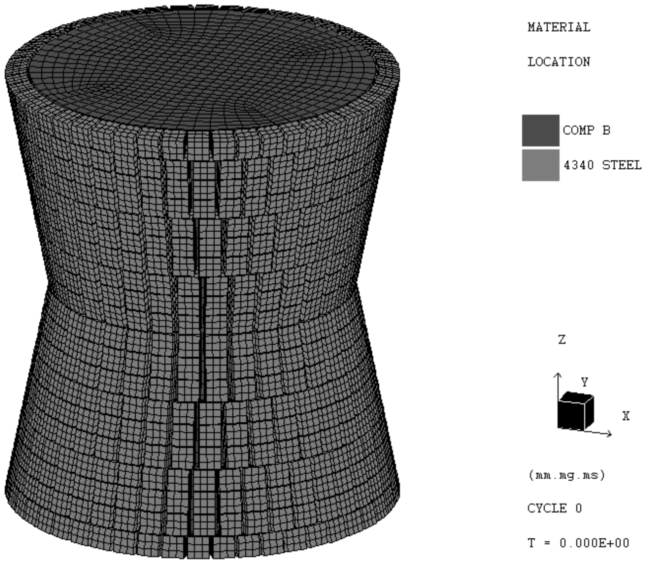

Figure 10 Example Warhead Geometry

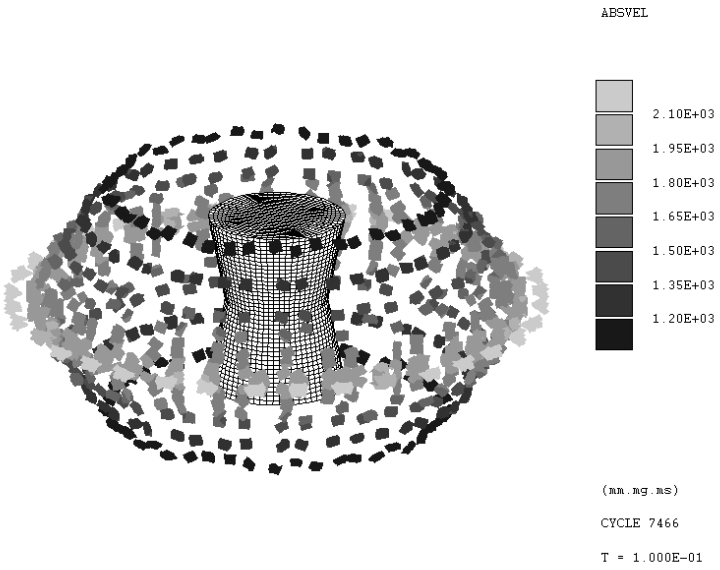

Figure 11 Absolute Fragment Velocity at 100μs

After completion of the analyses, fragment position and velocity data can be produced in any desired format. For example, a tabular data file suitable for direct input to vulnerability codes, which contains the co-ordinates of the centre of each fragment and the fragment velocity components.

3. Conclusions

Numerical software tools are increasingly useful in solving highly non-linear problems involving high explosives. Effective use of these tools occurs when they are used together with other techniques, including experimental validation. The case studies described above were applied successfully in actual design/safety studies and were used in association with physical test programmes and/or analytical techniques.

The case studies show that complex non-linear phenomena can be simulated using modern desktop computers. The examples illustrate some of the wide range of numerical techniques that are necessary to effectively solve blast and explosion problems. Of course, these numerical techniques should be stable, and find an optimal balance between accuracy and speed. Nevertheless, these qualities alone do not lead to effective use of numerical simulations; for this the numerical techniques must be encapsulated within a software tool which is robust and user-friendly. Also the vast amounts of data generated by 3D analyses, the complexity of the problems being solved and the usefulness of quickly interrogating analysis results, requires that the software should be interactive and graphical.

4. References

[1] R W Gurney, “The Initial Velocities of Fragments from Bombs, Shells and Grenades”, BRL Report 405, September 1943

[2] CONDAT GmbH and Century Dynamics, “SPLIT-X User Manual”, 1995

[3] D W Hyde, “‘CONWEP’ Conventional Weapons Effects Programme”, USAEWES, 1992

[4] E L Lee, H C Hornig, J W Kury, “Adiabatic Expansion of High Explosive Detonation Products”, Lawrence Radiation Laboratory, May 1968

[5] N J Robertson, C J Hayhurst, G E Fairlie, “Numerical Simulation of Impact & Fast Transient Phenomena Using AUTODYN-2D and 3D”, Proc. 12th Intl. Conf. on Structural Mechanics in Reactor Technology IMPACT IV Seminar, Berlin, Germany, August 1993.

[6] N J Robertson, C J Hayhurst, G E Fairlie, “Numerical Simulation of Explosion Phenomena”, Int. J. of Computer Applications in Technology, Vol. 7, No. 3-6, 316-329, 1994.

[7] C E Anderson, “An Overview of the Theory of Hydrocodes”, Int. J. Impact Engng., Vol. 5, 1987.

[8] W & B Pilkey (eds.), “Shock and Vibration Computer Programs; SVM-13”, SAVIAC, Booz Allen & Hamilton, Virginia, USA, 1995.

[9] C J Hayhurst, R A Clegg, I H Livingstone, N J Francis, “The Application of SPH Techniques in AUTODYN-2D to Ballistic Impact Problems”, 16th International Symposium on Ballistics, San Francisco, USA, September 1996.

[10] C J Hayhurst, R A Clegg, “Cylindrically Symmetric SPH Simulations of Hypervelocity Impacts on Thin Plates”, Int. J. Impact Engineering, vol 20, 337-348, 1997.

[11] E L Lee C M Tarver “Phenomenological Model of Shock Initiation in Heterogenous Explosives”, Phys. Fluids, 23 (12), December 1980

[12] G M Zintilis, G E Fairlie “Protection of Commercial Buildings Against Blast and Ballistic Threats”, 7th International Symposium on Interaction of the Effects of Munitions with Structures, 1995.

[13] L J Feng, “Modelling Blast in an Urban Area”, Cranfield University Weapons Effects on Structures MSc Project, Royal Military College of Science, Shrivenham, UK, 1997

[14] G E Fairlie, “Efficient Analysis of High Explosive Air Blast in Complex Urban Geometries Using the AUTODYN-2D & 3D Hydrocodes, Analytical and Experimental Methods”, 15th International Symposium on the Military Applications of Blast and Shock, September 1997.

[15] N K Birnbaum, J.Tancreto, K. Hager, “Calculation of Blast Loading in the High Performance Magazine with AUTODYN-3D”, Proc. of 26th DOD Explosives Safety Seminar, Miami, USA, August, 1994.

[16] K Weimann, “Research and Development in the Area of Explosively Formed Projectiles Charge Technology”, Propellants, Explosives, Pyrotechnics 18, 1993.

[17] D Davison, A Nordell, “Hydrocode Analysis of Acceptable Limits on Fabrication of Explosively-Formed Penetrator (EFP) Liners”, 15th Int. Symp. On Ballistics, 1995.

[18] XYZ Scientific Application Inc, “TrueGrid User’s Manual”, 1997