Projectile Impact

Modelling Techniques and Target Performance Assessment

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Preface

High energy impact phenomena have been investigated by engineers of various backgrounds and disciplines. Structures often need to be designed against possible car or plane impact or the consequences of potential terrorist attack; on the other hand, the removal of decommissioned offshore platforms, high-rise buildings, iron bridges and cranes may be achieved by shaped charge impact, alternatively known as explosive cutting. Aircraft engine casings are exposed to potential release of blade or disc fragments. Protection of space vehicles from particle impact is carefully balanced against low weight requirements; component separation in solid rocket boosters is accomplished by explosive cutting. Environmental concerns prompt the use of soft, energy absorbing targets in bullet firing ranges. The penetration and perforation of armour plates and body armour by projectiles of various types and sizes is the concern of ballistics where design of effective weaponry is countered by the aim of protecting military vehicles and personnel from missiles of various kinds.

Simple analytical models can, under certain conditions, provide reliable predictions of missile penetration but only numerical analyses address the impact problem in all its generality and thus allow the assessment of the influence of all material and geometric parameters. For this purpose, advanced finite element codes are built with features and functionalities specific to the physics of the problem. Alternatively, modelling can be based on powerful commercial software enhanced by additional procedures and algorithms. Such models are used in parametric studies to assess the influence of various modelling or configurative features such as constitutive relations, lateral target confinement or oblique impact. Confidence in the numerical analyses is built by comparison of their predictions with relevant experimental data.

In low-energy impacts against soft targets, the projectile may be assumed rigid but it is more realistically modelled as deformable in most cases. When the focus of the investigation is on the projectile performance, the accurate representation of its geometry or material behaviour is essential. This is the case of complex designs of armour piercing projectiles or explosively cutting linear shaped charges.

Most characterisation and modelling work has been concerned with the performance of various types of targets whose effective resistance to missiles is a key design objective. Experimental investigations provide empirical data on the impact response of specific target materials such as fibre reinforced concrete, rubbers or ceramics. The latter require additional attention due to the potential influence of damage on their behaviour during projectile penetration and perforation. Ballistic test results are also used for calibration and validation of special numerical models developed for various less common targets such as super alloys, woven fabrics, graphitic foams and coarse sand. Elaborate mathematical modelling, based on continuum mechanics theory, is also possible for particular types of target material such as rock.

Defensive targets are usually complex structures comprising several layers of different materials. Such suitably arranged combinations may resist more effectively and efficiently penetration and perforation. Numerical and experimental studies are carried out to assess and optimise their performance. Such studies may also account for an existing mounting system which may transmit a significant part of the missile kinetic energy.

The topic of ballistic impact is wide-ranging since it encompasses various levels of kinetic energy input as well as a multitude of projectile-target materials and geometries. It has thus become the object of many experimental and analytical investigations resulting in numerous sparsely-spread articles in periodicals and conference proceedings as well as monographs narrowly focusing on specific types and ranges of impact scenarios. The present volume, comprising distinguished contributions from the Transactions of the Wessex Institute, describes a broad spectrum of analytical and experimental work in this area thus providing considerable insight into the complexity and diversity of impact phenomena. By addressing a significant number of important issues, it combines, rather uniquely, subject breadth and density with in-depth study of impact events of great engineering interest.

Stavros Syngellakis
The New Forest, 2014

Acronyms

ACE	Army corps of engineers
ALE	Arbitrary Lagrangian Eulerian
AMS	Armor mounting system
AP	Armour piercing
APDS	Armour piercing discarding sabot
APFSDS	Armour piercing fin stabilized discarded sabot
ARL	Army Research Laboratory (USA)
CFL	Courant–Friedrichs–Lewy (condition)
CRH	Calibre radius head
CSC	Conical shaped charge
DAFL	Differential area force law
DTHPB	Direct tension Hopkinson pressure bar
EFP	Explosive forming projectile
EOS	Equations of state
FDM	Finite difference method
FEM	Finite element method
FSP	Fragment simulating projectile
HE	High explosive
IED	Improvised explosive device
IFV	Infantry fighting vehicle
JC	Johnson-Cook (constitutive model)
KE	Kinetic energy
LAV	Light-weight army vehicle
LSC	Linear shaped charge
MLFP	Multilayer fabric packages
NDE	Non-destructive evaluation
PKE	Projectile kinetic energy
RHA	Rolled homogeneous armour
SCJ	Shaped charge jet
SBP	Sub calibre projectile
SPH	Smooth particle hydrodynamics

SRB	Solid rocket booster
TKE	Target kinetic energy
WES	Waterways experiment station (US Army Corps of Engineers)
WHA	Tungsten heavy alloy
XCT	x-ray computed tomography
ZA	Zerilli-Armstrong (constitutive model)

Contents

Recent advances in Lagrangian computations for ballistics problems involving severe distortions

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Network Computing Services, Inc., Minneapolis, Minnesota, USA

Abstract

This article presents an overview of recent developments for Lagrangian algorithms applied to ballistics problems involving severe distortions. The primary development is a new algorithm that automatically converts highly distorted finite elements into meshless particles during the course of the computation. A large number of computations are provided to illustrate this capability, including parametric computations that examine the response of a small caliber projectile impacting a body armour component. The parameters include the projectile velocity, the projectile core material, the target thickness and the projectile impact point on the target.
Keywords: Lagrangian computations, finite elements, meshless particles, impact, terminal ballistics.

1 Introduction

A characteristic of ballistics problems is that the material is often highly distorted due to high-velocity impact and/or explosive detonation. During the past years this has limited the classes of problems for which Lagrangian approaches have been appropriate, because the traditional finite element grid can represent only limited distortions. In recent years, however, there have been significant improvements in material models, sliding/contact algorithms and element formulations. Meshless particle methods have also been developed, and some of these algorithms allow for very severe distortions in a Lagrangian framework. Furthermore, some significant advantages have been achieved by combining finite elements and meshless particles in the same problem.

2 Lagrangian approaches

Finite elements are the most popular form of Lagrangian techniques, but meshless particles are being used more and more. Finite elements are limited in the amount of distortion they can accurately represent, but meshless particles can represent any degree of distortion as the particle algorithms have variable nodal connectivity. Fig. 1 shows a particle node surrounded by five neighbor nodes, but these neighbors are not fixed and each particle node can acquire different neighbor nodes as the solution progresses. The neighbor nodes are used to determine the velocity gradients (strain rates) for the center node, and the stress gradients (forces between particles). Important components of these algorithms are the searching routines that are required to accurately identify the correct neighbors, and the contact algorithms that are required for particles of different materials [1]. Generally finite elements are more accurate and more efficient for mild distortions, but meshless particles are more robust, accurate and efficient for highly distorted material.

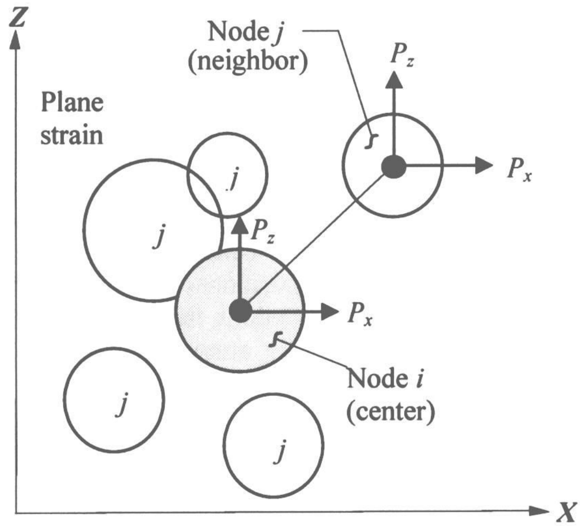

Figure 1: Meshless particle with neighbor nodes.

Fig. 2 shows a finite element grid with three elements on the surface (A, B, C) that are designated as candidates for conversion. An element is converted into a particle when the element has at least one side on the surface and the equivalent strain exceeds a user-specified value (in the range of 0.3 to 0.6). All of the converted element variables are transferred to the new particle node, the element is removed from the computation, and the surfaces of the remaining elements are updated. The particle is then attached to the adjacent element face until the element containing that face is converted to a particle [2, 3]. In addition, it is possible for the standard (finite element) nodes, and the particle nodes, to contact and slide along the external surfaces of the finite elements [4].

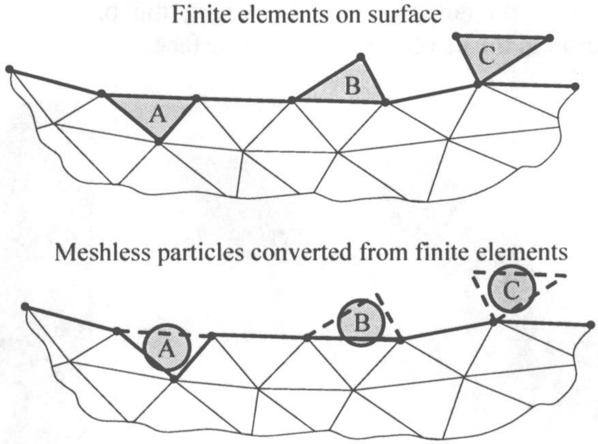

Figure 2: Conversion of elements into particles.

3 Examples and parametric computations

The first example, in fig. 3, demonstrates the capability to perform computations for a complex target composed of multiple spaced plates. Here, a tungsten projectile has an impact velocity of 1500 m/s, and it perforates an array of steel, mild steel and aluminum plates. The distorted elements are converted into particles and they travel through the spaces between the plates without losing definition (as they would with an Eulerian formulation that requires the material to pass through a fixed grid). The sliding/contact is determined automatically, without requiring the user to specify any contact surfaces [4].

The next set of 16 computations is for a small caliber projectile (8.62 mm diameter) impacting a body armor component (51 mm square) composed of silicon carbide [5] over aluminum. Fig. 4 shows the projectile, two hit locations (center and quarter point) and two target thicknesses (thicker and thinner). The projectile impact velocities are 700 m/s and 850 m/s, and two projectiles are considered; one with a mild steel core and the other with a hard steel core. A copper jacket surrounds the core in both cases. Figs. 5 through 8 show the results of the computations at 20 μs and 130 μs after impact. As expected, the higher impact velocity, the harder steel core, and the thinner target result in more damage to the target. The off-center impacts cause different failure patterns in the ceramic, but the penetration/perforation behavior of the projectiles is not significantly affected.

For all of the conditions, the projectile tends to initially dwell on the surface of the hard ceramic, and the jacket and core move radially outward along the surface of the ceramic. This is shown on the left side of the figures at 20 μs after impact. Some interesting crack patterns are also formed. There are no predetermined locations of the cracks, but rather they are automatically determined by the Johnson-Holmquist (JH-1) ceramic model [5]. For the off-center impacts that do not perforate the target, the projectile experiences a significant rotation in the direction of the free surface.

Figure 3: Projectile perforation through spaced plate array.

The formation of damage is shown in fig. 9 and it corresponds to the computation at the bottom portion of fig. 5. The left side shows the plane of symmetry and the right side shows the entire geometry. At 10 μs after impact the projectile dwells on the surface and the ceramic is damaged under the projectile. At 20 μs cracks begin to form in the ceramic and at 30 μs the projectile has penetrated much of the ceramic. The bottom of the aluminum plate is also damaged. Another interesting item is that the copper jacket has moved forward relative to the steel core, and this is because the weaker copper material cannot provide as much resistance as can the stronger steel core. At 60 μs after impact the cracks are well formed and the target has been defeated.

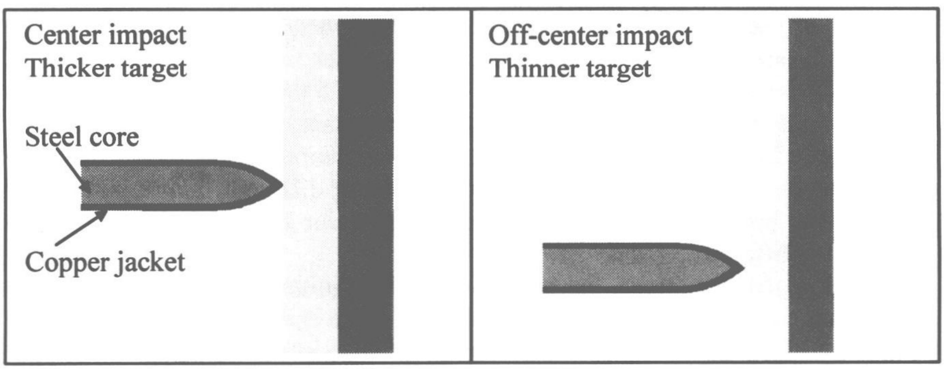

Figure 4: Description of the initial conditions for the parametric computations.

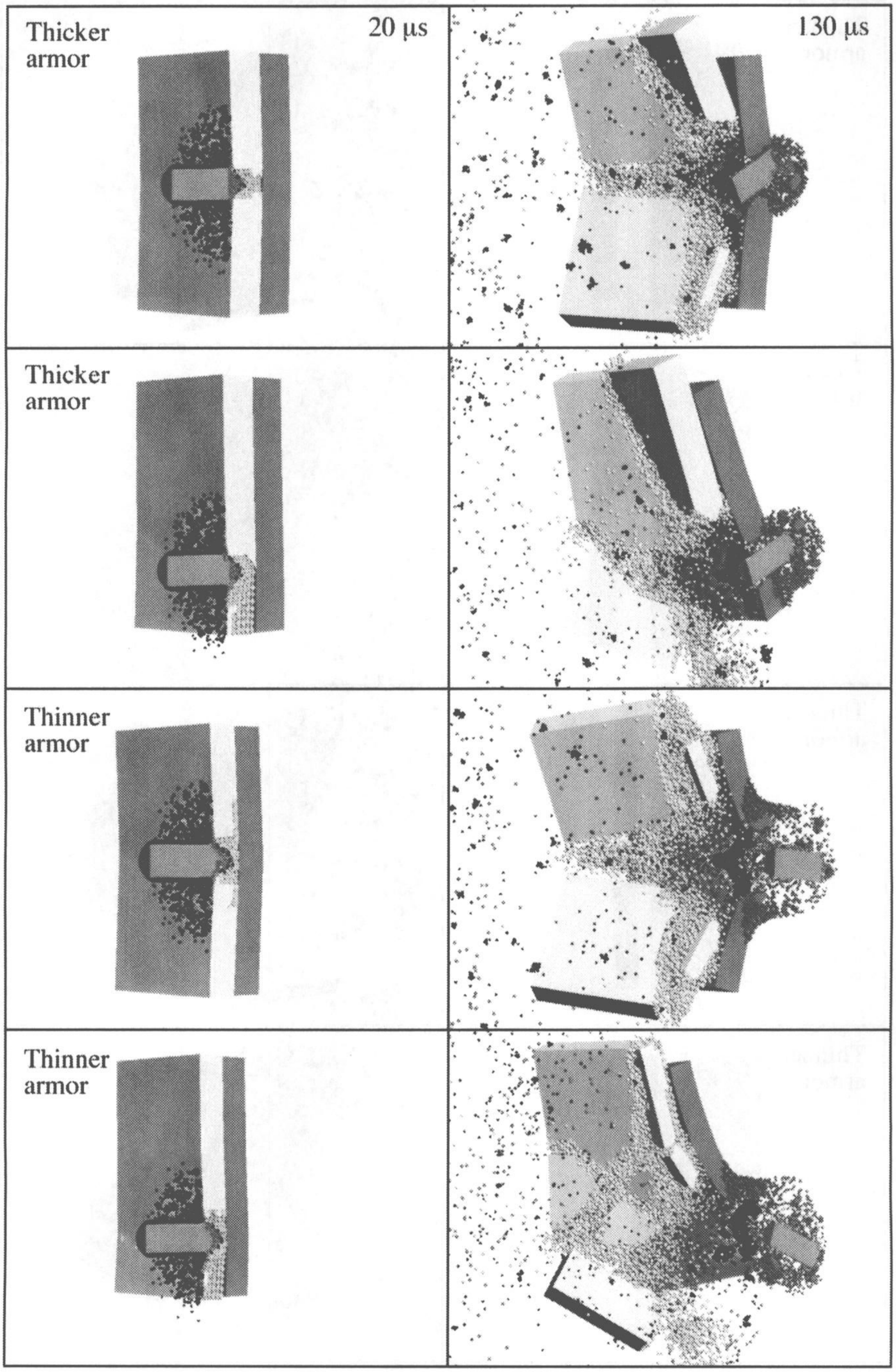

Figure 5: Higher velocity impact (850 m/s) with the hard steel core.

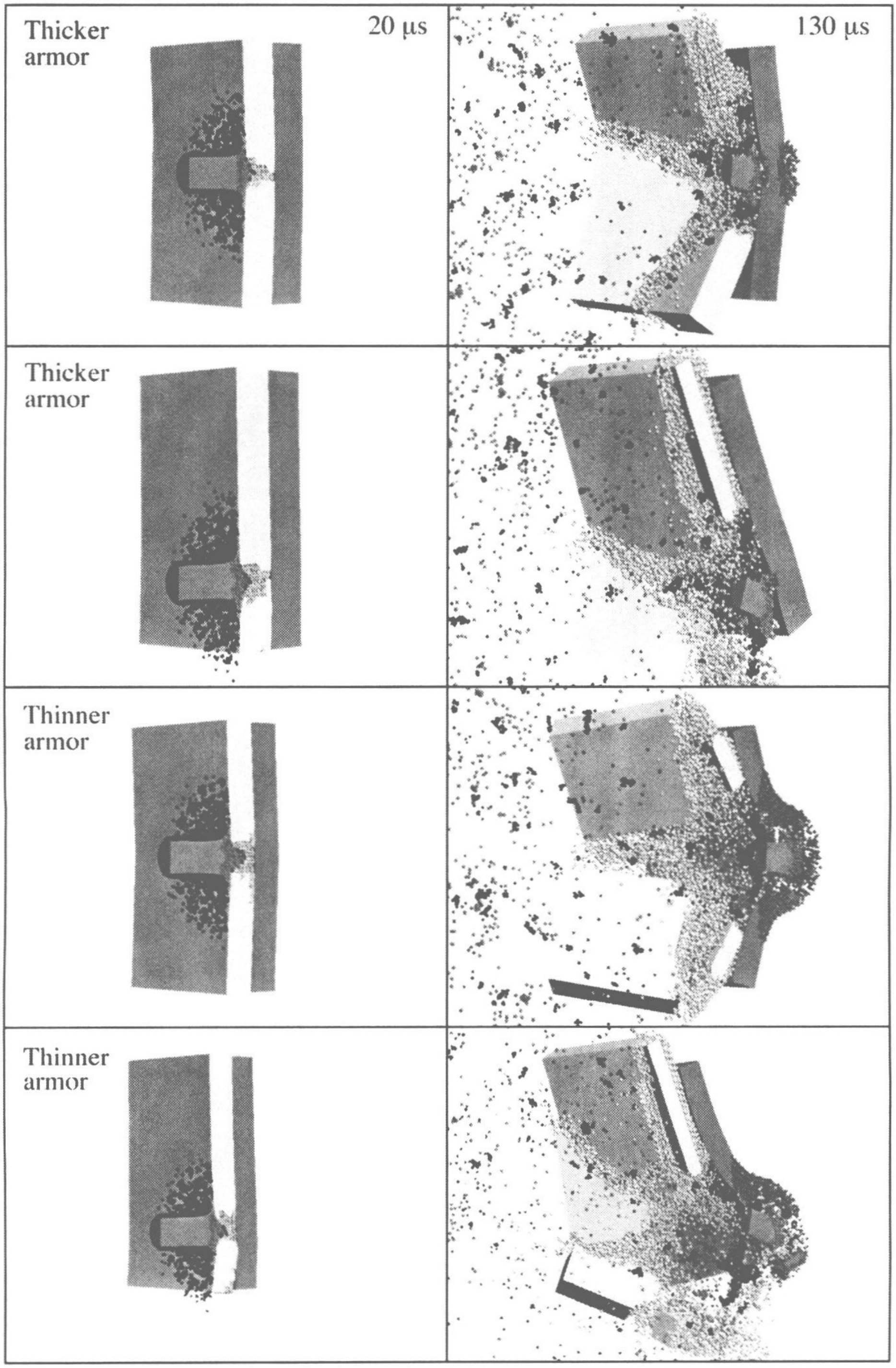

Figure 6: Higher velocity impact (850 m/s) with the mild steel core.