What is the effect of composite covers on ceramics in hard armour plates?

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Abstract. Hard armour plates in body armours are often constructed of a single ceramic tile, which is covered by a high-strength sheet material and backed with several layers of aramid and/or ultra-high molecular weight polyethylene (UHMWPE) fibres. The main role of the hard ceramic strike face is to erode, blunt and shatter an impacting projectile, such as hard-cored 7.62 mm armour piercing projectiles. However, ceramics are inherently brittle materials and they will fracture in a brittle manner when subjected to high stress loads. To mitigate this brittle fracture, the ceramics may be covered with one or more layers of high-strength fibres in polymer matrices in order to maintain the integrity of the ceramic. This can improve the ballistic performance of the first strike, will definitely improve the multi-hit properties and will ultimately increase the robustness of the plate. Several studies have looked into how the failure of the ceramic tiles is affected by composite covers and how different designs affect the penetration performance. In all the studies, however, the target design (e.g. the ceramic, sheet material, number of layers, etc.) and the experimental conditions (e.g. type of projectile, impact velocity, ballistic test procedure, etc.) were different. Different effects have been found from wrapping the ceramic in a glass fibre fabric, or from adding front or back covers. Hence, the studies do not fully agree on how the ballistic performance changes with addition of a composite cover to a ceramic tile. A meaningful comparison of the studies can therefore be difficult. This paper explores the findings in the literature of the effect of composite covers on ceramics in hard armour plates, and also suggests potential future developments in hard armour plate designs.

1. INTRODUCTION

The two main components in a typical body armour system for torso protection are a soft ballistic panel and a hard armour plate [1, 2]. In a military context, the soft panel is designed to give protection against various types of relatively small primary and secondary fragments from indirect fire munitions, and in many cases handgun rounds. The hard armour plate, on the other hand, provides protection against projectiles with higher kinetic energy, of which high-velocity armour piercing (AP) rifle bullets is the most serious threat. The hard armour plate is typically designed to be used in conjunction with the soft panel to give the required level of protection. This is effective in reducing both the lethality and injuries. Body armour systems for soldiers are made of combinations of materials, with the aim of making them as light-weight as possible given the specific threats they are designed to protect against. This is to reduce burden and thus improve the mobility, endurance and comfort of the soldier, at the same time as keeping the cost at an acceptable level. Hence, there is always a drive amongst armour manufacturers to implement new, more efficient materials, and to improve designs and manufacturing methods to be able to provide systems with improved performance. The design of hard armour plates with ceramics as the strike face is one area that has received some attention over the last few decades. One way to improve penetration resistance of the hard armour plates is to cover the ceramic with a high-strength composite sheet material.

This paper discuss the findings in the literature of composite covers on ceramics in hard armour plates. The literature gives some indication of what designs of composite-covered ceramics that give the most efficient solutions. Recent work that has been conducted at the Norwegian Defence Research Establishment (FFI) and collaborating partners on this topic is also summarised. Some recent results seem to indicate an unexplored potential of new designs and manufacturing methods in the development of composite sheets in hard armour plates.

2. CONSTRUCTION OF HARD ARMOUR PLATES

2.1 Typical design

The hard armour plate typically consists of a monolithic, double-curved ceramic tile which is wrapped in a thin composite material, Figure 1. The tile thickness is around 10 mm, but will vary with the defined threat level and type of ceramic. Additionally, at the back of the wrapped ceramic tile, there is a backing material consisting of several layers of high-performance ballistic fibres, such as aramid or ultra-high molecular weight polyethylene (UHMWPE). Although some hard armour plates are designed to be used

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as a stand-alone plate, it is more common that it must be used in conjunction with (icw) the soft panel in order to give the required protective performance.
Many hard armour plates are designed to protect against hard-cored AP projectiles up to caliber 7.62 mm, with the typical impact velocities being around 900 m/s. The ceramic tile acts as the strike face and is usually composed of alumina (Al2O3), silicon carbide (SiC) or boron carbide (B4C). The main reason for using ceramics as the strike face is that they are very hard materials with a relatively low density.
The soft panel is also made of aramid or UHMWPE. Used on its own, the soft panel typically provides protection against various types of relatively small primary and secondary fragments from indirect fire munitions, and in many cases handgun rounds. This is achieved from the fibres' ability to absorb and disperse the kinetic energy of the fragments or the bullets. The same mechanisms apply when the soft panel absorbs the kinetic energy of fragments formed during impact on the hard armour plate.

2.2 Failure mechanisms

When a projectile impacts on the hard armour plate at a given velocity it is desirable, from a protection point of view, that the core material of the projectile is eroded at the tip and fragmented as much as possible, Figure 2, and that the core fragments are considerably slowed down. This reduces the kinetic energy and makes it easier to prevent the projectile from perforating the armour system. The high hardness of ceramics makes them beneficial for eroding and fragmenting the projectile.
However, ceramics are brittle materials and they will fracture during impact due to the high stress loads that are involved, hence failure will be observed. Figure 3(a-c) shows some of the failure mechanisms that occur in the ceramic tile. These particular tests were conducted at relatively low velocities, but still serve as a good illustration of the mechanisms. The impact causes the formation of radial cracks, cone cracks and fragmentation of the ceramic [3, 4]. At the point of impact, the formation of a comminuted ceramic takes place in the area in front of the projectile. Here, the ceramic becomes less confined, resulting in lower resistance to penetration. Fragmentation of the steel-core of an AP projectile is also shown in the figure.
For ceramic tiles that are not well supported or confined, the ceramic will shatter into relatively large fragments, which will reduce its ability to stop the projectile. To improve the ballistic performance of the ceramic tile, it can be covered by, or wrapped in, a sheet of high-tenacity fibre composite material [5-12]. When the ceramic is covered by a sheet material, the ceramic will be partly held together both during and after impact from the projectile. The fractured ceramic is then prevented from moving and is held in place in the path of the projectile. This may give more time for erosion and fragmentation of the core of the projectile. The sheet material may also contribute to improved multi-hit performance, since it introduces radial constraint on the ceramic surface. This prevents through-thickness cracks from opening and confines larger ceramic fragments, hence improving the integrity of the tile after impact. This is illustrated in Figure 3(b), where it is obvious that longer interaction times with the projectile also results in the formation of smaller ceramic fragments. Another possible effect of the sheet cover is to reduce the angle of spall that is ejected from the strike face.

2.3 Importance of composite covers in hard armour plates

Some insight into the importance on composite covers can be found from studies on hard armour plates [11, 13, 14]. In these studies, the V50 ballistic limit for hard armour plates with cracks in the ceramic tile, and the results were compared with intact, un-damaged plates. A reduction in V50 from 3 to 10 % was observed, also when the shots were placed directly on or in the vicinity of the cracks. This suggests that the protective ability was not catastrophically affected by a limited number of cracks in the ceramic. The tested plates in these studies all had composite covers on the ceramic. The cover probably contributed to maintaining some integrity of the ceramic during impact by holding the ceramic fragments in place.
However, a more recent study showed that the presence of cracks in the ceramic significantly affected the protective ability [15]. A reduction in V50 of around 30 % was observed. An important difference from the other studies was that hard armour plates designed for single-hit impacts were employed, as opposed to plates designed for multi-hit in the other studies. The lower performing single-hit plates did not have composite covers on the front and back of the ceramic, which may have influenced the performance. A similar effect was observed in an older study [16]. Cracks with a relatively large crack opening, i.e. cracks where the fracture surfaces were not in contact, resulted in reduced protective ability. This might have been avoided if the ceramic was surrounded by a composite material.

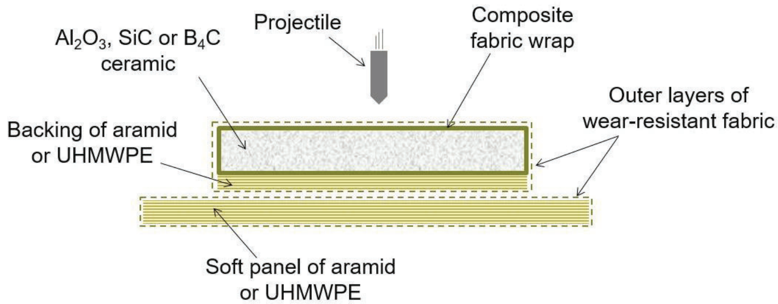

Figure 1. Cross-sectional view of what a typical construction of a hard armour plate can look like. Hard armour plates are often designed to be used in conjunction with a soft panel; also shown.

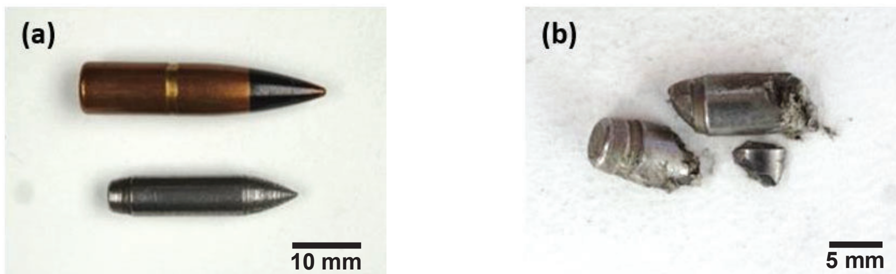

Figure 2. Example of fragmentation of the hard steel core of the 7.62×63 mm M2 AP projectile after impact on a ceramic tile: (a) intact core prior to impact (mass 5.19 g), and (b) fragmented core.

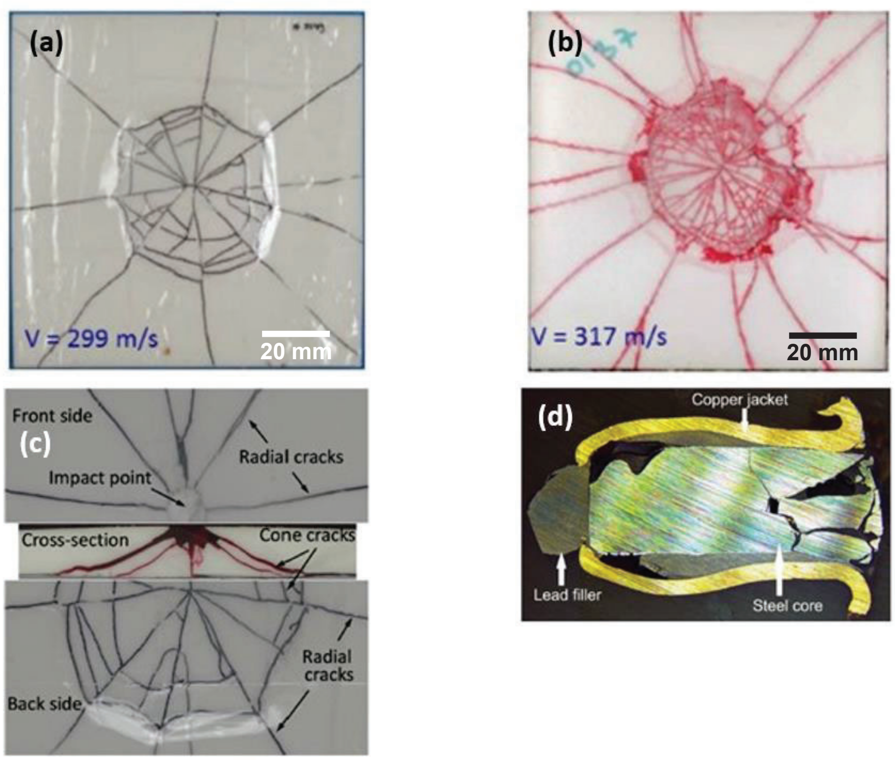

Figure 3. Relatively low-velocity impacts at around 300 m/s on alumina/composite targets: (a) Back side of alumina in (a) un-covered and (b) covered targets. (c) Ceramic damage; front, cross-sectional and rear view after impact on an alumina tile. (d) Cross-section of a 7.62 mm AP M61 projectile after impact. This work was a collaboration between FFI and SRI International. Adapted with permission from Rahbek et al. [8].

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3. STUDIES ON COMPOSITE COVER DESIGNS

Several studies have performed experiments in efforts to better understand how ceramic tiles fail, and how failure is affected by a composite cover. An overview of this literature is given in Table 1. Other sheet materials have been investigated, but the focus here will be on composite materials.

One complicating matter is that the target design (e.g. the ceramic, sheet material, number of layers) and the experimental conditions (e.g. type of projectile, impact velocity, ballistic test procedure) were different. Some studies were performed using regular AP projectiles at typical muzzle velocity of around 800-900 m/s, while other studies have employed other projectile geometries at lower velocities. The studies therefore do not fully agree on how the ballistic performance changes with addition of a composite cover to a ceramic tile.

3.1 Role of projectile

Ceramic hard armour plates are often required to protect against AP projectiles with hard core materials. Although important lessons can be learned by using other types of projectiles, the most interesting studies from a ‘real-life’ scenario are therefore the ones that use AP, or similar, projectiles. It has been shown that the perforation ability of AP projectiles can be directly correlated with the hardness of the core material [17]. Harder core materials will generally have a higher penetrative ability, while more core erosion and fragmentation will occur particularly when the ceramic has a higher hardness than the core material. On the other hand, projectiles with lower hardness, for example Ball projectiles, will result in other deformation modes, such as e.g. mushrooming or petalling.

In addition to the penetrator material, the penetrator shape will also have an effect, meaning that a different shape of the nose of the projectile may lead to different penetration mechanisms and perforation velocities [18]. Conical or ogival tipped projectiles may penetrate at lower velocities than cylindrical/blunt projectiles. To complicate things further, the same projectile core with and without the jacket and lead cap can also have different penetration ability [10, 19].

3.2 Role of cover

3.2.1 Ceramic failure

The application of a composite cover has a significant effect on the failure of the ceramic during impact. Crouch has shown that the addition of an aramid fibre-reinforced composite cover to the ceramic tile in a hard armour plate may lower the back-face deformation upon multi-hit [11]. In the same study, Crouch observed that the addition of the composite cover affected the failure mechanisms of the ceramic. An increase in the number of radial cracks from an average of 10.8 without cover to 16 for a covered ceramic was observed. Similar effects have also been observed in other studies, including Rahbek et al. [8], which observed an increase in radial cracks from 9 to 14 for tests conducted at ~300 m/s. The density of cracks in the cone region was also much higher in the covered tile and, as a result, a much higher number of incipient fragments were formed in the covered target. In another study, Reddy et al. [7] found that the size distribution of the ceramic debris created during impact changed toward smaller fragment sizes when a ballistic fibre front cover was added (the ceramic was backed by a glass fibre composite).

3.2.2 Front constraint

Several studies have shown that covering of ceramic tiles with fibre composites (glass or carbon fibres) or ballistic fibres (aramid or UHMWPE) may lead to improved ballistic performance in terms of increased core fragmentation, reduced residual velocity of the core fragments, and increased kinetic energy-loss. The studies do not fully agree on how the performance changes with addition of a composite cover, but positive effects on an areal density basis has been observed.

One proposed mechanism which contributes to the increased performance is the constraining effect on the ceramic debris at the front of the ceramic (strike face). This constraint increases the flow of ceramic debris towards the penetrator, gives more time for penetrator-ceramic interaction since the ceramic is kept in front of the penetrator for a longer period of time, and slows down propagation of cracks in the ceramic [5-7]. This effect was observed in a study conducted by Sarva et al. [5], which found a significant improvement in the ballistic performance from front covers made of different materials. Significantly higher kinetic energy-loss and more projectile erosion were observed. However, Sarva et al. employed a

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cylindrical flat-ended tungsten heavy alloy penetrator in their impact experiments. This penetrator was continuously consumed by erosion by the penetration, and did not shatter or break.

3.2.3 Pointed projectiles

Pointed AP projectiles made of hard steel, with one example being the 7.62×63 mm M2 AP, have been observed to fragment during impact due to their high hardness [7, 19]. Still, noteworthy effects of a composite front cover or wrapping on ceramic damage, core erosion, fragmentation, and back-face deformation, have been observed also for pointed AP 7.62 mm projectiles of hardened steel [6, 7, 11]. Nunn et al. [6] found a >40% increase in the V50 of a boron carbide tile by adding a composite cover that led to an increase in areal density by 9%. The suggested mechanisms that contribute to the improved performance were quite similar to those proposed by Sarva et al. [5], i.e. increased flow of ceramic debris against the projectile.

Contrary to the observations by Sarva et al., some studies have found that adding a composite cover layer to the ceramic tile does not have a significant effect on the projectile core [8, 10]. This is interesting, since erosion of the projectile is an important mechanism for defeating such threats. Hence, it is not obvious that ceramic flow against pointed AP projectiles will always be a noteworthy effect.

3.3 Role of target design

The effect of target design was investigated in a study at FFI where the main aim was to isolate the possible differences of adding front or back composite covers on ceramic tiles [12]. Very few studies have tried to isolate the effects of front and back covers, since the composite layer was usually present on both sides, or the composite was wrapped around the tile. In this study, two or four layers of a glass fibre-reinforced composite material were applied to the front and/or backside of an alumina tile, which resulted in a maximum increase in areal density of 9.5% compared to a bare tile. The composite-covered targets were tested with a 7.62 mm AP projectile at 800 m/s, which always resulted in perforation and fragmentation of the hard projectile core (as illustrated in Figure 2).

The results showed that the core fragmentation and the kinetic energy-loss of the projectile were most significant for the targets with the composite-cover on the back of the alumina; the core mass was reduced by up to 61%, while the kinetic energy was reduced by up to 84% (mainly as an effect of reduced mass, and to a less extent reduced velocity), Figure 4. It was obvious that the target configuration had a significant influence on the fragmentation of the projectile core, and that front covers did not give increased fragmentation.

The observed effects were somewhat different from several studies in the literature, as discussed above, where positive effects were mainly attributed to front covers or to wrapping of the ceramic. For example, Sarva et al. [5] found minor additional improvements when also adding a back cover, although increased energy absorption from a back cover has been reported for very thin (2 mm) alumina tiles [9]. The most likely mechanism is that the support and restraint of the back cover contributes to a time-delay in the opening of tensile cracks on the back of the ceramic, perhaps in combination with reduced reflection of stress waves into the ceramic. This time-delay gives more time for interaction with the penetrator, hence improving the ballistic performance of the target. If this hypothesis is true, then the composite cover on the rear may be more important than the cover on the front. In hard armour plates, the aramid or UHMWPE backing may provide the sufficient support.

3.4 Numerical modelling

Numerical modelling has been used to describe the effect of a composite wrapping around alumina tiles impacted by 7.62 mm AP projectiles. Rahbek et al. [8] found significantly more damage in covered tiles at sub-muzzle velocities (180 and 310 m/s), compared with bare tiles. The modelling successfully reproduced the experimentally observed failure mechanisms; radial cracks were first initiated at the back of the tile beneath the impact zone, followed by the formation of cone cracks that connected the radial cracks. Although covering resulted in more ceramic damage, an influence on projectile erosion was not observed.

Projectile impact at muzzle velocities and higher velocities was modelled by Guo et al. [20] for bare and covered tiles. The modelling showed that the composite cover resulted in increased resistance to perforation and that it had an effect on the fracture process of the ceramic tile. The fracture cone was slightly larger in the covered tile, which helped to distribute the load to a larger area on the backing plate that was employed. The fracture cone was also formed faster and, similar to the observations by Rahbek et al. [8], more ceramic damage was observed inside the cone.

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Table 1. Experimental work in the literature that discuss the effect of adding composite covers to ceramic tiles. Adapted from Rahbek and Johnsen [12].

Reference	Projectile; impact conditions; ceramic	Cover material; target design	Main conclusions on effect of cover
Nunn et al., 2005 [6]	7.62 mm AP M61; V_{50} (625-878 m/s); 6.2 mm PAD B_4C	UD carbon fibre/epoxy, PBO/vinylester; Front and back cover, 2-8 layers on each side, 1 mm spall cover and 7.25 mm backing of UHMWPE	Penetration resistance increases with increasing number of plies
Sarva et al., 2007 [5]	6 mm tungsten heavy alloy (WHA), cylindrical flat-ended, mass 10.68 g; ~900 m/s; 12.7 mm 99.5% Al_2O_3, 12.7 mm SiC	UD glass fibre tape, E-glass/epoxy weave, carbon fibre/epoxy weave; Mainly front cover, 1-9 composite layers	Front-face restraint gives reduction in projectile residual kinetic energy, mass and velocity
Reddy et al., 2008 [5]	7.62 mm AP projectile, mass 10.44 g, 5.2 g hardened steel core; 820 ± 10 m/s; 7 mm 99.5% Al_2O_3	UD UHMWPE, aramid fabric; Wrapping in 2-4 layers, i.e. 2-4 layers on each side, backed by 10 mm E-glass laminate	Higher energy absorption, lower projectile residual mass and velocity with increasing number of wrapping layers
Crouch, 2014 [11]	7.62 mm M2 AP; 868-887 m/s, multi-hit; 9 mm SiC	Elastomeric film, polyester or polypropylene fibre/epoxy, aramid fibre/epoxy; Hard armour plates with clad ceramic, UHMWPE backing and nylon fabric wrap	Increase in number of radial ceramic cracks, and decrease in back-face deformation with fibre-reinforced cover
Crouch et al., 2015 [10]	7.62 mm AK-47, mass 7.91 g, 3.59 g mild steel core; 697-739 m/s, reverse ballistics; 3, 4 and 5 mm B_4C	Aramid fibre/epoxy; Front and back cover, with or without 30 ply UHMWPE backing, some targets with air gap between backing and sabot	Little effect on projectile deformation and erosion
Öberg et al., 2015 [9]	8 mm spherical projectile, 52100 type steel, mass ~2 g; 220-230 m/s; 2 mm Al_2O_3	Carbon fibre/PET weave; 1 layer back cover	Higher energy absorption from back cover
Rahbek et al., 2017 [8]	7.62 mm AP M61, 3.7 g hardened steel core; 176-351 m/s; 10 mm 98% Al_2O_3	Glass fibre/PET fabric; Front and back cover, 2 layers on each side	Increased ceramic damage, no difference in projectile core damage
Rahbek and Johnsen, 2019 [12]	7.62 mm M2 AP; ~800 m/s; 8.2 mm 98% Al_2O_3	Glass fibre/PET fabric; Front and/or back cover, 2 or 4 layers on each side	Back cover gave higher projectile core fragmentation
Rahbek et al., 2023 [21]	7.62 mm M2 AP; V_{50} (376-802 m/s); 7.0 mm 98% Al_2O_3	Fabric wrap or filament-wound yarn of glass fibre/PET; One 0º/90º layer on each side, with 8 mm PC backing	Filament winding gave significantly higher V_{50}

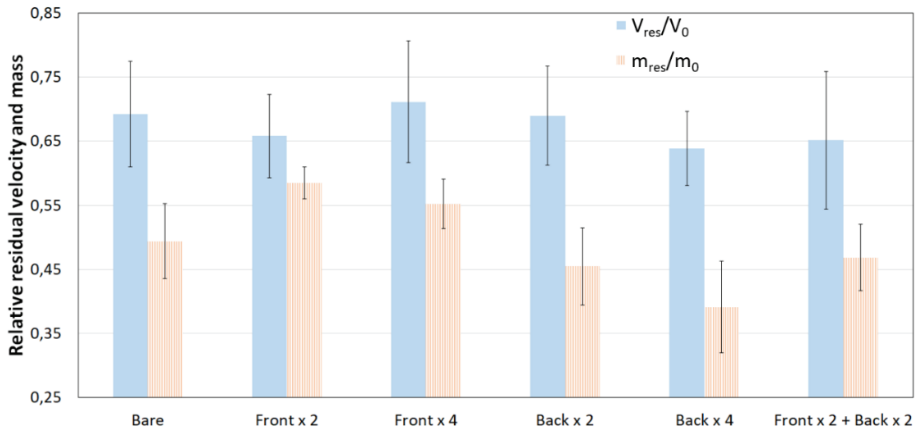

Figure 4. Relative residual mass, mres/m0, and relative residual velocity, Vres/V0, for the largest core fragments. Average values ± 95% confidence intervals. Adapted from Rahbek and Johnsen [12].

4. POTENTIAL FUTURE DEVELOPMENTS

In the studies discussed above, the targets were all produced by manufacturing technologies where the method of application of the composite covers or the fabric wraps are well known. It was more the effects of using different sheet materials, designs and lay-ups that were investigated. One area that has not received a lot of attention, at least in the open literature, is different manufacturing technologies. This is, however, an area that should have the potential to significantly improve the protective ability of hard armour plates, and there are a few examples of this in the recent literature.

4.1 Pre-tensioning of fabrics

The number of studies that discuss the effect of pre-tensioning of composite materials layers on ceramics is very low or non-existent. This is not to be confused with radial pre-tensioning which has been shown to improve the resistance to penetration [22]. However, Jaitlee [23] investigated the effect of a composite cover on the rear side of 4 mm silicon carbide tiles. In this work, the cover was an aramid fabric that was pre-tensioned and then held in place by a cured epoxy. Ballistic testing with a 7.62 mm mild steel core projectile indicated that the pre-tensioning in the fabric gave a reduction in back face signature. (No V50 data were presented.) No explanation for this observation was given.

A few studies have investigated the effect of pre-tensioning in composite laminates and woven fabrics (not as covers on ceramics) [24, 25]. For example, decreased V50 has been observed for a glass fibre-reinforced plastic (GFRP) that was loaded in uniaxial tension, partly explained by less energy absorption in the preloaded composite, while the V50 of a high-strength fabric that was pre-tensioned in the warp direction was increased up to a critical level of pre-tension, after which the ballistic limit was reduced. These studies are not directly relevant for the understanding of the pre-tensioned composite covers on ceramics but they may, as discussed below, provide some supporting insight.

4.2 Filament winding with yarns

In a recent study, a new method of applying the fibre-composite cover around the ceramic tile was investigated in a collaboration between FFI and NFM Group [21]. The method consisted of filament winding of glass fibre/polyester yarns under some pre-tension, Figure 5, around an alumina tile. The filament winding was conducted in two directions around the tile to produce a composite sheet layer consisting of two plies with a 0o/90o lay-up on each side of the tile. These targets were compared with targets where a similar glass fibre/polyester fabric was wrapped around the alumina, which is a more traditional way of producing hard armour plates, and also with bare alumina targets. All targets were backed by polycarbonate and had the same overall areal density. Ballistic testing was conducted using the 7.62×63 mm M2 AP projectile, and the projectile fragments were collected and analysed.

The target with the filament-wound composite cover gave a much higher V50 than the target with the fabric wrap; values of 622 m/s and 536 m/s, respectively, were measured, Table 2. The 16% difference between the targets was remarkable considering the identical areal density. The bare alumina target had a V50 of 586 m/s, which was also considerably lower than the filament-wound target.

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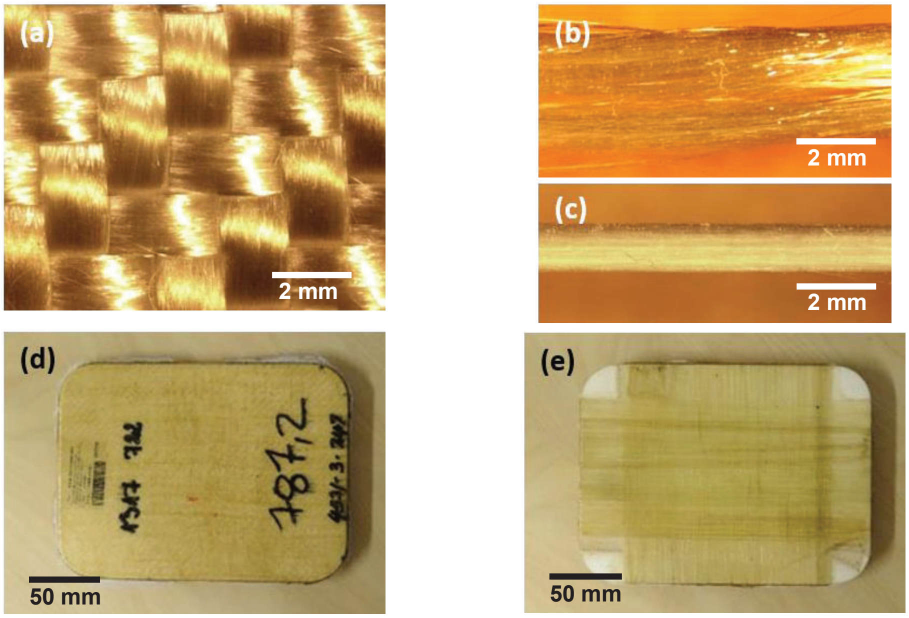

Figure 5. Microscopy images of (a) the commingled glass/PET woven fabric, and (b) un-tensioned and (c) pre-tensioned commingled glass/PET yarn. Targets made of (d) fabric and (e) pre-tensioned yarn.

Table 2. V50 ballistic limit velocity with 90% confidence interval (CI) for targets where the composite cover was applied by different manufacturing methods. Depending on the type of target, the alumina thickness was 7.4 or 7.0 mm. A PC backing with an areal density of 9.6 kg/m3 was bonded at the back of all targets, giving an overall areal density of 38.1 kg/m3. The average residual core mass, mres, of the largest fragment of perforating (CP) shots is also provided. Adapted from Rahbek et al. [21].

Type of composite cover	Areal density of alumina (kg/m3)	Areal density of composite (kg/m3)	V50 (m/s)	90% CI at V50 (m/s)	mres of CP shots just above V50 (g)
Bare alumina	28.5	n/a	586	[574-596]	~3.4
Fabric wrap	27.0	1.5	536	[506-552]	~3.7
Filament-wound yarn	27.0	1.5	622	[608-637]	~2.5

The two production methods gave a very different residual projectile core mass for shots at velocities just above the V50. For the fabric-covered target, the mass was ~3.7 g, while the mass was much lower at ~2.5 g for the filament-wound target. It could be argued that the lower residual mass of the latter target was due to higher impact velocities, giving more tip erosion and higher fragmentation, but the difference existed even at similar impact velocities. Hence, it seemed clear that composite covers produced by filament winding gave higher core fragmentation of perforating bullets.

The only difference between the two composite-covered targets was the application method of the composite resulting in different lay-ups. The filament-wound composite had plies with unidirectional fibres in a 0o/90o lay-up, while the fabric-covered-targets had woven fibres with a certain degree of waviness, Figure 5. The most likely explanation for the higher performance of the filament-wound target was related to the higher degree of fibre orientation and, to some extent, the fibre pre-tension during manufacture. It is known that fibre waviness can reduce the mechanical properties of fibre-reinforced composites [26]. It has also been observed that the energy absorption and V50 of glass fibre-reinforced laminates can be decreased with increasing preload [24]. This suggests that straining of the fibres may be negative for the capability of absorbing projectile energy. On the other hand, due to the high fibre alignment, the unidirectional fibres in the composite cover may be 'activated' and able to take up load more quickly during projectile impact. One hypothesis is that the initiation of radial cracking from tensile forces may then be delayed due to the support on the backside of a ceramic. In addition to the fibre orientation, the pre-stress in the fibres may be also be beneficial since the fibres have already partly been

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strained during the manufacturing process. Overall, these results, together with the study by Jaitlee [23], seem to indicate a potential effect of pre-tensioning of composite sheets in hard armour plates.

5. CONCLUSION

The resistance to perforation of hard armour plates can clearly be increased when the ceramic tile is covered with a sheet layer of a fibre-composite material, at the expense of only small increases in areal density and little additional weight added. Typical failure of the ceramic is the formation of radial cracks and cone cracks, and a composite cover increases the amount of radial cracking and results in smaller fragments inside the cone area. Through-thickness cracks are prevented from opening and the ceramic fragments are confined, hence the integrity of the ceramic after impact is improved.

Front covers are usually added to manage spall ejection. However, one proposed mechanism for the increased ballistic performance is related to the front constraint of the ceramic strike face. The constraint increases the flow of ceramic debris towards the penetrator, and gives more time for penetrator-ceramic interaction since the ceramic is kept in front of the penetrator for a longer period of time. This effect has also been observed for pointed AP projectiles. On the contrary, front covers have also been observed to give no significant effect on projectile erosion or core fragmentation.

There are indications that the target design and manufacturing method may have a significant effect on the ballistic performance. More core fragmentation and higher kinetic energy-loss have been observed when the composite cover is placed on the back of the ceramic. This was explained by increased support and restraint introduced by the back cover, which contributes to a time-delay in the opening of tensile cracks on the back of the ceramic.

Recently, positive effects were observed from composite covers with some added pre-tension or with a high degree of fibre orientation (less waviness). These effects are currently unexplored, but suggest that new designs and manufacturing methods may improve penetration resistance. If these effects can be utilized, hard armour plates with a lower areal density can be produced. It should also be acknowledged that the double-curvature of the ceramic tile makes manufacturing more challenging.

One relevant topic that has not been discussed in this paper is the effect of adhesion between the ceramic and the composite cover. This may also influence on the occurrence of ceramic/composite delamination and the ballistic performance.

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