BALLISTIC IMPACT ON CERAMIC/ARAMID ARMOUR SYSTEMS

(Report-draft version)

09/03/2003

1. SUMMARY

A combined numerical and experimental study for the analysis of Ceramic/Kevlar 29 composite armour system against 4.0g NATO 5.56 mm calibre bullet has been performed. In all cases the projectiles impacted orthogonal to the target and the ceramic tile is not bonded to the aramidic plate.

The ballistic performance of the lightweight armour systems was examined to obtain an estimate for the V_{50} and the global damage of the composite plates. All estimates were performed by varying the thickness of ceramic tiles, while maintaining equal areal density of the system. Simulation predictions and trial results is demonstrated both in terms of deformation and damage of the laminates and ballistic performance.

The Mohr-Coulomb (MC) strength model and linear equation of state (EOS) are used to model the ceramic layer. The micro mechanical failure of ceramic is modelled using a cumulative damage model. An advanced orthotropic model [ ] implemented in Autodyn hydrocode, which use non-linear equation of state in conjunction with an orthotropic stiffness matrix is used to model the Kevlar 29/Epoxy layer. A model of the bullet was developed using material data available from existing Autodyn model libraries and parameters modified based upon the measured hardness of the bullet´s individual components.

In numerical programme two models in the Autodyn software are realised to capture the main events in failure processes: projectile erosion, crack propagation, ceramic conoid formation and failure of backing plate. One is made of Lagrangian brick elements only, and the second one uses SPH elements for the ceramic layer of plate.
The numerical simulations provided some useful insight into the penetration mechanisms. A discussion is proposed on the different methods used to deal with the penetration. Three comparison parameters have been chosen: the residual velocity of the projectile, the shape of the deformed plate and the time for performed the analysis. Also the simulation results reveal an optimum value of the ceramic layer to aramidic back plate thickness ratio. All estimates are compared with experimental data to illustrate the performance of the simulation.

2. CERAMIC ARMOUR SYSTEMS

Armour technologists seek to develop protective systems which are both effective and lightweight. It has been accepted that ceramic materials can play an important part in ballistic protection. Their high hardness and low density make them ideal candidates for armour systems.

The main requirements of materials involved in armour design are: low density to reduce the total weight of the protected system; high bulk and shear moduli to prevent large deformations; high yielding stress to preserve the armour resistance to failure; and high dynamic tensile stress to avoid material rupture when tensile waves appear.

Ceramics satisfy the first three demands but are brittle, which makes for extensive fragmentation due to the tensile waves generated by the compressive waves reflected from the free surfaces. Consequently, mixed armours made of ceramic tiles and a composite laminated plate, seem to form a very efficient shield against low and high velocity impact, since they combine the high resistance of ceramic with the lightweight and ductility of composite laminated materials.

The presence of the ceramic tile is important to ensure the ballistic efficiency of the armour, but the ceramic material need a backing plate to confine the ceramic fragments and to absorb the kinetic energy of the projectile and the ceramic rubble during target penetrations. This way greatly improving its ballistic performance without adding significant weight.

The response of a ceramic to impact, perforation and penetration is complex and only limited physical instrumentation can be used in experiments. Although experimental approach offers most accurate results, it is expensive and sometimes does not provide detail information of the impact event. An alternative method is the simulation by hydrocodes to analyse the detailed penetration process and damage, but this involves to develop or use analytical model able to simulate accurately the material and failure models, penetration process, a large number of data of the materials behaviour, which usually are not fully available, thus the utilisation of hydrocodes involves some degree of parametric approximation, its predictive capacity being limited.

Based on the experimental observation the ceramic materials experience little ductility and the strength is highly dependent on the pressure, cohesion and compaction behaviour of these materials result in an increasing resistance to shear up to a limiting value of yield strength as the loading increases. Experimentally, the major features of composites armours systems failure modes such as, projectile damaged, crack propagation, progressive crushing and weakening of ceramic component, ceramic conoid formation and failure of the back plate must be identified in the analytical models.

The complexity of the system analysis lies in the fact that different deformations and failure mechanisms contributing to target perforation occur at different stages of the penetration process. Besides many parameters for each material description, the front plate to back plate thickness ratio and impact velocity can also govern the penetration process. Hence, the design of composite armour system based on the understanding of real impact events is really challenging subject and deserves a sophisticated research work.

3. MATERIAL MODELS

The numerical simulation of impacts on brittle materials, such as ceramics, requires the definition of appropriate material constitutive relations. Due to complexity of material parameters, description of various aspects of the interaction between the projectile and the add-on composite armour target requires advanced material and failure modes.

There have been some efforts directed to develop constitutive models for brittle materials subjected to high strain rate and high pressures. Based on the observation that these materials experience little ductility and the strength is highly dependent on the pressure, the Mohr-Coulomb (MC) strength model and linear equation of state (EOS) are used. The micro mechanical failure of ceramic is modelled using a cumulative damage model.

3.1 Mechanisms of ceramic armour failure

Impact into the lightweight armour plates involves several events in failure processes:

- The projectile tip is destroyed
- A fracture conoid initiates at the interface between the projectile and the target. The cones that are formed spread the load of the projectile onto a relatively wide are enabling the energy of the impact to be dissipated by the plastic deformation of a ductile backing material.
- The backing plate yields at the ceramic interface.
- The tension that results in the ceramic as it follows the motion of the backup plate initiates an axial crack. This failure mechanism has since been argued as being a result of the impedance mismatch in two composite structures.

3.2 Strength Model for Ceramics: Mohr-Coulomb Model

This model is an attempt to model the behavior of dry soils, rocks, concrete and ceramics where the cohesion and compaction behavior of the materials result in an increasing resistance to shear up to a limiting value of yield strength as the loading increases. This is modeled in AUTODYN by a piecewise linear variation of yield stress with pressure (see Figure 1) up to a value Y_{max}. With the introduction of version 4, the Mohr-Coulomb strength model has been modified to allow any number of pressure-yield points, up to a maximum of 10, to define the material strength curve. In tension (negative values of p) such materials have little tensile strength and this is modeled by dropping the curve for Y(p) rapidly to zero as p goes negative to give a realistic value for the limiting tensile strength.

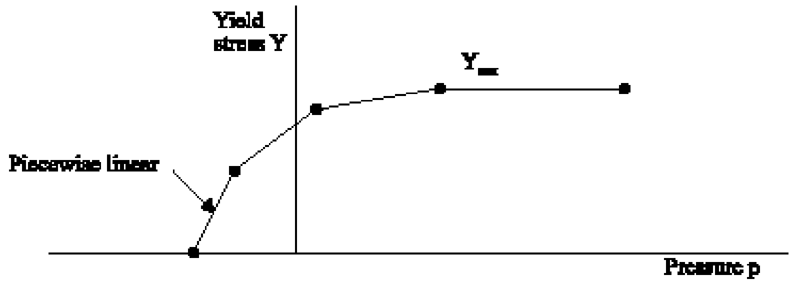

Fig 1. Mohr-Coulomb Model: Yield Stress as a Piecewise Linear Function of Pressure

3.3 Failure Model for Ceramics: Cumulative Damage Failure

This model has been introduced to describe the macroscopic inelastic behaviour of material such as ceramics and concrete where the strength of the material can be significantly degraded by crushing. The model can be used only with the Linear equation of state but can be used in conjunction with any strength model currently available in AUTODYN (except Johnson-Holmquist which has its own associated "cumulative damage" model). However, since experiments indicate that ceramics show a marked increase in compressive strength as the hydrostatic pressure is increased, it is most likely that this model will be used in conjunction with the Mohr-Coulomb model which uses a yield strength that is a function of the local hydrostatic pressure.

To model the progressive crushing and subsequent weakening of ceramic materials the model computes a "damage" factor which is usually related to the amount of straining the material is subjected to. This damage factor is used to reduce the elastic moduli and yield strength of the material as the calculation proceeds. In the standard model damage is represented by a parameter D which is zero for all plastic deformation for which the effective plastic strain is less than a value EPS1 (Effective Plastic Strain at Zero Damage). When the strain reaches EPS1 the damage parameter D increases linearly with strain up to a maximum value D_{max} (<1) (Maximum Damage) at a value of the effective plastic strain EPS2 (Effective Plastic Strain at Maximum Damage), as shown in Figure 2 below.

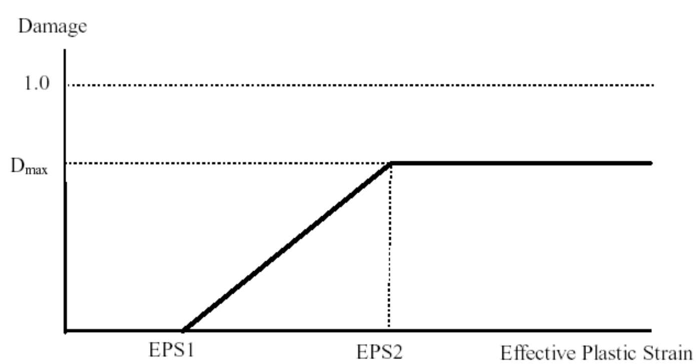

Figure 2. Cumulative Damage as a Function of Effective Plastic Strain

Thus

$$D = D_{\max} \cdot \left(\frac{EPS - EPS1}{EPS2 - EPS1} \right) \tag{1}$$

If a different damage function is required this can be programmed by the user by means of the user subroutine EXDAM. To describe the progressive crushing of a material the damage function is used to reduce the material's strength. Fully damaged material has some residual strength in compression but none in tension. The current value of the damage factor D is used to modify the bulk modulus, shear modulus and yield strength of the material.

a) The yield strength is reduced as follows:

If the hydrostatic pressure is positive

$$Y_{Dam} = Y \cdot (1 - D) \tag{2}$$

(providing some residual strength when D reaches its maximum D_{max})

If the hydrostatic pressure is negative

$$Y_{Dam} = Y \cdot \left(1 - \frac{D}{D_{\max}} \right) \tag{3}$$

These are illustrated graphically in Figure 3 below.

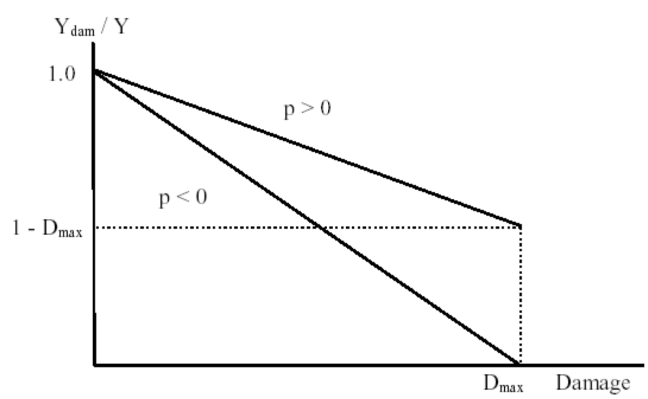

Figure 3. Yield Stress as Function of Cumulative Damage

b) The bulk modulus and shear modulus are unaffected in compression, while in tension they are progressively reduced to zero when damage is complete. In tension therefore they are both reduced by the factor ($1 - D/D_{max}$) as shown graphically in Figure 4 below.

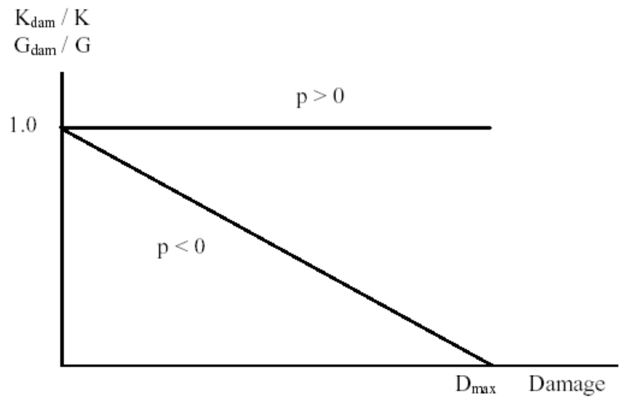

Figure 4. Bulk and Shear Modulus as Functions of Cumulative damage

3.4 Material model for Kevlar/Epoxy

A new material model, specifically designed for the shock response of anisotropic material such as Kevlar/Epoxy and for brittle failure materials such as ceramic materials, has been implemented in Autodyn, and couples the non-linear constitutive relations with the equation of state [ ]. Its main draw is the ability to take into account the typical damage mechanisms for composite and ceramic materials. In the case of composite material: extensive delamination due to matrix cracking and/or matrix fibre debonding, tensile failure and combined delamination and fibre failure leading to bulk failure.

4. EXPERIMENTAL PROGRAMME

Armours of ceramic backed by Kevlar 29 against NATO 5.56 mm steel projectiles are designed to determine the ballistic limit velocity V_{50}, below which the projectile fails to perforate the armour system. The experimental tests were conducted at Navy School in Lisbon. Based on the probabilistic technique using a substantial base of data, a series of impact experiments was conducted by changing the impact velocity until the ballistic limit is determined.
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5. NUMERICAL PROGRAMME

The numerical simulation is conducted by using the specialized software for non-linear transient dynamic events such as ballistic impact, penetration and blast problems, AUTODYN-3D [ ].

This software is based on explicit finite difference, finite volume and finite element techniques that use both grid based and griddles numerical methods. A set of partial differential equations for conservation of mass, momentum and energy is solved together with the constitutive equations using an explicit time integration scheme [10]. These, together with a material model and set of initial and boundary conditions, define the complete solution of the problem. For Lagrange brick elements, the impact is controlled by a so-called impact/contact procedure, allowing impacted material to erode, so that deep penetrations can be accounted for. The erosion is a numerical procedure that allows automatic removal of elements when they become heavily distorted.

Spatial discretization is by the finite difference, finite element, finite volume or a meshless method depending on the solution options selected. In such representations a lattice of points, or a grid, is generated to approximate the geometry of interest. The spatial derivatives in the differential equations are replaced by discrete equations; for example for finite methods, central difference equations are used to calculate discrete pointwise approximations. The value computed at a point are taken to represent the physical parameter over some finite region of the space, usually a complete cell in the grid. Autodyn use an explicit time integration scheme to calculate the state of the material at a time $t+\Delta t$, from the known state of the material at time t. the time step Δt used in solving the differential equations, is based on the time taken for a sound wave to travel across the minimum dimension of any cell in the grid. This methodology gives a stable and very efficient solution.

Autodyn-3D currently includes seven different solver types for spatial discretisation: Lagrange, Shell, Beam, ALE, SPH, Euler-FCT, Euler-Godunov. For ballistic impact problems the Lagrange and SPH solvers are frequently used. Lagrange processor works with hexahedral brick elements in a finite volume formulation with exact equivalence to single integration point finite elements. SPH- smoothed particle hydrodynamics-, which is a meshfree Lagrangian method, based on interacting neighbouring particles. Lagrangian scheme requires an artificial technique to treat large deformation event even if it is more accurate to calculate the material interface.

SPH is a griddles technique for solving computational continuum dynamics problems and has some potential advantages over the grid based two schemes. SPH is a meshfree lagrangian method developed initially to simulate astrophysical problems [ ] From a computational point of view, we represent a fluid with a set of moving particles evolving at the flow velocity. Each SPH particle represents an interpolation point on which all the properties of the fluid are known. The solution of the entire problem is then computed on all the particles with a regular interpolation function, the so-called smoothing length. The equations of conservation are then equivalent to terms expressing flux or inter-particular forces.
Since SPH does not require a numerical grid, there is no grid-tangling problem for large deformation problems, no need for erosion to obtain efficient solutions. Furthermore, allows efficient tracking of material deformation and history dependent behaviour.

An important capability of the developed SPH is it is ability to interact with surfaces and particles of other Lagrange processors, such that we can couple together both solvers for analyse a complex problems.

6. NUMERICAL SIMULATIONS

A numerical study using both Smoothed Particle Hydrodynamics and hexahedral brick Lagrangian scheme for the analysis of Ceramic/Kevlar 29 composite armour system against 4.0g steel projectiles – NATO 5.56 mm calibre- has been performed. The ballistic performance of the armours system was examined by varying the thickness of tiles, while maintaining equal areal density (i.e. the areal density of an armour system is the mass in kg of a 1 metre square slab of the armour).

The projectile has several angles of impact with a velocity of 920 m/s. However, in this report only the impact with 90^o angle of incidence is displayed.

The ballistic performance of the lightweight armour systems was examined to obtain an estimate for the V_{50} and the global damage of the composite plates. All estimates were performed by varying the thickness of ceramic tiles, while maintaining equal areal density of the system.

In numerical simulations two models are realised to capture the main events in failure processes: one is made of Lagrangian brick elements only, and the second one uses SPH elements for the ceramic layer of plate. A discussion is proposed on the different methods used to deal with the penetration. Three comparison parameters have been chosen: the residual velocity of the projectile, the shape of the deformed plate and the time for performed the analysis. All estimates are compared with experimental data to illustrate the performance of the simulation.

The difficulty of these tests is the good modelisation of the projectile and target failure. Two solutions seems to be convenient: on the first hand, the lagrangian method with an erosion criterion, on the other hand the use of the SPH elements.

6.1 Modelling

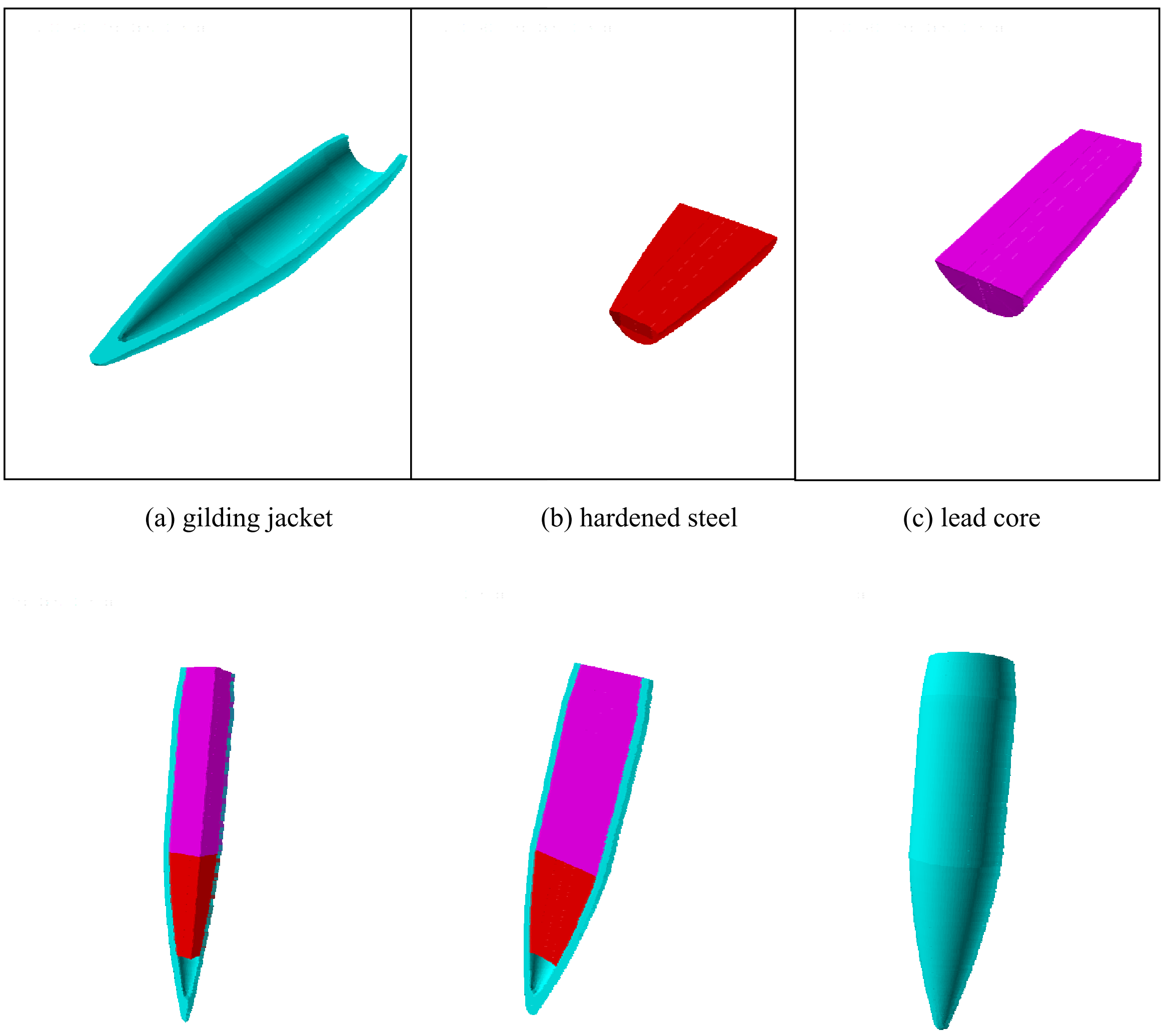
NATO 5.56 calibre bullet

The NATO 5.56 mm calibre bullet consists of a hard steel tip and a lead core encapsuled in a copper-alloy gilding metal. Due to the bullet´s three-part construction, its penetration mechanisms are relatively complex and vary depending on the nature of the target. Hydrocodes such as Autodyn can provide useful insight into the penetration event as the user can interrogate a number of material-dependent parameters during the penetration and subsequent perforation. However, there is a still limited published data available on the dynamic material properties of the bullet and target materials and, without extensive dynamic testing, a number of approximations have to be made.

Therefore some form of calibration with experimental data is needed. Nevertheless, these models can still provide useful insight into the penetration mechanisms.

All material models for the bullet were retrieved from the Autodyn material libraries. The bullet is of three-part construction with a hard steel tip a relatively soft lead core and a cooper-alloy gilding jacket. There is a small gap between the front of the steel tip and the gilding jacket. The nominal mass of the bullet is 4.0 g and it has an average velocity of 920 m/s when fired from a standard proof mount and with a standard cartridge case.

A shock equation of state and Johnson-Cook constitutive model was used to simulate the material response to dynamic loading of bullet´s tip. The copper gilding metal was modelled using simple linear equation of state and Johnson-Cook constitutive model. The lead core was modelled using a simple linear equation of state and a Steinberg-Guinan constitutive model. The failure of jacket was simulated using a principle strain failure model. Figure 5 shows the different parts of the bullet. Part (a) represent the gilding jacket, part (b) represent the hardened steel tip and part (c) represents the lead antimony core.



(a) gilding jacket (b) hardened steel (c) lead core

(d) quarter model (e) half model (f) full model

Figure 5. NATO 5.56 calibre bullet

The projectile is modelled with Lagrange brick elements using the general purpose mesh generation program TrueGrid. The code written in TrueGrid is depicted in Appendix 1.

Ceramic/Aramid system

The target consists of two layers of ceramic and Kevlar29/Epoxy respectively, and the ceramic tile is not bonded to the aramidic plate. The front plate to back plate thickness ratio (h_1/h_2) is varied while maintaining equal areal density. The areal density of an armour system is the mass (in kg) of a 1 metre square slab of the armour:

$$AD = \rho \cdot t \tag{4}$$

where ρ is the average bulk density of the armour system (kg/m^3) and t is thickness of the armour (m). The maximum thickness of ceramic and Kevlar plate is 5 and 2 mm respectively. Thus, for this system the areal density is AD=16.905 kg/m^2.

Table 1. Areal density of the system

	Thickness (m)	Reference density (kg/m^3)
Ceramic	0.005	3430
Kevlar	0.002	1400
	t=0.007 m	**ρ=2415 kg/m^3**

***AD*=16.905 kg/m^2**

In order to obtain the best ballistic efficiency of the composite armour system five configurations of the armour system was take into account in numerical simulations, varying the front plate to back plate thickness ratio, maintaining equal areal density to AD=16.905 kg/m^2. The configurations are contemplated in the table 2.

Table 2. Data for ballistic limits at equal areal density

Configuration	Ceramic/Kevlar thickness ratio (h_1/h_2)
C1	0.5
C2	1.0
C3	1.5
C4	2.5
C5	4.0

The target is modelled as a rectangular plate of 100 x 100 mm and we apply some non-reflecting boundary elements around the plate to simulate an infinite plate.

In numerical simulations two models are realised to capture the main events in failure processes: one is made of Lagrangian brick elements only, and the second one uses SPH elements for the ceramic layer of plate. In the first model, in order to represent the perforation of the projectile through the armour system, an erosion criterion on both projectile and target is applied. In the last model, the center of the ceramic plate is meshed with SPH elements. Around of these particles a set of hexahedral brick elements is defined, joined with SPH particles. The main difference with the full lagrangian model is that in this case no erosion criterion is necessary for the ceramic tile.

The Mohr-Coulomb (MC) strength model and linear equation of state (EOS) are used to model the ceramic layer. The micro mechanical failure of ceramic is modelled using a cumulative damage model. An advanced orthotropic model [ ] implemented in Autodyn hydrocode, which use non-linear equation of state in conjunction with an orthotropic stiffness matrix is used to model the Kevlar 29/Epoxy layer. The material models and data are summed up in the following table.

Table 3. Material models and data.

Ceramic-Gceramic (Autodyn material libraries)	
Equation of states : Linear Reference density (g/cm^3) ***3.43*** Bulk modulus (kPa) **1.54E8** Strength : *Mohr-Coulomb* Shear modulus (kPa) **8.30E7** Failure : *Cumulative Damage* Reference Temperature (K) **300**	Strength Model:Mohr-Coulomb Pressure #1(kPa) **–5.00E5** Pressure #2(kPa) **0.00** Pressure #3(kPa) **1.01E20** Pressure #4(kPa) **1.01E20** Yield Stress #1 (kPa) **0.00** Yield Stress #2 (kPa) **3.80E6** Yield Stress #3 (kPa) **3.80E6** Yield Stress #4 (kPa) **3.80E6** Failure: Cumulative Damage Eff. Pl. Strain at Zero Damage: **0.01** Eff. Pl. Strain at Max. Damage: **0.03** Maximum Damage: **0.7**
KEVLAR/EPOXY - EMI	
Equation of states : *Orthotropic* Sub-Equation of States : *Polynomial* Reference density (g/cm^3) *1.40* Young modulus 11 (kPa) *2.392E+05* Young modulus 22 (kPa) *6.311E+06* Young modulus 33 (kPa) *6.311E+06* Poisons ratio 12 *0.115* Poisons ratio 23 *0.216* Poisons ratio 31 *3.034* Strength : *Elastic* Shear modulus (kPa) *1.54E+06* Failure : *Material Stress/Strain*	Tensile failure Stress 11 (kPa) *5.00E+04* Maximum Shear Stress 12 (kpa) *1.00E+05* Tensile Failure Strain 11 *0.01* Tensile Failure Strain 22 *0.20* Tensile Failure Strain 33 *0.20* Post Failure Response *Orthotropic* Fail 11 & 11 Only Fail 22 &22 Only Fail 33 & 33 Only Fail 12 & 12 and 11 Only Fail 23 & 23 and 11 Only Fail 31 & 31 and 11 Only Residual shear Stiff. Frac. *0.20*

The resulting model was obtained taking into account the two planes of symmetry, using the general purpose mesh generation program TrueGrid [ ]. The geometry and the grid at the initial time step are illustrated in Figure 6.

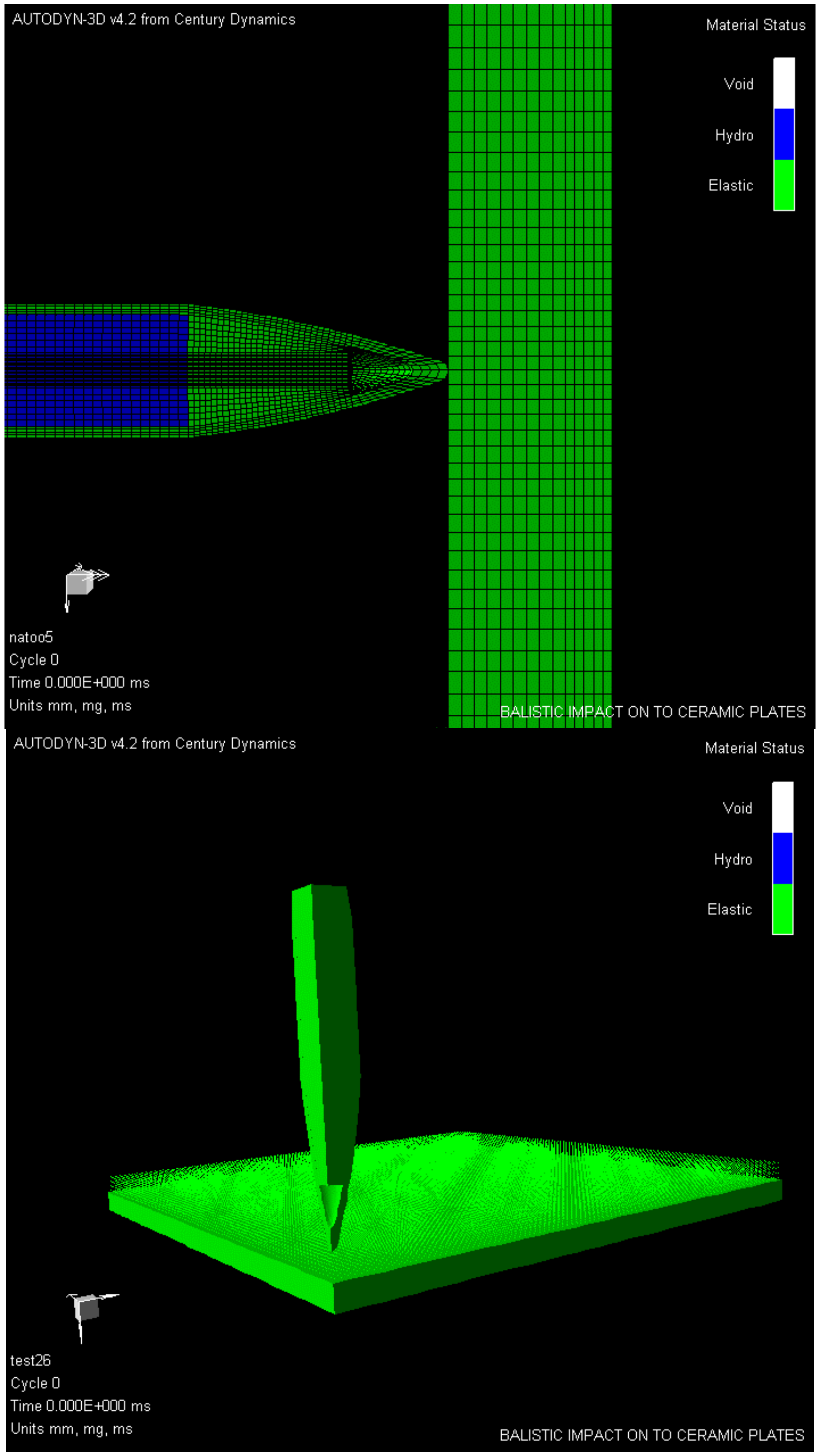


Figure 6. Full Lagrange and SPH models

6. Comparison of simulations and experiment

Figure 7 shows the minimum perforation velocities (ballistic limit, V_{50}) determined numerically for 4.0 g NATO 5.56 calibre striking onto different target configurations. In this analysis, D_{max}=0.7 at ε_{p2}=0.3 and D=0 at ε_{p1}=0.01. It is shown that the results obtained from the present simulation match fairly well with the theoretical ones. Theretical data was obtained by the Florence model [13]. Florence made the empirical observation that the radius of the base of the ceramic fracture conoid was given by $a_p + 2h_1$, where a_p is the radius of the penetrator and h_1 is the thickness of the ceramic front plate. He then assumed that the back plate deformed as a circular membrane of radius ($a_p + 2h_1$), pinned around its periphery. The kinetic energy of the round and ceramic is equated to the work done in stretching the membrane until it reaches its tensile breaking strain. By this method the following expression is derived for the ballistic limit velocity of the projectile:

$$V_{50} = \sqrt{\frac{\varepsilon \cdot S}{0.91 \cdot M_p \cdot f(a)}} \tag{5}$$

where M_p is projectile mass (kg), $S = \sigma \cdot h_2$, σ is breaking stress of backing plate (N/m^2), h_1 is thickness of front plate (m), h_2 is thickness of back plate (m), ε is breaking strain of backing plate and

$$f(a) = \frac{M_p}{\left(M_p + (h_1\rho_1 + h_2\rho_2)\pi a^2\right)\pi a^2} \tag{6}$$

where $a = a_p + 2h_1$ (m) and ρ_1 and ρ_2 are densities of front and back plates respectively (kg/m^3).

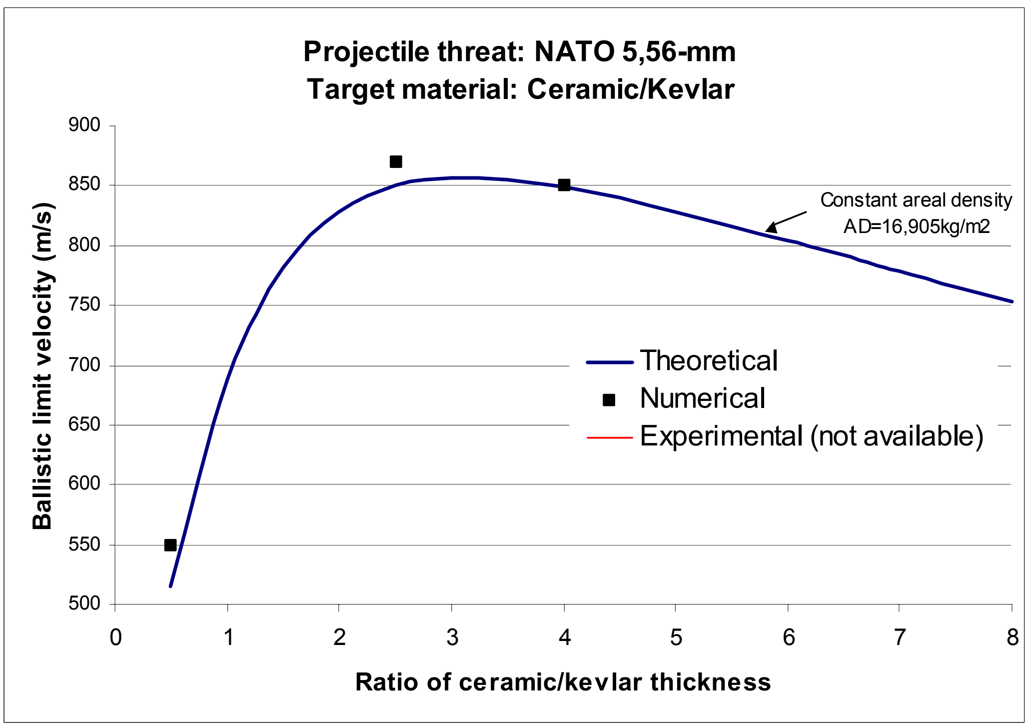
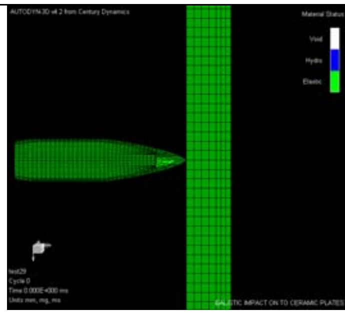
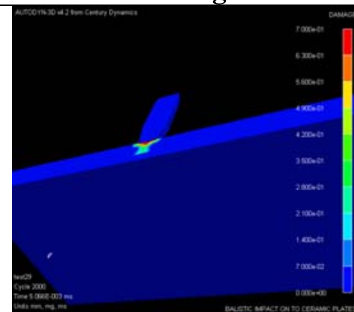
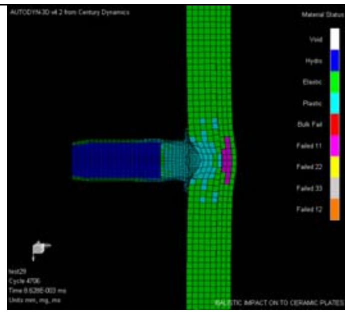
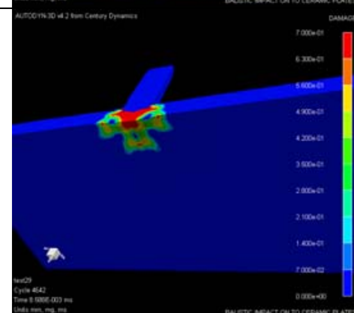
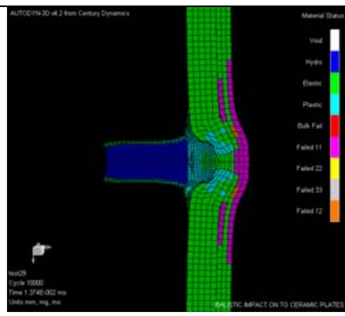
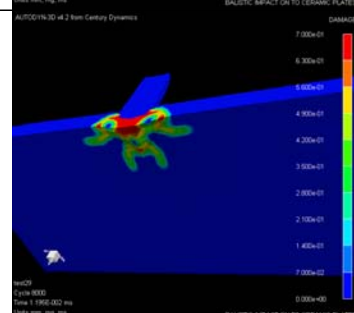
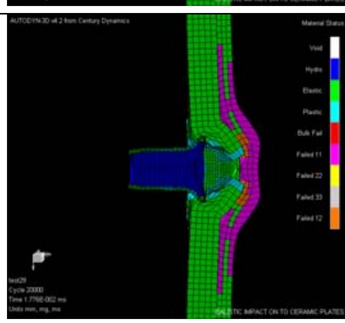
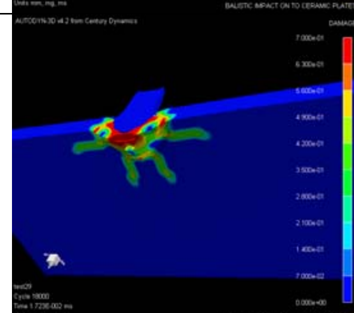
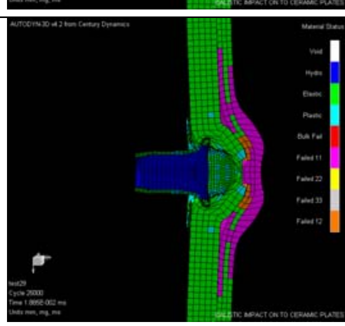
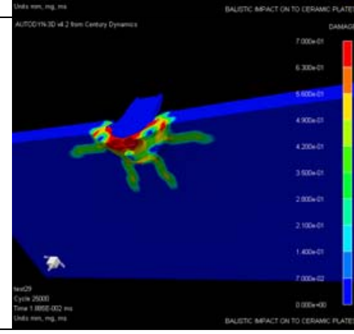


Figure 7. Constant areal density optimisation of ceramic-faced armours

Table 4. Simulated penetrated process for configuration C4

Material status	**Evolution of damge in ceramic**
	
	
	
	
	

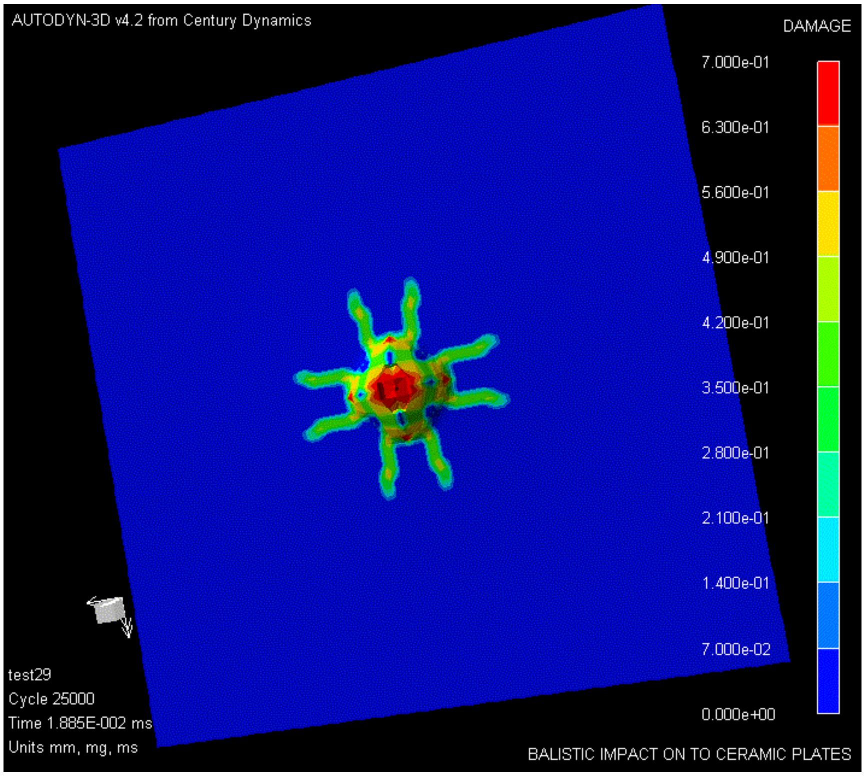


Figure 8. Crack propagation in Ceramic tile. Back view.

In the numerical simulations configuration C5, which has the thinnest backing plate and configuration C1 that has the thickest backing plate, shows relatively the worst ballistic efficiency. In the simulation the worst ballistic performance is observed in the C1 configuration. Optimum composite thickness ratio is in the region of 2.5.

The simulated penetration process of the C4 configuration by projectile is shown in Table 4. The impact velocity is 870 m/s. Conical cracks produce a volume of fragmented ceramic of a distinct conoid shape. The projectile experiencing erosion continues penetration into the volume of damaged ceramic.

7. DISCUSION. COMPARATIVE MODELS

IS NOT YET FINISHED.

8. CONCLUSION

IS NOT YET FINISHED.

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