DESIGN AND DEVELOPMENT OF PASSIVE ARMOUR FOR SAF VEHICLES

TEO Ee Sheng Wilson

ABSTRACT

Passive armour is required to protect vehicles against attacks from Kinetic Energy threats, mines and Improvised Explosive Devices (IEDs). Passive armour typically makes up to 46% of the weight of a typical Main Battle Tank. The weight gain of protected vehicles can be as much as 50% due to protection add-ons during their service life. Therefore, in order to keep the weight of vehicles within practical limits, there is an impetus to conduct research into lighter armour materials. This article presents the design, development and choice of armour materials used on the Singapore Armed Forces' (SAF) vehicles. The way to test and qualify armour systems on the SAF's vehicles is also discussed, followed by an overview on the use of finite element software to investigate ways of packaging these materials together to improve the effectiveness of an armour system.

Keywords: passive armour, armour materials, armoured vehicle, vehicle protection

INTRODUCTION

Passive armour is the solution for protecting Armoured Fighting Vehicles (AFV) against long rod penetrators fired by tank guns and medium calibre cannons. Consequently, armoured vehicles experience a weight growth of around 50% during their decades of in-service life (Hetherington and Moss, 2009), and up to 46% of the weight of a typical modern Main Battle Tank comes from its armour (Hetherington and Littleton, 1987). Hence, there is an impetus to conduct research on developing lighter armour designs. This article presents the design principles behind armour used on the Singapore Armed Forces' (SAF) vehicles and the considerations behind the choice of armour materials. This is followed by an overview of the qualification and testing process of armour systems for SAF vehicles, and how modelling and simulation (M&S) was used to understand the penetration mechanics behind an armour's design, which can be used to optimise armour design and reduce the number of live firings required.

GENERIC PASSIVE ARMOUR DESIGN

Before proceeding to discuss about armour materials, it is useful to know the general passive armour design principles that are applied on the SAF's protected vehicles, as shown in Figure 1.

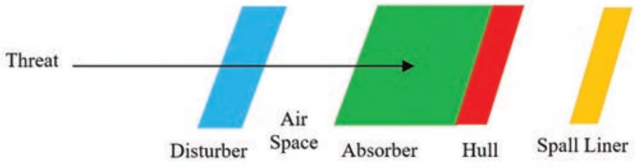


Figure 1. Generic armour design (Hazell, 2006)

The purposes of the different layers are as follow (Bryn, 2009):

Disturber

This layer tends to be made from high-strength materials such as high hardness steel and ceramic materials. The purpose of this layer is to fragment the incoming projectile or rapidly erode it.

Air space

This space is to allow the disturbed projectile and/or fragments of the projectile to yaw and spread, significantly reducing the kinetic energy density (defined as the kinetic energy over the impact area) of the projectile and its fragments, and the resulting penetration.

Absorber

This layer absorbs the kinetic energy of the projectile and its fragments through large amounts of plastic deformation, thereby converting it to a lower form of energy such as heat. This layer can be made from metals with high toughness (which could be the hull itself) and composites.

Hull

The hull provides structural support to the Disturber and Absorber layers. Good structural support of the Absorber from the hull would improve the ballistic performance of the Absorber.

Spall shield

This layer is also known as the 'spall liner'. This layer reduces the fragment cone from the back face of the hull, should the projectile perforate or cause high-speed spalls to flake off the back face of the hull. The spall liner may be adhered or bolted onto the back face of the hull, or with an air-gap in between.

The Disturber and Absorber layers can be fixed to the hull as add-on armour kits. The advantages of using add-on armour kits are: (a) ease of replacing damaged modules; (b) ease of upgrading the armour modules with advanced armour materials; and (c) the ability to tailor a vehicle's protection to the threats that a vehicle might encounter in its theatre of operations. An example of a modern AFV using a modular armour concept is the SAF's BIONIX Infantry Fighting Vehicle (see Figure 2).

Figure 2. Modular armour of BIONIX IFV (Hazell, 2006)

PASSIVE ARMOUR MATERIALS

The following paragraphs give an overview of the pros and cons of the three classes of materials that are used in the passive armour of the SAF's protected vehicles, namely metals, ceramics and polymer composites.

Metals

There are three main metallic contenders for armour applications, namely steel, aluminium and titanium (Hazell, 2016).

Steel

Steel is the most common material used in armour because it has a good balance of hardness, toughness, fatigue resistance, ease of fabrication and welding, and is relatively low cost. Most of the SAF's protected vehicles use armoured steel for their base hull, providing a base level of protection. By controlling the heat treatment process and the alloying elements in steel, a range of hardness and toughness can be achieved. A form of steel that has an extraordinary combination of strength and toughness is martensitic steel. Martensitic steels have an ultimate tensile strength (UTS) of 2250 MPa and hardness of 600 to 615HV, compared to conventional high hardness armours with around 1600-1900 MPa (UTS) and 500-550HV in hardness, making martensitic steel possess superior ballistic protection performance. However, martensitic steels' hardness makes them much more difficult to process, and they are used as add-on armour on the SAF's armoured vehicles.

Aluminium

Aluminium armour was first used in the ubiquitous M113 armoured personnel carrier, which is also in service with the SAF. This vehicle was born from operational lessons the US Army learned during the Korean War, which led to a requirement for a vehicle that was lightly armoured, air-transportable on board the C-130, air-droppable and amphibious. Aluminium armour was an appropriate choice as its density was approximately one third that of steel whilst the tensile strength range from 60-600MPa.

However, aluminium has a number of disadvantages for use in AFVs. The chief disadvantage of aluminium is that its harder alloys suitable for armour applications are susceptible to stress-corrosion cracking. Stress-corrosion cracking occurs when the aluminium alloy is attacked by a corrodent whilst being subjected to tensile stress. This is a particularly insidious failure because the magnitudes of stresses that are required to encourage failure are frequently lower than the yield strengths of the alloy. Residual stresses induced during machining, assembling or welding can also lead to failure. Aluminium also possesses lower spall strength than steel and is hence more prone to spalling. It is necessary to employ internal spall shields in vehicles made of aluminium alloys. Lastly, aluminium dust is pyrophoric, thus the debris generated in the event of perforation could burn.

Titanium

Titanium is an attractive material for armour designers as its ballistics grade form (Ti-6A1-4V) has a density that is approximately half that of steel while possessing relatively high strength (900-1300MPa) and hardness (320-370Hv). Titanium is also weldable and heat-treatable.

However, the Tungsten Inert Gas welding process for titanium is not as easy as that for steel because an inert gas environment is required to prevent the titanium from reacting with the environment during the welding process, which weakens the weld.

One other drawback of titanium alloys is that they are highly susceptible to adiabatic shear. This occurs when a material is subjected to a large amount of high-rate deformation. As the deformation occurs rapidly, there is little or no time for heat to conduct and diffuse from the plastically deforming zone. This localised heating can lead to thermal softening of the material and further plastic flow. Due to titanium armours' tendency to fail by adiabatic shear, and the fact that they can also spall when subjected to ballistic attack, Titanium is normally used in combination with other materials such as steel. Titanium also costs around 10-20 times that of steel, depending on price fluctuations in the world's metal markets. In addition, titanium's machining and welding costs are also relatively high as compared to steel. Thus, titanium armour is used selectively to protect certain parts of the SAF's armoured vehicles.

Ceramics

Due to their high hardness and relatively light weight, ceramics have been used to protect the crews of US helicopters in Vietnam from bullets since the 1960s. The material properties of some ceramic armour materials are shown in Table 1. In terms of relative costs and weight, boron carbide is the most expensive and lightest, followed by silicon carbide and alumina, being the cheapest and heaviest. Ceramic armour is also used selectively to protect certain parts of the SAF's armoured vehicles.

	Alumina (98-99% purity by mass)	**Silicon Carbide**	**Boron Carbide**
Density (kg/m^3)	3,810-3,920	3,090-3,220	2,500-2,520
Hardness (HV)	1,500-1,900	1,800-2,800	2,800-3400

Table 1. Material properties of some ceramic armour materials

As ceramics are brittle materials, they must be coupled with a sufficiently rigid yet tough material that supports them throughout the penetration process. Combined with their relatively low density, ceramics can provide a weight-efficient but sometimes costly means of protection, as illustrated in Figure 3 (Hazell, 2006). Note that the 'Areal Density' is simply the mass per unit area of an armour system and it reduces as the hardness of the ceramic increases and a fibre-matrix composite material backing is used.

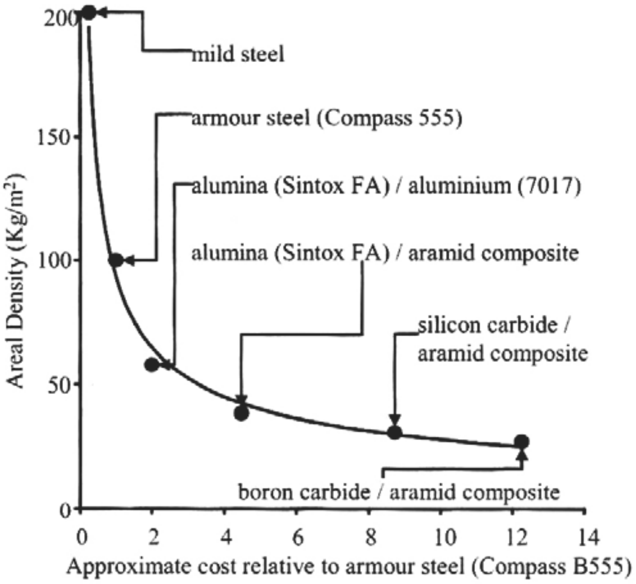


Figure 3. Approximate relative costs of ceramics coupled with suitable backing material vs. cost of armour steel for protection against a 7.62mm armour-piercing round (Hazell, 2006)

The penetration process of a small arms bullet into ceramic-faced armour is illustrated in Figure 4. Upon impact with the ceramic, the bullet's tip is destroyed and a crack is initiated at the point of impact. As the penetration progresses, the bullet is eroded by a process of yielding and plastic flow in a direction perpendicular to the direction of bullet travel (also known as 'dwell'). Approximately 40% of the bullet's mass and initial energy are carried off by the eroded projectile material. The crack grows into a ceramic cone that spreads the load of the bullet onto a larger back-plate area. Researchers have observed that even in a pulverised state, the ceramic pieces can still help to erode the bullet further. The back-plate then undergoes plastic deformation to absorb the impact. If the backing material is strong enough, the bullet will come to a stop. However, if the kinetic energy of the bullet is sufficient, the back-plate will fail and the projectile will perforate the target with a reduced residual velocity, and can then be stopped more easily by the Absorber layer.

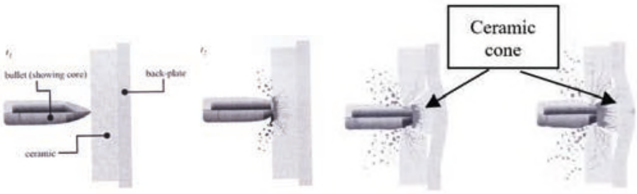


Figure 4. A small arms bullet impacting and penetrating a ceramic-faced armour (Hazell, 2006)

To increase the efficiency of ceramics further, the ceramic must be confined laterally (i.e. from the sides) to delay the formation of cracks and to contain the pulverised ceramic. If a ceramic is inherently hard and strong enough to withstand the impact, or a weaker ceramic is well-confined, the projectile will simply dwell on the surface of the ceramic and not penetrate it, as shown in Figure 5. Dwell is the lateral flow of a penetrator's material across the surface of a hard target upon impact, because the strength of the target overmatches the strength of the penetrator. After dwelling on the ceramic tile's surface, a penetrator may be blunted or shattered, but its remnants may still continue the penetration process into the ceramic, although with reduced energy levels. If the penetrator is completely stopped at the ceramic tile's surface via dwell with no penetration into the ceramic, it is termed as 'interface defeat'.

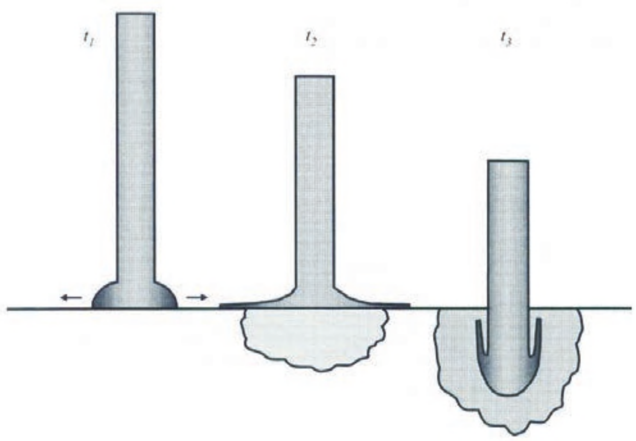


Figure 5. A small arms bullet impacting and dwelling on a ceramic-faced armour (Hazell, 2006).

Besides costs, the other disadvantage of ceramics is its lack of multi-hit capability. Nonetheless, armour designers mitigate this by using a mosaic of ceramic tiles (instead of one monolithic piece) embedded within a structural matrix to limit crack propagation as shown in the X-ray of a ceramic composite armour after one shot in Figure 6.

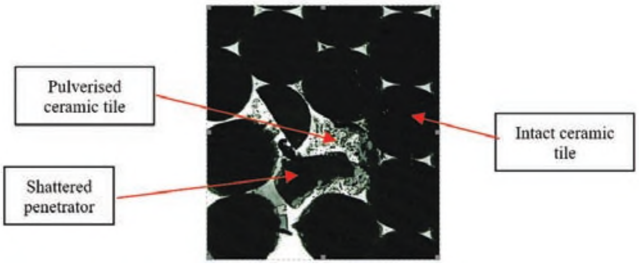


Figure 6. X-ray showing shattered penetrator and mosaic of ceramic tiles taken from one SAF project

Transparent Ceramics

A vehicle's crew and sensor systems need to have optically transparent armoured windows to see through. Commonly, armoured glass made from laminates of soda-lime glass with rubbery interlayers (such as polyurethane or polyvinyl butyral) and a backing layer of polymer (such as polycarbonate) has been used for this purpose. However, to stop a 7.62mm armour-piercing bullet, such armoured glass would require a thickness in the region of 60-100mm. As the thickness increases, transparency reduces and distortion increases, and eventually the weight can become prohibitive for lighter-weight vehicles. The likelihood of thick laminates delaminating is also higher due to the differences in thermal expansion rates between different materials.

To improve the performance of armoured glass, a layer of transparent ceramics such as aluminium oxynitride (ALON), magnesium aluminate (SPINEL) or a single crystal aluminium oxide (SAPPHIRE) can be used as a Disturber layer. The thickness of the armoured glass can then be reduced with weight savings of about 30% (ST Engineering Land Systems, 2017). The key to producing a transparent ceramic is to use a material that is intrinsically transparent, i.e. the atoms do not absorb the photon energy of incoming light. SAPPHIRE has to be 'grown' as a single crystal of aluminium oxide, which is a slow and costly process. ALON and SPINEL could be produced using conventional ceramics sintering techniques which allow for mass production, and are much faster and thus more cost effective to produce as shown in Figure 7 (Surmet Corporation, 2013).

Powder preparation

After powder compaction

After sintering

After grinding and polishing

Figure 7. Conventional processing techniques for ALON and SPINEL
(Reprinted with permission from Surmet Corporation.)

Figure 8. Transparent Armour developed by DSO and the local defence industry (left) and conventional ballistic glass (right)

Similar to opaque ceramics, the drawbacks of transparent ceramics are costs and a lack of multi-hit capability. To improve its multi-hit capability, the same principle of using smaller tiles to compartmentalise the damage is applied. This is illustrated by the transparent armour developed by DSO National Laboratories (DSO) and the local defence industry in Figure 8. Another benefit of this design is that the driver would still be able to see through the undamaged sections of a window after an attack, as compared to conventional armoured glass where the cracks would propagate over the entire pane and obscure the driver's view. Transparent ceramic armour technology is currently being considered for potential implementation on a small number of SAF vehicles as a pilot study.

Polymer Composites

Composites in this section refer to laminates of matrix bonded fibres. The matrix provides a continuous phase to transfer loads on the laminates to the stronger and stiffer fibres. The typical values of some material properties of fibre materials are shown in Table 2. Fibres that are used in ballistic applications have reasonable strains to failure of 3% to 6%, which means that they have excellent energy-absorbing abilities. This makes polymer composites suitable as backing plates to brittle ceramics, provided the ceramics are bonded well to the polymer composites.

	Aramid (e.g. Kevlar)	**Polyethylene (e.g. Dyneema)**	**E-glass**	**S-glass**
Density (kg/m^3)	1,440	970	2,600	2,500
Tensile strength (MPa)	2,900	3,200	3,500	4,600
Failure strain (%)	3.6	3.7	4.8	5.2

Table 2. Material properties of some fibre materials

Polymer composites are also suitable as spall liners to arrest spalls that may flake off the internal wall of a hull when the hull is subjected to external impact, and are used on some SAF vehicles. For protection against low level threats from small arms, laminates of polymer composites offer the lightest possible standalone protection solutions. Polymer composites can also conform to complicated shapes such as a vehicle's firewall which separates the engine from the driver compartment as shown in Figure 9.

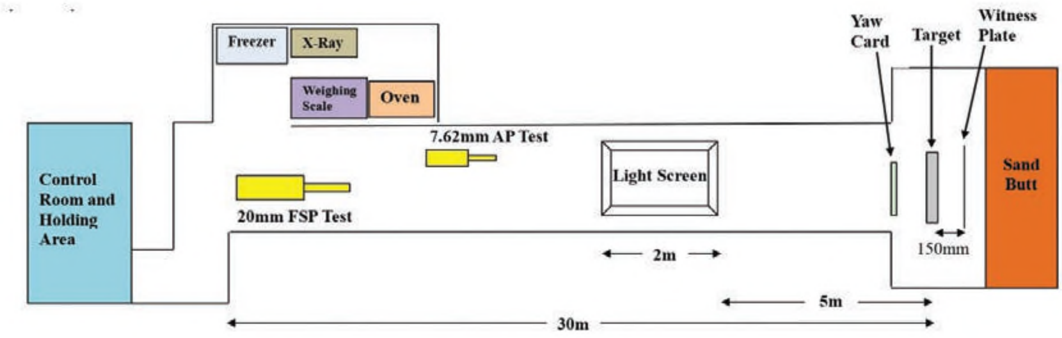
Figure 9. Composite used in an SAF project to protect the firewall of passenger compartment

QUALIFICATION AND TESTING

After it is designed, an armour has to be tested and qualified according to the procedures stated in AEP-55 Volume 1, Edition 2. This is a document that describes the system qualification and acceptance procedure for determining the Protection Level of armour vehicles for kinetic energy (KE) and artillery threats, and is also used for qualifying the protection of the SAF's vehicles. A typical set-up for the range is shown in Figure 10.

Launcher and Projectiles

The typical test guns used to qualify armour in the SAF's armouring projects are shown in Figure 11. The test guns are fired single-shot, usually aimed using a laser aiming device and triggered remotely to ensure accuracy. For small and medium calibre firing, the range is typically enclosed to remove disturbances from the weather and environment. The guns are sited very close to the target at 30m to ensure accuracy, so that the required multi-hit shot spacing can be achieved.



FSP: Fragment Simulating Projectile
AP: Armour Piercing
Freezer and Oven are for temperature conditioning of targets
X-ray is for capturing the extent of damage of armour targets.
Weighing scale is for measuring areal density of target.
Yaw card is for measuring the yaw angle of the projectile.
Witness plate is for checking the pass/fail criteria. Perforation of the witness plate would mean a fail.

Figure 10. Range set up for qualification of armour

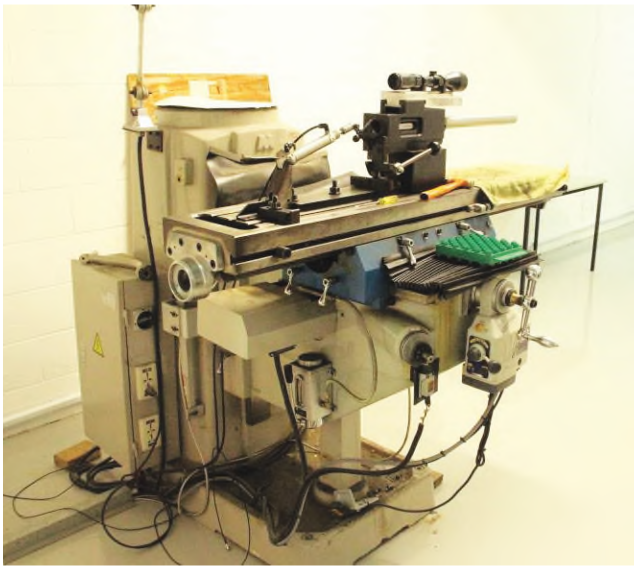


Figure 11. Test gun used to qualify armour

As the firing distance is very close to the target, projectiles need to have the appropriate amount of propellant removed from their cartridge so that the impact velocity at 30m matches that of the projectile fired from a further distance of 200m (for protection against 14.5mm ammunition) or 500m (for protection against 25mm and 30mm ammunition), as stated in STANAG 4569. For rounds where the burn rate of the propellant contained in the cartridge is reduced by low temperatures, the round could also be chilled to sub-zero temperatures to reduce the rate at which propellant gases are produced, thus reducing the bullet’s velocity. The advantage of the latter method is that it removes the need to modify the round.

Target

For qualification, Fully Engineered Targets or Vehicle Targets can be used (see Figure 12). Fully Engineered Targets are targets that are constructed to be fully representative of an actual vehicle armour system. This is achieved by using the same materials, hardware, construction techniques, fixing and mounting method that would be used in the actual vehicle system.

Passing Criteria

The level of damage on the 0.5mm thick aluminium witness plate placed at 150mm behind the target is the performance criterion for evaluating the success or failure of a target against a particular projectile. After each shot, the witness plate is examined for damage. A Complete Penetration (CP), which indicates failure, is recorded when light is observed to pass through the damage in the witness plate. A Partial Penetration (PP), which indicates a pass, is recorded when no light is observed. This means that even if there is a hole in the target, or if there are spalls off the rear of the target, it is considered a pass as long as there is no CP of the witness plate, as the energy level of a fragment that cannot penetrate a 0.5mm aluminium plate is considered to be low enough not to cause serious injury to a soldier. See Figure 13 for some examples of targets with PP and CP.

Figure 12. Fully Engineered Target for an SAF project (left) and Vehicle Target (right)
Photo of Mercedes-Maybach S 600 Guard
(Reprinted with permission from Cycle & Carriage Singapore.)

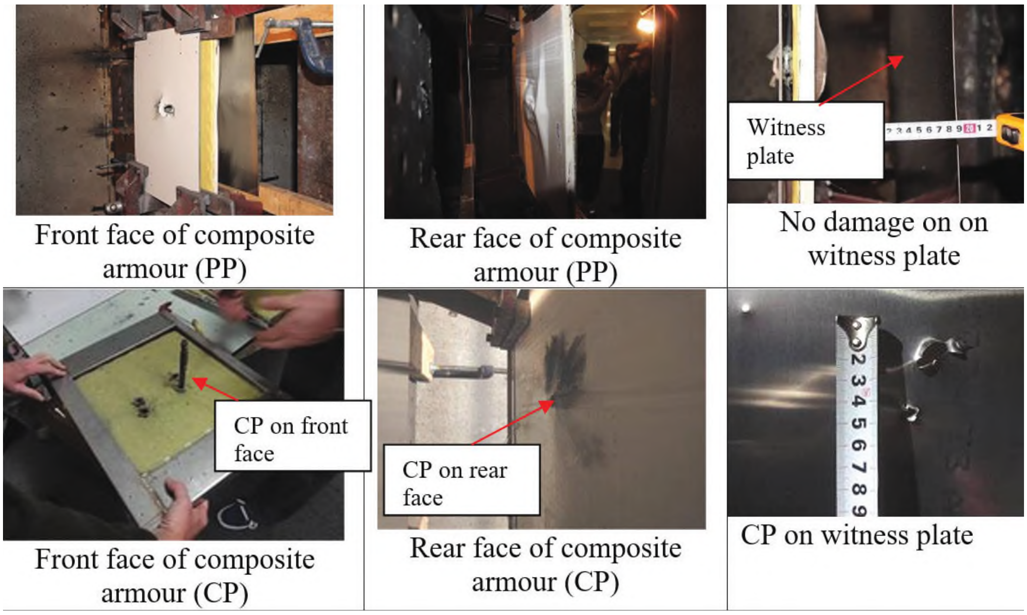


Figure 13. Examples of targets for an SAF project with PP and CP

MODELLING AND SIMULATION

With so many different materials to choose from, how do armour designers package all these materials together to form a composite armour system that meets the user's requirements of light weight with high ballistic protection capability? Repeated live fire tests are costly as they are destructive tests requiring ballistic materials, ammunition, range time and manpower. Besides depending on experience and repeated testings, one additional tool at the designer's disposal is the use of Finite Element software to explore novel ways of packaging armour materials together.

The following M&S example from a joint project by the SAF, DSTA and DSO illustrates a case where a validated model helped designers understand the penetration mechanics behind an armour's design. The model simulates a KE penetrator impacting on a metallic Add-On-Armour (AOA) module spaced at a certain distance from the base hull and spall liner. The impact velocity and impact angle measured during live fire tests were provided as initial conditions in the simulation. Validated material models were also used for the materials of the penetrator, AOA and base hull. The software used for the simulation was AUTODYN, which can simulate dynamic transient events such as ballistic penetration, shaped charge jet formation and penetration, and blast.

At the start of the simulation, only the penetrator and the AOA were modelled (see Figure 14). The simulation was performed in 3D with an axis of symmetry, simplifying the geometry and reducing the computation time significantly. The meshing was denser near the impact point and coarser further away to reduce the computational time (see Figure 15). After the penetrator had exited the AOA and was still in the air space between the AOA and the base hull, the base hull and spall liner were added into the simulation just before the penetrator impacted on the base hull (see Figure 16). The AOA was then deleted from the simulation. This method was used to reduce the computation time and resources required.

The penetration process is shown in Figure 17. Upon impact with the AOA, the tip of the penetrator bent. As the penetration continued, the tip broke off within the AOA at 0.140ms, ricocheted, and exited from the front of the AOA at 0.140ms. The remaining fragments of the penetrator carried on in the direction of impact and exited from the rear of the AOA at 0.210ms. Upon exiting the AOA, the remnants of the penetrator yawed in the air space between the AOA and the base hull before striking the base hull at a shallow angle and ricocheting off it.

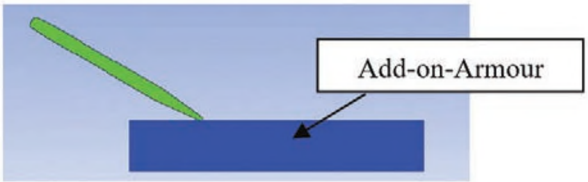


Figure 14. Initial simulation set-up showing penetrator and Add-on-Armour at 0 time-step

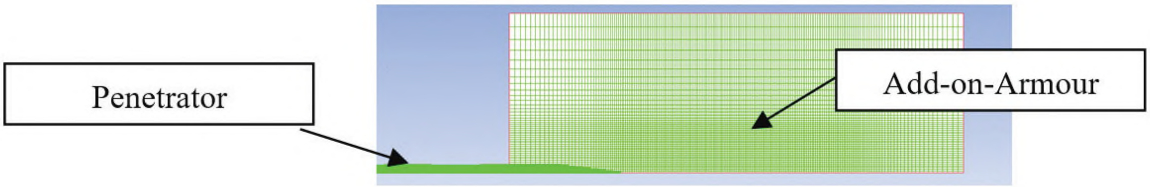


Figure 15. Meshing of half-model used in the simulation (top view) at 0 time-step

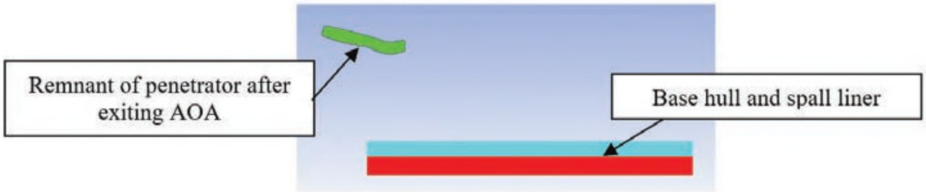


Figure 16. Insertion of base hull and spall liner at 0.21ms into the simulation, after the penetrator had exited the AOA

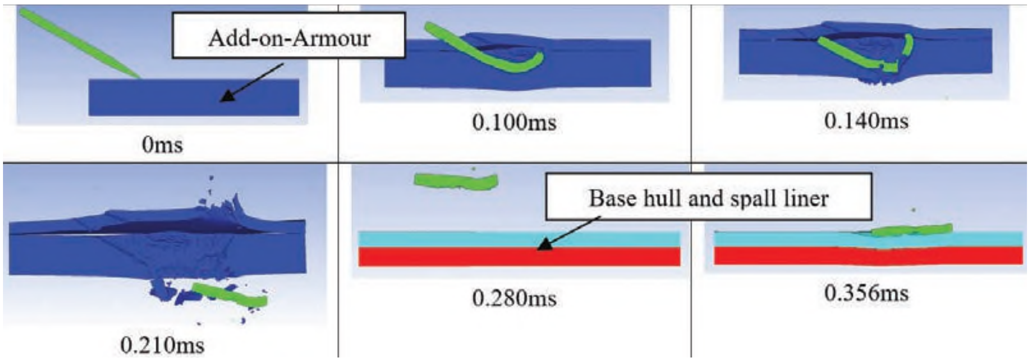
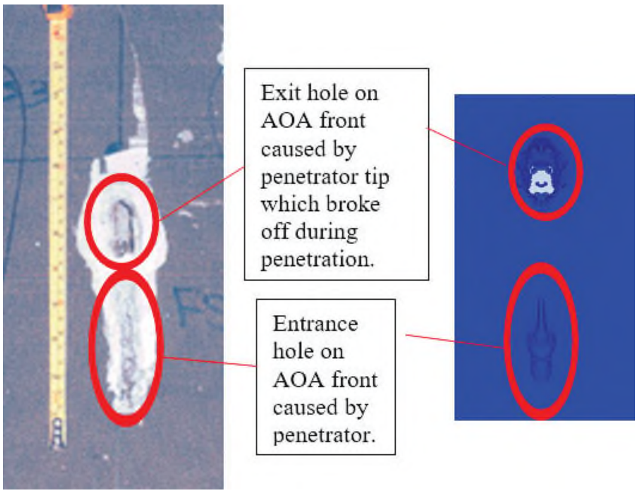


Figure 17. Penetration simulation results

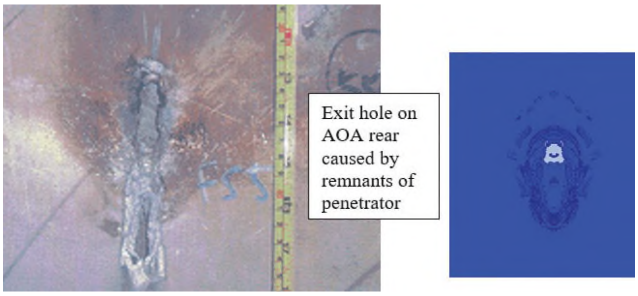
As shown in Figure 18, the entry and exit holes in the simulated AOA approximated that observed in actual trials.

Similarly, the residual damage on the base hull caused by the remnants of the penetrator in the simulation closely approximated that which was measured on the actual base hull (see Figure 19). Having validated the model for the AOA and base hull, studies can now be made for other threats such as a new KE penetrator. However, accurate dimensional and material properties for the new KE penetrator and a validated material model for the penetrator's material must be available for meaningful studies to be made.

It must be cautioned that all simulations inherently possess some degree of error. Although there is a wealth of information in the literature on conventional armour materials, the data and material models need to be compared and calibrated through comparisons with some baseline live firing test data for specific threats or armour materials, in order to validate M&S models sufficiently before the results can be reasonably accurate. For example, the simulation model of a projectile should give a good approximation of the actual penetration depth, entry and exit hole sizes on each RHA plate at NATO 0 degrees[1], before the projectile's model can be used to predict interactions against an inclined RHA plate. New materials (e.g. new formulations of metals, ceramics or polymer composite)



AOA Front Face (Entry)



AOA Rear Face (Exit)

Figure 18. Comparison of damage on the front and rear faces of the Add-On-Armour

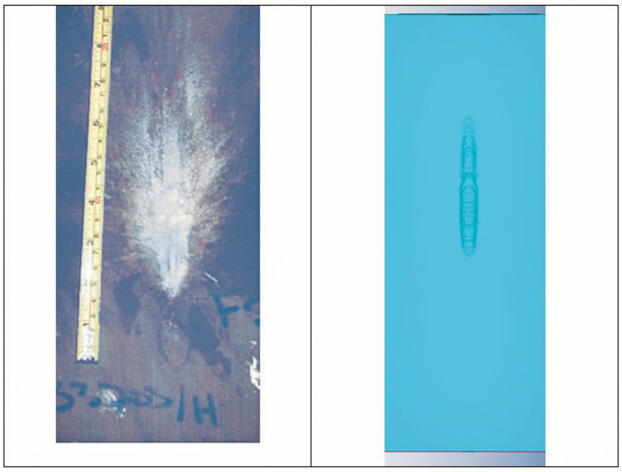


Figure 19. Comparison of dent on base hull

that are developed will also need to be modelled using new equations that model the behaviour of the materials under dynamic loads, and these equations (i.e. material models) will take time and effort to be derived and validated by researchers. Due to these reasons, some Original Equipment Manufacturer still rely heavily on experience and repeated live fire tests to develop their armour designs.

CONCLUSION

Passive armour is required to protect against attacks from KE threats, mines and Improvisioned Explosives Devices. In this respect, research into new armour materials has enabled passive protection to become lighter. To investigate the effectiveness of various designs, finite element software tools can be used to aid armour designers. In addition, it is essential that reasonably accurate material models are available in the finite element software and that actual tests are carried out to validate the simulation results. The final armour design needs to be qualified by a trial by fire according to the AEP-55 Volume 1, Edition 2.

ACKNOWLEDGEMENTS

The author would like to thank his supervisor, Mr Matthew Leong Kwok Hoe, for his encouragement in the submission of this article.

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ENDNOTES

[1] The NATO angle is measured with respect to the normal to the target's surface. An impact at NATO 0 degrees means a perpendicular impact of a projectile on a target's surface.

BIOGRAPHY

TEO Ee Sheng Wilson is a Principal Engineer (Protection) in the Land Systems programme centre. He has extensive experience in the testing and evaluation of armour systems, and in-depth understanding on the modelling and simulation of ballistic penetration problems. As a recipient of the DSTA undergraduate scholarship, Wilson obtained a Bachelor of Engineering (Mechanical Engineering) degree with Honours from the National University of Singapore (NUS) in 2004. He further obtained a Master of Science (Military Vehicle Technology) degree from Cranfield University, UK, in 2009 under the DSTA postgraduate scholarship. He was awarded the DESM department prize for academic excellence in his postgraduate course.