An Investigation into the Kinetic Penetration Resistance of Steel Armour Plating

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Abstract

High strength steel is typically used in armour plating for ballistic protection due to its high yield strength and hardness, and while it may be capable of protecting from simple steel penetrators, more advanced materials such as depleted uranium alloy cast doubt on the capabilities of such armour plating. Finite element analysis was used to compare how a typical armour plate would withstand penetration from a simple steel projectile verses a depleted uranium projectile. While some plate failure occurred in both, catastrophic failure was only present in the case of depleted uranium, likely due to its increase momentum, owning to the high density of the material. Failure was attributed to a combination of tensile stress induced weakening and shear induced plugging. Criticisms of the methodology were also given.

Introduction

High strength steel plating is often used in military armoured applications to prevent penetration via kinetic payloads, including both conventional bullets and fragmentation, and is typically chosen due to its high yield stress and hardness [1]. This usually means that a ballistic projectile, upon contact, will be slowed and deformed by the plate, absorbing its kinetic energy and dispersing its impact force over a larger area, creating reduced stress via the deformation.

For this reason, different materials are selected for different purposes in ballistics design. For unarmoured targets, simple steel is often used in the form of fragmentation, however it often has difficulty penetrating armour plating. For this reason, harder and denser materials are chosen for armour piercing rounds. One such material is depleted uranium alloyed with molybdenum (DU), which boasts increased hardness, yield stress, density and a self-sharpening effect upon fragmentation. This combination of traits makes DU an excellent material for ballistic penetration [2].

As such, it is of great interest to recognise whether the materials used for standard armour plating would be capable of withstanding the enhanced penetration threat presented by DU munitions. While practical testing would provide the most adequate assurance, finite element analysis offers an affordable alternative that allows for in situ investigation of failure modes.

Analysis approach

Finite element analysis was performed with the Abaqus Explicit solver. A single high strength steel (named Secure 500) armour plate of moderately low-density mesh, measuring 30x30x5 cm, was modelled using Johnson-Cook damage parameters obtained from Kılıç et al. [3], see [table 1]. A small impact region in the middle of the plate was selected for Johnson-Cook deformation. Two kinetic impacts were modelled using the same moderate density tetrahedral meshed projectile, each one with a different material, the first being a simple steel and the second being depleted uranium. Processing limitations did not allow for Johnson-Cook damage modelling of both the plate and the projectiles, so simple physical parameters for the projectiles were selected as a compromise [table 2] [4,5,6].

Table 1: Physical properties and Johnson-Cook damage coefficients of the steel plate

Depleted Uranium	-
Density ρ	7850 kg m^{-3}
Elastic modulus E	206 GPa
Shear modulus G	80 GPa

Poisson's ratio v	0.3
Strain hardening:	-
A	1200 MPa
B	1580 MPa
n	0.175
Strain rate hardening C	0.004
Reference strain rate $\dot{\varepsilon}_0$	1×10^{-4}
J-C failure:	-
D_1	0.1
D_2	0.4
D_3	-1.3
D_4	0.05
D_5	0

Table 2: Physical properties of the projectiles

Steel	-
Density ρ	7850 kg m^3
Ultimate tensile stress	1000 MPa
Elastic modulus E	200 GPa
Poisson's ratio v	0.3
Melting temperature	1650 K
-	-
DU	-
Density ρ	18000 kg m^3
Ultimate tensile strength	943 MPa
Elastic modulus E	148 GPa
Poisson's ratio v	0.335
Melting temperature	1473 K

Results and Discussion

Simple steel projectile

Kinetic impact from a simple steel projectile demonstrated the expected behaviour of a high strength steel designed for use in modern armour, with the projectile being entirely stopped with approximately two thirds of the plate being penetrated.

Immediately upon impact, maximum principal compression stress was observed building up below the tip of the projectile. Due to the deletion of damaged elements and the lower-density mesh, the true shape of this compression zone cannot be fully appreciated, however peak stresses of just under 4.79 GPa indicate significant kinetic energy dissipation [fig.1].

Similarly, significant shear stresses in the order of 500 MPa were present after impact as the metal in the compression zone was pushed downward past the metal surrounding it [fig.2]. This indicated early signs of shear plugging.

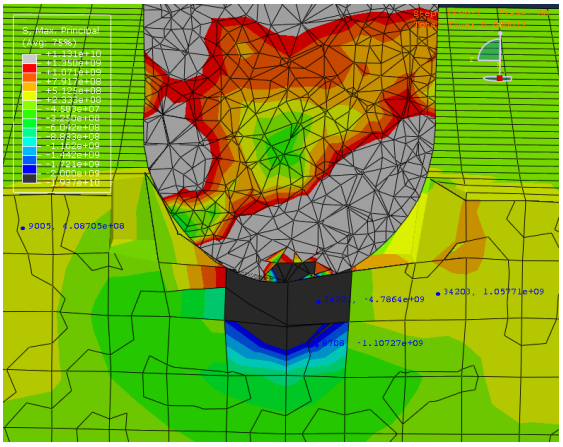

Figure 1: Steel projectile, frame 80 showing maximum principle stress

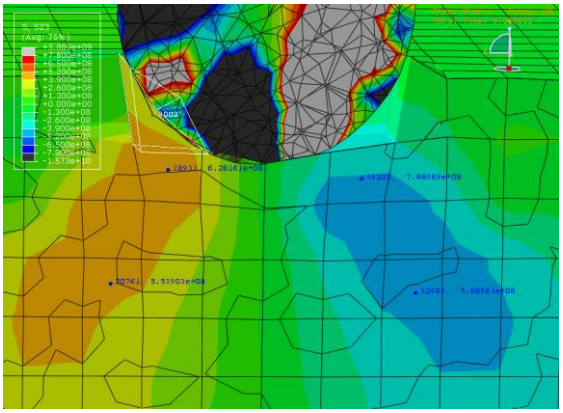

Figure 2: Steel projectile, frame 80 showing shear stress

After further penetration, the compression wave was observed to have moved deeper into the plate, although the maximum principal compressive stress had lessened, indicating significant deceleration of the projectile [fig.3]. Significant stress was also observed building in the bottom of the plate due to mechanical stretching caused by the bulging of the compression zone.

Shear analysis at this time indicated that while the initial shear stresses were increasing in magnitude, new sources of shear were occurring further up the plate as the projectile passed by the metal along the sides of its path, pulling it down with it [fig.4].

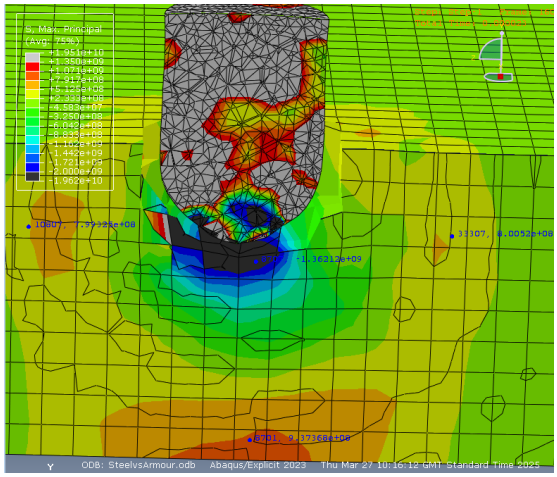

Figure 3: Steel projectile, frame 160 showing maximum principle stress

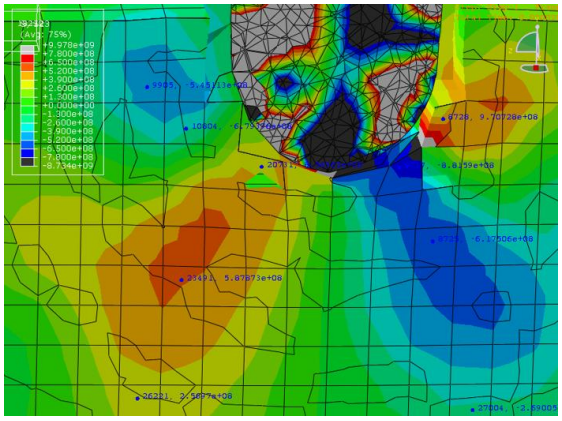

Figure 4: Steel projectile, frame 200 showing shear stress

During frame 432 [fig.5], the max principle tensile stress was observed in contrast with the shear stress. This demonstrated a peak tensile stress of over 1.92 GPa, compared to the peak shear stress of just 657 MPa. Combined with the centrally located plate damage present in frame 462 [fig.6], it can be inferred that wherein the plate failed, it was due to tensile stress caused by plate bulging rather than shear.

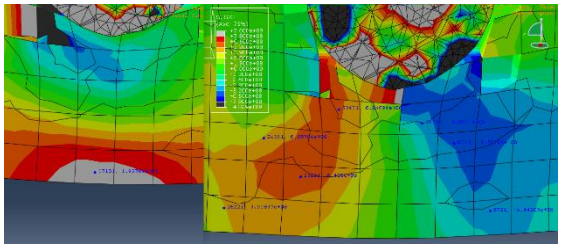

Figure 5: Steel projectile, comparing max. principal stress against shear before breakage, frame 432

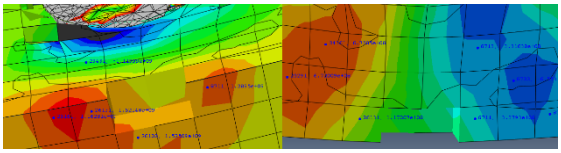

Figure 6: Steel projectile, comparing max. principal stress against shear after breakage, frame 462

Depleted uranium projectile

The depleted uranium impact simulation proceeded similarly to that of the steel projectile initially, with similar patterns of high compressive stress, plate bottom stretching and lower magnitude shear from plugging and projectile dragging, see [fig.7].

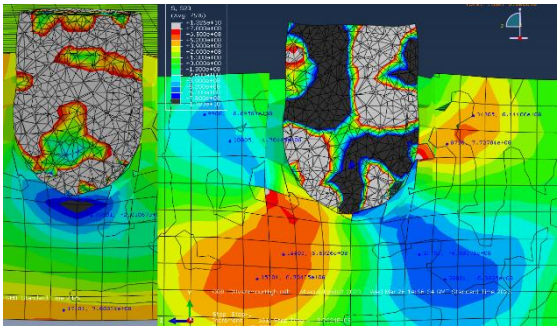

Figure 7: DU projectile, comparing max. principal stress against shear, frame 160

However, as the projectile penetrated deeper, signs of plate failure began, as the bottom of the plate was placed under immense mechanical stress [fig.8]. This caused significant plate breakage shortly after [fig.9].

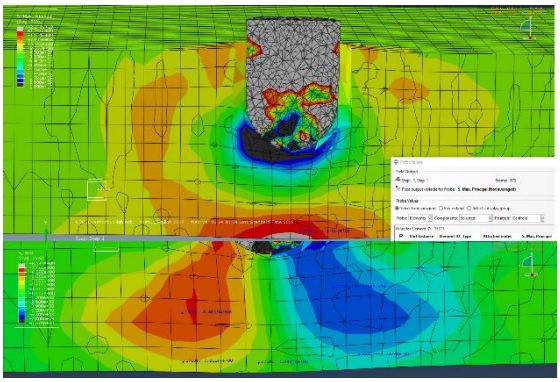

Figure 8: DU projectile, comparing max. principal stress against shear before breakage

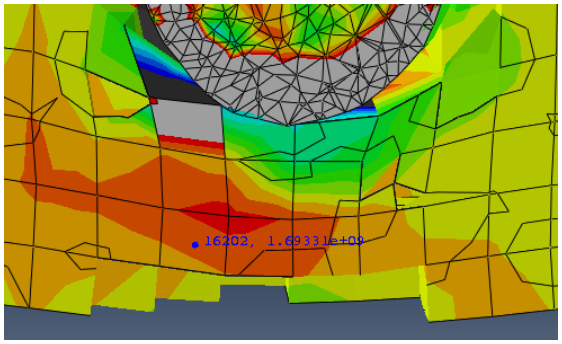

Figure 9: DU projectile, comparing max. principal stress against shear after breakage

In the aftermath of this, shear forces were still peaking at just under 900 MPa [fig.10], and shortly afterwards, complete penetration occurs [fig.11], suggesting that failure can be considered to initially be caused by mechanical stretching of the bottom of the plate, weakening it enough for shear plugging to occur, leading to complete catastrophic failure.

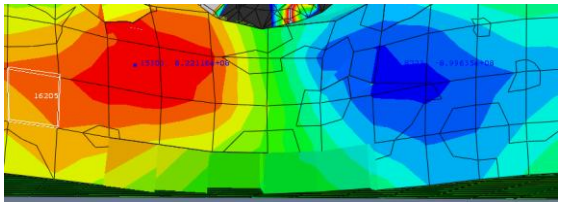

Figure 10, DU projectile, demonstrating shear present after intial breakage

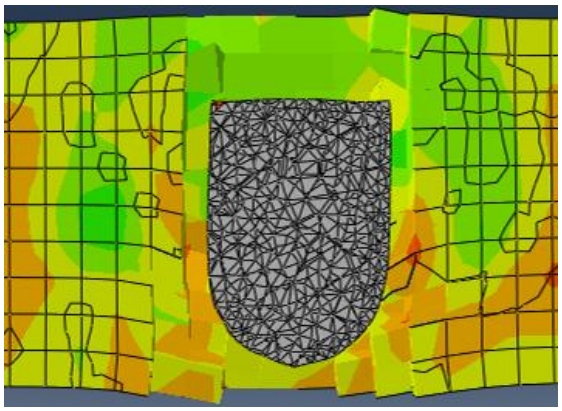

Figure 11: DU projectile, complete penetration

Comparison

While both plates did receive damage and undergo at least some amount of failure, it is clear that the steel kinetic payload carried significantly less kinetic energy than the DU projectile. This can be observed from the speed graphs in [figs.12,13] wherein, the steel projectile is fully stopped, while the DU projectile continues to move at over 450 m/s, more than half its starting velocity. Evidently, the increased density of the DU was the main contributing factor to plate failure, as it allowed the bullet to carry more momentum, and impart a greater force upon the plate thereafter.

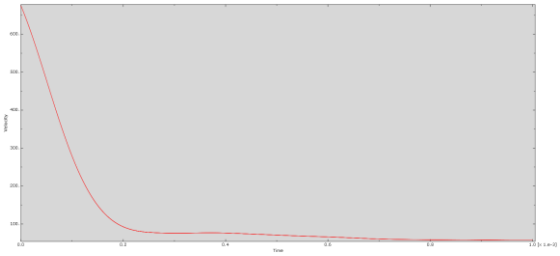

Figure 12: Chebyshev filtered absolute velocity (speed) against time for the steel projectile

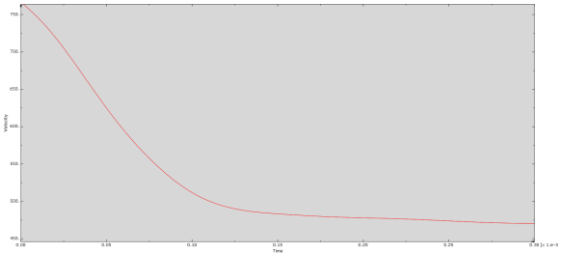

Figure 13: Chebyshev filtered absolute velocity (speed) against time for the DU projectile

Limitations

While plate failure has been analysed and a failure mode has been determined, it cannot be stated with much certainty that this would be reflective of reality, as there are several flaws in this modelling process.

Primarily, neither projectile was damage modelled due to computational constraints. Projectile deformation is a significant component of the damage mitigation process for armour plate materials due not only to the redirection of energy into damaging the projectile, but also due to the flattening of the projectile leading to lower total pressure. Due to this, it can be said with certainty that the simulations are not representative of reality, and it cannot necessarily be assumed that the DU projectile would have penetrated the plate.

Furthermore, failure mode analysis was made more challenging due to the limited mesh density on the plate, combined with the lack of temperature and friction modelling. Ordinarily, the steel plate's physical properties would be different under the increased temperature induced by the impact and following projectile friction. As such, damage such as adiabatic shearing cannot be analysed and the properties of the plate during the simulation cannot be said to be accurate.

Element deletion also results in a lack of spalling and fragmentation after impact which in a real scenario may cause damage to any target behind the plate.

The absolute velocity analysis also carries significant limitations due to poor node selection. Since the node selected was at the tip of the projectile, it was subject to considerable motion as the projectile warped while passing through the plate in each case. This led to extremely varied velocity data which required post-processing via a Chebyshev filter. This process was not lossless and gave only a general representation of the velocity-time relationship, specific values could not be relied upon.

Conclusion

From these simulations, it can be concluded that DU munitions could pose a conceivable threat to steel armour plating owing to their superior material qualities, however future work should be performed to account more accurately for physical parameters and mechanics at play during a kinetic impact to ensure complete simulation efficacy.

References

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[6] J. T. Creasy, "Thermal Properties of Uranium-Molybdenum Alloys: Phase Decomposition Effects of Heat Treatments," Feb. 2012.

Bibliography

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