Computational simulations and ballistic verification tests for 7.62mm AP and 12.7mm AP bullet impact against ceramic metal composite armours

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Abstract

In this study, perforation performance tests of multi layered ceramic-metal composite armours consisting of alumina ceramics (99.5% Al_2O_3) and aluminium Al 2024-T351 back-up materials against a 7.62mm armour piercing (AP) bullet and a 12.7mm AP bullet impact were numerically simulated and then these simulations were verified by the ballistic tests. Nonlinear dynamics finite element simulations are solved with the LS-DYNA lagrangian solver. In the study, new sets of material constants for appropriate material models, which describe the bullet's steel core and aluminium target material deformation better, are obtained. These new material constants are obtained by evaluating stress-strain curve data and also making Depth of Penetration (DOP) simulations and verification tests for each AP bullet and Al 2024-T351 material before perforation performance simulations of ceramic composite structures. The 3D finite element model is generated and compared with 2D simulations. For DOP simulations, the steel core of the bullet is only modelled, but for perforation simulations a full bullet (copper jacketed and filler material) model is used in simulations for the 12.7mm AP bullet. According to the DOP simulation results, Plastic-Kinematics hardening material model is reasonable enough to describe material damage modelling for both bullets and Al 2024-T351 material. Failure strain (FS), which is the most critical value in the simulations, is obtained from stress-strain curve data and also evaluating DOP test results with some correlation for high strain rate condition. The FS value for Al 2024-T351 against a 12.7mm bullet impact is estimated higher than a 7.62mm bullet impact, which is well expressed by strain hardening due to the increased impact area and energy of the bullet. In perforation simulations, bullets and Al 2024-T351 are simulated with a plastic-kinematics hardening material model, but for the ceramics material, a Johnson-Holmquist (JH2) ceramic material model is selected for a good estimation. Ballistic verification tests performed show that numerical simulations are overlapped successfully with the test results with an acceptable difference. With these appropriate material model constants; the fracture conoid in ceramics, bullet deviation from the line of impact and then stopping, bullet end deformation and aluminium bulging is well shown in the simulations.

Keywords: perforation performance simulation, depth of penetration simulation, 7.62mm AP bullet, 12.7mm AP bullet, alumina ceramics (Al_2O_3), aluminium 2024-T351, new material constants, ballistic tests.

1 Introduction

Ceramic composite armour systems are designed to defeat armour piercing (AP), kinetic energy projectiles mainly in the small arms and heavy machine gun category. These AP projectiles are purely inertial rounds, most commonly made of hard steel of moderate density (7.85 gr/cm^3). The hard core is generally encased in a thin jacket in a more ductile metal for aerodynamic consideration [1]. Ceramic armours require a backup metal, which delays the initiation of the tensile failure in the ceramic at the ceramic/backing plate interface, allows more projectile erosion and enhances the ballistic performance of add-on armour systems [2]. The subject of ceramic materials backed by ductile metal plates against small and medium calibre projectiles is of interest to many researchers [3,4]. However, the design of composite armour systems based on an understanding of real impact events is a really a challenging subject and deserves sophisticated research work. Most of the works in this area are experimental in nature. The cost of experimentation is expensive and the results obtained cannot be extrapolated to a large number of cases. The impact events can be modelled on the computer and tested against a large number of threats via computer simulations. The utilization of modelling and simulation tools for the design of armour systems is critically based on material models, which should accurately reflect the physical behaviour of the armour systems. In the current study, perforation performance tests of multi layered ceramic-metal armours against 7.62mm AP bullet and 12.7mm AP bullet impacts were conducted and data were used for verification of the numerical approach. In the simulation the 3D impact analyses of the armours are conducted using nonlinear explicit dynamic finite element code LS-DYNA to simulate the perforation performance of the ceramic-metal target. The materials used are alumina ceramic (99.5% Al_2O_3) for the frontal plate and aluminium (Al-2024-T351) for the backup plate.

2 Experimental work

In order to get the better material constants for the bullet's steel core and aluminium target material to be used in numerical simulations, two types of ballistic test were performed experimentally, one is a Depth of Penetration (DOP) test of aluminium plates, and the other is a perforation performance test of ceramic armours (with aluminium back up). DOP tests of tightly framed Al-2024-T351 aluminium plates were performed at different distances. Firstly, DOP tests of total 216mm thickness aluminium plates (tightly confined 18 plates, each 300mm x 300mm x 12mm in size) at 235m against 7.62mm AP and 12.7mm AP projectiles were performed. In order to see the projectile stopped distance easily without cross-section cutting, multilayered aluminium plates were used instead of mono block materials, although the fracture mechanics behaviours of them may be slightly different. According to projectile stopped distance results of the first DOP test, a new DOP test with a reduced layer thickness of 72mm (6 plates with a better steel-framed confinement, each 12mm thickness) at 25m and 50m against a 7.62mm AP projectile were performed.

Perforation performance tests were first carried out for alumina ceramic (99.5% Al_2O_3, 10mm thickness) backed by an Al-2024-T351 aluminium plate (10mm thickness) by a 7.62mm AP projectile at 235m. A special type of adhesive is used to attach the ceramic tiles into the aluminium plate. They are enclosed with a soft aluminium cover in order to avoid ceramic parts scatter. Secondly, the ballistic performance of two layers of 10mm alumina ceramic backed by a 10mm Al-2024-T351 aluminium plate against a 12.7mm AP projectile was investigated again at 235m. All the experiments were performed by the expert personnel of a state owned company called Mechanical and Chemical Industry Corporation (M.K.E.K). All the target plates were placed in a vertical position on a test table. Both the 7.62mm AP projectile and the 12.7mm AP projectile were fired against the target at a normal incidence angle and their muzzle velocities are approximately 838m/s and 869m/s, respectively. The mechanical properties and material characterisation of the 7.62mm AP and the 12.7mm AP bullets and the Al2024-T351 material was obtained in laboratory tests by a tensile test (at low strain rate), a hardness test and scanning electron microscopy (SEM) measurements. Both of the projectile's cores are made of hard steel (100Cr6) while the jacket is made of copper. The maximum Rockwell hardness value (Rockwell C) of the 7.62mm AP and the 12.7mm AP projectile cores were measured as 62 ± 2 Rc.

2.1 Experimental results

According to the DOP test results of Al2024-T351 at 235m, the 7.62mm AP projectile was stopped at a distance of 25.5mm ± 0.5mm on the third plate. However, the 12.7mm AP projectile penetration distance was measured as 51.5mm ± 0.5mm on the fifth plate. The 12.7mm AP projectile was seen as welded between the second and the third plates, therefore it was difficult to separate. The copper-jacket of the projectile was stripped in the first plate and only the projectile's core penetrated into the aluminium plates by the sharpened edge due to metal-to-metal friction. In Figure 1, test apparatus, deformations on the first five plates and the stopped 12.7mm projectile are shown step by step.

The second DOP test result, which was performed at 25m and at 50m for the 7.62mm AP projectile only, shows a longer penetration distance than the first DOP test due to a higher impact velocity and better steel-framed confinement, meaning there was no separation of plates relative to each other. The penetration distance was measured as 33mm ± 0.5mm at 25m firing. The perforation performance test result of one layer of 10mm alumina ceramic backed by Al202-T351 against a 7.62mm AP bullet impact at 235m is shown in Figure 2. After the soft aluminium cover was opened, as seen in the figure, only a small portion of the ceramic plate was fractured and destroyed. However, substantial damage on the projectile occurred as the copper-jacket of the projectile was stripped, the tip of projectile's core was destroyed and the core stopped before almost reaching the aluminium plate. There is also deformation on the aluminium plate possibly due to fractured ceramic particles. The last perforation performance test result of two layers each of 10mm alumina ceramic backed by an Al202-T351 plate (12mm thickness) against a 12.7mm AP bullet impact at

235m is shown in Figure 3. Two bullets were fired in this test because of the first bullet impact corner of the frame. After the soft aluminium cover was opened, as seen in the figure, the 12.7mm AP bullet perforated this armour and the deformed bullet is not caught. The first bullet impact to the corner destroyed some of the ceramic tiles near the second bullet impact point.

Figure 1: 7.62mm AP and 12.7mm AP DOP tests on Al 2024-T351 plates at 235m.

3 Numerical simulations

3.1 Numerical modelling

In this work ballistic perforation performance of ceramic-metal armours are investigated by using nonlinear explicit dynamic finite element code LS-DYNA. There are three different targets namely; a 72 mm Al-2024-T351 aluminium plate, a 10mm ceramic backed by a 10mm Al-2024-T351 aluminium plate and a 20mm ceramic (two layers of 10mm ceramic) backed by a 10mm Al-2024-T351 aluminium plate. The projectile geometry was obtained with an ATOS digitizing device. The 3D finite element model is generated and compared with 2D simulations. For DOP simulations, only the steel core of the bullet is modelled, but for Perforation simulations a full bullet (copper jacketed and filler material) model is used in simulations for the 12.7mm AP bullet. The boundary of all the

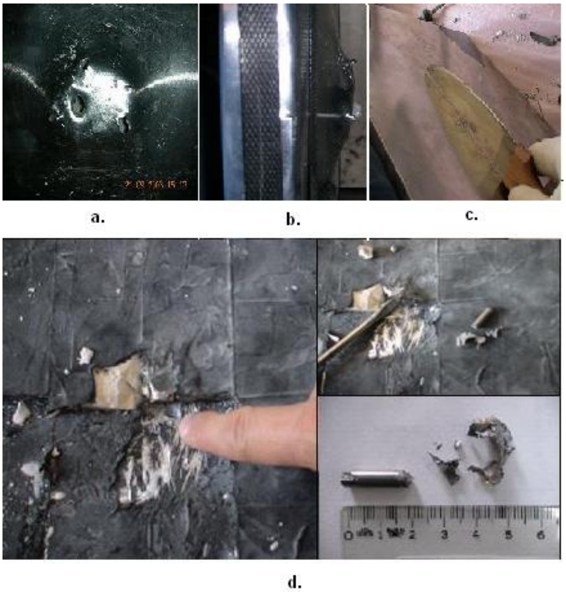

Figure 2: 7.62mm AP ballistic test on one alumina ceramic layer backed by an Al2024-T351 layer. a. Front Aluminium cover, b. Side view, c. Bulging at back of Aluminium plate, d. Alumina ceramic and 7.62mm AP projectile deformations.

Figure 3: 12.7mm AP firing on two layers of alumina ceramic backed with an Al2024-T351 plate.

plates was specifically chosen to be circular instead of other shapes such as rectangular, because of the symmetry of the stress wave propagation and reflection in the circumferential direction of the plate. A 3D FE mesh for the target and the projectile was created as shown in Figure 4 by using the ANSYS-LS-DYNA pre-processor. The circular plate is divided into two regions in mesh in the radial direction inner and outer region. The mesh is coarsening from the inner to the outer region. The target and projectile are meshed with an explicit 8-noded hexagonal element (SOLID 164) of varying size between 0.25mm to 0.5mm. The translational nodal degrees of freedom along the boundary of the plate layers are constrained to prevent any translational movement. Contact behaviour between the projectile and armour mesh was simulated with eroding surface-to-surface contact algorithms of the LS-DYNA.

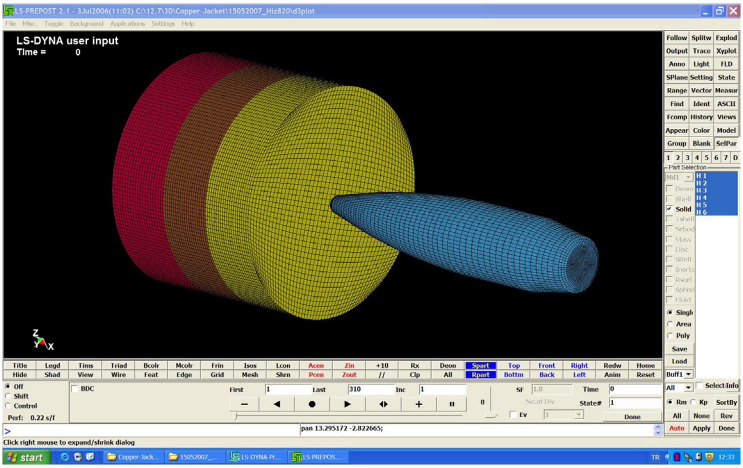

Figure 4: The 3D FE mesh of the 12.7mm AP bullet including copper jacket, filler material and steel core and two layers of ceramic target backed by aluminium.

In the numerical analyses, after the different projectile velocities were tried between 750m/s and 860m/s, 800m/s was used for the 7.62mm AP bullet impact and 840m/s for the 12.7mm AP bullet impact at 25m firings.

3.2 Constitutive model

The utilization of modelling and simulation tools for the design of armour systems is critically based on material models, which should accurately reflect the physical behaviour of the armour systems. In this work plastic-kinematic hardening (material 3 in LS-DYNA *MAT_PLASTIC_KINEMATIC) [5] and Jonhson-Holmquist-2 (JH-2) constitutive models (material 110 in LS-DYNA *MAT_JOHNSON_HOLMQUIST-CERAMIC) [6] were used to simulate the behaviour of the armour layers and the projectiles in the numerical modelling. Plastic-kinematics hardening material model is a strain-rate dependent elastic-plastic model with the Cowper-Symonds model [7]:

$$\sigma_Y = \sigma_{Y0}\left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{p}}\right] \quad (1)$$

where σ_Y, σ_{Y0} are yield stress limits of the material defined with and without the influence of strain rate $\dot{\varepsilon}$; C and p are constants. The plastic-kinematics hardening material model is utilized to predict the response of the rear plate (Al-2024-T351 aluminium plate) and projectile made of hard steel. The JH-2 (rather than JH-1) constitutive model, which allows the progressive damage, was used for the ceramic plate damage modelling.

3.3 Numerical results and determination of new material constants

New material constants were obtained by evaluating stress-strain curve data and a series of ballistic firing test results. Then, a series of DOP test simulations were carried out by assuming the dynamic material parameters of bullets and aluminium materials at high velocity impacts according to the stress-strain data and ballistic test results. For the 7.62mm AP bullet both at 235m and at 25m ballistic tests were performed, for the 12.7mm AP bullet only 235m ballistic tests were performed. Some material constants for Al2024-T351 were obtained for the 12.7mm bullet impact at 235m. Then, a correlation on these constants was made for the 12.7mm bullet impact at 25m, based on a 7.62mm impact at 25m. According to the DOP simulation results, the Plastic Kinematics hardening material model is reasonable enough to describe material damage modelling for both bullets and the Al 2024-T351 material. The Plastic Kinematics hardening material model constants for the 7.62mm AP and the 12.7mm AP bullets hard steel core materials and Al2024-T351 were obtained and are given in Table 1 and Table 2, respectively. Alumina ceramics data was taken from the literature [8]. Failure strain (FS), which is the most important value, is taken as 0.03 for both bullet steel cores. The FS value of Al2024-T351 is taken as 0.21 against a 7.62mm AP bullet core impact, but against a 12.7mm AP bullet impact, it is taken as 0.56 due to a much greater strain hardening effect.

Table 1: Plastic Kinematic hardening constants for bullet hard steel cores.

Parameter	ρ **[ton/mm^3]**	**E [MPa]**	ν	σ_Y **[MPa]**	E_T **[MPa]**	β	**C**	**p**
Value	7.85E-9	205E3	0.3	1500	670	0.0	40.0	5.0

Table 2: Plastic Kinematic hardening constants of the Al2024-T351 material.

Parameter	ρ **[ton/mm^3]**	**E [MPa]**	ν	σ_Y **[MPa]**	E_T **[MPa]**	β	**C**	**p**
Value	2.71E-9	73.1E3	0.34	345	1500	0.0	6500	4.0

In DOP simulations, the penetration depth is obtained as 32.8mm for the 7.62mm AP bullet at 25m firing. In the ballistic tests, the penetration depth was measured as 33mm ± 0.5mm, with approximately 1% error between the test and the simulations. Based on the 7.62mm AP bullet simulation at 25m, the 12.7mm AP bullet simulation was carried out and the depth of penetration was obtained as 64.8mm. In Figure 5, the DOP simulation of Al2024-T351 against a 7.62mm AP at 25m firing was shown. In Figures 6 and 7, different views of projectile, the deviation from the line of impact and then stopping, and ceramic fracture and deformation on aluminium are shown respectively for perforation performance simulations of one layer alumina ceramic (10mm thickness) backed by an Al2024-T351 plate (10mm thickness) against a 7.62mm AP bullet impact. In Figure 8, Fracture conoid formation is shown in a plastic strain view for perforation performance simulations of two layers of alumina ceramic (2x10mm) backed by an Al2024-T351 plate (12mm thickness) against a 12.7mm AP bullet impact.

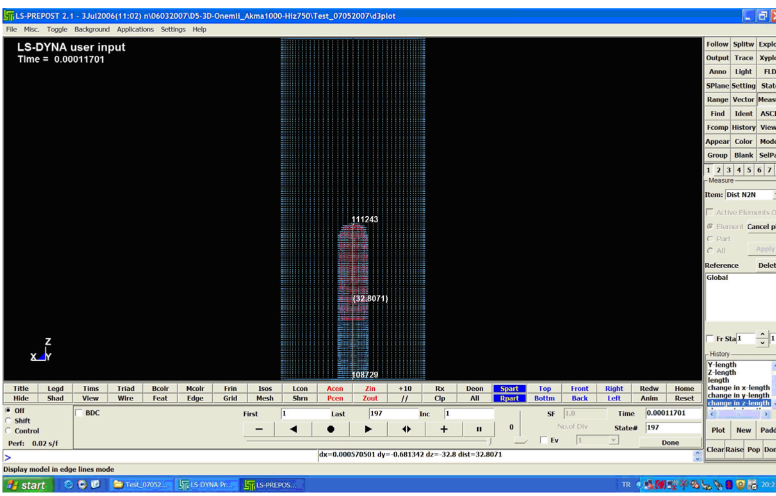

Figure 5: DOP simulations of Al2024-T351 against a 7.62mm AP bullet.

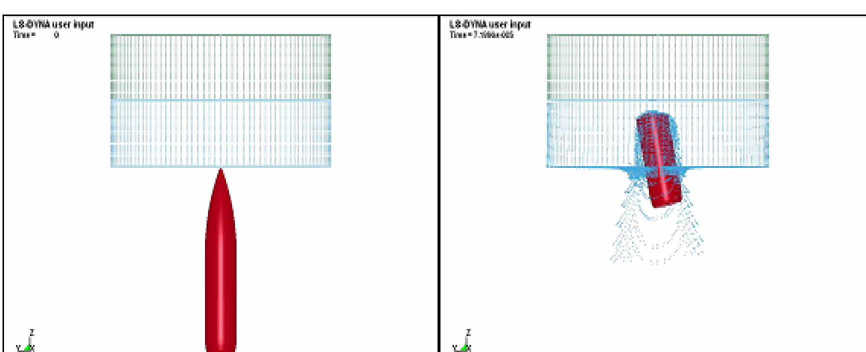

Figure 6: 7.62mm AP bullet: Deviation from the line of impact and stopping.

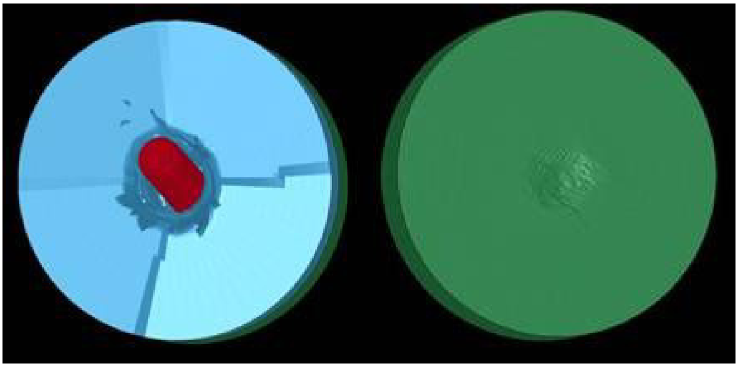

Figure 7: Left: Ceramic fracture. Right: Plastic deformation on Al2024-T351 (7.62mm).

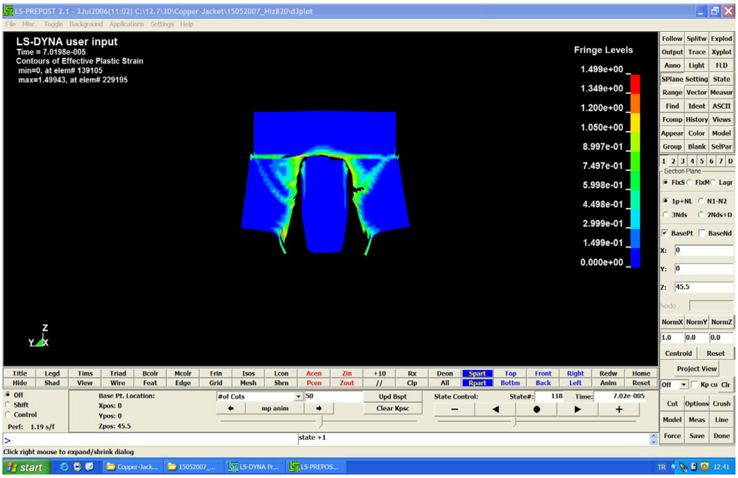

Figure 8: Fracture conoid shown in plastic strain (the 12.7mm AP bullet impact).

4 Conclusions

Ballistic DOP and perforation tests on Al2024-T351 and on one or two layered alumina ceramics (99.5% Al_2O_3) backed by aluminium Al 2024-T351 materials against a 7.62mm AP bullet and a 12.7mm AP bullet have been performed. Then, FE analyses of these 7.62mm AP bullet and 12.7mm AP bullet impacts were carried out by assuming new sets of material constants for appropriate material models which describe the bullets' steel core and aluminium target material deformation better. The main goal of the presented work is to develop a fine numerical model with better material model constants for hard steel bullet core and backed Al2024-T351 material. Adhesive and cover aluminium were ignored during simulations. Simulation results and ballistic firing test results show that the FE model used and the obtained constants can be very useful in future simulations.

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