“The Numerical Simulation of Warheads, Impact and Blast Phenomena using AUTODYN-2D and AUTODYN-3D”

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AUTODYN-2D and AUTODYN-3D are interactive, integrated hydrocodes in worldwide usage on personal computers through to supercomputers. They provide a number of fully coupled numerical processors, including Lagrange, Euler, SPH (Smooth Particle Hydrodynamics), ALE (Arbitrary Lagrange Euler) and Shell, which make them suited to a wide range of non-linear dynamics problems. The codes are particularly suited to the modelling of impact, penetration, blast and explosive events.

The results of a number of selected analyses are presented, to illustrate the application of various modelling techniques available for the numerical simulation of warheads, impact and blast phenomena. These analyses also illustrate the importance of selecting the appropriate processor or combination of processors to facilitate both an accurate and computationally efficient solution.

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 in both the design process and in safety assessment studies. The paper will concentrate on five particular case studies associated with impact, explosion and blast problems, including the analysis of loading, response and fluid-structure interaction effects.

Blast, explosion and impact loading and response problems involve highly non-linear phenomena of a transient nature. A great range of physical processes must be taken into account in order to accurately characterise 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. 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. Because of difficulties in modelling these highly non-linear phenomena, **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 another approach to blast, explosion and impact studies. Their advantage is that they, at least attempt to, model the full physics of the phenomena. In other words, they are designed to solve the governing conservation equations that describe the behaviour of the system under consideration. 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 a “perfectly instrumented numerical experiment”.

Thus parameters that are virtually impossible to measure in physical experiments can be examined in whatever detail is appropriate.

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. 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. impact) 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. explosions 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 modelling is a major vehicle in developing our understanding of these complex phenomena.

The paper will start by reviewing the current status of the numerical software tools AUTODYN-2D and AUTODYN-3D which are used in the analyses illustrated here. Following this each of the applications will be described together with sample results from the analyses. For each application the key numerical techniques and issues involved will be discussed.

1.2. AUTODYN-2D & 3D

The specific features and capabilities of AUTODYN-2D and AUTODYN-3D (collectively referred to as AUTODYN) 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 and AUTODYN-3D are fully integrated engineering analysis codes specifically designed for non-linear dynamic problems [1]. They are particularly suited to the modelling of impact, penetration, blast and explosion events [2,3]. The explosion types modelled by AUTODYN must consist of a **detonation**; deflagration is not considered. AUTODYN-2D and 3D are explicit numerical analysis codes, sometimes referred to as **"hydrocodes"** where the physical equations of mass, momentum and energy conservation coupled with materials descriptions are solved. **Finite difference, finite volume and finite element** methods are used depending on the solution technique (or "processor") being used. Reviews on the theoretical methods used in hydrocodes can be found in [4] and [5].

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 order Euler

FCT processor in both 2D and 3D has also been developed, to better 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 (ie grid fixed in space). A **Shell** processor is available for modelling thin structures and both codes include an **erosion** algorithm which enhances the ability of the Lagrange processor 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; a "multi-physics" approach.

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.

The ability of the Lagrangian (i.e. Lagrange and Shell) processors to simulate impact problems with large deformations can be enhanced by the use of an erosion algorithm. The erosion algorithm works by removing Lagrangian zones which have reached a user-specified strain, typically above 150%. In AUTODYN the user can optionally choose to discard or retain the mass and momentum of nodes associated with discarded zones. Although a very useful numerical technique for overcoming the problems of grid distortion, it is important to remember that erosion algorithms are not attempting to model the physics of the problem; in fact energy is being artificially removed from the problem.

An **SPH (Smooth Particle Hydrodynamics)** processor is also under development. SPH is a Lagrangian method which is gridless, so the usual grid tangling processes that occur in Lagrange calculations are avoided, and the lack of a grid removes the need 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 [6] and [7].

A large range of material equations of state and constitutive models are available and the user can incorporate further options through the provided user-subroutine facilities.

2. APPLICATION EXAMPLES

2.1. EXPLOSIVELY FORMED PENETRATOR

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 of 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.

It is well known that the EFP deformation path is very sensitive to the explosively driven loading pressures. The total impulse which 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. 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, 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 1. 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.

In all of these calculations, the interactive, graphics-oriented AUTODYN-2D provides a highly productive environment for the setting up, execution, and display of results.

The liner and confinement are modelled using Lagrange while the explosive is Eulerian. The empty quadrilateral regions in Figure 1 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 486/66 computer and the results compared with experiment. Computational time is ~4 hours on a PC 486/66. 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 50?s	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 with experiment

The final shape at 105 microseconds is shown in Figure 2. At any point we can introduce a target depending on the standoff 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 Lagrange zones.

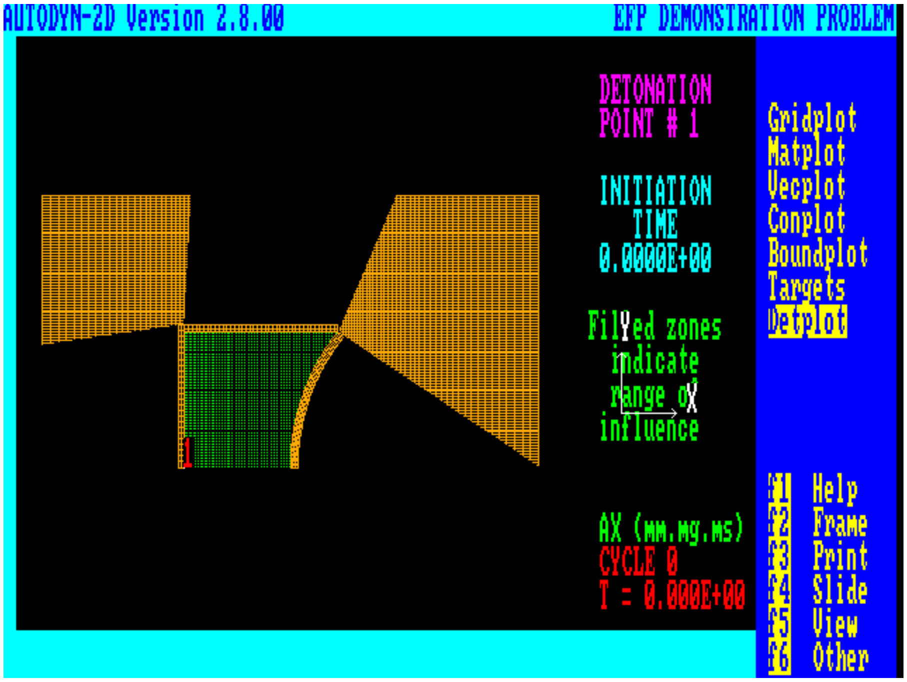

Figure 1: EFP Warhead Analysis

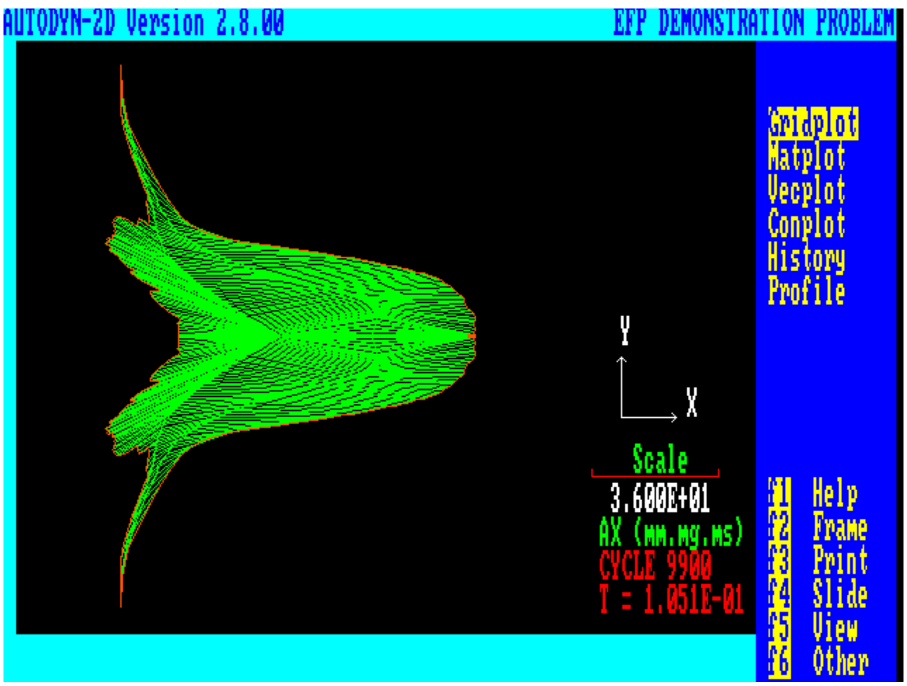

Figure 2: EFP after 105 microseconds (Cycle 9900)
(Euler removed, liner only, gridplot)

2.2. SHAPED CHARGE JET FORMATION

Shaped charge warheads are fundamental to many weapons systems, as well as to civilian applications such as rock fracturing for oil drilling and demolition. Over the past four decades, enormous amounts of effort have been invested in attempting to maximise the performance of these warheads 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 nodes (equivalent to a grid size of approximately 0.5mm) is used. The warhead configuration and resultant jet at 50 microseconds are shown in Figures 3 & 4.

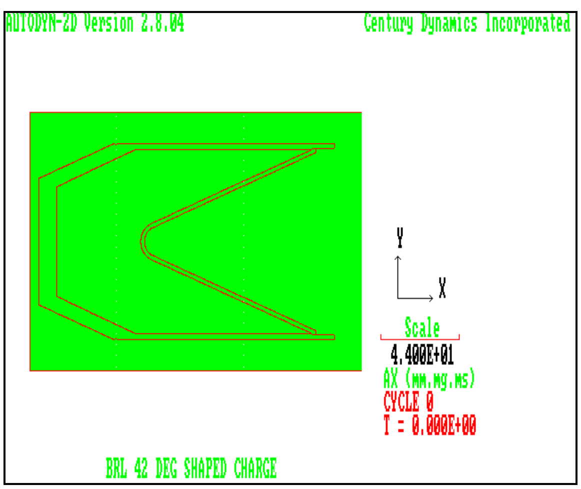

Figure 3: Shaped Charge Warhead

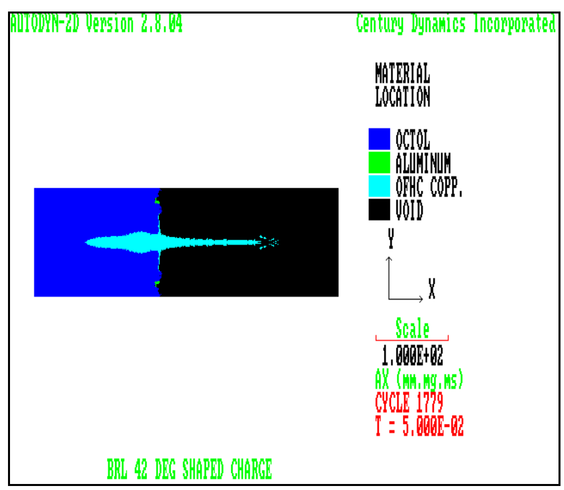

Figure 4: Shaped Charge Jet at 50 Microseconds

2.3. HARD PENETRATOR IMPACT ONTO CERAMIC ARMOUR

A number of ceramic armour experiments reported by Wilkins [8] have been simulated in AUTODYN-2D using both the Lagrange and the SPH processors for comparison purposes. The basic problem consists of a 4340 steel projectile impacting a ceramic (alumina) target backed by aluminium. The impact velocity was 853 m/s. In order to model the strength degradation of failed ceramic a brittle damage model was defined.

In the Lagrange simulation, 120 zones were used to represent the projectile while the ceramic and backing plate were represented by 420 uniform zones. Impact/slidelines were used at the interfaces between materials.

For the SPH simulation, it was found that finer resolution was required than for the Lagrange simulation; 600 particles were used for the projectile, while 4879 particles were used to represent the ceramic and backing plate.

The final deformations of the projectile and backing plate, and the damage in the ceramic material are shown in Figures 5a and 5b for Lagrange and SPH cases respectively.

The results of both the Lagrange and SPH calculations compare well with the experimental observations [8]. In particular, the SPH solution shows a very distinct conical damaged zone in the ceramic. Although the SPH calculation required finer zoning than Lagrange, the Lagrange calculation required more than three times the number of cycles to complete the analysis.

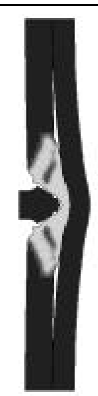

Figure 5a: Lagrange Simulation Result

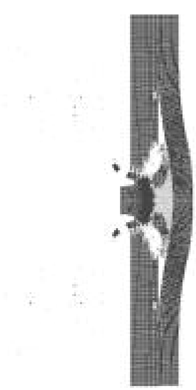

Figure 5b: SPH Simulation Result

Figure 5: Simulated Deformed Shapes at 50 ?s for a Hard Penetrator on Aluminium Backed, Ceramic Armour Showing Contours of Damage

2.4. OBLIQUE IMPACT ON A THICK COMPOSITE LAMINATE

The penetration of a standard NATO 1g fragment into a thick glass fibre reinforced laminate was analysed for the case of an oblique 45 degree impact using AUTODYN-3D. The results for the analyses of this case are shown below. The analysis is similar to several carried out for the case of a normal impact [9]; these normal impact cases were validated successfully with physical tests and subsequently used in design sensitivity studies to assess the effects of changing design parameters, such as fibre volume fractions, for the target plate. The case shown here consists of a laminate plate made up of 18 repeating sub-laminates of equal thickness, each with multiple layers of woven symmetric glass reinforced laminas. The impact velocity of the fragment was 800 m/s.

For reasons of computational efficiency and ease of implementation of failure models the laminate was represented using an equivalent homogeneous anisotropic solid. This was preferred to the alternative of modelling the individual layers explicitly and is the general approach taken by other investigators [10]. This method requires the calculation of the equivalent elastic homogeneous properties from the properties of the composite sub-laminates [11]; and is based on the assumption that the laminate can be considered as a thick plate consisting of multiple identical sublaminates. A laminate analysis program was written to derive the equivalent properties from the constituent static properties, the fibre volume fractions and the number and thickness of the laminas making up each sublaminate. Strain rate effects were neglected due to a lack of available data. The properties were used as input to an orthotropic elastic strength model of the laminate. Failure properties were derived from a combination of available static test data and calculated values based on a rule of mixtures approach.

Many different failure criteria have appeared in the literature for fibre reinforced composites. There is no established model for large deformation failure particularly when delamination is to be considered. A well known class of criteria are maximum stress criteria; these are simple and non-interactive, thus enabling easy identification of the mode of failure, but generally being unpopular due to poor correlation with experimental observations in relatively low deformation studies. The Tsai-Hill and Tsai-Wu criteria are two well known interactive criteria which are popular for low deformation analyses and identification of failure initiation. They are not however very suitable for calculating post-failure response and because of their interactive nature do not lend themselves to easy identification of the mode of failure. The Chang-Chang model attempts to combine the best features of the previous models but does not address matrix tensile failure (i.e. delamination) and delamination was the key failure mode in the problems being studied. Thus in the analyses reported maximum stress failure criteria were used for identifying the main phenomena of interest in this type of impact and in order to determine the post-failure response to be used: **Maximum stress criteria** were used for **delamination**, **tensile fibre** and **punching shear failures**. The post-failure behaviour of the composite was simulated, through the user-subroutines facility, by degrading the appropriate orthotropic elastic moduli based on the particular mode of failure.

By using the above material models and derived data it was possible to obtain a good correlation between the simulations and the normal impact physical tests. Nevertheless it was found that a critical parameter was the residual shear modulus of the failed material. In order to obtain satisfactory calibration of projectile residual velocity and volume of plate delamination it was necessary to derive this value through “numerical experimentation”. Further research is required before such analyses can be considered predictive. Nevertheless, the calibrated models were suitable for carrying out design sensitivity studies of the laminate using AUTODYN.

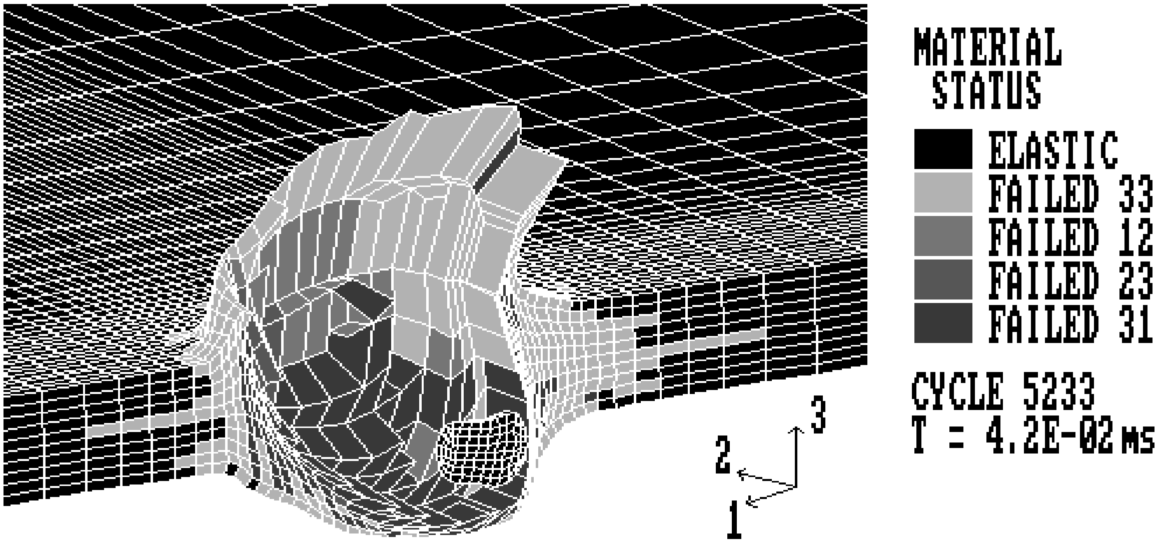

Figure 6: AUTODYN-3D Oblique Impact/Penetration Analysis of a Fragment on a Thick Laminated Glass Fibre Reinforced Plate

The fragment and the plate were discretized using **Lagrange** grids consisting of about 20,000 nodes. To transfer forces between the fragment and plate a Lagrangian **contact algorithm** was used. This algorithm uses a "visible gap" concept which enables very robust and efficient calculations to be performed. To avoid the grid tangling due to large deformations an **erosion** algorithm was used to remove elements which reached a large effective strain (300%). A plot from the analyses is shown in Figure 6; note that the half-symmetric nature of the problem was exploited so only half the physical situation was simulated as shown. The plot shows the material locations, at 4.2 microseconds after initial impact, and also the mode of failure initiation. It is noteworthy that the direction 33 is through the thickness of the plate and that a large region of the plate shows failure initiation for this direction; this represents the tensile cracking of the plate mainly due to delamination of the sub-laminates. The AUTODYN-3D analysis took approximately 25 hours on a 133 MHz Dec Alpha workstation.

2.5. STRUCTURAL/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 loadings and structural response for a particular explosive storage facility due a high explosive blast were analysed numerically using AUTODYN-3D [12]. 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 (as shown in Figure 7) 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 7, detonations being assumed to take place at multiple sites inside this room.

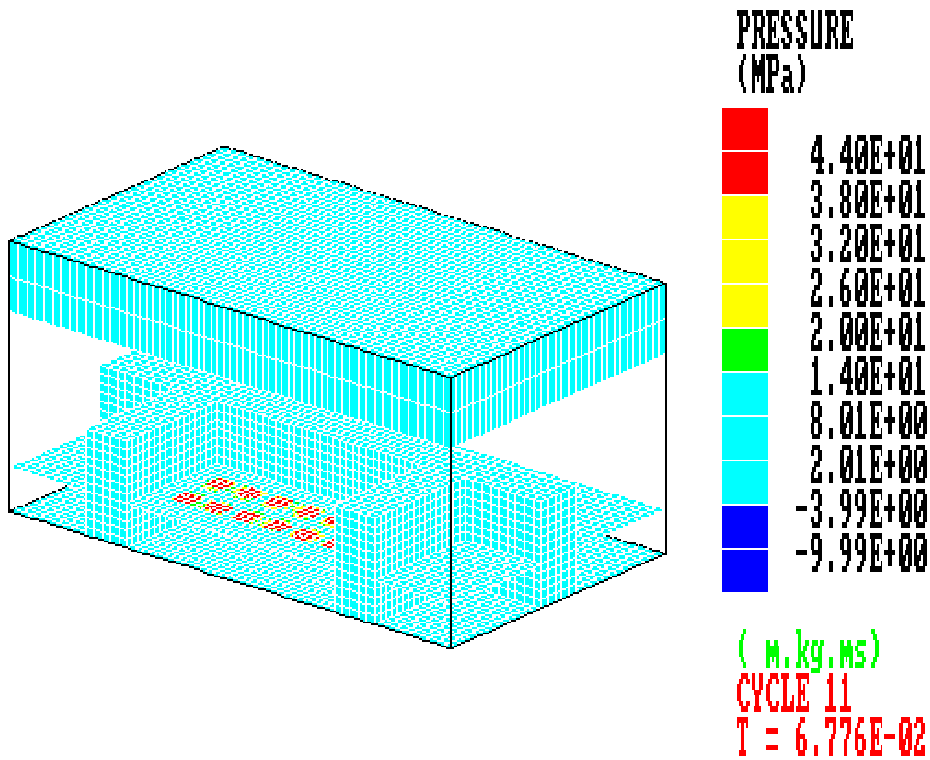

Figure 7: Slices through AUTODYN-3D Representation of an Explosive Store (Lagrange Grid for Walls & Roof, ALE Grid for Gases)

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 fine enough for obtaining impulses on and response of the structure. Note that halving the cell size 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.

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 use of a 1D model enabled fast computations for a model with fine zoning of the initial detonation and expansion. This **1D spherical model** consisted of the high explosive and the air modelled in a two material problem using a **multiple material Euler** simulation. The explosive products were modelled using the JWL equation of state. The results from this 1D model were then **remapped into the full 3D model** of the store, using automated procedures in the software. At this stage the detonation products are expanded enough that they can be considered as an ideal gas (which the JWL equation of state asymptotes to at high expansions). Thus in the 3D model the detonation products from the explosions and the air in the explosives store were modelled as one gas with a single ideal gas constant of 1.35 (this was a reasonable approximation as TNT detonation products have a value of 1.35 and ambient air has a value of 1.4). A plot of the resultant structural deformation is shown in Figure 8.

The 3D model consisted of a single ALE grid. The nodes representing the structures were modelled within the **ALE** framework as pure **Lagrange**, that is they move exactly with the structural deformations. The internal nodes representing the regions of the gases (air and detonation products) were modelled using two different ALE rezoning schemes at different stages of the analysis: At later stages of the analysis **equipotential rezoning** was used to automatically update the position of the nodes as gas flow and adjacent structural deformations occurred. In fact equipotential rezoning could have been used throughout the entire 3D simulation. However, it was found that the run times for the analyses could be improved significantly by running the initial stages of the analysis using **Euler rezoning** for the gases; with this situation the internal nodes in the gaseous regions remain fixed in space. The Euler rezoning scheme can only be run for a limited time however as the cells at the gas/structure interface become gradually more distorted.

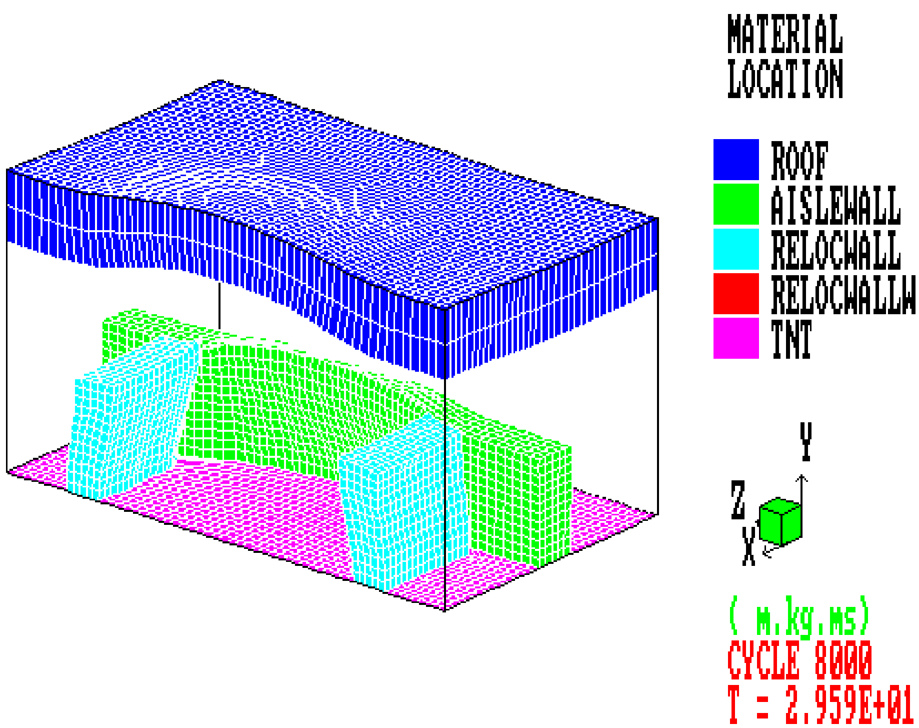

Figure 8: Structural Deformations in the Explosive Store (gases not plotted)

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).

3. CONCLUSIONS

Numerical software tools are increasingly useful in solving highly non-linear problems involving phenomena such as impact, explosion and blast. 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 analytical techniques.

The case studies illustrate some of the wide range of numerical techniques that are necessary to effectively solve impact, 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.

The case studies show that complex non-linear phenomena can be simulated in detail using modern desktop computers. They also demonstrate two very common key issues that occur when performing such simulations: Firstly the importance of constitutive models and associated material data in the case of solid dynamics, and secondly the need to use special techniques (e.g. remapping) to overcome resolution problems in fluid dynamics. Work aimed at improving these and other techniques is ongoing.

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