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Impact behaviour of lightweight armours

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Abstract

Lightweight armours are being increasingly introduced as protective structures against small and medium calibre projectiles, as well as explosive fragments in such different applications like body jackets, helmets, aircraft cockpit seats, military vehicles and ships. Performance of composite armours ceramic/metal and ceramic/composite shows a clear improvement with respect to monolithic metal armours.

The paper illustrates the experimental behaviour of several composite armours under impact of small calibre projectiles. Also, analytical models simulating the experimental behaviour of ceramic/metal and ceramic/composite armours are described, showing the possibilities of such models for helping the designer of protective structures impacted by small and medium calibre projectiles and fragments.

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1 Introduction

Armour design is important to develop more efficient protection systems against the impact of all kind of projectiles. Traditionally armours have been made monolithic, usually of high hardness steel. Although rolled armour steel is still and it will continue to be the most widely used material, the demands of achieving lightweight armours led to the investigation of alternate materials. Such needs arose from the growing interest on improving impact protection of military vehicles, helicopters and persons, whilst reducing the weight of existing armours.

The rise in the importance of lightweight armours has been accompanied by a corresponding increase in their variety. In the last decades, apart from the rolled steel, other metallic and non-metallic materials, such as ceramics and composites, have been incorporated into more efficient lightweight armours. Nowadays composites are widely used to produce lighter helmets and body armours. Ceramics are included to achieve more efficient armours for helicopter seats and automobile armours. Finally, improved designs offer additional protection to existing military vehicles and ships against modern kinetic energy projectiles and fragments.

Combinations ceramic/metal as well as ceramic/composite armours show the highest mass effectiveness compared to monolithic steel armours, with values over 3 against threats ranging from armour piercing rifle bullets up to APDS (armour piercing discarding sabot) projectiles [1]. Although the utilization of ceramics in infantry fighting vehicles is still very scarce, it is expected to develop considerably in the next years.

2 Impact behaviour of composites

Composite materials, constituted by the combination of a high strength fibre into a ductile resin matrix are being used successfully in lightweight armours such as helmets or body jackets competing satisfactorily with monolithic steel armours. The development of new fibres with higher impact resistance, such as the aramid (Kevlar) or polyethylene (Dyneema), has lead to new improvements in lightweight armour designs.

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However, all composites cannot be used efficiently to defeat armour piercing projectiles, its use being restricted therefore to small caliber balls or fragments.

Recently, composites have been included as backing materials in ceramic facing armours to defeat kinetic energy projectiles and its behaviour will be described in the next section. Therefore, in this section, we shall show experimental data of impact behaviour of different composite materials against small caliber balls and fragments.

Tables 1 and 2 show the ballistic limit of kevlar 49 and kevlar 29 and different matrices impacted by a 64 grain fragment simulating projectile (FSP) (mass 4.147 gram) whilst table 3 shows the ballistic limit of kevlar 29/polyester against different small caliber balls. Table 4 summarizes similar results for glass fibre/polyester.

Table 1. Ballistic limit of composites kevlar 49/resine

Fragment	V.	kg/m^2	Resine	%
64 gr.	360	9.28	Vinylester	31.1
64 gr.	352	9.28	Polyester	31.1
64 gr.	347	8.89	Vinylester	32.2
64 gr.	295	8.69	Epoxy	31.7
64 gr.	323	9.28	Vinylester	35.0
64 gr.	341	9.28	Epoxy	22.0
64 gr.	280	9.28	Epoxy	35.0
64 gr.	259	9.28	Epoxy	50.0

Table 2. Ballistic limit of composites kevlar 29/resine

Fragment	V.	kg/m^2	Resine	%
64 gr.	368	8.59	Vinylester	28.6
64 gr.	309	8.50	Epoxy	27.8
64 gr.	427	9.28	Vinylester	22.0
64 gr.	361	9.37	Epoxy	23.1

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Table 3. Ballistic limit of composites kevlar 29/resine

Projectile	V.	kg/m^2	Resine	%
.22	374	3.13	Polyester	27.9
.22	293	2.73	—	—
.22	374	3.40	Polyester	20-28
.38	321	3.13	Polyester	27.9
.38	321	3.02	Polyester	20-28
.38	258	2.70	Polyester	—
9 mm Par.	378	6.25	Polyester	27.9
9 mm Par.	418	7.13	Polyester	21.0
9 mm Par.	371	5.71	Polyester	—
9 mm Par.	371	6.00	Polyester	20-28
9 mm Par.	371	5.70	Polyester	—
.44 Magnum	368	7.86	Polyester	—
.44 Magnum	368	7.90	Polyester	—
.357 Magnum	390	5.62	Polyester	19.8
.357 Magnum	390	5.73	Polyester	20-28
.357 Magnum	357	5.70	Polyester	—

Table 4. Ballistic limit of composites glass fibre/resine

Projectile	V.	kg/m^2	Resine	%
.22	325	5.96	Polyester	25
.22	224	3.33	Polyester	—
.22	325	5.20	Polyester	20-28
.38	194	3.30	Polyester	—
.38	272	6.35	Polyester	25
.38	272	5.60	Polyester	20-28
9 mm Par.	233	6.60	Polyester	—
9 mm Par.	337	10.89	Polyester	25
9 mm Par.	233	6.64	Polyester	—
9 mm Par.	337	9.60	Polyester	20-28
.44 Magnum	311	9.90	Polyester	—
.44 Magnum	311	9.91	Polyester	—
.357 Magnum	315	10.89	Polyester	25
.357 Magnum	315	10.16	Polyester	—
.357 Magnum	264	6.63	Polyester	—

Finally, figure 1 illustrates ballistic limits of composite panels Dyneema SK 66-thermoplastic resin against different FSPs from which an empirical relationship can be derived:

$$E_{abs}/S = AD \times C$$

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where E_{abs} is the kinetic energy of the fragment in Joules
S is the surface area of the strike face of the FSP in mm^2
AD is the area density of the armour in kg/m^2
C is a material constant

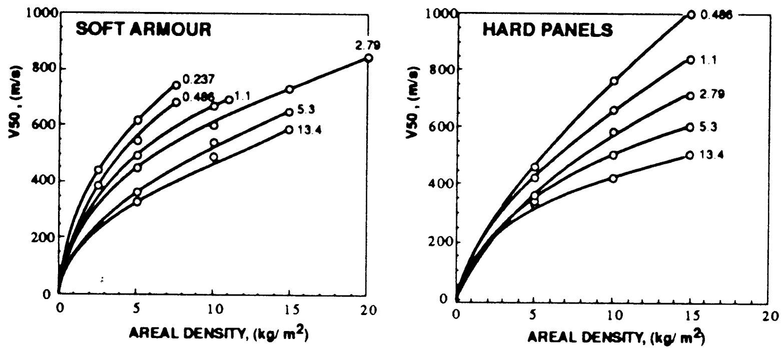

Figure 1

3. Ceramic Faced Armours

Due to their high protection performance, ceramics have been used in all kind of armours, i.e. lightweight, medium and heavy armours. Since the pioneering work of Wilkins et al. [2, 3], who tested ceramic tiles backed by aluminum plates against 7.62 mm projectiles, many researches have been carried out to determine the behaviour and protection provided by many kinds of ceramic materials against different projectiles and fragments. The main properties that are valuable in ceramic materials for armour applications are: low density, high hardness and high rigidity. However, they show a very low toughness, even those ceramics known as tough. Consequently, all ceramic materials fracture when subjected to high tensile stresses, thus they are unsuitable for armour applications unless they are backed with a more ductile material such as a metal or a composite.

Therefore, modern composite armours typically consist of three layers. A front spall liner, a ceramic tile and a ductile backing usually glued to the tile by an adhesive.

Experimental results of high speed impact on ceramic/metal armours are not abundant. As mentioned before, the first research is that of Wilkins [2],

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who analyzed the ballistic limit V_{50} of 7.62 mm diameter projectiles on AD85 alumina tiles backed by 6061-T6 aluminum plates, after which few more data have been published mainly on the empirical behaviour of ceramic/metal armours impacted by small caliber projectiles.

Figure 2 illustrates experimental results obtained by Wilkins, whilst figure 3 shows similar results as published by Mayseless et al. [4] who fired 12.70 mm projectiles against 6.35 mm thick AD-85 alumina tiles backed with different materials.

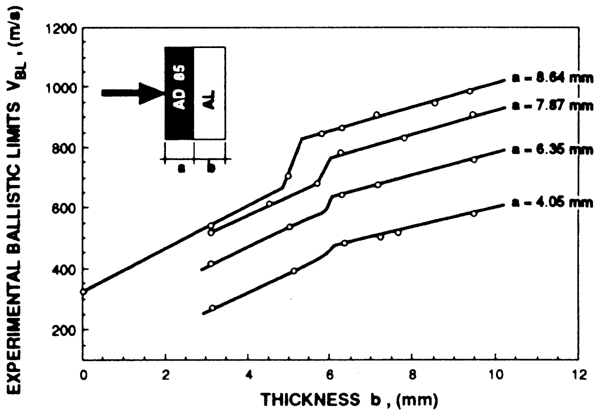

Figure 2

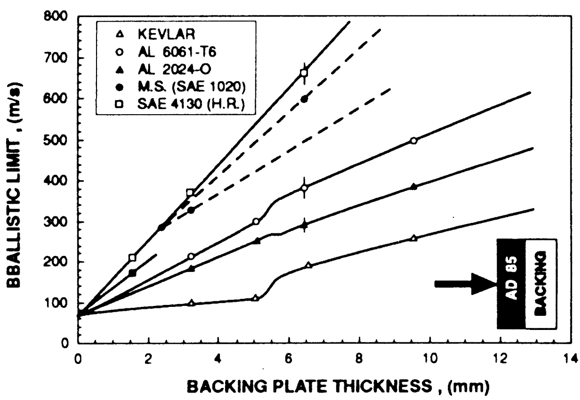

Figure 3

Empirical results published by den Reijer to support his analytical model refer also to 7.62 mm diameter projectiles [5]. See figure 4.

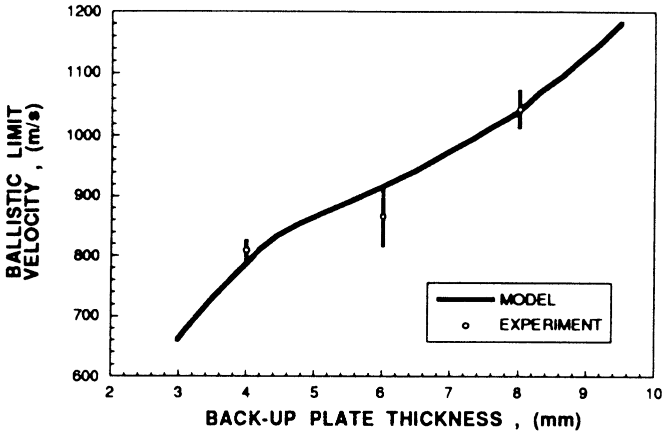

Figure 4

Recently, some experimental results have been published on the behaviour of ceramic/metal armours impacted by 25 mm APDS projectiles [6]. Ceramic facings used are 95% alumina 99.5% alumina and aluminum nitride. Backing metal is 5083 H111 aluminum alloy. Table 5 summarizes the experimental results published.

Table 5.

Armour	Residual length (mm)	Residual veloc. (m/s)	Deflection (mm)
AlN-25 mm + Al-19 mm	28	750	4.5 (50.9 μs) 18.0 (81.2 μs) 28.0 (91.0 μs)
AD95-20 mm + Al-19 mm	42	1100	5.0 (39.5 μs) 12.0 (55.0 μs) 13.0 (75.4 μs)
AD95-25 mm + Al-19 mm	38	1000	14.0 (71 μs) 21.0 (80.9 μs) 37.0 (91 μs)

Experimental data of impact behaviour of ceramic/composite lightweight armours are still scarce. Figure 3 shows ballistic limits obtained by Mayseless

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et al. with AD85 alumina tiles backed with kevlar as fired with 12.70 mm projectiles. Figures 5 and 6 illustrate experimental results recently published of high speed impact behaviour of different ceramic/composite armours developed under the tradename of BRISTOL [7].

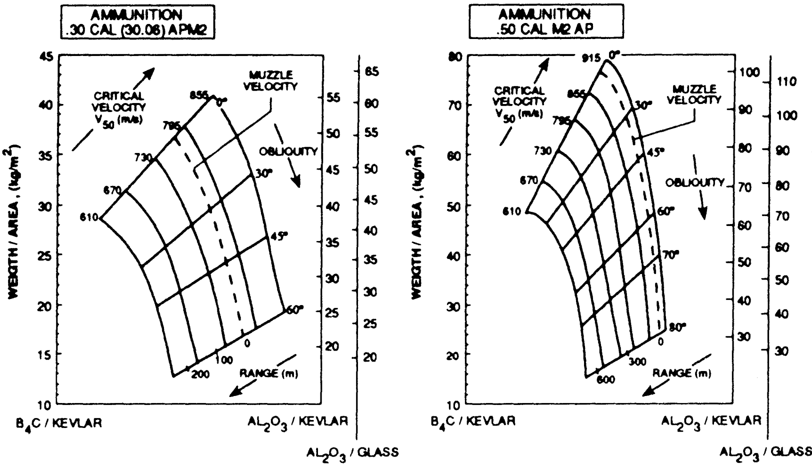

Figure 5

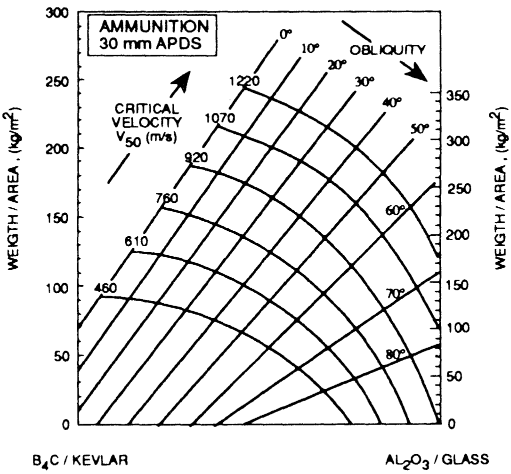

Figure 6

As can be seen, the results offer a valuable information of empirical behaviour of alumina/kevlar, alumina/glass and boron carbide/kevlar against several kinetic energy projectiles.

4. Analytical Models

Traditionally, the design of lightweight armour systems has been carried out based predominantly on experimental ballistic data. However the large number of parameters influencing such an armour's performance make the sole use of traditional experimental data inefficient. The most appropriate approach is a clever combination of experiments and the utilization of analytical models. An analytical model requires only a limited amount of experimental data, yet is able to present the user with details of the penetration process as well as the prediction of residual mass and velocity of the projectile after perforation of the armour.

The majority of analytical models have been developed for simulating projectile impact on metallic plates, for which there are several well established models able to predict quite accurately the armour response. However, analytical models for treating high speed impact on lightweight composite armour are still scarce.

Florence [8], Woodward [9], den Reijer [5] and Sánchez-Gálvez et al. [10] have developed models for the impact on ceramic tiles backed by metallic plates. In Florence's model, the ballistic limit is assumed to be given by the simple expression,

$$V_p = \left(\frac{\varepsilon_c\ S}{0.91\ M_p f(a)}\right)^{1/2}$$

where	ε_c	is the breaking strain of the backing plate
	S	is $\sigma_c\ h_2$
	σ_c	is the breaking stress of the back plate
	h_1 and h_2	are front plate and back plate thicknesses
	M_p	is the mass of the projectile

and

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$$f(a) = \frac{M_p}{(M_p + (h_1 d_1 + h_2 d_2)A)\ A}$$

where d_1 and d_2 are front and back densities

$A = \pi a^2$

$a = a_p + 2h_1$

a_p is projectile radius

On the other hand Woodward and den Reijer's models are more elaborated, although more accurate ones, as can be seen in figure 7 taken from den Reijer's thesis, where a comparison is made on the prediction of the above mentioned models and experimental results of Wilkins.

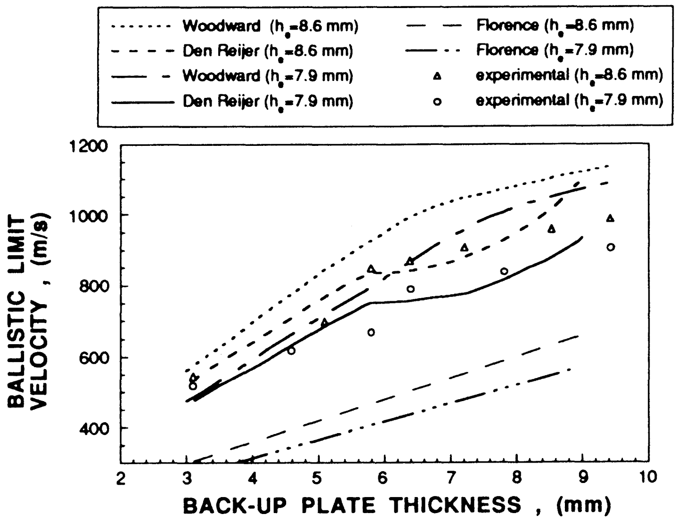

Figure 7

As can be seen, Woodward and den Reijer's models are closer to experimental data of ballistic limit of 7.62 mm AP projectiles simulators than Florence's model. Finally, Sánchez-Gálvez's model has been developed to simulate with better accuracy the experimental behaviour of ceramic/metal armours impacted by medium caliber projectiles (12,70 AP, 20 mm APDS, 25

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mm APDS). Table 6 summarizes some results and shows a good agreement between theoretical predictions and experimental results.

Table 6.

20 APDS against AD95

thickness AD95 (mm)	thickness Al (mm)	Experim. Results Lres (mm)	Experim. Results Vres (m/s)	Analytical Results Lres (mm)	Analytical Results Vres (m/s)
12	16	29-30	1034-1078	29.7	1072
18	16	27-28	963-983	27.1	1010
20	10	25	990	26.8	1030
20	15	25	930-977	26.4	996
25	12	28	923	24.8	945
25	14	22	918	24.6	939
25	16	22	1099	24.4	923

20 APDS against AD99.5

thickness AD99.5 (mm)	thickness Al (mm)	Experim. Results Lres (mm)	Experim. Results Vres (m/s)	Analytical Results Lres (mm)	Analytical Results Vres (m/s)
20	10	22	924-967	24.4	1043
20	15	24-27	930-958	23.3	1002
25	10	25	960	22.3	992
25	12	17	873	21.9	975
25	15	24	939	21.2	948

20 APDS against AlN

thickness A1N (mm)	thickness Al (mm)	Experim. Results Lres (mm)	Experim. Results Vres (m/s)	Analytical Results Lres (mm)	Analytical Results Vres (m/s)
25	10	–	944	17.8	967
25	14	11	686	16.9	932
25	16	16	832	16.5	914

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