Interaction between High-velocity Penetrators and Moving Armour Components

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Abstract

This work was aimed at understanding mechanisms of importance for the design of weight-efficient armour against long-rod projectiles (LRP) and shaped charge (SC) warheads. The focus was on how to achieve effective mechanical disturbances on the threat before it hits the target.

Methods were developed for laboratory tests in full and reduced scale, and for registration and evaluation of the fast and violent events involved. For numerical simulations, the Xue-Wierzbiicki fracture model was implemented and used for the LRP in order to allow fractures due to shear load without extensive damage of the entire projectile. In order to reproduce the scattering of the SC jet after interaction with reactive armour, use was made of a very fine computational mesh.

Severe disturbances and fractures of the penetrators (LRP and SC jet) originate from the interaction phase in which a plate slides along the penetrator. In the case of an SC jet, this sliding contact results in severe scattering of the SC jet due to instabilities of the same kind as those between two fluids in contact, moving in parallel with different tangential velocities (Kelvin-Helmholtz instabilities). The generation of such instabilities is caused by the very high velocity (in the order of 10000 m/s) and the relatively low material strength of the SC jet in combination with the high contact pressure and the motion of the plate. In the case of an LRP, the high strength of the material of the projectile and its low velocity (in the order of 2000 m/s) relative to that of an SC jet, prevent the generation of KH-instabilities. Instead, fractures of the projectile may occur due to abrupt change of contact pressure at the exit of the plate. The positive pressure gradient and longer interaction time of forwards moving plates compared to backwards moving plates make the former plates more effective. A side-hitting steel rod gives approximately the same effect on an LRP as that of a steel plate with the same thickness, velocity and angle of obliquity.

The results obtained can be used for assessment and optimisation of reactive armour modules and active protection systems.

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Preface

I would like to express my heartfelt gratitude to Bengt Lundberg, Professor of Solid Mechanics at Uppsala University, for his guidance and for all his encouragement that finally made me finalize this thesis. He has shown a genuine interest in this research work, far more than can be expected from a supervisor. Thank you!

The work was carried out at FOI, the Swedish Defence Research Agency, Defence & Security, Systems and Technology Division, as part of research on Weapons effects and Physical Protection and was funded by the Swedish Armed Forces. It has lasted over many years and many colleagues have contributed significantly. In the experimental work with long rod projectiles I was assisted by John Ottoösson, Bo Johansson and Olof Andersson, while the experimental tests with shaped charge jets were performed by Jonas Lundgren. For the numerical simulations Anders Tjernberg, Håkan Hansson, Saed Mousavi and Andreas Helte were my co-workers. I thank all of you for great cooperation, interesting discussions and enjoyable company.

I would also like to thank my former head of division, Bo Janzon, for encouraging his staff to continue their education and for always believing in what I was doing. I highly appreciate that FOI gave me the opportunity to carry out the work that resulted in this thesis.

During the course of my work, I have attended several courses at Uppsala University where I had the opportunity to get to know inspiring people with whom I have had interesting technical discussions and friendly contacts. I want to thank my fellow PhD students from FOI, Patrik Lundberg, Lars Westerling and René Renström, the PhD students Anders Jansson and Lars Hillström, and Urmas Valdek, Senior Lecturer of Solid Mechanics, for good fellowship.

I have enjoyed the opportunity to be a part-time PhD student and to perform this work. I had never managed to dedicate time for this without the never-ending support from my loved ones: my mother, my father, Jenny, Marie and Andreas.

Dec 2010
Ewa Lidén
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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The author’s main contributions to these papers are as follows: planning, evaluation, interpretation, writing, and parts of the experimental work and the development of the evaluation code.
## Abbreviations

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>APFSDS</td>
<td>armor-piercing fin stabilized discarding sabot</td>
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<td>ERA</td>
<td>explosive reactive armour</td>
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<td>HE</td>
<td>high explosive</td>
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<td>HEAT</td>
<td>high-explosive anti-tank</td>
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<td>JC</td>
<td>Johnson-Cook</td>
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<td>KE</td>
<td>kinetic energy</td>
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<td>KH</td>
<td>Kelvin-Helmholtz</td>
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<tr>
<td>L/D</td>
<td>length-to-diameter ratio</td>
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<td>LRP</td>
<td>long rod projectiles</td>
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<tr>
<td>MBT</td>
<td>main battle tank</td>
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<tr>
<td>NERA</td>
<td>non-explosive reactive armour</td>
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<td>RPC</td>
<td>residual projectile constituent</td>
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<td>RPS</td>
<td>residual projectile system</td>
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<td>SC</td>
<td>shaped charge</td>
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<td>XW</td>
<td>Xue-Wierbicki</td>
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1. Introduction

This thesis presents parts of recent work at the Swedish Defence Research Agency FOI, aimed at understanding mechanisms of importance for the design of weight-efficient armour against anti-tank weapons, i.e. long-rod projectiles (LRP) and shaped charge (SC) warheads.

Traditionally, armour against anti-tank weapons consists of very thick high-performance steel. The development of warheads has increased the penetration capability to such an extent that use of homogeneous armour steel has become impossible in vehicle applications. At the same time there is an increased demand for lower weight and better protection of military vehicles. To achieve weight-efficient armour against the capable threats by long rod projectiles and shaped charge warheads, modern armour makes use of arrangements of weight-efficient materials and components that are intended to disturb the threat before it hits the target. This thesis is devoted to the problem of how to achieve such a mechanical disturbance.

A very efficient type of armour against shaped charge warheads, reactive armour, was introduced already in the early eighties. Reactive armour makes use of moving plates to disturb and defeat the threat, and the motion is initiated by the impact of the penetrator. The effect of such armour against shaped charge warheads became so effective that advanced optimisation was considered unnecessary. Long rod projectiles are more difficult to disturb. If reactive armour shall be used to defeat long rod projectiles, the thickness, angles, velocities, number of plates, etc. have to be tailored to the LRP threat. The main emphasis of this work has therefore been on the possibility to disturb a projectile with moving armour components, especially plates as in reactive armour (Papers I, II and IV).

Active protection systems are similar to, but more advanced than, reactive armour. In such systems, the motion of the armour components are initiated by sensors that detect a threat approaching the target. When the threat is located, an armour component is thrown against the threat at some distance. In this case the geometry of the armour component is not restricted to that of a plate, and it is also possible to hit the projectile from the side. The effect of side impacting cylindrical rods on LRPCs is studied to highlight the potential of this kind of armour (Paper III).

Reactive armour panels have been used on main battle tanks for many years as protection against SC warheads, and the main features of the defeat mechanisms of the armour are well known. However, the increased require-
ment on protection against SC warheads also for lighter armoured vehicles means that the effectiveness of the reactive armour has to be increased. The mechanisms when a shaped charge jet interacts with a reactive armour panel are studied in Paper V.

A large number of experimental studies of the interaction between long rod projectiles and plates can be found in the literature, most of them for stationary plates. See for instance [1-5]. The effect of one stationary plate on a projectile was studied by Hohler et al. [1] and Holmberg et al. [2]. Hohler et al. studied the reduction in length and velocity of a projectile after penetration of stationary plates with varying thickness and obliquities. Holmberg et al. studied the influence of plate obliquity and projectile velocity on the behaviour of the projectile. The influence of the projectile material and its composition on penetration in triple-plate targets was investigated by Lynch [3] and Bruchey et al. [4]. Lynch compared four different tungsten alloys, while Bruchey et al. studied fibre-reinforced penetrator materials. Complex oblique pre-perforated plates in single, double and triple plate configurations were studied by Weber [5]. Few published results have been found from direct impact tests concerning the effects of moving armour components on long rod projectiles. In [6], a method for acceleration of single plates by means of electromagnetic forces is described, and a few results of direct impact tests with long rod projectiles are presented. The results from direct impact experiments often show considerable scatter as a result of, for example, defects in the projectile material and small variations in the test parameters. Especially projectile yaw has strong influence on the results as reported by Anderson et al. [7], Normandia [8] and Behner et al. [9] who all investigated yawed impact into a finite target at normal and oblique incidence.

To obtain better control of the test parameters, and to simplify the experiments, the reverse impact technique was used in Papers I-III. This technique commonly implies that the experiments have to be performed in reduced scale. In [10, 11] Lundberg et al. showed that replica modelling can be used for studies of LRPs penetrating an infinite steel or ceramic target and in [2, 12] Holmberg et al. and Lundberg et al. showed that replica modelling can also be used for LRPs penetrating thin oblique stationary plates. In the direct impact experiments performed by Holmberg et al. corresponding results could be found from tests in different scales even though there was large scatter in the results. By using reverse impact technique Lundberg et al. verified these results. Paper I describes an experimental method and computer software developed and used to quantify the geometry and motion of the residual projectile system (i.e., what remains of the projectile) after interaction with an armour component. Also, the first results regarding the effect of thin oblique moving plates on long rod projectiles are presented in this paper. Paper II presents the results from an extensive experimental parameter study in which the experimental method and evaluation code from Paper I were used. The influence of plate velocity, obliquity and thickness

10
as well as of projectile velocity and slenderness was studied. The basic case were tungsten projectiles with length-to-diameter ratio $L/D=15$ (Paper I) or $L/D=30$ (Paper II) and velocity 2000 m/s, interacting with a steel plate with obliquity 60 degrees and thickness equal to the diameter of the projectile. For all parameters studied, stationary plates and plates moving backwards (as the front plate in a reactive armour) and forwards (as the rear plate in a reactive armour) with velocity 200 m/s were included in the investigation.

In Paper III, the effect of moving armour components in the form of a single rod or a frame of three parallel rods, hitting the side of the LRP, was investigated. Again, the study was based on small-scale reverse impact experiments. The rods were hitting the side of the LRP at an angle of attack of 60 degrees. Rod velocities of 200 and 600 m/s and hitting points in the front and in the middle of the LRP were studied. The velocity of the LRP was 2000 m/s. Also, numerical continuum dynamic simulations were performed to highlight the interaction process. In these simulations, Lagrange formulation and the Johnson-Cook strength and fracture models [13, 14] were used.

In Paper IV, numerical simulations were performed with focus on the possibility of reproducing the fragmentation of an LRP impacted by a moving oblique plate. Fracture of the projectile is a principal defeat mechanism and it is essential to have the ability to perform numerical simulations that properly describe the interaction of projectile and armour and the resulting fractures in the projectile. The conditions for fracture are different during the initial perforation phase, in which the projectile nose is consumed, and during the subsequent sliding phase, in which fractures presumably occur due to shear loading. Therefore, a fracture model suggested by Xue-Wierzbicki [15] was implemented in LS-DYNA and used for the projectile together with the Johnson-Cook strength model [13]. This fracture model is based on an equivalent plastic strain of fracture which depends on a stress triaxiality parameter and a deviatoric stress parameter. These parameters were assumed to allow accurate description of both the initial consumption of the projectile nose and the subsequent fractures along the projectile. The results of the simulations were compared with some of the experimental results of Paper II in which the impact conditions were varied in such a way that the projectile fractured in some but not all tests. The performed simulation was also used for a discussion of the mechanisms leading to fragmentation of the projectile.

The well-known irregular disturbances on a shaped charge jet after interaction with reactive armour did not appear in the initially performed numerical simulations of the interaction between a shaped charge jet and a reactive armour panel. As scattering of the jet provides the main protection mechanism of such armour, a study of the details of the interaction between an SC jet and reactive armour plates, and of the origin of the disturbances, was performed (Paper V). The interaction between the jet from an ordinary copper liner SC warhead and inert as well as explosive reactive armour was
studied experimentally. Also a few experiments with single plates moving backwards as well as forwards were performed. Numerical simulations with a simplified but highly refined model were performed to show the difference in the mechanisms of backwards and forwards moving plates when interacting with the jet. The results of simulation showed similarities to processes leading to Kelvin-Helmholtz (KH) instabilities in fluid mechanics [16]. The instabilities on the jet are therefore proposed to be flow instabilities of the same type as KH instabilities. A numerical parametric study was performed on how the strength of the jet and plate materials and the friction between them influence the development of the instabilities in the interface between the jet and an armour plate.
2. Armour and armour-piercing weapons

2.1. Anti-tank weapons

Anti-tank weapons are designed to defeat main battle tanks (MBTs). The function of the weapons is to penetrate the ballistic armour and destroy interior components in the vehicles to make the vehicle and its crew unable to perform their tactical function. As these vehicles are very heavily armoured, the weapons have to be optimized for maximum penetration capability. The effect in an MBT is mainly achieved by the residual penetrator and secondary fragments from the inside of the target. This is often enough to defeat MBTs as the narrow compartment inside a tank is filled with vital components.

There are two different principal types of anti-tank weapons called shaped charge (SC) warheads and kinetic energy (KE) projectiles. In military literature these weapons are often called High-explosive anti-tank (HEAT) projectiles and Armor-piercing fin stabilized discarding sabot (APFSDS) ammunition. SC warheads are used in anti-tank missiles, gun-fired projectiles, rifle grenades, mines, bomblets, torpedoes and various types of air/land/sea-launched guided missiles. The warheads are fired against the target with moderate velocity (300-600 m/s) and detonate when they arrive at the target. As a result of the detonation, a metallic jet or projectile which constitutes the penetrator is created. KE-projectiles are heavy armour-piercing projectiles. They require weapons that transfer all the kinetic energy to the projectile at launch. As the desired velocity is high, around 1800 m/s, an
MBT gun or high velocity rocket is required for the launch of the projectiles. Modern KE-projectiles are very long and slender and are therefore often called long-rod projectiles. Figure 1 shows examples of anti-tank weapons.

The SC warhead consists of a rotationally symmetrical explosive body with a conical metallic liner which is transformed to a jet at initiation, see Fig. 2. The most common liner/jet material is pure copper. The jet can have an effective length 0.5–1 m, diameter 2–3 mm, mass 20–150 g and tip velocity up to 10000 m/s. The extremely high velocity of the jet implies that the penetration event can be seen as a hydrodynamic event in which the jet and the target behave as fluids. When the forces due to strength can be neglected in comparison with those due to inertia, the penetration capability $P$ of the jet in a given armour is $P = L_{\text{jet}} (\rho_{\text{jet}}/\rho_{\text{armour}})^{0.5}$, i.e. the length of the jet influences directly on the penetration capability. The thin and very long jet creates a narrow penetration channel in the thick armour which means that the jet has to be straight. Otherwise, the rear part of the jet will hit the wall of the channel instead of the bottom. In order to achieve such a straight jet, the precision of the warhead has to be high.

Figure 2. Jetting of an SC warhead. Above is the warhead before initiation. Below the liner has collapsed and is being transformed into a stretching jet.

Figure 3 shows a comparison between a small calibre projectile, a long rod projectile and an SC jet. Small calibre projectiles, with relatively low velocity, 800 m/s, (forces due to strength dominate) are designed to withstand the loading at impact and preferably penetrate as rigid bodies. This circumstance and the requirement of low air drag are the reasons for the ogival nose shape of such projectiles. The increased velocity of the long-rod projectiles, around 1800 m/s, makes the forces due to inertia have more influence on the penetration event. This means that the nose of the projectile will be consumed due to the contact forces during the penetration and the projectile must have enough length to be able to perforate the target. The length-to-diameter ratio of long-rod projectiles is often around $L/D=15-30$. The forces due to strength cannot be neglected at this velocity, as in the case
of the penetration of an SC jet. Therefore, long rod projectiles is made of high-strength and high-density materials such as tungsten heavy alloys or depleted uranium (density between 17000 and 18500 kg/m³).

Figure 3. a) Small calibre projectile, velocity about 800 m/s. b) Long rod projectile, velocity about 1800 m/s. c) SC jet, velocity about 10000 m/s at the tip and about 3000 m/s in the rear part of the jet.

The most effective SC jets and LRPs can penetrate about one meter of armour steel. Therefore, it is obvious that modern armoured vehicles cannot rely on homogeneous armour steel. New types of armour intended to destroy the threat before it hits the target enforces further development of the warheads. An LRP is difficult to destroy or disturb as it does not involve any intelligence; once it is fired it is independent of sensors, initiation systems etc. It is also mechanically robust. If sensor initiated protection systems should be used, the high velocity of the projectile results in a demand for sensors with short reaction times. A grenade, on the other hand, may contain vulnerable components in addition to the warhead such as a target seeker, a guidance system, and an ignition system which can be defeated by different kinds of protection systems. For example, the guidance system could be decoyed, the warhead could be initiates at a non optimal distance or it could be destroyed before jet formation.

2.2. Armoured vehicles

A main battle tank is a vehicle with a large calibre gun (calibre 100 to 125 mm) and ballistic armour that makes it possible for the tank to act in the toughest threat scenarios. The MBT main gun can fire KE-projectiles, SC warheads and also anti-personnel fragmentation warheads. Except for the main tank gun, the MBT is equipped with at least one machine gun that can fire small calibre projectiles. The weight of an MBT is about 60-70 tons and it moves on treads which allow mobility in most terrain and allow the MBT to climb over most obstacles. The maximum speed of an MBT is about 65 km/h and the operational range is near 500 km.

Traditionally, the armour consisted of very thick armour steel that served both as construction material and ballistic armour. The first British main
battle tank from WW1 had an armour thickness of the order of 10 mm, while
the thickest homogeneous steel armour introduced in the 1960s was of the
order of 300-400 mm. At that time, the SC weapons became so effective and
commonly used that the thickness and weight of the armour necessary for
protection became unrealistic. New armour concepts had to be introduced,
and the secrecy around these concepts is very high. Weight efficient materi-
als such as fibre composite materials, ceramics, light metal alloys and dual
hardness steel were introduced, and the armour material could be applied as
add-on armour. The most famous armour of this type is called Chobham
armor and was introduces in the 1970s. It proven to be very effective against
SC warheads, and the exact composition is still classified. Additional, geo-
metrical designs such as spaced armour and exterior components (skirts, rods
and chains) were included.

An armour concept that changed the balance completely in the early
1980s was the explosive reactive armour (ERA) that very effectively de-
feated the SC threat. The reactive armour design is very simple; it consists of
a sheet of high explosive (HE) sandwiched between two thin steel plates.
The panels are arranged at a large obliquity on the hull and turret of the
MBT, see Fig. 4. When the SC jet impacts the armour panel, the HE deto-
nates and throws the plates apart. The moving plates act on the jet which
becomes so severely disturbed that its penetration capability can be de-
creased by around 80-90%. The residual penetration capability is easily de-
feated by the thick structure of the MBT.

![Figure 4. Left: The Patton tank M60A1 with the Israeli Blazer ERA, effective
against SC warheads. Right: The T-90S with Russian Kontakt-5 ERA, also effective
against LRPBs.](image)

The early reactive armour panels (Blazer armour) were not effective
against LRPBs. Special types of reactive armour, with thicker plates, more
explosives and special arrangements of more than one panel, were later de-
veloped for the defeat of LRPBs.

Advanced autonomic armour systems, called active protection systems,
are considered for protection on many vehicles. These systems incapacitate
the threat before it reaches the vehicle. The purpose of the protection system can be to decrease the risk of hit (soft-kill) or to decrease the penetration capability of the threat (hard kill). In both cases a sensor system is used to detect the incoming threat, and a processor is used to classify the threat and calculate if, when, and where the threat shall be fought down. The soft-kill systems shall decrease the possibility for the threat to detect, identify and follow the target and in this way decrease the risk for a hit. Such systems are useful against guided missiles, but not against unguided threats such as handheld SC-grenades, or LRPs. For these threats, hard-kill systems have to be used to mechanically destroy the function of the threat. The hard-kill devises make use of either a cluster of fragments, other massive geometries, or focused blast. The active protection system often consists of few modules that can be directed against the incoming threat which results in light-weight armour.

![Figure 5. Example of an active protection system, Iron Fist. The counter measure grenade is fired from the vehicle and detonates near the incoming SC warhead threat.](image)

In addition to the main battle tank, there are many other types of armoured combat vehicles. The trend is that these vehicles are provided with more and more armour protection. Add-on armour capable to defeat anti-tank weapons such as handheld SC weapons and middle calibre projectiles, has become a requirement also for this kind of vehicles. Reactive armour as well as active protection systems can be used also on these vehicles. As they have a thinner structure, the requirements on the add-on armour are stronger. An almost total destruction of the threat is requested. Also, the vehicles shall be used in urban environments which means that the moving armour components may constitute a risk for supporting infantry as well as surrounding civilians. Reactive armour components without HE, so called inert or non-explosive reactive armour (NERA), has therefore been an interesting alternative to the ERA. NERA panels use rubber, reinforced plastic, glass or similar materials as reactive material.
3. Experimental studies

3.1. Long rod projectiles

All experiments in Papers I-III regarding the interaction between LRP and different armour components were performed in a two-stage light-gas gun at FOI Grindsjön. The experiments were performed in small scale using the reverse impact technique. Thus, the armour component, embedded in a sabot, was launched towards a stationary projectile having a preset angle to the velocity vector of the sabot.

![Figure 6. High pressure section, launch tube, impact tank and flash X-ray system of two-stage light-gas gun.](image)

The reverse impact technique allows a case with a moving armour component impacting a high-velocity projectile to be transformed into a case in which one of the objects is stationary. This increases the control of the impact conditions and facilitates the registration of the penetration process. As it is essential to control the projectile yaw, the projectile was chosen to be the stationary object. The transformation between the cases of direct and
reverse impact for a plate moving in its normal direction is illustrated in Fig. 7, where it is shown that the transformation can be used to simulate a plate moving backwards as well as forwards. The motion of the plate is referred to as “backwards” if the component of plate velocity on the axis of the projectile is opposite to the velocity of the projectile (cf. the front plate of a reactive armour panel). Otherwise, the velocity of the plate is referred to as “forwards” (cf. the rear plate of a reactive armour panel). By varying the preset angles of the projectile $\gamma$, the velocity $v_{\text{sabot}}$ of the sabot and the angle $\beta$ of the armour component in the sabot, different cases of direct impact can be simulated.

Figure 7. Transformation from direct to reverse impact for LRP interacting with plates moving (a) backwards and (b) forwards.
The reverse impact parameters \( \gamma \), \( v_{\text{sabot}} \) and \( \beta \) can be obtained in terms of the direct impact parameters \( \alpha \), \( v_{\text{plate}} \) and \( v_{\text{proj}} \), and vice versa, by use of the relations

\[
\gamma = \arctan \left( \frac{v_{\text{plate}} \sin(\alpha)}{v_{\text{proj}} + v_{\text{plate}} \cos(\alpha)} \right)
\]

\[ (1) \]

\[
v_{\text{sabot}} = \frac{v_{\text{proj}} + v_{\text{plate}} \cos(\alpha)}{\cos(\gamma)}
\]

\[ (2) \]

\[ \beta = \alpha - \gamma, \]

where \( v_{\text{plate}} \) and \( v_{\text{proj}} \) are the plate and projectile velocities, and \( \alpha \) is the plate obliquity in the direct impact case. See Fig. 7. The quantities \( v_{\text{plate}} \) and \( \gamma \) are defined as positive for a plate moving backwards and negative for a plate moving forwards. Equations corresponding to Eqs (1) and (2) can be used also when the armour component involves one or more moving rods. Cartesian coordinates were introduced as shown in Fig. 7 so that (i) \( z \) is the direction of the projectile velocity and (ii) all expected motions take place in the horizontal \( zx \) plane.

The designs of the sabot for launching the armour components in the different studies are shown in Fig. 8. In *Papers I-II*, where the effect of stationary and moving oblique plates was studied, the plate constituted an integral part of the sabot. In *Paper III*, where the effect of side-impacting cylindrical rods was studied, the rods were mounted in drilled holes in the sabot, see Fig. 8. In all cases the sabot, including the plate and the rods, was made of steel SS 2541-03 with a surrounding polycarbonate casing to reduce the mechanical wear on the surface of contact with the barrel. A two-piece pusher at the rear end of the sabot was used in the experiments in *Papers I and III*. For the experiments in *Paper II*, the design of the sabot was simplified by excluding the pusher.

![Figure 8. Sabots for launching the armour components used in the different studies.](image)

(a) Moving plate, sabot with pusher (*Paper I*), (b) Moving plate, sabot without pusher (*Paper II*), (c) Moving cylindrical rods (*Paper III*). In the pictures there is a break-out in the sabot for visualisation of the interior components.
The two-stage light-gas gun used for the experiments has a launch-tube diameter of 30 mm which decided the scale of the experiments. The basic case in all studies was a cylindrical tungsten projectile with velocity 2000 m/s interacting with an armour component with the obliquity 60° and a thickness/diameter equal to the diameter of the projectile. In Papers I and III, a projectile diameter of 2 mm was used, while the modified sabot design used in Paper II permitted a larger scale with a the projectile diameter of 3 mm. All dimensions and times of registration were then changed by use of replica scaling [17] to achieve comparable results. In all cases, the material of the projectile was a sintered tungsten alloy Y925 from Kennametal Hertel with 92.5% tungsten by weight, density 17700 kg/m³, and yield stress 1300 MPa.

Figure 9 shows the set-up for the reverse impact experiments. The projectile was mounted in a foam fixture in front of the barrel of the gun. In order to achieve the stipulated angle \( \gamma \) between the axes of the stationary projectile and the barrel, a laser beam, co-linear with the barrel, was used to align the projectile. First, the projectile was aligned and then it was turned the angle \( \gamma \) in the horizontal plane by means of a positioning instrument. The adjustment procedure gave an angular deviation estimated to less than 0.05°. The sabot was turned in the barrel so that the plates or the rods were contained in a vertical plane. Therefore, any motion in the vertical direction would indicate imperfect conditions.

A total of eight (Papers I and II) or nine (Paper III) X-ray flashes were used as shown in Fig. 9. Usually six flashes were used, two by two, for registration of the residual projectile system (RPS), i.e., what remains of the projectile after the interaction with the armour component, three for registration in the horizontal plane (where ideally all motion should take place) and three for registration in the vertical plane. In some cases only two flashes in each plane were used. The RPS was registered at three instants of time after initial contact between the armour component and the projectile. In addition, a pre-launch exposure of the projectile was used as a reference. This means that each test resulted in two X-ray pictures of the RPS, one in the horizontal and one in the vertical plane, each consisting of three to four shadowgraphs of the RPS (two or three instants of time after initial contact and one pre-launch exposure). The additional two flashes were used for registration of the sabot in the horizontal plane in order to measure the velocity \( v_{sabot} \) of the sabot and make sure that there was no substantial angle of rotation \( \phi \) of the sabot around its axis. Finally, in Paper II, one flash was used for registration of the penetration channel in the plate after the interaction with the projectile.
An evaluation code was developed and used to quantify the geometry, inertial properties and motion of the RPS and its constituents from the X-ray pictures and to produce pictures adjusted with regard to the positions of the X-ray flashes. The projectile was in some cases broken into a number of pieces, residual projectile constituents (RPCs), and each shadowgraph of an RPC was manually identified and matched to the correct time registration and the corresponding shadowgraph in the other projection. The geometry was extracted into digital form by manual contour determination of each RPC (two length-wise and two end curves). After that digital 3D bodies were created from the projections in the two orthogonal planes and the positions of the X-ray tubes. Figure 10 shows an example of the difference between the original X-ray-pictures and the evaluated picture. The X-ray pictures show the yawed reference projectile and the RPS as it was projected on the film. In the evaluated pictures, the corrections for the non-coinciding positions of the X-ray flashes and the rotation of the system to the direct impact case imply that the pictures show the deformation, rotation and translation caused by the interaction with the armour component.
Figure 10. Example showing the difference between the original X-ray pictures and the 3D-visualization created.

From the digitalized geometries, the mass, the moment of inertia and the position of the individual RPCs for each time registration were evaluated. These data were used to quantify the properties and motion of the RPS relative to those of the projectile immediately before impact. A detailed description of the procedure used is given in Paper I.

The consumption of the projectile during the perforation of the plate was quantified by the change in length, referred to the total length of the RPCs. Also, the maximum length of a RPC relative to the original projectile length was evaluated. The motion of the RPS was determined on the basis of the motions of all RPCs. The quantities evaluated were (i) the change in velocity, referred to the centre of gravity of the RPS; (ii) the change in linear momentum; (iii) the change in angular momentum; and finally (iv) the change in the translational and rotational parts of the kinetic energy. The changes in the angular momentum and in the rotational part of the kinetic energy are quantitative measures of the rotation transferred to the projectile by the plate. The angular momentum represents the rotation of the entire RPS with respect to its centre of gravity, while the rotational part of the kinetic energy is due to the rotations of the individual projectile parts around their own centres of gravity.

With the additional X-ray flash used in Paper II, the penetration channel in the plate after the interaction with the projectile was registered for evaluation of the difference in contact between the projectile and the plate in the cases of backwards and forwards moving plates and a stationary plate. Also inspection of the surface of the projectile after the interaction was used to assess if the contact was continuous or intermittent. In Paper III, the duration of the interaction between each rod and the projectile was measured by inspection of the projectile surface.

The cases studied with the experimental method described were:

- Tungsten LRP with length-to-diameter ratio $L/D = 30$ and velocity 2000 m/s, interacting with a steel plate with the obliquity 60 degrees, velocity 200, 0 and -200 m/s, and thickness to projectile ratio $t/D = 0.5$, 1 and 2.
- Tungsten LRP with length-to-diameter ratio $L/D = 30$ and velocity 2000 m/s, interacting with a steel plate with a thickness equal to the diameter of the projectile, velocity 200, 0 and -200 m/s, and obliquity 30, 60 and 70 degrees.

- Tungsten LRP with length-to-diameter ratio $L/D = 15$ and 30 and velocity 2000 m/s, interacting with a steel plate with a thickness equal to the diameter of the projectile, obliquity 60 degrees, and velocity 300, 200, 100, 0, -100, -200 and -300 m/s.

- Tungsten LRP with length-to-diameter ratio $L/D = 15$, 30 and 45 and velocity 2000 m/s, interacting with a steel plate with a thickness equal to the diameter of the projectile, obliquity 60 degrees, and velocity 200, 0 and -200 m/s.

- Tungsten LRP with length-to-diameter ratio $L/D = 30$ and velocity 1500, 2000 and 2500 m/s, interacting with a steel plate with a thickness equal to the diameter of the projectile, obliquity 60 degrees, and velocity 200, 0 and -200 m/s.

- Tungsten LRP with length-to-diameter ratio $L/D = 30$ and velocity 2000 m/s, interacting with one cylindrical rod with rod diameter equal to the diameter of the projectile, impacting perpendicular to the projectile with obliquity 60 degrees, velocity 200 and 600 m/s, and hitting point in the front and in the middle of the LRP.

- Tungsten LRP with length-to-diameter ratio $L/D = 30$ and velocity 2000 m/s, interacting with three cylindrical rods with rod diameter equal to the diameter of the projectile, impacting the projectile with obliquity 60 degrees, velocity 200 and 600 m/s, and hitting points distributed along the projectile. Two different hitting point patterns were studied, see Fig. 11.

![Figure 11](image)

Figure 11. Hitting points along the projectile as a result of the relation between the rod distances, the rod velocity and the projectile velocity. (a) Rod velocity 200 m/s. (b) Rod velocity 600 m/s, same rod distances as in (a). (c) Rod velocity 600 m/s, same hitting points as in (a).
3.2. Shaped charge jets

The experiments in which the interaction between a shaped charge jet and a reactive armour panel were registered were performed outdoors at FOI Grindsjön as static vertical firings.

An 84 mm point-initiated SC warhead with a copper liner, producing a jet with tip velocity 7300 m/s, was used. The warhead was positioned in a shock wave deflector on the top of a steel plate 1.5 m above a pile of armour steel plates. A reactive armour panel was arranged below the top plate at an impact angle of 60°. The distance between the cone base in the warhead and the hit point on the panel was 280 mm. A plumb line was used in order to hit the stipulated point at the centre of the panel. The front and rear plates were marked with different patterns for after-test identification, see Fig 12.

![Figure 12. A reactive armour panel positioned below the top plate in the vertical test set-up. The plates were marked for after-test identification. A trig foil was glued on the impact surface. A plumb line was used to hit the stipulated point.](image)

The experimental set-up is shown in Fig. 13. A 450 kV X-ray flash was used for registration of the interaction between the jet and the reactive panel. To achieve a time sequence of registrations, two or three different experiments were performed with the same set-up but with exposures at different times. Multiple exposures in the same test were avoided as the different registrations would have overlapped. Two additional 150 kV X-ray flashes were used for registration of the residual jet at two instants of time after the interaction. The trig pulse to the X-ray flashes came from a trig foil glued to the impact side of the panel.

Both explosive and inert reactive armour were investigated. The panels consisted of two plates, 300×150×3 mm³, with an intermediate layer of reactive material. The material in the plates was steel Domex Protect 300. In the case of explosive reactive armour, a layer of 3 mm Swedish PETN-based
plastic explosive m/46 (performance similar to C4) was used, while in the case of inert reactive armour a layer of 5 mm rubber was used as reactive material.

Experiments with single moving plates were performed to assess if the perturbations on the jet results from interplay between the two plates in the panel or if they originate from the interaction between one of the plates and the jet. The same experimental set-up and type of plates, as in the symmetric panels, were used and the plates were accelerated with a layer of high explosive in front or behind of them. In these cases, the thickness of the high explosive was 7 mm in order to achieve a plate velocity comparable to those achieved in the earlier used explosive reactive armour panels (3 mm HE sandwiched between two steel plates with thickness 3 mm).

In order to assess if the materials had been melted in the contact surface between the jet and the plate, the edge of the penetration channel in one of the plates was inspected with an optical microscope. A 10×15 mm² piece, was sawed off the plate, cast in Bakelite, ground to reach the middle of the plate, and polished on the surface. The sample was then etched, washed with ethanol, and dried with a hair-drier to avoid rusting.

Figure 13. Experimental set up for study of interaction between SC jet and reactor armour module.
4. Simulation studies

The possibility of using analytical models for analysis of the complex impact and penetration events of a KE projectile or an SC jet interacting with moving armour components is very limited. Instead numerical simulation codes are used. The codes used have to be capable of handling transient wave propagation problems with large strains, high strain rates and non-linear material responses. Two different pieces of commercially available solid mechanics computational software, AUTODYN and LS-DYNA, have been used in Papers III-V. The basis for these codes are equations expressing the conservation of mass, momentum and energy, expressed in discrete form on a spatial grid that may be either fixed in space (Euler) or moving with the deforming material (Lagrange). Explicit time integration is used, which means that the time step has to be small.

In Paper III, where the interaction between perpendicular rods impacting the side of an LRP was studied, the simulations were performed using AUTODYN and Lagrange formulation. Mie-Grüneisen’s equation of state [18] and von Mises’s yield criterion with associated flow role were used for the rods and the LRP. The yield stress was taken as

$$\sigma_y(\varepsilon, \dot{\varepsilon}, T) = \left( A + B\dot{\varepsilon}^n \right) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right]$$

according to the JC strength model [13]. Here $\varepsilon$ is the equivalent plastic strain, $\dot{\varepsilon}$ is the equivalent plastic strain rate, $T$ is the temperature, $\dot{\varepsilon}_0$ is a reference strain rate, $T_m$ is the melting temperature, $T_r$ is a reference temperature, and $A$, $B$, $C$, $n$ and $m$ are material parameters which were determined from material tests [19, 20].

Fractures in the LRP were postulated to occur when the damage parameter $D_f = \Sigma \Delta \varepsilon / \varepsilon_f$ attains the value one. Here $\Delta \varepsilon = \sqrt[2/3]{\Delta \varepsilon_{ij} \Delta \varepsilon_{ij}}$ is the incremental equivalent plastic strain and $\varepsilon_f$ is the equivalent plastic strain at fracture. When $D_f = 1$, the yield stress is set to zero so that the material can withstand only hydrostatic pressure. The equivalent plastic strain at fracture was defined by the JC fracture model [14]

$$\varepsilon_{fJ}^{JC}(\eta, \dot{\varepsilon}, T) = \left( D_1 + D_2 \dot{\varepsilon}^{Dy} \right) \left[ 1 + D_4 \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 + D_5 \frac{T - T_f}{(T_m - T_r)} \right].$$
In this model the equivalent plastic strain at fracture depends on the stress triaxiality parameter $\eta = \sigma_{\text{mean}} / \sigma_{\text{eff}}$, where $\sigma_{\text{mean}}$ is the mean stress and $\sigma_{\text{eff}}$ is the effective stress.

The fracture model involves the material parameters $D_1 - D_5$. Earlier experiments with moving plates and a simplified simulation model were used to determine appropriate parameter values. Simulations of the interaction between moving plates and projectiles had shown that the force component transverse to the projectile during the sliding contact along the projectile was relatively constant. Therefore, a simplified simulation model where a constant force moves along the side of the projectile was used for the determination of the material parameters, see Fig. 14. Thus, the interaction between the projectile and plate during the perforation of the plate was not taken into consideration. To reduce the number of free parameters, all parameters except $D_2$ and $D_3$ were set to zero. These two parameters were determined by iterative comparisons between the simulations and the experiments.

Figure 14. Simplified simulation model. The steel cap (blue) is subjected to a constant pressure on its external face and sliding along the projectile (green).

No fracture model (except for numerical erosion) was used for the rods.

The models described were used for studies of the effect of one or three cylindrical rods impacting the LRP. The geometrical configurations, the material and the velocities used in the simulations correspond to those used in the experimental study in Paper III.

In Paper IV, where the interaction between a moving oblique plate and an LRP was studied, the different conditions at the initial perforation of the plate and at the subsequent sliding of the plate along the projectile, had to be taken into consideration. The initial perforation of the plate results in bending and consumption of the nose of the projectile while any fractures that may possibly occur during the subsequent sliding of the plate along the side of the projectile are presumably due to shear loading. A fracture model capable of distinguishing the two different loading conditions is the Xue-Wierzbicki (XW) model [15]

$$\varepsilon^{XW}_t(\eta, \xi) = C_1 e^{-C_2 \eta} - \left(C_1 e^{-C_2 \eta} - C_3 e^{-C_4 \eta}\right)\left(1 - \xi^{1/p}\right)^p.$$  

(6)
This fracture model is based on an equivalent plastic strain of fracture which depends on the stress triaxiality parameter $\eta$ and also on the deviatoric stress parameter 

$$\zeta = \frac{27}{2} \frac{(\sigma_1 - \sigma_{\text{mean}})(\sigma_2 - \sigma_{\text{mean}})(\sigma_3 - \sigma_{\text{mean}})}{\sigma_{\text{eff}}^3}. \quad (7)$$

where $\sigma_1$, $\sigma_2$ and $\sigma_3$ are the principal stresses. The model involves the material parameters $C_1$-$C_4$, and $p$, where $p$ is a hardening exponent such that $1/p$ is an even integer [15].

Assuming $\sigma_1 \leq \sigma_2 \leq \sigma_3$, one can show that $0 \leq |\zeta| \leq 1$, $\zeta=0$ if $\sigma_2 = (\sigma_1 + \sigma_3)/2$, $\zeta=1$ if $\sigma_1 = \sigma_2$, and $\zeta=-1$ if $\sigma_2 = \sigma_3$. Thus, with disregard of a superimposed hydrostatic state of stress $\sigma_1 = \sigma_2 = \sigma_3 = \sigma$, the values $\zeta=0$, 1 and -1 correspond to pure shear, uniaxial tension and uniaxial compression, respectively. The use of this parameter in the fracture model was assumed to allow accurate description of both the initial consumption of the projectile nose and the subsequent fractures along the projectile.

The XW fracture model is not incorporated in the most commonly used hydrocodes for penetration mechanics simulations. For this study, the model was implemented in LS-DYNA version 971 [18] and used for the projectile together with the JC strength model. The material parameters in the model were determined from material tests. For the plates, the JC strength and fracture models were used with material parameters determined from material tests.

Earlier experiences with sliding contact between eroding Lagrangian entities have shown that artificial interlocking can create large spurious contact forces. In order to avoid such numerical interlocking at the sliding contact, a Lagrange formulation was used for the projectile, while a multi-material Eulerian formulation was used for the plate (steel and vacuum).

The models described were used for simulations of two pairs of cases from the experimental study in Paper II. Each pair illustrates a transition from a loading condition that results in a deformed essentially non-fractured projectile to a loading condition that leads to a severely fractured projectile. In the first pair of cases, a plate with thickness to projectile diameter ratio $t/D=2$ and obliquity 60° was considered. In one case the plate moved backwards (velocity 200 m/s), and in the other case it moved forwards (velocity -200 m/s). In the second pair of cases, a plate with thickness to projectile diameter ratio $t/D=1$, obliquity 60° and forward flight direction was considered. The plate velocities were -200 and -300 m/s, respectively. The geometrical configurations, the material and the velocities used in the simulations correspond to those used in the experimental study.

The numerical simulations of the interaction between a shaped charge jet and reactive armour panels were performed using LS-DYNA v. 971. As for the interaction between an LRP and reactive armour panels, the interaction process can be divided into two different phases. In the first, the impact of
the tip of the jet results in perforation of and energy transfer to the plates. In the second, the interaction between the jet and the penetration channel in the moving plate results in severe disturbances on the jet.

The initial simulations included the entire SC jet and the reactive module. They were used to study the first phase in the interaction. Both explosive and inert reactive armours were considered. In these simulations, multimaterial Eulerian formulations were used for all parts. The cases studied corresponded to the experiments presented previously. The strength models used were: the JC strength model with material parameters for 4340 steel [13] for the plates, and “elastic-plastic hydro” with material parameters taken from [21] for the rubber material in the inert reactive panels. The HE in the explosive reactive armour panels was described by a beta burn model and a JWL equation of state [18]. The initial geometry and the velocity distribution of the stretching jet were obtained from an experimental characterization of the used warhead. As little is known about the real material properties of a shaped charge jet, the use of an advanced material model for the jet was considered to be of little value. Instead, an ideal elastic-plastic material model with the constant yield stress 270 MPa was used, corresponding to a deformation-hardened copper jet as given by numerical simulations of the liner collapse. The Mie–Grüneisen equation of state was used for the rubber, jet and plate materials.

To study the details in the interaction and the possibility to resolve the disturbances of the jet in the second phase, a simplified but highly refined model of the geometry (960,000 elements with the element size of 0.125 mm in the plate and 0.25 mm in the jet) was used in the numerical simulations, see Fig. 15. The model consists of the part of the stretching copper jet interacting with the edge of the moving steel plate. The experimental characterization of the used warhead, combined with the initial numerical simulations of the total event, gave the location and properties of the jet involved in the transverse interaction with the moving plate. When the transverse interaction starts the jet velocity at the interaction point is approximately 6.2 km/s, the radius of the jet is approximately 1.4 mm, and the strain rate is 25000 s⁻¹. The small portion of the steel plate included in the model is approximated as an initially flat plate with uniform thickness and velocity. The initial plate velocity was 200 m/s perpendicularly to the jet, approximately corresponding to the result from the initial full simulations. To eliminate the effect of different plate velocities in the jet direction for the backwards and the forwards moving plate, both plates were assumed to travel only in the direction perpendicular to the jet but at different plate angles, see Fig. 15. The impact angle was adjusted from 60 to 55 degrees to account for the bending of the plate during the plate acceleration. The change in interaction angle during the event was not considered in the simulations. The contact between the materials was modelled as frictionless.
As in the study of an LRP sliding along the penetration channel of a plate, a coupled Euler–Lagrange setting was used and the jet was modelled as a Lagrangian entity while the steel plate was modelled as an Eulerian entity. As the plate is subjected to large deformations, an Eulerian approach was used for the plate to avoid numerical erosion and achieve a smooth contact surface. As the jet deforms much less and moves and stretches at high rates, a Lagrangian approach was appropriate for the jet. For the copper jet, the numerical erosion strain (set to 2) was used as damage model while no damage model was used for the plate.

Frictional forces were included in the simulations by using the Coulomb friction option in the Euler–Lagrange coupling in LS-DYNA, i.e.  \( F_{\text{fric}} = \mu F_n \) where \( \mu \) is the coefficient of friction and \( F_n \) is the normal force.

The simplified model was used for studies of how different interaction and material parameters influence the development of instabilities of the interface between the jet and the armour plate. The influence of the material strength of the jet was studied by three cases denoted virgin, normal, and high jet strength. Virgin means strength corresponding to undeformed copper (90 MPa), normal means strength corresponding to a deformation hardened copper jet as given by numerical simulations of the liner collapse (270 MPa), while high strength was arbitrarily chosen as ten times higher than normal. The influence of the plate strength was studied by two simulations where the yield stress of the steel was decreased and increased by a factor of ten. To study the effect of friction, simulations were performed both with friction between the jet and the plate and with frictionless contact. The coefficient of friction was chosen as 0.5, which is close to the value at low velocity interaction between copper and steel.

Both in the case of an LRP interacting with moving oblique plates and in that of an SC jet interacting with the edge of a moving plate (the simplified model) mesh resolution tests were performed. In the LRP case the element size in the projectile was reduced from 0.30 to 0.10 mm. In the SC jet case three different mesh sizes were used with element sizes in the jet 0.5, 0.25 and 0.125 mm.
5. Results and discussion

5.1. Long rod projectile vs moving armour components

5.1.1. Influence of plate or rod velocity

The main difference in the effect on the projectile of a moving plate and a stationary plate is that the moving plate acts both on the nose and the side of the projectile while stationary oblique plates act mainly on the nose. The X-ray pictures in Fig. 16 show the penetration channels in plates that have been moving backwards or forwards, and the penetration channel in a stationary plate. A main initial hole, with approximate diameter 1.5D, has been created by the penetrating projectile in each case. For the cases of moving plates, additional slots with approximate width D have been created by the sliding projectiles. Examination of the surface of the residual projectiles shows that the sliding interaction between the projectiles and the moving plates is continuous rather than intermittent.

Figure 16. X-ray pictures of the penetration channels in plates that have been moving backwards (left) or forwards (right), and the penetration channel in a stationary plate (centre).

Figure 17 shows experimental results from Papers I and II, regarding the effect of a 60 degrees oblique plate on a projectile with velocity 2000 m/s. The effect of plate velocity at different length-to-diameter ratio of the projectile is shown in the figure. It can be seen that moving plates transfer a transverse velocity and a rotation to the projectile and that such transfer does not occur when the plate is stationary. This difference can be explained by the sliding interaction of the moving plates along the projectile.
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<tr>
<th>L/D = 15</th>
<th>L/D = 30</th>
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Figure 17. Residual projectile system before and 150, 225 and 300 µs after start of interaction with an oblique plate. Influence of plate velocities (positive backwards and negative forwards) and length to diameter ratio L /D of the projectile. The results for L /D =15 obtained by use of replica scaling. The side of the squares is 10 mm.
For backwards moving plates (positive plate velocities), the interaction resulted in rotated, almost intact projectiles slightly bent at their noses. The effect of the interaction does not increase with increasing velocity. In contrast, especially for the L/D=30 projectiles, the effect decreases with increasing plate velocity. For forwards moving plates (negative plate velocities), the interaction with the plate resulted in increased fragmentation with increasingly negative plate velocities.

The evaluation showed that the length of the projectiles is only slightly reduced by the interaction with the plate and that the decrease in total length is slightly increasing with plate velocity decreasing from 300 m/s to -300 m/s. The reduction of projectile velocity in the launch direction is also very small. The changes in projectile velocity in the launch direction as well as in the transverse direction are larger in the case of forwards moving plates than for backwards moving plates. Also, the changes in angular momentum and in the rotational part of the kinetic energy are larger in the case of forwards moving plates than for backwards moving plates.

One explanation to the trend of increasing effect with velocity decreasing from 300 m/s to -300 m/s could be the difference in sliding velocity between the plate and the projectile

\[ v_{\text{slide}} = v_{\text{proj}} + v_{\text{plate}} / \cos \alpha \]  

which results in longer time of interaction between the plate and the projectile in the case of forwards moving plates.

The reasons for the increased effect from forwards to backwards moving plates were further discussed in Paper IV on the basis of the numerical simulations performed. Sequences of damage plots for the projectile during its penetration of a backwards and a forwards moving plate, respectively, are shown in Fig. 18. The sequences illustrate the difference in contact geometry between the two cases. As seen in the X-ray pictures in Fig. 16, the nose of the projectile creates a penetration channel with greater diameter than that of the projectile in the plate. Due to the oblique orientation of the plate, the entrance part of the penetration channel expands more on the upper than on the lower side of the projectile. The reason for this lack of symmetry is that the projectile is supported by more material on its lower than on its upper side at the entrance. In the case of a backwards moving plate, the plate pushes the projectile upwards which immediately results in a sliding contact on the lower part of the penetration channel. In the case of a forwards moving plate, the plate approaches the projectile downwards. Because of the asymmetry of the penetration channel, the establishment of contact between the projectile and the plate along the upper part of the penetration channel is delayed. With the plate and projectile velocities used, the contact is not established until the nose of the projectile has reached the rear side of the plate.
Figure 18. Sequences of damage plots for the projectile during its penetration of the plate in the case of a backwards and a forwards moving plate. The contour plots indicate the level of damage. Blue to red corresponds to $D_t = 0$ to 1.

When the projectile perforates the oblique plate, the exit part of the penetration channel expands more at its lower side where there is less supporting material than at its upper side. As the lower side in the case of a backwards moving plate is the main contact surface, the sliding contact between the
projectile and the penetration channel is released before the exit. In the case of a forwards moving plate, there is no contact between the projectile and the lower side of the penetration channel during perforation. Yet, successive high-damage regions arise on the lower side of the projectile at the exit of the plate. Subsequently this leads to the initiation of fractures.

Clearly, there is a difference in load on the projectile already in the perforation phase when backwards and forwards moving plates are used. The difference between the two cases in the load on the projectile when the plate slides along its envelope can be seen in Fig. 19, where the lateral stress $\sigma_{xx}$ on the upper and lower side of the mid-section of the projectile versus time has been evaluated from simulations.

![Image of projectile and stress graphs]

Figure 19. Lateral stress $\sigma_{xx}$ versus time $t$ from impact at the upper and lower side of the mid-section of the projectile during the sliding perforation of a backwards and forwards moving plate. The contour plots indicate the level of stress in the symmetry plane. Blue to red corresponds approximately to $\sigma_{xx} = 0$ to 3.5 GPa.

The figure shows that in the case of a backwards moving plate the magnitude of the stress abruptly increases to a maximum at the arrival of the plate. Then, it decreases to approximately half its value, till it abruptly drops to zero when the plate leaves. In the case of a forwards moving plate there are
also corresponding abrupt changes in the magnitude of the stress. However, the magnitude of the stress increases, doubles, and is maximal when the plate leaves the mid-section of the projectile. At certain sections this gives rise to high-damage regions in the projectile where subsequently fractures occur. The figure also shows the longer duration of contact in the case of a forwards moving plate than in the case of a backwards moving plate.

Figure 20 shows the evaluated pictures from the experiments with a single side-impacting rod and an $L/D=30$ projectile with 60 degrees obliquity (*Paper III*). Rod diameter to projectile diameter ratio $d/D=1$, projectile velocity 2000 m/s, rod velocities 200 and 600 m/s and hitting points in the front and in the middle of the projectile were used. It can be seen that the rods transfer bending and rotation to the projectile and that the higher velocity is required to achieve fracture of the projectile.

The rod velocity 200 m/s resulted in a rotation of the projectile, giving approximately the same amount of yaw irrespective of the hitting point. A comparison with the results from the moving plate experiments shows that the impact from the rod resulted in approximately the same effect (some yaw but no fracture) as that of a steel plate with the same thickness (one projectile diameter), velocity and angle of obliquity.

The rod velocity 600 m/s resulted in a fracture in the projectile. The fracture surface is roughly perpendicular to the axis of the projectile and situated at a distance of 1.5 - 2 projectile diameters behind the (initial) hitting point.

![Figure 20](image.png)

The contact surface on the LRP from the interaction with the rod were investigated by inspection after the interaction, see Fig. 21. (The bending of the projectile in the plane perpendicular to the impact is probably a result of hitting the wall of the tank system where the experiments were performed.) The position and length of the contact surfaces and the position of the frac-
tures with respect to the hitting point were evaluated. Unfortunately, the projectile from the case of a 200 m/s rod hitting the front of the projectile could not be retrieved and thus could not be evaluated with respect to the contact surface. It can be seen that there has been an uninterrupted contact between the rod and the projectile over a distance of 15-17 mm.

<table>
<thead>
<tr>
<th>Hitting point in the front of the projectile</th>
<th>Hitting point in the middle of the projectile</th>
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<tr>
<td>$v_{\text{rod}} = 200$ m/s</td>
<td><img src="image1.png" alt="Diagram 1" /></td>
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<tr>
<td>$v_{\text{rod}} = 600$ m/s</td>
<td><img src="image2.png" alt="Diagram 2" /></td>
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</table>

Figure 21. Contact surfaces on the projectile resulting from the interaction with the rods. The measurements indicate the position and length of the interaction and the position of fracture in the cases where the projectile was broken.

Figure 22 shows the results from simulation of a single rod impacting the projectile at 600 m/s at the front of the projectile. The left picture indicates that the rod slides along the projectile, while heavily deforming. The conclusion from this plot together with the finite length of the contact surface in Fig. 23 is that the rod is consumed during the interaction. The position of the fracture in the simulation approximately coincides with the position achieved in the experiment (2.6 mm from the hitting point to be compared with 3 mm in the experiment). In the case of 200 m/s, the simulation indicated that no fracture of the projectile took place in accordance with the experimental result.

Figure 22. Simulation of one rod hitting the projectile at 600 m/s in the front of the projectile. To the left: material properties at 4.5 μs after hit. To the right: the frontal part of the projectile indicating the position of fracture.
5.1.2. Influence of plate thickness

Figure 23 shows experimental results from Paper II, in the form of the evaluated pictures of the RPS, for plates with thickness to projectile diameter ratios \( t/D = 0.5, 1 \) and 2, obliquity \( \alpha = 60 \) degrees, and velocities \( v_{\text{plate}} = 200, 0, \) and \(-200 \) m/s interacting with projectiles with \( L/D = 30 \) and velocity 2000 m/s. It can be seen that the effect of the plate on the projectile increases substantially with increasing plate thickness, especially in the interval \( 1 < t/D < 2 \). This effect concerns rotation and translation as well as bending, length reduction and fragmentation of the projectile. All evaluated quantities confirm the significant influence of the plate thickness.

![Figure 23. Residual projectile system before and 150, 225 and 300 \( \mu \)s after start of interaction with an oblique plate. Influence of plate thickness to projectile diameter ratio \( t/D \) at different plate velocities (positive backwards and negative forwards). The side of the squares is 10 mm.](image-url)
5.1.3. Influence of increased number of rods

Figures 24 and 25 shows the results from the experiments with three side-impacting rods impacting an $L/D=30$ projectile with 60 degrees obliquity (Paper III). The rod diameter to projectile diameter ratios $d/D=1$, projectile velocity 2000 m/s, and rod velocities 200 and 600 m/s were used. The hitting points for the rods were distributed along the projectile. In the 600 m/s rod velocity case, two different hitting point patterns were studied: one where the rods had the same distance between each other as in the 200 m/s case, and one where the hitting points on the projectile agreed with the 200 m/s case, see Fig. 11.

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<th>$v_{rod} = 600$ m/s</th>
<th>$v_{proj}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>i3 i2 i1</td>
<td>$v_{proj}$</td>
</tr>
<tr>
<td>Ref 100 µs 150 µs 200 µs</td>
<td></td>
</tr>
</tbody>
</table>

Figure 24. Residual projectile system before and 100, 150 and 200 µs after interaction with three perpendicular rods hitting the side of the projectile with 60 degrees obliquity. Influence of rod velocities and hitting point.

<table>
<thead>
<tr>
<th>$v_{rod} = 200$ m/s</th>
<th>$v_{proj}$</th>
</tr>
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<tbody>
<tr>
<td>23 17 12 37</td>
<td>$v_{proj}$</td>
</tr>
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<table>
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<tr>
<th>$v_{rod} = 600$ m/s</th>
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<tr>
<td>17 17 16 41 21</td>
</tr>
<tr>
<td>18 15 24</td>
</tr>
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</table>

Figure 25. Contact surfaces on the projectile resulting from the interaction with three rods. The measurements indicate the position and length of the interaction and the position of fracture in the cases where the projectile was broken.
In the cases of 200 m/s rod velocity, the interaction resulted in a rotation of the projectile, giving approximately the same amount of yaw irrespective of the increased number of rods. However, the additional rod impacts resulted in an increased transverse velocity of the projectile.

Although one rod impacting the LRP with a rod velocity of 600 m/s resulted in fracture of the projectile near the hit point, the experiments with three rods impacting the projectile did not result in fractures except in one case. Inspection after impact of the surfaces of the projectiles indicates that the rods did impact the projectile as intended. In the case of hitting points distributed along the entire length of projectile, the impact by each subsequent rods starts behind the contact surface of the preceding rod. When closely spaced rods were used the contact surfaces overlapped.

Simulations were performed in an attempt to understand the reasons for the decreased effect from three rods compared to the effect of a single rod hitting the projectile. Figure 26 shows results from simulation of the case of three rods impacting the projectile at 600 m/s with hit points distributed along the entire length of the projectile. The simulation indicates fractures from all the rod impacts, although the experiment did not result in any fracture at all. In the simulations, the LRP was not translated or rotated before the impact of the succeeding rods and the rods did not interfere with each other.

Figure 26. Simulation of three rods hitting the projectile at 600 m/s with hit points-distributed along the entire length of the projectile.
Inspection of the rod motions after impact, in the X-ray picture of the sabot after the interaction, indicate that the attachment of the rods to the sabot probably differed between the rods, see Fig. 27. Some of the rods had been released due to the interaction (or firing of the sabot). This could eventually be an explanation to the lack of fractures in the case of three high velocity rods. However, the contact surfaces on the projectile contradict this attempt to explanation as the hitting patterns are as intended.

![Hitting points distributed along the entire length of projectile, rod velocity 200 m/s.](image1)
![Hitting points distributed along the entire length of projectile, rod velocity 600 m/s.](image2)
![Hitting points distributed along part of the length of projectile, rod velocity 600 m/s.](image3)

Figure 27. X-ray pictures of the sabots with three rods after impacting with the LRP.

5.1.4. Influence of plate obliquity

Figure 28 shows experimental results from Paper I, in the form of evaluated pictures of the RPS for plates with obliquity $\alpha = 30, 60$ and 70 degrees, thickness to projectile diameter ratios $t/D=1$, and velocities $v_{\text{plate}}= 200, 0$, and -200 m/s interacting with projectiles with $L/D=15$ and velocity 2000 m/s. For obliquity 70 degrees, the plate velocities 0 and -200 m/s are missing as those cases required very long and slender sabots that resulted in unsuccessful tests, including the collapse of a sabot.

In all cases with obliquity 30°, the residual projectiles were unbroken while fragmentation of the projectile occurred at obliquity 60 and 70°. It appears that the fragmentation increased with plate obliquity and that the rotation of the main part of the residual projectile increased when the obliquity decreased.

The evaluation of the RPS showed that the decrease in length of the projectile more than doubled for the largest obliquity compared to the smallest. For moving plates, the velocity in the transverse direction increased in a similar way (doubled; stationary plates do not cause any transverse velocity or rotation). In the case of obliquity 30°, the reductions in length, linear momentum, velocity in launch direction and kinetic energy were independent of plate velocity. Also, in this case, the change in velocity in the transverse direction and the rotation were independent of the direction of plate velocity. For obliquity 60°, all these quantities tended to increase for forwards moving plates. The highest effects were obtained with obliquity 70°.
5.1.5. Influence of projectile geometry and velocity

The influence of projectile length to diameter ratio can be seen in Fig. 19, were the evaluated pictures of the RPS for projectiles with $L/D = 15, 30$ and $45$ and velocity $2000 \text{ m/s}$ interacting with plates with obliquity $\alpha = 60$ degrees, thickness to projectile diameter ratios $t/D=1$ and velocities $v_{\text{plate}} = 300, 200, 100, 0, -100, -200$ and $-300 \text{ m/s}$. The shorter projectiles showed larger rotation than the longer ones for all plate velocities. This can be explained by the larger moment of inertia of the longer projectiles. The shorter projectiles also fragmented at lower negative plate velocities than the longer ones.

The influence of projectile velocity is shown in Fig. 29 were experimental results from Paper II, in the form of the evaluated pictures of the RPS for projectiles with velocities $v_{\text{proj}} = 1500, 2000$ and $2500 \text{ m/s}$ and $L/D = 30$ interacting with plates with obliquity $\alpha = 60^\circ$, thickness to projectile diameter ratios $t/D = 1$ and velocities $v_{\text{plate}} = 200, 0$ and $-200 \text{ m/s}$ can be seen.
For plates that are stationary or moving backwards, the influence of projectile velocity is relatively small. For plates moving away from the projectile, however, the fragmentation of the projectile shows a strong dependence on the projectile velocity. At the lowest and highest projectile velocities, the projectile breaks up into many parts, while at intermediate velocity (2000 m/s) the projectile is almost intact. The longer interaction time in the low-velocity case and the higher load in the high-velocity case may possibly explain this observation.
5.2. Shaped charge jet vs moving armour plates

5.2.1. Reactive armour panels

The results from the registrations of an SC jet interacting with a reactive armour panel can be seen in Fig. 30. Explosive, as well as inert, reactive armour panels were studied.

![Fig. 30. Shaped charge jet penetrating reactive armour panels: (a) explosive reactive armour and (b) inert reactive armour. The appearance of the jet 110 µs after impact is shown in (c) for explosive reactive armour and in (d) for inert reactive armour.](image)

It can be seen that the plates in the reactive armour panels have started to move in a direction perpendicular to their normal. In the case of inert reactive armour, the reaction in the panel was slower and less widespread than for the explosive reactive armour. The interaction between the SC jet and the panels results in bulges on the jet that continue to grow and result in a severe scattering of the jet. In the case of inert reactive armour, the slower reaction in the panel means that the first bulge appears further back on the jet and the lower plate velocity results in less bulging. However, it is clearly seen in both cases that there are some kind of repeated perturbations initiated on the jet.

Figure 31 shows a time sequence of registrations of the SC jet interacting with an inert reactive panel. The sequence is based on three different experiments with the same set-up but at different exposure times as multiple exposures result in an overlap of the pictures. In the first exposure, no disturbance can be seen at the jet and this part of the jet is still unaffected in the
following pictures. The development of disturbances can be seen in the two later exposures. The general appearance of the jet disturbances in the two experiments is similar but differs in details, e.g., the distances between and the magnitude of the bulges. This indicates that there is some degree of randomness in the process. However an average distance between the disturbances can be calculated and is approximately 14 mm.

![Image](image_url)

Figure 31. Shaped charge jet penetrating inert reactive armour. The time sequence is composed from three different experiments with the same set-up.

The microscopic inspection of the edge of the penetration channel in the plate showed a layer of melted material with a thickness of approximately 25 μm at the edge of the penetration channel.

The results from the simulations of the SC jet penetrating reactive armour panels, can be seen in Fig. 32. Plot (a) shows the interaction with explosive reactive armour, plot (b) the interaction with inert reactive armour and these plots can be compared with the X-ray registrations in Fig. 30. The results showed good agreement with the experiments with respect to plate bending.
and motion and time of interaction between the jet and the plates. However, plot (c) in Fig. 32 shows that the characteristic disturbances of the jet could not be reproduced.

![Figure 32](image)

Figure 32. Numerical simulation of the interaction between a shaped charge jet and reactive armor panels using multimaterial Eulerian approach. (a) Explosive reactive armour 12 µs after impact, (b) inert reactive armour 17 µs after impact and (c) inert reactive armour 39 µs after impact. The colours in the jet correspond to transverse jet velocity: red more than 50 m/s downward, blue more than 50 m/s upward, and green low transverse velocity.

A well-recognized theory regarding the origin of the disturbances of the jet is that the impacting jet causes an expanding crater in the plates enabling the jet tip to pass without interacting with the plate and that the combined decrease in crater expansion velocity and normal plate acceleration result in a renewed contact between the jet and the edge of the crater. The process will be repeated, giving rise to a cyclic rebound phenomenon analogous to the skipping of a pebble stone on free water surface. This pebble stone effect cannot be verified by the numerical simulations, in which the jet seems to have a sliding contact with the plate after the initial tip passage. Similarly, experiments do not show any bounces between the jet and the plates even as it is hard to evaluate whether there is such a dynamic effect.

5.2.2. Single moving armour plates

In order to study the details in the interaction between the jet and the plates, and to find the origin of the disturbances on the jet, the interaction between a single plate and the jet was studied. The results from the experiments with
single-plate panels are shown in Fig. 33. In the case of a back-wards moving plate a relatively long segment of the jet seems to be unaffected although some smaller disturbances can be seen at some distance from the jet tip. Probably, these disturbances are due to the interaction with the large amount of explosive used to accelerate the plates. The detonation gases probably caught up with the jet tip and caused the disturbances. In the case of a forwards moving plate, bulges can be seen on the entire jet in contrast to the case with a backwards moving plate. Mayseless et al [22], have studied the effect of single-plate interaction with SC jets by using pre-detonated two-plate panels. In their experiments, the backwards moving plate gave a relatively smooth deflection of the jet without the characteristic instabilities while the jet was severely scattered by the forward moving plate. Our results agree with the results in their study and show that the instabilities, which constitute the main incapacitation of the jet, can be initiated by one single moving plate under special conditions.

Figure 33. A shaped charge jet penetrating single-plate reactive panels: (a) backwards moving plate and (b) forwards moving plate.

Figure 34 shows a comparison between the effect of a backwards and forwards moving plate according to the simulations performed with the simplified refined simulation model. The pressure between the jet and the moving plates during the time interval 13.8–15.0 µs after the initial contact is shown. There is a constant sliding contact between the jet and the plate which in the case of a backwards moving plate gives rise to a constant pressure. In the case of a forwards moving plate, the pressure is increasing during the time interval and the high-pressure region moves along the contact surface and gives rise to a disturbance on the jet. This behaviour seems to be of the same kind as Kelvin-Helmholtz (KH) instabilities in fluid mechanics.

5.2.3. Kelvin-Helmholtz instabilities
It is well known in fluid mechanics that instabilities can appear between two fluids in contact moving in parallel with different tangential velocities, so
called Kelvin–Helmholtz instabilities. This can be observed, for example, as wave ripples on the water surface on a windy day and in cloud formation in the atmosphere. The initiation and strength of KH instabilities depend on the tangential velocity difference, the viscosity, and various external and internal forces in the materials involved [16]. Surface tension and gravity are stabilizing forces for KH instabilities in fluids.

KH instabilities are seldom seen in solid materials as the strength of the material has a stabilizing effect. An exception is explosive welding [23], where one material is accelerated against another material by use of high explosives. The collision creates a wave pattern at the surface with the same structure as a KH instability between two fluids. Another example of KH instabilities at the interface between two solid materials is when two solids in contact are subjected to an oblique shockwave. This case has been studied by Mikhailov et al. in a series of papers, see Ref. [24] and references therein.
In Paper V we proposed and investigated if the instabilities on a shaped charge jet interacting with a moving plate are governed by flow instabilities of the same type as KH instabilities. The hypothesis is that it should be possible for KH instabilities to develop at the interface between the jet and the moving plate, in spite of the stabilizing strength of the solids, because of the high tangential velocity discontinuity at the interface and the high contact pressure. The mechanism of KH instabilities could then explain the two different types of interaction in the cases of backwards and forwards moving plates based on the relative velocity at the interaction point and the angle of inclination between the materials.

In explosive welding applications, it is known that welding occurs only if conditions for jetting are fulfilled, i.e., if the collapse point is moving at subsonic speed or, for supersonic speed, if the collapse angle is above a critical angle [25]. In our case, one of the materials (the jet) is moving at supersonic speed while the other material (the plate) is moving at subsonic speed with respect to the collision point (point A in Fig. 15). When using a backwards moving plate an attached shockwave is created in the jet, which bends the materials away from each other, similar to the supersonic welding case, and thus reduces the contact pressure in the other region of the interface. As long as no plate material will be pushed downstream and toward the interface, initiations of instabilities are not expected.

For a forwards moving plate it appears that no attached shockwave is produced at the intersection between the materials (point A in Fig. 15) even though the jet is travelling at supersonic speed. The plate is, in this case, wedge-shaped at the collision point and thus has a small areal density there, which inhibits accumulation of pressure at this point. Instead, the plate edge will be bent away from the jet and a maximum collision pressure builds up somewhere inside the interaction region. For any initial disturbance of the interface, propagating more slowly than the jet, the disturbance will be amplified due to the stagnation pressure when the jet catches up the disturbance, see, e.g., Ref. [26]. This phenomenon can be seen in Fig. 34.

Figure 35. Kelvin-Helmholtz instabilities observed in (a) cloud formations and (b) in the contact surface between two materials explosively welded [23]
KH instabilities in fluid mechanics are influenced by parameters such as sliding velocity, fluid density, stabilizing forces (gravity and surface tension), and viscosity. For our problem, stabilizing forces are mainly the strength of the material. The friction between surfaces is important for two reasons; it adds forces between the surfaces, especially in regions with high contact pressure and it also generates heat that lowers the strength of the materials in contact.

A parameter study was performed in the case of a forwards moving plate to investigate the influence of the material strength in the jet and the plate, and the friction between them, on the development of instabilities. The simplified simulation model was used and the results can be seen in Figs. 36-37. Figure 36 shows the influence of jet strength and friction, and Fig. 37 shows the influence of plate strength. Low jet strength and frictional contact gave rise to the largest disturbances while high jet strength and frictionless contact did not result in instabilities, at least not with the mesh resolution used. This highlights the significance of strength as a stabilizing effect and friction as an amplifying effect on KH instabilities. The steel plate with low strength gave smaller perturbations on the jet than the base case (normal strength and friction). The plate with high strength displaces the jet more than in the base case but perturbations are not developed on the jet in this case. The smaller disturbances in the case with low-strength steel depend on the lower structural strength of the plate, which decreases the contact pressure. The absence of perturbations on the jet after interaction with high strength steel is due to the stabilizing effect of strength on the development of KH instabilities.

<table>
<thead>
<tr>
<th>Case 1. Low jet strength, no friction, normal plate strength</th>
<th>Case 2. Low jet strength, friction, normal plate strength</th>
</tr>
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<tbody>
<tr>
<td>Case 4. High jet strength, no friction, normal plate strength..</td>
<td>Case 5. High jet strength, friction, normal plate strength.</td>
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Figure 36. Simulated disturbances on the jet after interaction with a forward moving plate using different jet strength with (right) and without (left) friction.
5.3. Applicability of the simulation models

Figures 38-39 show the results from the comparison of experimental and simulation results regarding the interaction between an LRP and a moving oblique plate when using the XW fracture model. Geometry and position of the projectile 150 μs after impact, according to experiments and simulations, relative to the position of a free-flight projectile are shown. The transition from a non-fractured to a severely fractured projectile was captured, and the deformation and rotation of the projectile and its fragments, and the locations of fractures, agree well with the experimental results.

Figure 38. Results of simulations (black) compared with experimental results (grey) 150 μs after impact for Cases I and II with opposite plate flight directions. The straight free-flight projectile (grey) is shown as a reference.
The influence of the deviatoric stress parameter $\xi$ in the XW fracture model was investigated by comparing results from simulations performed with variable parameter $\xi$, and with preset fixed values $\xi=1$ (uniaxial stress) and $\xi=0$ (pure shear), respectively. In addition, the state of stress in the projectile during the interaction was evaluated in an attempt to see if the fractures along the projectile occurred due to shear loading (an attempt that made us use the XW fracture model).

Figures 40-41 show the results from the simulations with variable and preset fixed values of the deviatoric stress parameter. In the cases where the projectiles were mainly deformed in the experimental tests, the results of simulation with variable $\xi$ and with fixed value $\xi=1$ agree equally well with the experimental results, while those with fixed value $\xi=0$ result in too much damage and fractures. In the cases where the projectile was severely fractured in the experimental tests, the number of fragments is best reproduced in the simulations with fixed value $\xi=0$ although the overall damage of the projectile is overestimated. In these cases, the simulations with variable $\xi$ and with fixed value $\xi=1$ miss some of the fractures. However, more of the fractures are captured with variable $\xi$, and those missing are represented by high levels of damage. Clearly, the deviatoric stress parameter $\xi$ of the XW model has significant influence on the results of simulation. It allows fractures along the projectile without extensive damage of the entire projectile.

Figure 42 shows the effective stress $\sigma_{eff}$ versus time $t$ from impact along the projectile, in the cases of backwards and forwards moving plates, respectively. In these figures, where colours represent levels of effective stress, dark blue colour indicates zero stress and represents either an uninfluenced element (in the back of the projectile at an early time) or an eroded element (eroded nose elements and elements where fracture appears). It can be seen
that when the projectile impacts the plate, large stresses arise at the nose of the projectile, which is continuously consumed during perforation. An elastic compressive wave propagates along the projectile and reflects as an elastic tensile wave at the free rear end of the projectile. The front of the elastic compressive wave can be seen as the first sloping straight line in the diagrams. A sloping dark red region, representing high effective stress, with a different slope can also be seen in the diagrams. It represents the sliding contact with the plate.

Figure 40. Results for Cases I and II from a study of the influence of the deviatoric stress parameter $\zeta$ of the fracture model. The contour plots indicate the level of damage in the symmetry plane. Blue to red corresponds to $D_f=0$ to 1.

In the case of a backwards moving plate the sliding contact on the lower side of the projectile results in bending of the projectile. That gives rise to large axial tensile stresses on the upper side of the projectile and large compressive stresses on the lower side. Correspondingly, large regions of high effective stress are formed on the upper and lower sides of the projectile.
Because of the influence of the lateral stress (compressive on the lower side and zero on the upper side) on the effective stress, these high-effective-stress regions are larger on the upper side of the projectile than on the lower side. The relatively uniform distribution of effective stress on the upper side of the projectile seems to be related to the absence of fractures in the case of a backwards moving plate.

In the case of a forwards moving plate, similarly, the sliding contact on the upper side of the projectile results in bending of the projectile. That gives rise to large axial tensile stresses on the lower side of the projectile and large compressive stresses on the upper side. On the lower side of the projectile this leads, as can be seen in Fig. 42 (d), to localised regions of high effective stress and damage at which fractures are initiated.

Figure 41. Results for Cases III and IV from a study of the influence of the deviatoric stress parameter $\xi$ of the fracture model. The contour plots indicate the level of damage in the symmetry plane. Blue to red corresponds to $D_1=0$ to 1.
Figure 42. Effective stress $\sigma_{\text{eff}}$ versus time $t$ from impact along the projectile. (a) A backwards moving plate, upper side. (b) A forwards moving plate, upper side. (c) A backwards moving plate, lower side. (d) A forwards moving plate, lower side. The colour indicates the level of effective stress. Blue to red corresponds approximately to $\sigma_{\text{eff}} = 0$ to 1.8 GPa. The contour plots of the projectile below, indicating were fractures occur, are shown as a reference.

Figure 43 shows the shear stress $\sigma_{zx}$ versus time $t$ from impact at the side of the projectile where the fractures are initiated, i.e. at the upper side of the projectile in the case of a backwards moving plate and at the lower side of the projectile in the case of a forwards moving plate. The localised regions of high shear stress in this diagram agree well with the localised regions of high effective stress in Fig. 42 (d) as well as with the positions of the fractures in the projectile. This indicates that the fractures originate from shear stress and supports the introduction of the deviatoric stress parameter $\xi$ in the fracture model so that the sensitivity of the material to shear stresses can be taken into consideration.
Figure 43. Shear stress $\sigma_{xz}$ versus time $t$ from impact at the side of the projectile where the fractures are initiated, i.e. at the upper side of the projectile in Case I and at the lower side of the projectile in Case II. The colour indicates the level of shear stress. Blue to red corresponds approximately to $\sigma_{xz} = -0.5$ to 0.5 GPa.

Figure 44 shows the results from the study of the influence of mesh resolution. It can be seen that the results from the simulations with refined meshes agree well with those of the original simulations. In the case of a forwards moving plate, however, two additional fractures occur with the finer mesh at positions where only high levels of damage are indicated with the original mesh.

Figure 44. Results from study of mesh resolution. The contour plots indicate the level of damage in the symmetry plane. Blue to red corresponds to $D_f = 0$ to 1.
The mesh resolution tests for the interaction of an SC jet and forwards moving plate were performed with the simplified model and in this case the need for a refined mesh was clearly seen, see Fig. 45. The amplitude of the disturbances was significantly increased in the simulations with the medium and fine mesh compared with the course mesh. The evenly spaced distribution of the disturbances for the course mesh was gradually replaced by a double bulging appearance where each disturbance was followed by a smaller one.

![Coarse mesh](image1)

![Medium mesh](image2)

![Fine mesh](image3)

Figure 45. The effect of mesh resolution on the predicted development of disturbances on the jet.

The numerical simulations with the finest mesh showed good agreement with the experimental results. In Fig. 46, the simulated and experimentally registered results for the jet after interacting with an inert reactive armour can be compared.

![Comparison between experimental registered and numerical simulated disturbances on the jet after interaction with a forward moving plate (30 µs after impact and 13 µs after initial contact). The backward moving plate has not yet started to interact with the jet.](image4)
6. Conclusions

The studies presented in this thesis show similarities as well as differences in the interaction mechanisms between SC jets and reactive armour plates on one hand, and between KE projectiles and reactive armour plates on the other hand. In both cases, the interaction can be divided into two phases, an initial phase and a subsequent sliding phase. In the initial phase, the penetrator impacts an armour plate which results in perforation and energy transfer to the plate. In the sliding phase, the armour plate slides along the penetrator. In both cases, severe disturbances and fractures of the penetrator originate from the sliding phase. During the sliding interaction, there is uninterrupted contact between the penetrator and the plate. In both cases, the major effect on the penetrator originates from the forwards moving plate. Obliquity results in a negative pressure gradient for a backwards moving plate as such a plate has more supporting mass at its impact side and less towards its exit side. For a forwards moving plate the situation is opposite which results in a positive pressure gradient.

The severe scattering of an SC jet is due to instabilities of the same kind as can be found in two fluids in contact moving in parallel with different tangential velocities (Kelvin-Helmholtz instabilities). Although this kind of instability is seldom observed in solid materials, the very high velocity and relatively low material strength of the jet, in combination with the high contact pressure and the motion of the plate allow instabilities to occur in spite of the stabilizing effect of the material strength. It is recognized in fluid mechanics that an accelerating flow is more stable than a decelerating flow, and the negative pressure gradient due to obliquity of a backwards moving plate accelerates the flow in the jet direction while the positive pressure gradient in the case of a forwards moving plate decelerates the flow in the jet direction.

KH-instabilities do not occur in the case of an LRP interacting with reactive armour. In this case, the high strength of the projectile material and the low projectile velocity relative to that of an SC jet prevent the generation of instabilities. Instead, the abrupt change in pressure at the exit of the plate gives rise to fracture of the projectile. The positive pressure gradient and longer interaction time make forwards moving plates more effective than backwards moving plates. Besides from the direction of motion of the plate, the most significant plate parameter for effectively disturbing the projectile is the thickness. Increased plate thickness results in substantial increases in
rotation, translation, bending, length reduction and fragmentation of the projectile. For fractures to occur in the projectile, the plate velocity has to be relatively high, 300 m/s for a plate thickness of one projectile diameter and 200 m/s for a plate thickness of two projectile diameters (only forwards moving plates). Lower projectile velocity results in longer interaction time which increases the effect of the moving plate on the projectile. The experiments also indicated increased effect at higher projectile velocity which has not been explained in these studies.

The use of the XW fracture model in the simulations of the interaction between an LRP and a moving plate showed that it is possible to reproduce fractures in a tungsten LRP impacted by a moving oblique plate and that this can be done without use of a very fine mesh. For example, the transition from a deformed non-fractured projectile to a severely fractured projectile due to a small increase in the magnitude of the plate velocity or a change from a backwards to a forwards moving plate can be captured. The deviatoric stress parameter used in the XW model has significant influence and allows fractures due to shear loading to occur without extensive damage of the entire projectile.

The simulation of the interaction between an SC jet and reactive armour showed that it was not possible to reproduce the scattering of the jet with an ordinary mesh size. To simulate the interaction and the development of instabilities it is necessary to use a very fine mesh. When this is done, instabilities on the jet can be observed.

Cylindrical rods thrown against the treat may be of interest as an alternative to the use of plates. A steel rod with the same diameter as the LRP hitting the projectile at 200 m/s gives approximately the same effect (some yaw but no fracture) as that of a steel plate with the same thickness (one projectile diameter), velocity and angle of obliquity. Increasing the velocity of the rod to 600 m/s resulted in fracture of the LRP. As hard kill components in an active armour system, rods can probably also be able to partly destroy an SC warhead (not investigated in this study).

The main conclusions from the study regarding the design of reactive armour panels that are effective against both SC jets and LRPs are as follows: (i) The backwards moving plate should be used just as a confinement of the HE or inert reactive material. (ii) The forwards moving plate should be quickly accelerated to a high velocity. (iii) The panel should have large obliquity, and the strength of the plates should be a compromise between high strength, providing structural stability and high contact pressure with an LRP, and low strength promoting development of KH instabilities in SC jets. (iv) The thickness of the plate should be as large as the weight of the armour permits to be effective against LRPs. This thickness is larger than that of a reactive panel designed against the SC threat only.
De presenterade studierna är en del av arbete som utförts vid FOI, Totalförsvarets forskningsinstitut, avseende värdering av skydd mot pansarvärnsvapen (KE-projektiler och RSV-stridsdelar). Omfattande experimentella studier och relaterade numeriska simuleringsstudier har genomförts avseende mekanismerna vid växelverkan mellan projektiler respektive RSV-strålar och rörliga pansarkomponenter. Pansarkomponenterna kan utgöra delar i reaktiva pansarmoduler eller i aktiva skyddssystem. En ökad förståelse av vilka parametrar som starkast bidrar till att störa RSV-strålar och förorsaka brott i projektiden ger ökad möjlighet att utforma viktesteckta skydd och bedöma förevisade skyddsutformningar.

Ett reaktivt pansar består av två stålplåtar med ett mellanliggande lager av explosivämne. Det monteras på skydds föremålet så att anslagsvinkeln vid träff ska bli så stor som möjligt. Reactiva pansar infördes först på stridsvagnar som tilläggs skydd mot RSV-stridsdelar och visade sig vara mycket effektiva. Då en RSV-stråle träffar pansaret initieras explosivämnet, varigenom plåtarna kastas ut åt varsitt håll. Eftersom plåtarna rör sig i vinkel mot strålen kommer kanten av penetrationskanalen att glida längs strålen. Denna glidande kontakt resulterar i kraftiga störningar av strålen, som därmed förlovar. Detta fyller in ett paradigma för tillämpningen av reaktivt pansar uppmärksammat av författaren.

Den ursprungliga typen av reaktivt pansar ger mycket mindre effekt på KE-projektiler (pilprojektiler) än på RSV-strålar. Projektilmaterialets höga hållfasthet och, i förhållande till RSV-strålen, låga hastighet (upp till 2000 m/s) omöjliggör bildandet av KH-instabiliteter. I stället kan projektilen under vissa förhållanden brytas sönder i fragment. Inte heller i detta fall handlar det om någon intermittent last som slår av projektiden. Under växelver-
kansförloppet glider plåten med nästan konstant last längs projektilens mantylyta, och de brott som uppstår initieras i samband med avlastningen vid utträdet ur plåten.


En experimentell parameterstudie avseende växelverkan mellan pilprojektiler och sneda rörliga plåtar har genomförts där inverkan av plåtens hastighet, vinkel och tjocklek samt projektilens hastighet och slankhetstal studerats. I det parameterrum som studerats (plåthastighet -300 till 300 m/s, plåtvinkel 30 till 70 grader, plåttjocklek halv till två gånger projektildiameter, projektilhastighet 1500 till 2500 m/s och slankhetstal 15 till 45) uppstår brott endast till följd av påverkan från medflygande plåtar. För att detta ska ske krävs att plåten har tillräcklig hastighet, tjocklek och vinkel. Vid lägre projektilhastighet och lägre slankhetstal på projektilen uppstod fler brott i projektilen än i referensfallet (2000 m/s och L/D=30). Även vid den högsta projektilhastigheten uppstod ett flertal brott på projektilen. Detta inträffade inte i referensfallet och inte kunnat förklaras i detta arbete. Vid studien av slankhetstalets inverkan användes konstant projektildiameter.

References


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